Sustainability assessment of electric mobility scenarios with a life cycle perspective

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PSL UNIVERSITÉ PARIS

THÈSE DE DOCTORAT

DE L'UNIVERSITÉ PSL

Préparée à MINES ParisTech

Sustainability Assessment of Electric Mobility Scenarios with a Life Cycle Perspective

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Analyse de durabilité de scénarios de mobilité électrique avec une perspective de cycle de vie

Soutenue par

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Le 13 décembre 2021

Ecole doctorale n° 621

Ingénierie des Systèmes, Matériaux, Mécanique, Energétique

Spécialité

Energétique et Procédés

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Remerciements

L'expérience de cette thèse est pour moi comparable à un long voyage en mer. D'abord, par toutes les émotions traversées de peur et de colère comme un voilier aux jours de tempête, mais aussi par les émotions de joie, de fierté et de soulagement graduels jusqu'à l'arrivée à destination. Au long de cette aventure, des personnes formidables m'ont accompagné pour rendre ce projet le plus riche intellectuellement et le plus agréable qu'il le puisse être personnellement et professionnellement. Ainsi, je ne saurais être comblée sans les remerciements et la reconnaissance que je leur doive.

Je commence par exprimer la plus grande gratitude à mes encadrantes. Je remercie Prof. Isabelle Blanc, ma directrice de thèse, qui a su apporter et transmettre tout son recul scientifique et son expertise de chercheure et coach pour que cette thèse soit mon expérience la plus enrichissante et constructive. Je remercie Dr. Paula Pérez-Lopez, mon maître de thèse, pour l'engagement et l'investissement qu'elle a porté durant ces trois ans à ce projet. Merci à toutes les deux de m'avoir donné la place pour grandir autant que je le veuille.

J'adresse mes sincères remerciements aux membres du jury, rapporteurs et examinateurs. Merci pour le temps consacré à l'examen de ce manuscrit de thèse et l'intérêt exprimé pour les travaux réalisés. J'ai été honorée des retours constructifs et admirables des rapporteurs Prof. Bernard Yannou et Prof. Marzia Traverso, mais aussi de la qualité scientifique de la discussion lors de la soutenance où Prof. Matthias Finkbeiner, Dr. Alessandra Zamagni et Prof. Dominique Millet ont également pris part.

Je tiens aussi à remercier Laurent Gagnepain de l'ADEME qui a contribué à l'évaluation de l'avancement de ces travaux de thèse durant les trois ans ainsi que toutes les personnes de l'ADEME, pour leurs retours et échanges au cours de la thèse, Maxime Pasquier notamment. Je remercie également Philippe Blanc pour l'intérêt continu qu'il a porté à ces travaux et le suivi par l'évaluation et la relecture des rapports annuels et du manuscrit.

Le Centre O.I.E, où j'ai fait ma thèse, regroupe des merveilleuses personnes avec beaucoup de bienveillance, d'humour, de conseil et de soutien, chacun m'ayant marqué de sa manière, je voudrais toutes les remercier : Thierry, Lionel, Philippe, Isabelle, Paula, Yves-Marie, Sandra, Benoît G, Raphaël, Romain, Joris, Benoît T, Fuqiang, Mélodie, Manel, Hadrien, Mélanie, Jérémie, Rodrigo, Sara, Xuamei, Alejandra, Mahefa.

Philippe et Lionel, merci pour votre écoute et les discussions en or qui ont accompagné nos cafés. Philippe, merci pour les opportunités d'enseignement qui étaient toutes exceptionnelles ! Thierry, merci pour ta bienveillance continue. Sandra, merci pour tout. Les meilleurs informaticiens Raphaël et Benoît G., merci pour votre aide, vraiment beaucoup ! Manel, merci d'avoir pris soin de moi aux moments les plus faibles de la rédaction. Mélanie, merci pour tes très bons conseils. Dr. Besseau, le grand frère de mon aventure, merci de m'avoir accompagné lors de mes premiers pas (sur python) et aux moments les plus hauts et les plus bas, littéralement, en montagne avec les plus belles vues de l'Esterel ou du Mercantour et en mer avec parfois des poissons mordeurs. Benoît T., merci pour ton écoute continue, les balades au bord de mer et les mauvais raccourcis de randos qui nous ont permis de passer de très bons moments. Je remercie aussi les futurs docteurs Joris, Fuqiang et Jérémie pour tous les moments que nous avons partagé et la qualité des échanges que nous avons eue.

Mes parents à qui je dédies cette thèse car elle n'aurait pu s'accomplir sans vous, votre confiance et votre soutien inconditionnel et permanent. Merci pour tout, Je suis très fière de vous avoir près de moi. Un grand merci à mes deux petits frères Marouane et Adam et toute ma famille qui m'ont sans cesse encouragé, je vous aime beaucoup ! Merci Hélène pour votre énergie continue, pour les meilleurs smoothies que j'ai jamais goûtés et pour les petites balades qui rafraîchissent les idées.

A tous mes chers ami-e-s, Najima, Audrey, Gaëtan, Sara, Afou, Scarlett, Anas, Hatim, Mehdi, un grand merci. Enfin, cher Hamza, de très près, tu as vécu cette expérience de thèse avec moi. Et, jour après jour, tu as connu les contraintes les plus simples et les plus ardues que j'avais à résoudre. Merci alors, pour tous ces moments d'incertitudes où tu as su me donner la force, et pour ces moments de joie où tu étais parmi les premiers à les célébrer avec moi. Au-delà du soutien moral, merci pour les relectures infinies que tu aies fait jusqu'à connaître par cœur mon sujet de thèse (ou presque).

Résumé étendu Français

Le transport fut depuis jadis un pont entre les civilisations et leur développement. Il a été le rouage du progrès industriel et le moteur du développement économique. La place du transport dans notre société moderne continue à être primordiale pour assurer la mobilité géographique de la main d'œuvre et de la marchandise. Devant des besoins croissants de mobilité et des villes de plus en plus urbanisées, les systèmes de transport vont jusqu'à façonner les modes de vie des individus et les modes de production et de consommation.

Le transport est devenu ainsi un pilier majeur pour le développement socio-économique. Cela se manifeste notamment à travers la création d'emplois et le développement des infrastructures et routes. En outre, le développement de nombreux autres secteurs repose sur sa capacité à acheminer les matières premières et les produits finis. Or, le transport est aussi une source majeure d'impacts qui menacent l'environnement et la société dans son ensemble. Les systèmes de transport actuels, ayant recours aux ressources fossiles comme principale source d'énergie, ont conduit à l'accentuation des problèmes environnementaux. Ceux-ci se traduisent par la détérioration de la qualité des écosystèmes, de la biodiversité et de la qualité de l'air local, mais aussi par l'épuisement des ressources naturelles et le changement climatique. Ce dernier nécessite aujourd'hui la mise en place d'un ensemble d'actions d'atténuation et d'adaptation face à des scénarios climatiques prospectifs de plus en plus pessimistes.

Afin de relever ces défis, les acteurs de la société (industriels, publics, et ceux de la société civile) se mobilisent vers une transition énergétique qui touche tous les secteurs, et celui du transport en particulier. Une telle transition requiert, non seulement, de renoncer aux systèmes actuels de transport basés sur les énergies fossiles, mais aussi de se tourner vers des modèles de mobilité plus durables. En effet, afin d'assurer « la durabilité » des systèmes de transport, il est nécessaire de tenir compte des trois dimensions inhérentes au développement durable en évaluant les impacts (positifs et négatifs) environnementaux, sociaux et économiques. A cet égard, la mobilité électrique s'annonce comme une solution technologique prometteuse qui pourrait relayer les technologies conventionnelles de transport à plus ou moins grande échelle.

En effet, les véhicules électriques offrent la possibilité de réduire l'empreinte carbone du transport à condition d'utiliser un mix électrique bas carbone. Cependant, la durabilité ne pouvant pas être réduite à un seul indicateur environnemental, elle demeure méconnue et nécessite davantage d'être investiguée. Une première question identifiée par ces travaux de recherche dans cette thèse est donc :

Dans quelle mesure la mobilité électrique peut-elle contribuer à des modèles de mobilité plus durable tout en répondant aux besoins quotidiens des utilisateurs ?

Depuis quelques années, les ventes de véhicules électriques ont explosé au niveau du marché français. Promues par le gouvernement, d'un côté, à travers des primes de conversion et de bonus écologiques, et de l'autre avec la taxation du carburant. Ainsi les technologies électriques se sont de plus en plus démocratisées. Ces actions favorisent un déploiement massif de ces alternatives focalisé principalement sur un usage individuel du transport. Il est à noter que depuis l'avènement de l'ère pétrolière, le recours aux voitures particulières s'est ancré dans les habitudes de déplacements en ville. Un lien direct s'est ainsi créé entre la possession du véhicule et le sentiment d'autonomie et de liberté. En conséquence, le transport individuel des personnes, ne cessant d'augmenter, constitue aujourd'hui 80% du nombre total des kilomètres parcourus en 2020 en France, et est responsable de plus de 51% des émissions totales de CO_2 associées au transport[1]. En contraste, les transports collectifs sont de plus en plus délaissés et les infrastructures, notamment ferroviaires, sont stagnantes voire décroissantes.

En France, la mutation vers la mobilité électrique est soutenue par un cadre réglementaire précis, instauré dans l'objectif de réduire les émissions de Gaz à Effet de Serre (GES) et d'atteindre la neutralité carbone en 2050[2]. Depuis la loi de la transition énergétique, annoncée en 2014, la Stratégie Nationale Bas Carbone (SNBC) a suivi en 2015, puis la « Loi Orientation de Mobilité » (LOM) en 2018[3]. Ces mesures réglementaires ont également été accompagnées par le développement de scénarios prospectifs. Ils soulignent l'importance de considérer le report modal comme étant un des facteurs clés pour adopter un modèle de mobilité plus durable. Les modes de déplacement de personnes se ramifient de plus en plus entre des possibilités de covoiturage ou de partage d'usage. Ces solutions de mobilité partagée sont davantage facilitées par la transition numérique en cours. Celles-ci passent par des plateformes numériques pour proposer aux utilisateurs finaux une combinaison de différentes configurations de mobilité (e.g., technologies et services) afin de répondre à leurs besoins et attentes individuels. L'émergence de ces nouvelles formes de mobilité suit un rythme accéléré dépassant parfois nos connaissances sur les impacts environnementaux, sociaux et économiques qui leurs sont associés. Ce caractère, équivoque en termes de durabilité, que peuvent porter ces options innovantes du transport pourrait ralentir voire bloquer leur développement.

[1] CGDD. (2021). *Chiffres clés du transport—Edition 2021* (p. 92). Commissariat Général au Développement Durable, Ministère de la transition écologique.

[2] MTES. (2020). *La transition écologique et solidaire vers la neutralité carbone* (p. 192). Ministère de la Transition écologique et solidaire.

[3] LOI n° 2019-1428 du 24 décembre 2019 d'orientation des mobilités (1), 2019-1428 (2019).

Il est à cet égard primordial d'éclairer les décisions publiques et privées afin de gérer au mieux cette période de transition. Cela passe par l'évaluation des technologies de transport électriques et des services de mobilité, ainsi que leurs synergies. Les différentes parties prenantes impliquées dans les schémas décisionnels de la mobilité durable, ainsi que les liens entre elles, doivent être définis et examinés. Pour ces raisons, des méthodes d'évaluation robustes sont nécessaires pour l'identification, la caractérisation et l'analyse des impacts des systèmes de transport. Les méthodes d'Analyse de Cycle de Vie (ACV) sont largement reconnues pour leur capacité à évaluer les impacts environnementaux potentiels des produits et services tout au long du cycle de vie, i.e., allant de l'extraction de matières premières jusqu'à la fin de vie. L'intérêt porté à ces méthodes et la nécessité d'évaluer les trois dimensions du développement durable ont ainsi créé un terrain propice pour la naissance de l'Analyse de Durabilité de Cycle de Vie (ADCV). Bien qu'elle soit à un stade précoce de développement méthodologique, l'ADCV attire de plus en plus l'attention des industriels et autorités publiques, grâce à sa vision étendue sur les trois dimensions de durabilité et sa perspective de cycle de vie.

L'ADCV repose sur trois approches : l'Analyse de Cycle de Vie environnementale (ACV), l'Analyse Sociale de Cycle de Vie (ASCV) et l'Analyse de Coûts de Cycle de Vie (ACCV). Ces approches se sont développées dans des contextes temporels différents et se caractérisent donc par des niveaux de maturité différents. Ainsi, leur appréhension dans un cadre méthodologique global est freinée par un manque de cohérence au niveau des approches d'évaluation. En effet, l'ACV environnementale a gagné beaucoup en maturité et aujourd'hui s'appuie sur un cadre méthodologique normalisé par l'ISO 14040-44. En revanche, un manque de consensus marque l'avancement méthodologique de l'ASCV qui aujourd'hui doit relever plusieurs défis quant à son implémentation pour évaluer les impacts sociaux et socio-économiques des produits et services. L'ACCV s'intéressant aux coûts des produits et systèmes, fait appel à d'autres référentiels quant à sa conceptualisation dans un cadre méthodologique global pour l'ADCV.

Les travaux de recherche de cette thèse portent l'ambition de développer un cadre méthodologique cohérent et systémique pour l'évaluation de la durabilité reposant sur l'ADCV. De plus, ces travaux de thèse explorent comment les résultats de l'ADCV peuvent soutenir et contribuer à la prise de décision des acteurs publics et privés en intégrant les perceptions des utilisateurs. Ainsi, ces travaux de travaux de thèse étudient comment aider les décideurs à mieux adapter leurs offres de mobilité aux besoins et attentes des usagers lors du développement d'alternatives de mobilité durable. Pour atteindre cet objectif, deux questions de recherche ont été posées :

Première question de recherche (QR1) :

Comment les impacts environnementaux, sociétaux et économiques peuvent-ils être intégrés dans un cadre méthodologique global pour évaluer la durabilité dans une perspective de cycle de vie et en particulier celle liée à la mobilité ?

Deuxième question de recherche (QR2) :

Comment les résultats des ADCV peuvent-ils soutenir le processus de prise de décision par les décideurs dans le contexte de la mobilité électrique en tenant compte des perspectives des utilisateurs ?

Pour répondre à ces deux questions de recherche, la démarche de cette thèse consiste à proposer (1) **des lignes directrices pour mener une ADCV**, compte-tenu des trois dimensions de la durabilité, et (2) **un cadre méthodologique complet pour évaluer des scénarios de mobilité électrique en incluant à la fois les technologies et les services de transport**. Afin d'apporter des connaissances pertinentes sur la durabilité aux décideurs, l'analyse multicritère d'aide à la décision est introduite pour gérer les compromis émergents des résultats de l'ADCV tout en tenant compte des perspectives des utilisateurs. Cette proposition devrait faciliter la liaison entre les autorités publiques et les acteurs industriels qui sont impliqués dans le processus de prise de décision en leur fournissant des informations scientifiques sur les aspects de durabilité associés aux perspectives des utilisateurs. Ainsi la mobilité électrique est évaluée à travers différents scénarios qui permettent de comparer les différentes alternatives de mobilité y compris les modes de transport et les technologies existantes, électriques et thermiques. **La première question de recherche (QR1)** vise à conceptualiser **un cadre méthodologique pour l'ADCV en intégrant les trois piliers de la durabilité**. Pour atteindre cet objectif, plusieurs défis ont été identifiés. L'appréhension des trois approches dans un cadre méthodologique structuré et cohérent a été peu abordée car la plupart des publications tendent à se concentrer sur des cas d'études spécifiques sans pour autant répondre aux problématiques méthodologiques. En réponse à cela, cette thèse constitue un soutien majeur à la recherche dans ce domaine et fournit un aperçu des différentes voies à explorer pour développer une méthodologie plus robuste. Des lignes directrices sont proposées en définissant les éléments clés associés à chaque phase de l'ADCV, conformément aux normes ISO de l'ACV environnementale.

Les principaux défis soulevés par la revue de littérature sont soumis à une réflexion afin d'identifier des pistes d'amélioration. **La première problématique mise en évidence consiste à assurer une définition claire de l'objectif et du champ de l'étude** (première phase de l'ADCV) afin d'atteindre la cohérence entre les trois approches d'ACV environnementale, d'ASCV et d'ACCV. Cela comprend la définition de l'unité fonctionnelle, des limites du système et des catégories d'impact à évaluer. Les scénarios de mobilité évalués ont été définis selon quatre éléments, à savoir les technologies de transport, les types de service de mobilité, les infrastructures de transport et l'énergie utilisée par le véhicule. Ainsi trois scénarios ont été identifiés et analysés :

- **Scénario 1 :** mobilité personnelle qui repose sur l'utilisation individuelle de voitures particulières comprenant cinq groupes motopropulseurs électriques et conventionnels différents.
- **Scénario 2 :** transport partagé, consiste en un transport par autobus comprenant quatre groupes motopropulseurs conventionnels et électriques.
- **Scénario 3 :** mobilité partagée, qui consiste en une utilisation de covoiturage comprenant cinq groupes motopropulseurs électriques et conventionnels différents.

De plus, l'implication des parties prenantes est investiguée à travers une vision qui s'étend de l'évaluation à la prise de décision. En effet, la revue de littérature a révélé une lacune importante dans l'intégration des besoins et les attentes des usagers, ce qui s'avère essentiel pour assurer leur acceptation des stratégies de mobilité actuelles et futures proposées par les décideurs. Ce besoin a également été identifié dans la phase d'évaluation de l'impact, en particulier dans l'ASCV, où les sous-catégories d'impact relatives aux utilisateurs ont été peu évaluées dans les travaux précédents. Ainsi, l'introduction de la perception des usagers est une brique importante et nouvelle qu'ajoute la thèse à la définition des objectifs et du champ de l'étude. Cette nouveauté consiste à identifier les acteurs qui sont concernés par le schéma décisionnel de la mobilité : les principaux acteurs impliqués dans la prise de décision et également ceux qui sont affectés par ces décisions. Ce raisonnement a permis d'identifier trois acteurs clés qui sont directement impliqués dans une transition vers une mobilité plus durable :

- **Les acteurs publics** qui définissent les actions à mener pour répondre aux exigences de la loi sur la transition énergétique dans le secteur des transports (par exemple, les autorités locales) et qui guident les autorités locales dans la mise en œuvre des plans d'action et des réglementations en matière de durabilité.
- **Les acteurs privés** qui mettent sur le marché les technologies nécessaires à la fourniture du service de transport et qui développent l'infrastructure nécessaire (infrastructure, carburant et distribution d'électricité).
- **Les usagers** qui choisissent parmi les technologies et les services de mobilité ceux qui répondent à leurs besoins spécifiques de déplacement. **Ils ne sont pas des décideurs mais sont directement affectés par les schémas de décision en matière de mobilité.**

Cette définition permet d'orienter le développement du cadre méthodologique de l'ADCV et son application dans un but précis, à savoir – dans le cas présent– soutenir les décideurs publics et privés vers une mobilité durable en intégrant la perception des usagers.

La deuxième problématique concerne la phase d'évaluation des impacts (troisième phase de l'ADCV). Deux voies méthodologiques pour l'évaluation des impacts ont été identifiées et explorées. La voie 1 vise à évaluer de manière combinée pour les trois dimensions de durabilité à travers la définition des modèles de caractérisation spécifiques à chaque dimension. Bien qu'elle puisse être favorable pour assurer la cohérence du cadre méthodologique de l'ADCV, cette voie pose des obstacles majeurs en raison de la nécessité d'acquérir davantage de connaissances sur les dimensions sociales et économiques. En effet, le stade de développement actuel de l'ASCV et l'ACCV ne permet pas de couvrir un niveau de détail similaire à celui de l'ACV environnementale. Cette limitation est notamment liée à la complexité de la modélisation par l'intermédiaire de flux quantitatifs les effets à long-terme des changements sociaux et socio-économiques subis par les différentes parties prenantes affectées. En outre, la pertinence de ces modèles quantitatifs est remise en question en raison des limitations qui peuvent survenir pour traiter tous les impacts significatifs et toutes les catégories de parties prenantes. À cet égard, une deuxième voie a été explorée et adoptée dans cette thèse pour concevoir le cadre méthodologique de l'ADCV en faisant appel à une application individuelle des approches d'évaluation d'impact. Cette voie permet de tenir compte de la nature hétérogène de chaque dimension de durabilité en choisissant des approches d'évaluation compatibles entre les impacts environnementaux, sociaux et économiques. Par ailleurs, la mise en œuvre séparée des approches d'évaluation – d'ACV environnementale, d'ASCV et d'ACCV – a permis de répondre à certaines problématiques de manière ciblée et ainsi de contribuer aux avancées méthodologiques pour chacune d'entre elles. Ainsi, les trois scénarios retenus – mobilité personnelle, collective et partagée – sont évalués et comparés à l'échelle de chaque dimension de durabilité.

Pour l'implémentation de ce nouveau cadre méthodologique, l'évaluation a été menée dans un contexte français permettant ainsi de centrer la collecte des données sur le territoire national, y compris donc pour le mix électrique, les infrastructures, les coûts d'achat de véhicules, etc. Ces données nationales ont été complétées par une collecte de données plus ciblée sur le territoire de la Communauté d'Agglomération de Sophia Antipolis (CASA), siège du terrain d'études sélectionné en vue de son potentiel à expérimenter de nouvelles formes de mobilité durable et les problématiques de déplacement individuel qu'il pose. En effet, l'évaluation des impacts sociaux et socio-économiques requiert l'utilisation de données spécifiques aux politiques locales permettant ainsi d'obtenir des résultats plus représentatifs. Cette approche est applicable aussi à l'évaluation des coûts économiques associés aux services de mobilité dont le coût supporté par l'utilisateur dépend avant tout de la politique locale. Elle permet, par exemple, de tenir compte des mesures mises en œuvre pour la promotion de modes de déplacement alternatifs tels que la mobilité partagée ou de transport collectif.

La dimension environnementale : méthode d'évaluation par ACV paramétrée et résultats d'application aux scénarios de mobilité

D'après la revue de littérature, les catégories d'impacts environnementaux, le plus souvent analysées dans les études d'ACV, ont été identifiées, à savoir le changement climatique, la qualité de l'air, l'épuisement des ressources. D'autres catégories d'impacts ont également été relevées comme importantes, notamment les nuisances sonores malgré un manque de développement de modèles de caractérisation permettant leur intégration systématique dans l'ACV. De plus, une analyse par étape de cycle de vie des systèmes de transport (e.g., fabrication, usage et fin de vie) a permis de définir les principaux flux et paramètres qui sont à investiguer. Cette revue de littérature a été complétée par une analyse des inventaires de cycle de vie existants sur la base de données ecoinvent. Celle-ci a permis d'identifier les paramètres clés pouvant exercer une influence directe sur les résultats de l'évaluation. Ils ont été retenus pour la modélisation du cycle de vie des trois scénarios de mobilité. Ces paramètres sont notamment la masse totale des véhicules, la masse de la batterie, le nombre de kilomètres parcourus, les cycles de conduites, l'énergie consommée et le flux de carburant ou encore d'électricité utilisés pour l'alimentation du véhicule, etc.

Une démarche méthodologique a donc été formalisée pour générer des modèles paramétrés d'ACV. Elle a permis de réaliser l'évaluation environnementale des trois scénarios de mobilité en menant une analyse systématique des impacts selon les paramètres influents identifiés. Cette approche couvre les étapes nécessaires à l'intégration de modèles d'inventaires de cycle de vie paramétrés à l'évaluation des impacts. La représentativité des données utilisées peut ainsi être améliorée en incluant les multiples spécificités et avancées technologiques qui peuvent survenir au fil du temps. Ces modèles paramétrés ont été utilisés en ajustant les valeurs de paramètres d'entrée clés identifiés spécifiques aux scénarios de mobilité et au champ de l'étude définis dans cette thèse. L'interprétation des résultats pour les catégories d'impacts environnementaux n'a pas permis de distinguer une technologie de véhicule quant à la performance environnementale. En effet, les différentes motorisations ont démontré une grande variabilité des résultats :

- Les véhicules 100% électriques ont présenté la plus faible contribution au changement climatique en comparaison avec les véhicules électriques hybrides et les véhicules conventionnels. Ceci s'explique principalement avec l'utilisation du mix électrique français bas-carbone, dominé par l'utilisation de l'énergie nucléaire.
- En revanche, des impacts environnementaux plus élevés ont été enregistrés par les véhicules 100% électriques par rapport à leurs homologues conventionnels pour l'épuisement des ressources (e.g., l'utilisation des ressources en eau et en métaux) et la qualité des écosystèmes (e.g., les rayonnements ionisants, l'écotoxicité en eau douce et l'eutrophisation

marine). Ces impacts dérivent en grande partie de la production des batteries électriques, qui entraîne des incidences plus significatives dans le cas des véhicules 100% électriques que dans celui des véhicules électriques hybrides rechargeables.

- Les transports publics ont montré une meilleure performance environnementale que la mobilité personnelle et partagée ; notamment les technologies hybrides électriques qui peuvent être un levier pour réduire l'empreinte environnementale des transports et améliorer la qualité de l'air local dans les zones urbaines denses.

La dimension sociale : un nouveau cadre méthodologique d'analyse des impacts sociaux par ASCV et les résultats de son application aux scénarios de mobilité

La présente thèse contribue aux avancées méthodologiques de l'ASCV en se concentrant sur l'amélioration de chacune des phases de la méthode. À cette fin, une revue de littérature a permis d'identifier les limites actuelles des études d'ASCV pour la mobilité et les principales contraintes méthodologiques à résoudre. Celles-ci se manifestent notamment dans :

- La définition des sous-catégories d'impact à analyser dans les études d'ASCV, souvent floue, et nécessitant indirectement à une étape de sélection. La plupart des études précédentes utilisent la revue de littérature comme unique moyen pour effectuer cette sélection et manquent souvent de transparence. En revanche, les approches participatives impliquant les différentes parties prenantes ont rarement été introduites, malgré leur potentiel à légitimer un tel processus.
- L'évaluation des impacts sociaux et socio-économiques, rarement menée pour les parties prenantes « utilisateurs ». Ceci s'explique d'un côté par le manque de données et de leur accessibilité, et de l'autre par la complexité qui peut survenir lors de la modélisation des systèmes évalués et la réalisation d'une analyse d'impact spécifique.

En réponse à ces deux difficultés, un cadre méthodologique spécifique à la conduite de l'Analyse de Cycle de Vie Sociale (ASCV) est proposé dans cette thèse, en accord avec les normes ISO 14040. Ce nouveau cadre méthodologique intègre deux nouvelles étapes visant à pallier les limites rencontrées dans la sélection des sous-catégories d'impact et à contribuer aux avancées méthodologiques de l'ASCV. Ainsi, des lignes directrices et recommandations sont proposées pour chacune des phases itératives de l'ASCV tout en expliquant comment intégrer les deux nouvelles briques proposées -(1) *une approche participative pour l'identification et la priorisation des sous-catégories d'impacts* et (2) une *analyse spécifique en tenant compte des impacts sur les usagers des systèmes de transport*- et comment les adapter à d'autres systèmes de produits et secteurs.

(1) Une approche participative pour la sélection des sous-catégories d'impact pertinentes au sein de S-LCA (Bouillass et al. 2021)[4].

L'approche participative proposée comporte deux étapes : (1) l'étape d'identification, permettant de définir des sous-catégories d'impacts en analysant les risques sociaux sur le secteur investigué et pour chaque groupe de parties prenantes tout au long du cycle de vie du produit, et (2) un processus de consultation multi-acteur conçu pour permettre de hiérarchiser les sous-catégories d'impact identifiées et de sélectionner ainsi les plus pertinentes du point de vue de toutes les parties prenantes concernées. Les sous-catégories d'impact social sélectionnées sont ensuite évaluées lors de la phase III d'évaluation d'impacts sociaux permettant ainsi, de contribuer à une analyse complète dans la phase d'interprétation. Ce travail est publié dans un revue scientifique internationale « International Journal of Life Cycle Assessment ».

L'étape 1 de l'approche participative a permis de définir cinq nouvelles sous-catégories d'impacts qui ne sont pas incluses dans les lignes directrices de l'ASCV[5]. Celles-ci décrivent pour les usagers des systèmes de transport quels seraient les impacts sociaux et socio-économiques potentiels associés à **la sécurité** (accidentalité routière et agressions), **la performance du système de communication** (qualité des systèmes d'information des usagers, la transparence sur la performance environnementale et sociale, la protection des données personnelles), **la disponibilité et interopérabilité des infrastructures**, **la santé et le confort**, **l'accessibilité économique**. Ces sous-catégories d'impacts ont donc été ajoutées à la liste proposée par les lignes directrices de l'ASCV et soumises à l'étape 2 afin de les hiérarchiser.

Une enquête a été menée auprès de différents acteurs de la société (acteurs publics, académiques, industriels, syndicats de travailleurs, usagers de transport) en accord avec le processus de consultation qui a été conçu. Ce dernier a permis ainsi d'interroger ces acteurs identifiés de leur perception vis-à-vis de l'importance de considérer certaines sous-catégories d'impacts pouvant affecter cinq grandes parties prenantes (les travailleurs, les utilisateurs, les acteurs de la chaîne de valeur, la société et les communautés locales). Un échantillon de 67 acteurs a été constitué des différentes catégories d'acteurs. Ces derniers étaient consultés à travers trois questionnaires en ligne différents, adaptés en fonction du type d'acteur consulté, et complétés par des entretiens individuels permettant de comprendre la réflexion et les motivations derrières leurs choix. Les résultats de cette enquête ont alimenté une analyse comparant l'importance perçue pour les catégories d'impacts en termes des : (i) différences entre le

[4] Bouillass, G., Blanc, I. & Perez-Lopez, P. Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. *Int J Life Cycle Assess* **26,** 2408–2435 (2021). https://doi.org/10.1007/s11367-021-01988-w

[5] UNEP (2020), *Guidelines for Social Life Cycle Assessment of Products and Organizations* (C. Benoît Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A. Lehmann, M. Finkbeiner, & G. Arcesse, Eds.). United Nations Environment Programme (UNEP).

point de vue des acteurs, (ii) types de technologies ; électriques ou conventionnelles, (iii) types de services de mobilité ; partagée, collective et personnelle, et (iv) de la localisation géographique (hors Europe et en France).

Malgré la convergence des perceptions des acteurs sur l'importance de certaines sous-catégories d'impacts (e.g., travail d'enfants pour les travailleurs hors Europe), les résultats démontrent une grande variabilité de perception des acteurs consultés sur d'autres sous-catégories d'impacts. Par exemple, l'importance des sous-catégories d'impacts associées aux utilisateurs diffère en fonction de l'acteur consulté (e.g., industriels vs publics vs usagers), des types de mobilité et de technologies considérées. Les usagers de transport attribuent un niveau d'importance plus élevé à la sécurité, la santé et la transparence dans le cas de la mobilité personnelle, tandis que la sécurité, la disponibilité et l'interopérabilité des infrastructures et leur accessibilité économique sont perçues comme plus importantes dans le cas du transport public. Ceci peut s'expliquer par les intérêts divergents de chacun des acteurs consultés et l'influence du contexte socio-culturel et politique dans la détermination de cette perception. Cette divergence démontre la nature subjective que peuvent porter certaines études se limitant sur l'introduction d'une seule perspective, notamment celles des acteurs privés et industriels. Il est à cet égard nécessaire de justifier dans les études d'ASCV le choix des sous-catégories d'impacts qui sont retenues à l'évaluation. L'utilisation d'une approche participative proposée dans cette thèse peut démocratiser ce processus en impliquant les différents acteurs de la société mais également améliorer la représentativité des résultats obtenus. En revanche, l'application de cette approche peut être complexe en raison de la durée de l'étude, de la taille de l'échantillon nécessaire pour s'assurer de sa représentativité et de la complexité de mener à bien cette consultation auprès de certains acteurs. Il est donc recommandé aux études futures d'explorer davantage ces aspects.

(2) Une analyse spécifique des sous-catégories d'impact liées à l'utilisateur.

La deuxième brique introduite au cadre méthodologique de l'ASCV proposé vise à approfondir la phase d'évaluation. Celle-ci étant habituellement menée par le biais d'une évaluation générique, s'avère être limitée pour analyser tous les impacts sociaux et socio-économiques de manière systématique. A cela s'ajoute le manque de couverture de certaines catégories de parties prenantes notamment les utilisateurs dont la modélisation des systèmes peut être complexe. A cet effet, une analyse spécifique est proposée en complément à l'évaluation des impacts réalisée à travers la base de données pour l'ASCV « PSILCA » [6].

[6] Maister, K., Di Noi, C., Ciroth, A., & Srocka, M. (2020). *Product Social Impact Life Cycle Assessment (PSILCA) Database v.3 Documentation* (Databse Documentation version 1.0; Numéro version 1.0, p. 124).

L'analyse spécifique introduite dans cette thèse repose sur une approche d'évaluation centrée sur les usagers des services de mobilité. Les nouvelles sous-catégories d'impacts sociales définies les usagers sont ainsi évaluées afin de comparer les trois services de mobilité. Pour ce faire, un système d'évaluation est établi couvrant les indicateurs de performance pour chaque sous-catégorie d'impacts, les niveaux de performance et les points de référence de performance nécessaires à l'évaluation. Les données collectées pour la communauté d'agglomération de Sophia Antipolis (CASA) sont utilisées lors de cette étape. Le scénario du transport public a pu démontrer la meilleure performance sociale comparée à la mobilité personnelle notamment sur les aspects liés à l'accidentalité routière, l'accessibilité économique et la transparence environnementale et sociale tandis que pour la mobilité personnelle, le taux élevé des accidents routières dans la région comparé à l'échelle nationale ou le manque d'accessibilité économique des véhicules particuliers sont les principaux facteurs derrières cette performance. Sur le plan technologique, d'après l'évaluation réalisée à travers PSILCA, aucune distinction claire n'a été possible entre la performance sociale des technologies conventionnelles et électriques. A cet égard, pour chacune des sous-catégories d'impacts analysées, une analyse de contribution a été réalisée afin d'identifier les flux des activités responsables des impacts associés à la production des véhicules et le mix énergétique utilisé à l'alimentation du véhicule. Celle-ci a pu montrer que pour les véhicules électriques, la production de la batterie au Japon et l'extraction de matières premières localisée principalement en Chine sont les principales sources d'impacts sociaux. Cela est le cas pour les indicateurs tels que le travail d'enfants ou le travail forcé où les véhicules électriques peuvent présenter un risque social plus important que leurs homologues conventionnels. En revanche, d'autres indicateurs analysés pour la santé et sécurité des travailleurs ont présenté un risque social plus important pour les technologies conventionnelles. Cette observation suit la tendance hausse des indicateurs d'accidents de travail dans le secteur automobile à l'échelle de l'Europe. De manière générale, les résultats de l'évaluation relèvent – comme pour le cas de l'évaluation environnementale – de compromis quant à l'analyse des différents indicateurs sociaux et socio-économiques.

Outre ces deux ajouts méthodologiques, différentes boîtes à outils sont proposées pour aider les praticiens de l'ASCV à généraliser le cadre méthodologique proposé à d'autres filières. Celles-ci permettent de formaliser certaines exigences clés pour la conception du processus de consultation multi-acteur et la réalisation de l'analyse spécifique. Il est cependant important de souligner la difficulté de couvrir la phase d'évaluation de S-LCA avec un niveau de détail similaire à celui de la dimension environnementale, en raison de données manquantes et de la complexité de la modélisation des différents groupes de motorisations. Les recherches futures devraient se focaliser davantage sur le développement des modèles de caractérisation mais aussi des variables activités permettant de modéliser le cycle de vie des systèmes de produit en tenant compte différents groupes de parties. Les impacts sociaux associés aux utilisateurs devraient être davantage couverts par les études d'ASCV en se concentrant sur de nouvelles approches de modélisation d'impacts. Le cadre méthodologique proposé peut être utilisé, adapté et/ou ajusté pour analyser d'autres produits et secteurs en ajoutant de nouvelles sous-catégories d'impacts et de nouveaux groupes de parties prenantes, notamment ceux proposés dans la version la plus récente des lignes directrices l'ASCV (2020).

La dimension économique, une évaluation des coûts des scénarios de mobilité par ACCV

Dans le cadre de l'évaluation économique des scénarios de mobilité électrique, une revue de littérature a été menée afin d'identifier et d'analyser les études d'ACCV appliquées à la mobilité. Cette revue de littérature a pu souligner le large éventail d'études qui ont ciblé l'analyse des coûts de transports, y compris les technologies et les infrastructures, etc. Différentes catégories de coûts ont été distinguées. D'abord, les coûts internes ou directs qui sont supportés par l'organisation pour la production de technologies et la construction des infrastructures (e.g., routes, réseau de transports, etc.), ou des coûts supportés par les utilisateurs tout au long de l'opération du véhicule (e.g., acquisition, alimentation du véhicule par l'électricité ou le carburant, la taxation, les assurances, etc.). Une deuxième catégorie de coûts, dite des coûts externes, représente des coûts supportés par la société dans son ensemble suite aux dommages résultants des systèmes de transport (i.e., coûts associés à la santé publique à cause de la dégradation de la qualité de l'air). Les études ayant été analysées, ont utilisé différentes techniques pour l'analyse des coûts (e.g., analyse des coûts-bénéfices, coût total de possession, etc.). Celles-ci, en fonction de l'objectif de l'étude, adressent certaines phases de cycle de vie, des catégories de coûts particulières et reflètent une perspective d'acteur (organisation, société et usagers). Malgré la richesse des approches dont se confère l'ACCV, plusieurs limitations ont été relevées :

- Bien que l'ACCV ait été standardisée pour un domaine spécifique dans le secteur tertiaire (évaluation des coûts associés au bâtiment), il n'existe pas encore un cadre méthodologique normalisé pour l'ACCV qui serait générique à tout système de produit et secteurs d'activités. Ainsi, les études existantes ne se superposent pas systématiquement aux normes ISO, sauf si elles sont menées simultanément à une ACV environnementale.
- L'évaluation d'impact économique échappe à la majorité des études se concentrant souvent sur le calcul des coûts associés aux systèmes évalués. En effet, un impact économique – comme pour l'impact environnemental ou social – nécessite une modélisation sur une chaîne causale qui permet d'analyser les effets à long terme des changements économiques générés par le système analysé. Cela est d'autant plus critique lorsqu'il s'agit d'une évaluation combinée des impacts environnementaux, sociaux et économiques dans l'ADCV (voie 1), car elle fait appel à des modèles de caractérisation sur les trois dimensions de la durabilité.
- L'application de l'ACCV aux scénarios de mobilité : la plupart des études dans la littérature ont ciblé un niveau technologique, mais aucune étude antérieure n'a utilisé l'ACCV

pour l'analyse des services de mobilité. En outre, la perspective du cycle de vie n'est pas entièrement couverte, la plupart des études ne prenant pas en compte les étapes de fabrication et de fin de vie.

Compte tenu des défis identifiés, les travaux menés dans la thèse fournissent deux résultats principaux :

- ➔ Proposition des phases d'une étude d'ACCV, en accordance avec les normes ISO, en couvrant les éléments clés à définir dans chaque phase. Ces directives proposées aideraient les praticiens d'ACCV à mieux caractériser leurs besoins spécifiques selon l'objectif de leurs études pour permettre ainsi, la sélection de l'approche ACCV appropriée.
- ➔ Introduction d'une approche centrée sur l'utilisateur pour permettre l'évaluation des coûts des trois scénarios de mobilité définis. Cette approche implique l'évaluation des technologies de transport par le biais d'un modèle de coût total de possession (TCO), et des services de mobilité en calculant le rapport coût-efficacité des trois scénarios considérés.

Le TCO a été utilisé dans l'objectif de calculer les coûts supportés directement par les usagers. Cela vient en accord avec l'objectif de cette thèse d'adopter des approches centrées sur les usagers. Les coûts externes sont exclus de l'évaluation afin d'éviter un double comptage des impacts environnementaux et sociaux qui sont déjà évalués dans le cadre de l'ADCV. Les impacts économiques ne sont pas évalués car la présente étude se focalise sur un calcul direct des coûts, aux vues du manque de modèle de caractérisation des impacts économiques et leur complexité.

Le TCO est calculé – comme dans les études précédentes - pour les technologies de véhicules. Dans la présente thèse, cinq technologies de véhicules électriques, hybrides et conventionnelles sont analysées. L'ensemble des étapes de cycle de vie depuis l'acquisition du véhicule jusqu'à sa fin de vie sont prises en compte en couvrant trois grandes catégories de coûts : les coûts d'acquisition (achat et système d'acquisition de la batterie pour les véhicules électriques), les coûts d'opération énergétiques (carburant et/ou électricité) et d'autres coûts d'opération (maintenance, assurance, taxation, etc.).

Le TCO le plus élevé est obtenu pour l'utilisation des véhicules hybrides rechargeables, principalement en raison du coût d'acquisition élevé et des subventions de plus en plus réduites par rapport à celles des technologies 100% électriques à batterie. Les technologies 100% électriques thermiques à moteur diesel présentent le TCO le plus bas parmi les différentes motorisations évaluées. En fait, pour les véhicules 100% électriques, bien que le retour sur investissement soit généralement attendu après 12 ans, les résultats démontrent que dans les 5 ans de possession, le coût est égal à celui de l'utilisation des véhicules thermiques à moteur diesel. Pour les véhicules 100% électriques, le nombre de subventions attribuées en cas d'acquisition ou de conversion est un facteur déterminant et explique les tendances actuelles d'adoption de son adoption. Enfin, et compte tenu des évolutions attendues dans la mobilité urbaine, notamment en ce qui concerne, d'une part, les péages ou la taxation des pénalités sur les véhicules polluants et, d'autre part, les facilités de stationnement et autres mesures de promotion des véhicules électriques, il semble que l'avenir des véhicules compacts soit prometteur pour développer davantage la mobilité électrique. Néanmoins, au vu de la tendance actuelle à augmenter la taille de la batterie pour étendre l'autonomie, les véhicules 100% électriques pourraient être fortement concurrencés par les autres véhicules hybrides. Cela est notamment le cas des hybrides rechargeables, qui peuvent être bien plus intéressantes à la fois pour répondre aux besoins des utilisateurs en termes d'autonomie mais aussi sur le plan environnemental, comme démontré dans le cadre des travaux de cette thèse.

Afin d'analyser les services de mobilité, des méthodes de calcul ont été définies permettant ainsi de déterminer le coût par km associé à un service donné pour une durée définie. Ces méthodes de calcul tiennent compte du coût direct associé à un service par un utilisateur sur un an divisé par le kilométrage annuel parcourus sur un trajet spécifique. Pour calculer ces coûts, des données ont été collectées pour la communauté d'agglomération de Sophia Antipolis qui est choisie comme le terrain de l'application. Le scénario de mobilité collective a démontré la meilleure performance économique du point de vue utilisateur, tandis que la mobilité personnelle présente les coûts les plus élevés pour les utilisateurs, suivie de près par la mobilité partagée. Cela peut s'expliquer dans le terrain d'études choisi par les politiques locales adoptées visant à promouvoir l'usage de transport public et cela notamment en rendant plus abordable leur accessibilité. Il est cependant important de signaler que le coût supporté par les utilisateurs reflète une perspective d'un acteur parmi d'autres. Par conséquent, adopter une perspective d'autorités publiques ou encore d'acteurs privés pourrait orienter les méthodes de calcul définies et donc conduire à des résultats différents. Par exemple, si l'on considère le point de vue des autorités publiques, l'ACCV peut être très utile pour soutenir les décisions d'investissement et la définition des stratégies de mobilité. Cela peut donc contribuer à mieux informer les décideurs sur les coûts potentiels d'un développement massif de la mobilité électrique et à analyser la projection des coûts du marché automobile pour prévoir les futurs coûts directs et indirects pour la société. Il est important de définir la perspective adoptée dans l'analyse dès la première phase de l'étude d'ACCV afin de s'assurer de la cohérence des méthodes utilisées et les résultats obtenus avec l'objectif initial.

L'interprétation des résultats issus de l'évaluation de durabilité de cycle de vie

Les résultats issus des trois approches d'évaluation d'ACV environnementale, ASCV et ACCV des scénarios de mobilité alimentent la phase d'interprétation d'ADCV. Cependant, une interprétation directe des résultats s'avère être insuffisante pour aider les décideurs dans le cadre du développement des alternatives de mobilité durable. Cela est dû à la nature multidimensionnelle de la durabilité couvrant les impacts environnementaux de l'ACV, les impacts sociaux et socio-économiques de l'ASCV et les indicateurs de coûts du l'ACCV. Cette nature hétérogène des indicateurs induit un problème multicritère dans lequel les scénarios de mobilité analysés présentent des performances variables et parfois contradictoires entre les dimensions de la durabilité, mais aussi au sein de chaque dimension. Ces questions ont été abordées dans cette thèse de doctorat à travers l'introduction et l'exploration des approches d'analyse multicritère. Ces méthodes sont reconnues pour leur capacité à gérer les compromis émergeant des processus de prise de décision, dans le cas échéant, les résultats de l'analyse de durabilité par l'ADCV, dans le cas échéant. Cette contribution méthodologique est directement liée à la **deuxième question de recherche (RQ2)** :

Comment les résultats des ADCV peuvent-ils soutenir le processus de prise de décision dans le contexte de la mobilité électrique en tenant compte des perspectives des acteurs, y compris des utilisateurs ?

Ce travail de thèse cherche, à travers cette deuxième question, à **soutenir les acteurs privés et publics de la mobilité dans le choix d'alternatives de mobilité les plus durables tout en intégrant les besoins et les attentes des usagers.** A cette fin, **un nouveau cadre méthodologique est proposé couvrant quatre étapes à mener pour intégrer les approches MCDA à la phase d'interprétation de l'ADCV:**

1) Définition du « scénario de décision » : alternatives à comparer, acteurs, caractéristiques géographiques de la zone d'étude
2) Définition des critères de prise de décision. Ces derniers représentent dans cette thèse des critères de durabilité qui sont liés à ceux analysés par l'ADCV. La perception des usagers de transport est introduite dans cette étape afin de permettre leur implication directe dans le cadre méthodologique défini.
3) Application de l'approche MCDA sélectionnée pour le cas d'études,
4) Détermination des facteurs de pondération aux résultats de l'ADCV et interprétation des résultats quant à une prise de décision relative à l'alternative étudiée.

Ce cadre proposé peut être adapté et modelé en fonction du système analysé et des objectifs à atteindre. Afin de sélectionner l'approche MCDA adéquate, trois grands groupes d'approches de MCDA ont été identifiées : (i) les méthodes dites « approches basées sur les utilités » ou les approches faisant appel à une comparaison par paires des critères de décision, (ii) les méthodes dites basées sur le classement faisant appel à la hiérarchisation de préférences en passant par les valeurs des attributs plutôt que les attributs eux-mêmes, et (iii) les méthodes d'utilité décisionnelle qui sont orientées vers des approches statistiques d'exploitation de données en modélisant tous les scénarios et les possibilités de performance associées aux attributs aidant ainsi à sélectionner ceux qui répondent à un maximum de critères.

L'analyse conjointe a été sélectionnée parmi les différentes techniques MCDA identifiées pour son aptitude à intégrer les préférences des utilisateurs. Ce modèle de préférences permet aux acteurs publics et privés de mieux adapter leurs offres de mobilité aux besoins et attentes des usagers de transport lors du développement d'alternatives de mobilité durable. L'utilisation de l'analyse conjointe permet d'éviter le recours à une comparaison par paires qui nécessite généralement une connaissance élevée de la part des acteurs impliqués. Cela peut être très complexe notamment quand il s'agit de manipuler ou d'exploiter des résultats de durabilité. En effet, l'analyse des préférences se concentre sur la performance relative des différents attributs sélectionnés plutôt que leur hiérarchisation directe. Le recours à ces échelles de performance est important car les usagers peuvent être incapables de comprendre des valeurs brutes des résultats obtenus lors de l'évaluation. Ainsi, une échelle de référence qualitative peut faciliter l'application de l'analyse conjointe. Ceci permet de définir un ensemble de profils d'alternatives plus représentatifs des scénarios décisionnels réels. Cette technique peut ainsi améliorer la fiabilité des scénarios de décision étudiés.

Cependant, pour permettre l'application effective de l'analyse conjointe, seul un nombre limité de critères de décision peut être retenu afin de réduire le nombre de combinaisons possibles. Cela peut soulever des questions, notamment dans le cadre de l'analyse de durabilité, qui nécessite l'analyse d'un nombre important de catégories d'impacts. Pour explorer ces questions, une étude de cas a été menée dans laquelle l'analyse conjointe a été implémentée. L'objectif de cette étude de cas était de démontrer l'applicabilité de la méthodologie de la MCDA proposée pour améliorer la phase d'interprétation de l'ADCV. A cet effet, un trajet quotidien de domicile-travail entre Antibes et Sophia Antipolis a été choisi pour cadrer cette application comme dans le cas de l'évaluation économique par ACCV réalisée sur le territoire de la CASA.

Les éléments clés des scénarios de décision, y compris les acteurs de la mobilité dans la zone d'étude, les alternatives de mobilité qui y sont présentes et les caractéristiques des déplacements, sont caractérisés. Il est important de rappeler que dans cette thèse, les utilisateurs sont considérés comme des acteurs clés de la mobilité mais pas comme des décideurs. Ainsi, l'étude a cherché à comprendre leurs besoins et à les intégrer au même niveau que les résultats d'évaluation de durabilité pour soutenir les acteurs publics – Communauté d'Agglomération de Sophia Antipolis (CASA)– dans la prise de décision.

Au vu de l'objectif des travaux de thèse pour intégrer la perception des usagers, ces derniers ont été impliqués dans la deuxième étape du cadre méthodologique proposé pour identifier et sélectionner les critères de décision les plus pertinents en matière de durabilité. Ainsi, un focus groupe a été organisé avec les usagers de transport dans la zone CASA afin de recueillir leurs perceptions et d'identifier les facteurs clés guidant leurs choix de mobilité en matière de durabilité. Deux étapes ont été menées lors de ce focus groupe, la première qui permettait de générer un nombre maximum de critères à travers la méthode de citation directe et la deuxième étape qui consistait à hiérarchiser les critères par dimension afin de retenir les plus prioritaires. Cinq critères ont été donc considérés parmi les 69 qui ont été générés dans la première phase du focus groupe :

1. Accessibilité (dimension sociale)
2. Temps de trajet (dimension sociale)
3. Contribution au changement climatique (dimension environnementale)
4. Qualité de l'ai local (dimension environnementale)
5. Coûts mensuels (dimension économique)

Pour chacun de ces critères sélectionnés, trois échelles de performance ont été définies à partir des résultats de l'ADCV. A cet effet, une normalisation des résultats de l'ADCV a été réalisé pour définir pour chacun des critères sélectionnés trois niveaux de performance : performance favorable, défavorable et performance moyenne.

A partir des cinq critères sélectionnés et leurs trois échelles de performance, 125 combinaisons différentes ont pu été établies. Celles-ci ont ensuite été utilisées dans l'analyse des préférences. Cette dernière a été réalisée par le biais d'une analyse conjointe basée sur les choix (CBC) qui permet de réduire le nombre de combinaisons et donc de faciliter l'implémentation de l'approche. L'application de l'approche CBC réalisée auprès des différents usagers a permis de déterminer les facteurs de pondération pour chacun des critères : la dimension environnementale a été perçue comme plus importante que les autres dimensions et a été pondérée à 53% au total, dont 32% attribués au changement climatique et 21% à la qualité de l'air. La dimension économique a pris la deuxième place et a été pondérée à 31%. Enfin, la dimension sociale a pris la troisième place et a été pondérée à 16% avec 8% également attribués à l'accessibilité et au temps de trajet. L'interprétation des résultats a mis en évidence la conscience écologique des usagers vis à vis des aspects environnementaux, sociaux et économiques liés à leurs choix quotidiens. Ces résultats soulignent l'importance de prendre en compte la perspective des usagers dans la conception d'alternatives de mobilité durable. L'analyse conjointe a été pour cela très pertinente et a permis d'introduire les préférences des usagers de manière efficace en laissant les usagers de transport s'exprimer sur les performances environnementales, sociales et économiques attendues des différentes alternatives de mobilité.

Les études précédentes ayant tenté d'introduire des approches MCDA à l'ADCV se contentaient d'une application directe des facteurs de pondération aux résultats de l'analyse de durabilité ce qui n'a pas été retenu dans ces travaux de thèse. En effet, il est aussi important, avant de passer à l'application, d'analyser en amont la pertinence de ces facteurs de pondération et leur représentativité. En effet, un large éventail d'approches MCDA peut être utilisé, celles-ci peuvent parfois faire appel à des choix de valeurs qui ne sont pas suffisamment justifiés et transparents. Les facteurs de pondération, résultat direct de l'implémentation d'approches MCDA, peuvent varier selon l'approche utilisée, et les méthodes d'enquête employées. La fiabilité, représentativité et la pertinence de ces facteurs de pondération devraient être minutieusement examinées pour s'assurer de leur validité avant leur utilisation dans l'orientation des décisions.

Il est important de savoir que la CASA avait entrepris une démarche visant à tenir compte des perceptions des utilisateurs dans le cadre de la restructuration du réseau des transports. Cette démarche a été réalisée notamment à travers une série d'enquêtes auprès des usagers qui ont été interrogés sur les facteurs déterminant leurs choix de mobilité quotidienne. À cet égard, le présent travail a approfondi davantage la question de la représentativité des facteurs de pondération obtenus en analysant les résultats obtenus dans le cadre de l'enquête établie par la CASA auprès de 3 642 usagers des transports. Les résultats de cette enquête ont été collectées et traitées. D'abord, d'un point de vue méthodologique, l'enquête menée par la CASA a interrogé les usagers de transport sur l'ordre d'intérêt qu'ils portent aux trois dimensions de durabilité. Les répondants ont été amenés à hiérarchiser la dimension environnementale, sociale et économique sans qu'il y ait une hiérarchisation des critères et/ou impacts relatifs à chacune de ces dimensions. De plus, l'enquête utilisée n'a pas permis d'examiner les choix et les préférences des usagers face à des scénarios réels dans le cas de l'analyse de préférences. Cette approche différente a conduit à une divergence significative des résultats par rapport à ceux obtenus par l'analyse conjointe. La dimension sociale a obtenu le score le plus élevé parmi les différents facteurs de choix des usagers avec 40%. Les usagers ont classé la dimension environnementale en deuxième position avec 30% et enfin la dimension économique a pris la dernière position du classement avec 9%.

Ces résultats révèlent une limite majeure liée à l'influence du choix méthodologique sur l'orientation des résultats et leur fiabilité pour soutenir le processus décisionnel. En fait, l'intégration de telles approches peut conduire à une interprétation simpliste des résultats de la durabilité et à une mauvaise utilisation des résultats dans la prise de décision. Cela peut s'expliquer par les raisons suivantes :

- Le nombre de critères de décision sélectionnés doit être limité, de manière à faciliter la l'application de l'approche MCDA choisie. Par conséquent, cela empêche de prendre en compte toutes les catégories d'impact analysées au sein de l'ADCV pour soutenir la prise de décision.
- Les approches de pondération demandent l'introduction de choix de valeurs qui induisent systématiquement une représentation partielle de la part de l'acteur impliqué dans la compréhension des catégories d'impact significatives. En effet, le focus groupe, malgré sa capacité à transmettre des informations qualitatives essentielles pour la compréhension et l'analyse des résultats, peut, en raison de son caractère ouvert et non-directionnel, limiter la concordance des critères de prise de décision et ceux analysés par l'ADCV. Ainsi, certaines

catégories d'impacts et de parties prenantes évaluées dans le cadre de l'ADCV peuvent se retrouver non couverts dans le processus de prise de décision.

- La représentativité de l'échantillon utilisé peut influencer de manière significative les résultats finaux obtenus. En fonction de l'approche utilisée, qualitative comme le focus groupe ou quantitative comme les questionnaires en ligne, la taille de l'échantillon peut significativement varier.

Toutes les limitations mentionnées ci-dessus, identifiées par ces travaux de thèse, ouvrent des perspectives nouvelles à l'expérimentation des approches MCDA et leur potentiel à gérer les compromis induits par les résultats d'analyse de durabilité. A cet égard, cette thèse propose un ensemble de recommandations quant à l'application des approches MCDA à l'interprétation des résultats de l'ADCV assurant ainsi des processus décisionnels plus représentatifs et fiables :

- La cohérence des résultats obtenus doit être soigneusement analysée. Les recherches futures peuvent se concentrer sur l'expérimentation de différentes techniques MCDA et la comparaison des résultats pour examiner la variabilité et les incertitudes associées aux résultats.
- La méthodologie proposée dans le cadre de ces travaux de thèse suggère un approfondissement des sources de connaissances entreprises dans le contexte décisionnel associé à la mobilité électrique. Cela notamment en allant au-delà d'une simple hiérarchisation des dimensions de durabilité et en intégrant les résultats de l'évaluation de durabilité par des approches d'ACV.
- Les études futures doivent s'assurer que la perspective du cycle de vie est respectée, et que les critères de décision définis couvrent les impacts pour les différentes catégories de parties prenantes.
- La compensation entre les différents impacts positifs et négatifs, qui peut conduire à une mauvaise interprétation des résultats, doit être traitée avec soin. Par conséquent, les futures études de recherche devraient examiner comment éviter une telle compensation des impacts au sein d'une dimension de durabilité ou parmi les trois dimensions lorsqu'elles sont considérées conjointement.

Généralisation du cadre méthodologique proposé à d'autres scénarios de mobilité et à d'autres perceptions d'acteurs

Cette thèse portait l'ambition de contribuer aux avancées méthodologiques de l'ADCV ainsi que son implémentation à d'autres produits et filières. Le cadre méthodologique proposé intègre les trois dimensions de la durabilité et s'étend sur une perspective de cycle de vie. Ces deux caractéristiques sont désormais fondamentales pour baser les processus décisionnels futurs sur des connaissances approfondies des impacts générés sur l'environnement et sur les différentes parties prenantes. Les travaux de cette thèse ont porté une attention particulière à l'implication des acteurs et, plus spécifiquement, à une meilleure prise en compte des attentes et aux besoins des utilisateurs en termes de mobilité afin de soutenir la prise de décision vers une mobilité plus durable. L'implication des parties prenantes concernées et affectées a démontré son rôle majeur pour assurer une compréhension plus profonde des systèmes en question et son intérêt pour anticiper les résistances sociétales susceptibles de survenir. Plusieurs recommandations sont faites dans les points suivants pour faciliter l'adoption de la méthodologie proposée et étendre son application à d'autres produits et systèmes, mais aussi pour intégrer les perspectives d'autres parties prenantes :

a) L'étude doit accorder une attention particulière à l'objectif et au champ d'application de l'étude, afin de définir clairement les limites du système et d'éviter que d'importantes parties prenantes clés ne soient exclues. Dans l'ASCV, les groupes de parties prenantes des utilisateurs ou des consommateurs ne doivent pas être laissés de côté et des efforts doivent être déployés pour mieux prendre en compte leurs impacts sociaux et socio-économiques relatifs. L'implication des utilisateurs dans la phase de conception peut améliorer de manière significative la précision de la prise de décision en étudiant la résistance sociétale potentielle future du développement des alternatives.
b) L'implication des parties prenantes dans la définition des catégories d'impact s'est avérée très pertinente. Ainsi, l'évaluation des sous-catégories d'impacts notamment dans le cadre de l'ASCV peut se focaliser sur celles qui sont significatives au système analysé et celles perçues comme importantes au point de vue des différentes parties prenantes concernées. Si possible, l'étude devrait inclure une approche participative permettant de couvrir un large panel de perceptions des parties prenantes pour la définition des sous-catégories d'impact pertinentes. Les approches participatives peuvent être une alternative intéressante afin de légitimer davantage cette phase de sélection.
c) Les études futures peuvent utiliser les étapes proposées pour explorer d'autres techniques d'analyse multicritères (Multicriteria Decision Analysis en Anglais ou MCDA) et de les appliquer à d'autres scénarios de décision et tenir compte des points de vue d'autres parties prenantes dans le processus décisionnel. Ces études devraient sélectionner avec soin la technique MCDA la plus appropriée de manière à servir leur objectif et leur champ d'application spécifiques. Dans la présente thèse, l'analyse conjointe a permis de tenir compte de la perspective des utilisateurs. Néanmoins, il convient de noter que cette approche peut également être adaptée à d'autres parties prenantes. Les recommandations proposées dans la thèse peuvent être utilisées pour explorer d'autres procédures de collecte de données par la conception de différents processus de consultation pour impliquer les différentes parties prenantes.

Les travaux menés ont pour ambition de favoriser le développement des ADCV, qui peuvent fournir une vision approfondie des trois dimensions de la durabilité dans une perspective de cycle de vie. Une telle vision est plus que jamais nécessaire pour informer la transition en cours vers des modes de production et de consommation durables.

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Chapter I: Introduction

1. Transportation and sustainable development

1.1.The role of the transport sector in socio-economic development

For centuries**, transportation** has played a key role in socio-economic development of civilizations and their modernization. **Transportation is defined as the means by which people and freight are moved from point A to point B.** From hunter-gatherers' migrations to the silk road long-distance camel caravans and modern-day container ships, transport systems have been constantly evolving, shaping in the process our ways of living. Transportation has allowed connecting people and extending their accessibility to employment and to other essential goods and services. Thanks to national and international exchange of raw materials and energy, industrial progress has been significantly accelerated, driving the need for roads and infrastructure. Moreover, people's accessibility to markets has been eased by transportation (Rodrigue & Notteboom, 2020), which has further fostered an economic model driven by mass production and consumption.

Along with the economic growth, the rise in transportation demand has gone hand-in-hand with an ever-increasing demography and urbanization (Noussan et al., 2020). Cities have undergone drastic urban sprawl and mobility needs have evolved (OECD, 2018), bringing together a diversity of technologies and transportation modes.

Mobility[7] is distinguished from transportation by embracing a social relationship to movement. It describes people's ability of movement and their accessibility to transportation services, technologies, and infrastructure. Urban mobility has become increasingly complex, and its management requires considering trade-offs resulting from the interactions of different mobility services and technologies.

The 20th century has been marked by a substantial expansion of road vehicle technologies for both passengers and freight transport. Thanks to its high affordability (Rodrigue, 2020a), individual mobility has been democratized and massively adopted (OGL, 2019). The rise of personal car use occurred in conjunction with a decline of other transportation modes. For example, in France, passengers' transport has been widely dominated by the use of personal vehicles. Thus, individual road transport represented

[7] *The definition proposed is adapted from the one in Universalis Encyclopedia. Available in French in this link.*
*The aim was to clearly distinguish the use of both terms; "**mobility**" and "**transport**" throughout the present manuscript.*
"Mobility can be defined as the social relationship to change of place, i.e., as all actions that contribute to the movement of people and material objects. In this very broad sense, transport is the technical system directly dedicated to this movement. It is a relatively easy economic branch to isolate, but it is only one component of the field of mobility. Mobility also includes, on the one hand, the technical systems that support and enable transport (production of transportation systems, their management, and mobility services), and, on the other hand, the relationship between the practice of transport and its economic, sociological, anthropological and political purposes. Finally, as mobility is a fundamental element in the functioning of productive societies, it can only be thought of in terms of an approach that links it to major social dynamics."

80.6% of total passengers transported on the total traveled distance (passengers. kilometers) in 2018 (Datalab- CGDD, 2020), while rail transport represented 11.50% and road public transport only 6.2%.
From an economic point of view, employment and total expenditures are the most common macroeconomic indicators to assess the efficiency of transportation systems (Rodrigue & Notteboom, 2020) and thus, the economic development of countries. In France, total expenditures on transport sector reached 425.1 billion euros in 2018 which is equivalent to 18.1% of the Gross Domestic Product (GDP) (Datalab- CGDD, 2020). As for employment, transport sector plays a major role, accounting, in 2018, for about 1.4 million employees and 97,000 interims. In addition, total transport-related household consumption amounted to 181.8 billion euros in 2018, representing thus 14.9% of total household expenditures. Of these expenditures, 83.5% stand mainly for individual transport, including vehicles purchase (43.8 billion euros), fuels and lubricants (41.3 billion euros) and other related services (58.8 billion euros).

1.2.Energy consumption in the transport sector and associated environmental impacts

To turn the wheels of economic development, transportation systems have strongly relied on the energy sector. In fact, as illustrated in Figure 1, in 2019, 32% (45.14 Mtep) of the total final energy consumption (140 Mtep) in France was related to the transport sector. In particular, road transport accounted for 93% of the final energy consumed by the transport sector (CGDD, 2019). Most of this energy consumption corresponded to oil-derived products, which accounted for 91% of the French transports' consumption and were mainly associated to road transport (CGDD, 2019). Consumed electricity by transport systems only represented 1.9%, mostly related to the rail mode. Other used energy sources for transportation in France, includes 7.1% for biofuels, and 0.4% for natural gas in 2019. At the European level, the share of renewable energy in the transport sector was still limited to 8.1% in 2018 (EEA, 2020), and mainly dominated by biofuels (IRENA, 2018).
The intensive use of petroleum products in current road transportation systems results in major environmental problems such as climate change, resource depletion, and other forms of air, water, and soil pollution. Indeed, Greenhouse Gas (GHG) emissions are mainly dominated by the transport sector, which accounted for 40% of total GHG emissions in France in 2019 (CGDD, 2019). Road transport is the major contributor to these emissions with 95% of national emissions from transport in 2019, for which 56% is associated to individual mobility. Another concern is air quality, which has drastically decreased in dense urban areas worldwide causing a serious threat to public health (ADEME, 2018; EC, 2017a). The main reason is the significant exposure to particulate matter and NO_X emission. In addition, transportation sector generates other negative externalities such as road accidents, congestion, and noise emissions that involve significant social and economic costs for the society (EEA, 2020).

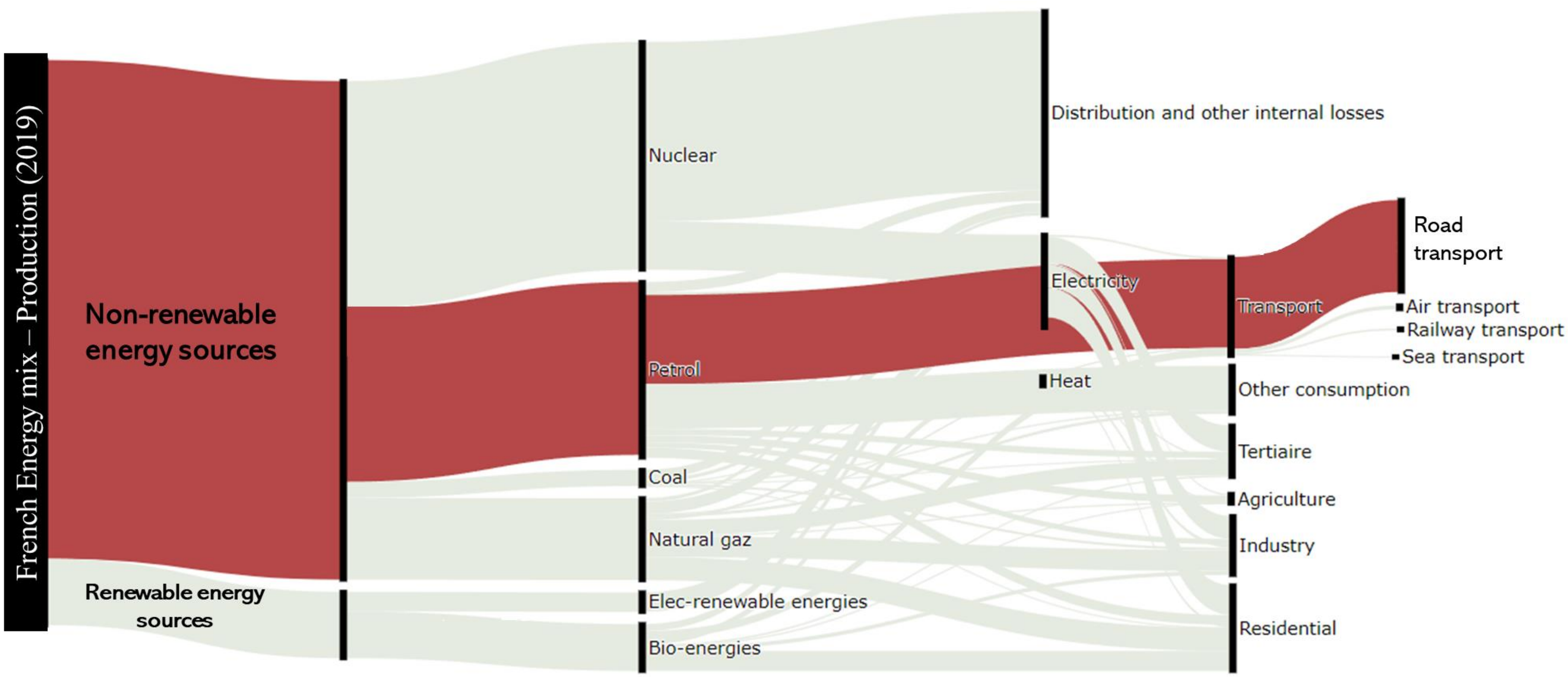

Figure 1 Sankey diagram of primary energy production and final energy consumption per sector in France in 2019, data from CGDD (2020).

1.3. Transport regulations and future challenges to be addressed

Such urgent environmental concerns call for a shift from the current car-based transport system, characterized by fossil-fuel dependency, to technologies with lower environmental impacts. On a global scale, since the publication of the report “limits to growth” (Meadows et al., 1972) and then the International Panel on Climate Change reports (IPCC, 1990), we now count 22 Conferences of the Parties (COP) aiming to bring together member states to set targets for the reduction of GHG emissions, primarily CO_2 emissions, and to address the effects of climate change. After the Kyoto protocol (UN, 1998), ratified in 2007, the Paris climate agreement (UN, 2015) was concluded after COP21 and became effective in 2016.

In accordance with these agreements, the European Commission published in 2011 the White Paper on transport: "Roadmap to a Single European Transport Area – towards a competitive and resource-efficient transport system" (EC, 2011). This document sets a target of at least 60% reduction of GHG emissions for transportation sector by 2050. Multiple strategies, regulations and roadmaps have also been established to foster an effective transition to low-emission mobility (Noussan, Hafner, et Tagliapietra 2020a) and, thus, meet the EU’s long-term policy objectives (EC, 2016, 2017a; EUR-Lex -On the road to automated mobility: An EU strategy for mobility of the future, 2018; ECA, 2018). The starting point of emissions’ strict limits were set in 1990, when the "Euro 0" standards were introduced in Europe for commercial vehicles. Since then, a series of standards have been gradually implemented, covering air quality indicators (PM, CO and NO_X emissions). The “Euro 7” is expected to develop stricter emissions standards for diesel vehicles, as part of the European Green Deal (EC, 2019).

In this regard, car manufacturers are expected to increasingly enhance the environmental performance of transportation technologies they provide to the market (Regulation EU, 2014). As a result, significant reductions of environmental impacts are taking place thanks to improvements within the design phase. This includes lightweight materials development (Field et al., 2017), alternative fuels and powertrain efficiency increase (Dell et al., 2014a, 2014b; Harison, 2018), materials recycling, and end-of-life recovery (Bobba et al., 2018; Hu et al., 2017; Pasquier, 2015).

On the other side, public authorities both at national and local scales, are setting up measures and incentive actions to encourage the adoption of more sustainable mobility alternatives. To face climate change, the French government has the ambition to achieve carbon neutrality by 2050. This objective has been formalized through the low-carbon national strategy in 2015 (MTES, 2020). A broad set of roadmaps and action plans have rapidly followed to promote a future national transportation scheme committing to a profound transformation of current travel patterns. Moreover, a new mobility regulation “Loi Orientation de Mobilité (LOM)” was adopted (2018) in accordance with the energy transition law (2015). The LOM regulation introduced 15 key measures, among which electric mobility appears as a key technological solution for decarbonizing transport. Moreover, several prospective scenarios lean toward electric vehicles adoption, to cease commercializing conventional vehicles by 2040 (OPECST 2019a).

1.4. Technological development of electric vehicles

Despite the appearance of Electric Vehicles (EV) as early as in the beginning of the 19^{th} century, Internal Combustion Engine Vehicles (ICEV) have dominated the market so far. Indeed, the first model of an electric vehicle goes back to 1834 and its production was even more intensified after the appearance of acid-lead batteries in 1859 (Sencier & Delasalle, 2015). Their development continued until the beginning of the 20th century and was slowed down by the rise of the oil era, when the production of thermal vehicle models gained the market in view of their multiple advantages in terms of weight, price, and driving range (Guignard, 2010). The crisis of 1973 drew the attention of Western countries to their high dependency on oil products and thus paved the way for the development of other alternatives.

Over the last years, the world has experienced the re-emergence of EVs in parallel with a widespread ecological awareness. Hence, between 2014 and 2019, the sum of annual average increase of both Hybrid Electric Vehicles (HEV) and Battery Electric Vehicles (BEV) market reached 60% (IEA, 2020a). The share of EV is expected to reach 80% of passengers transport market in Europe by 2050, which will result in an increasing electricity demand (EEA, 2016). In response, a higher share of Renewable Energy should be encouraged for power generation (IRENA, 2017) to substitute oil-derived fuels consumption. Major environmental benefits are therefore expected, including the decrease of exhaust emissions and noise levels thus, air quality improvement in urban areas (Niestadt et Bjornavold 2019). The underlying EV technologies have significantly gained in maturity thanks to high battery density improvement, which demonstrated 20 to 100% higher energy density in 2020 compared to that of 2012 (IEA, 2020a). Despite the ongoing technological advances, EVs development still faces multiple challenges related to their high initial costs, limited charging infrastructures and complex grid capacity management in case of a mass-market uptake (Tietge et al., 2016).

1.5. Moving from technologies-based paradigm to service-based paradigm

Although electric vehicles are likely favorable to achieve European Commission goal in terms of climate neutrality by 2050 as long as they rely on low-carbon electricity mixes (EC, 2018; EUR-Lex -On the road to automated mobility: An EU strategy for mobility of the future, 2018), it is legitimate to question their contribution to sustainable mobility patterns. In fact, sustainability stands on three pillars, namely the environmental, social and economic pillars. Hence, EV technologies should be evaluated with respect to these three dimensions. Moreover, while efforts have mainly focused on optimizing the existing technologies (EC, 2017b), achieving a sustainable mobility could require more profound transformations affecting the society through its public policies, technological advances and its mobility patterns.

In this regard, synergies between EV technologies and innovative mobility services could bring several environmental benefits (Bortoli & Feraille, 2015; EC, 2016) in terms of emissions' reduction, but also in terms of the social and economic dimension (i.e., urban congestion reduction, especially for highly dense cities). Moreover, all prospective mobility scenarios developed in line with the objectives set by the Energy Transition Law and the Low-Carbon National Strategy (LCNS) in transport, encourage the development of public and shared transport modes (Bigo, 2020). The LNCS has identified modal shift (i.e., transition towards the use of public, shared, cycling as alternatives for individual mobility) as one of the five major factors to achieve energy transition in the transport sector, together with the moderation of transport demand, optimization of vehicle occupation rate, vehicle efficiency, and the carbon intensity of the used energy. In the Sustainable and Smart Mobility Strategy (EC, 2020), the European Commission has also highlighted the need to boost modal shift to promote sustainable alternative modes, in particular for daily mobility.

As a response, over the recent years, and thanks to the current digitalization, transport modes have been increasingly branching out into emergent services such as carpooling and ride-sharing, to meet final users' needs (CGEDD et al., 2015; EC, 2017b). The concept of "Mobility as a Service" (MaaS), promoting mobility as a commodity for the final user, has substantially gained in importance at the European level (Kostiainen & Tuominen, 2019). MaaS is the integration of a diverse menu of transport options, combining various technologies (car, bike, bus) and transport services (public transport, ride-, car- or bike-sharing, etc.) (MaaS Alliance, 2017). This combination enables to reintroduce mobility services, technologies, policies, business models as facilitators for meeting end users' needs and thus, reduce the intensive use of individual mobility. Moreover, MaaS concept has introduced a user-centric vision that enables reconciling the needs and expectations of the final users for the design of sustainable mobility alternatives. The European Commission has also adopted this vision within The European Green Deal (EC, 2019), affirming that "*Achieving sustainable transport means putting users first and providing them with more affordable, accessible, healthier and cleaner alternatives to their current mobility habits*".

⇒ **Achieving sustainability in the transport sector is way beyond substituting internal combustion engines by electric motors.**

⇒ **Future efforts should focus on reintroducing mobility services and stakeholders needs jointly with low-impact technologies within the design of future sustainable mobility.**

⇒ **Mobility-end users are in the core interest of future sustainable mobility schemes at the European level and their needs and expectations are to be carefully considered.**

Given the above-mentioned aspects related to the interest of electric mobility, the overall question developed throughout this research work aims to investigate:

How far could electric mobility contribute to sustainable mobility patterns while meeting the daily needs of users?

To address this question, it is fundamental to further investigate sustainability of both EV technologies and mobility services as well as their synergies to guide public authorities and industrial actors with their decisions. The different stakeholders that are involved in the sustainable mobility schemes as well as the connections between them should be defined and investigated. For these reasons, thorough assessment methods are required for the environmental, social, and economic impacts (positive and negative) enabling a comprehensive sustainability evaluation of electric mobility scenarios.

2. Sustainability assessment methods: the key features and main methodological challenges

Thanks to its focus on the three dimensions of sustainable development and its life cycle perspective, **Life Cycle Sustainability Assessment (LCSA)** has significantly gained in importance in the last years. It allows the identification and the evaluation of environmental, social, and economic impacts along the value chain, that is, from raw materials' extraction to the end of life of products or services.

LCSA relies on three approaches: environmental Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC) (Finkbeiner et al., 2010; Kloepffer, 2008). Formulation for LCSA was proposed by Kloepffer (2008), and consists of separately conducting LCA, S-LCA and LCC while continuously ensuring their connectedness. However, this is far from being a simple task as the three approaches are targeting different dimensions, have different methodological backgrounds and reflect different levels of maturity. This is reflected in the LCSA literature by several shortcomings such as the lack of accordance with ISO standards, lack of connectedness among sustainability dimensions, and lack of transparency (Valdivia et al., 2021).

Although environmental LCA has gained sufficient maturity to become widely adopted and standardized (ISO14044, 2006), S-LCA and LCC still lag behind due to the complexity rising from the definition of characterization models and impact assessment approaches. Such difficulty is also reflected for the mobility sector. While LCA has been fairly developed to investigate potential environmental impacts of mobility technologies and services (Cerdas et al., 2018; Cox, 2018; Del Duce et al., 2016a), a global S-LCA framework applied to mobility scenarios is still lacking and no general standardization has been yet established for LCC, apart from the one specific to the construction sector (ISO 15686-1, 2011). As a result, LCSA still faces major challenges to consistently address into one core methodology the three sustainability dimensions. Hence, the first challenge to be covered by the current research work is the following:

Challenge 1: Design of a comprehensive methodological framework integrating the life cycle thinking to the three sustainability dimensions.

One of the major interests for LCSA consists of supporting informed decision-making process. In fact, incorporating life cycle perspective to sustainability pillars could provide decision makers with wider insight towards more sustainable design of products, technologies and services (Valdivia & Lie, 2012). To support the decision-making process, the final step of LCSA, namely results interpretation, may be insufficient and inconsistent for several reasons including

- Interpretation step is often judged as subjective (De Luca et al., 2017a).
- LCSA delivers multidimensional results, including environmental, economic, and social impact categories, that could induce trade-offs between the three sustainability dimensions (Tarne, Lehmann, & Finkbeiner, 2019).
- Weighting of impact categories is controversial and often too dependent on subjective judgment (ISO14044, 2006).

Furthermore, transportation users are becoming more aware not only of the environmental issues, but also of the social and socio-economic impacts related to their choices. Private actors (technology, services level) and public actors (policy level) in the mobility sector are, therefore, compelled to design more sustainable mobility technologies and services that fulfill users' growing needs and expectations. In this regard, it is necessary to investigate explicit stakeholders' involvement within an integrated vision from the sustainability assessment to the decision-making process. Following these observations, the second challenge identified within this research work is expressed as:

Challenge 2: Contribution to better-informed decisions on sustainability by integrating both LCSA results and stakeholders' perspectives

3. Objective and research questions

The scientific objective of present PhD thesis seeks to design a comprehensive sustainability evaluation framework, adopting a life cycle perspective, through **Life Cycle Sustainability Assessment (LCSA).** The methodological challenges sketched above are thus investigated and addressed within each phase of its implementation. The proposed framework is applied to evaluate electric mobility scenarios by including both mobility technologies and services.

Stakeholders' involvement – either those who are affected, involved or concerned by the ongoing shift towards sustainable mobility – is to be thoroughly investigated within an integrated vision from LCSA to the decision-making. Transportation users are to be given a particular focus to allow accounting for their perspectives within the context of mobility decision-making.

In order to bring and integrate relevant knowledge on sustainability for decision makers, multicriteria decision analysis is introduced to manage the emerging trade-offs from LCSA results while accounting for users' perspectives. This is expected to ease the connection between public authorities and industrial actors that are involved in the decision-making process by providing them with scientific-based information on sustainability aspects and users' perspectives.

Such comprehensive LCSA framework developed in this research should provide generic methodology and reliable information to be used by LCSA experts. This research is, moreover, contributing to the ongoing advances in LCSA. As such, this work comes in support for the recently published ten principles, in a position paper from the Life Cycle Initiative (Valdivia et al., 2021), to strengthen the consensus around LCSA. Two main research questions are addressed:

1st Research Question (RQ1)

How can environmental, societal, and economic impacts be integrated into a comprehensive methodological framework to address sustainability with a life cycle perspective?

2nd Research Question (RQ2)

How can LCSA results support the decision-making process within electric mobility context considering actors perspectives including users?

4. Thesis outline and structure

To address the defined research questions, this thesis is structured as illustrated in Figure 2 and comprises the following chapters:

Chapter I: General introduction

Chapter II: The defined methodological framework: An integrated vision from LCSA to the decision-making process

- This chapter includes the core methodological aspects addressed in the present thesis; An overview of sustainability assessment methods and tools is presented together with the methodological background of environmental LCA, S-LCA and LCC, detailed in the first section of chapter II.
- A literature review of LCSA studies dealing with mobility is presented, allowing the main shortcomings associated with current development of LCSA to be highlighted. This second section proposes a definition of electric mobility scenarios following four elements: vehicle technologies, mobility services, transportation infrastructures and energy consumption. A new feature is introduced to the scope of LCSA, namely the definition of mobility key actors. Three mobility scenarios are settled for further implementation of the proposed LCSA framework: personal, public and shared transportation, with a focus on electric and conventional transportation technologies.
- A step-by-step explicit description of LCSA aligning with the ISO standards recommended phases is provided. Key features and issues to be solved are detailed, including: the goal and scope definition, the impact assessment approaches and the life cycle sustainability interpretation. Two methodological pathways are identified for the conceptualization of a comprehensive LCSA framework, and their relative challenges are highlighted. The comprehensive LCSA framework proposed in this thesis is presented and claims to cover an integrated vision from LCSA methodological framework to the decision-making process. The expected methodological outcomes are settled for each LCA approach (environmental LCA, S-LCA and LCC).
- A step-by-step approach is presented introducing MCDA techniques to support LCSA results interpretation, tackling thus the trade-off induced by the sustainability assessment. Various MCDA

techniques are identified and analyzed to select the most appropriate one. Guidelines based on four stages are proposed to support decision makers (public and private mobility actors) in using LCSA results while accounting for users' expectations and needs: (1) definition of the decision scenario, (2) definition of sustainability criteria, (3) selection and application of the relevant MCDA technique, and (4) results interpretation. The conjoint analysis is adopted in accordance with the user-centric perspective enabling the consideration of final users' needs and expectations in terms of sustainable mobility alternatives.

Chapter III: Environmental evaluation of electric mobility scenarios through LCA

This chapter starts by analyzing the existing LCA studies for electric mobility scenarios and existing models to identify the main impact categories and life cycle stages (section 2) and thus, define a set of key input parameters to be entailed in the LCA modeling (section 3). Such LCA modeling is performed by running parametrized LCA models fitting the electric mobility scenarios settled within this thesis. Such parametrized LCA models clearly enhance the representativeness of the existing datasets by including the multiple technological advances that may occur over time. The defined approach together with the steps to be followed for the establishment of the parametrized models are detailed in section 4 all along the four iterative LCA phases. The concept of environmental LCA is mature enough prior to this thesis, so the focus is made on (a) formalizing a systematic protocol to generate parametrized LCAs fitting mobility scenarios and on (b) S-LCA development and LCC adaptation for the overall sustainability evaluation method. The results are discussed from an environmental perspective for the three considered scenarios (i.e., personal, public and shared transportation)

Chapter IV: Social evaluation of electric mobility scenarios through S-LCA

This chapter seeks to support the development of S-LCA methodology by introducing two novelties: (1) the definition of a participatory approach to enable the selection of impact subcategories from all concerned stakeholders' perspectives, (2) the introduction of a user-centric impact assessment approach to S-LCA. The chapter presents in detail the S-LCA framework developed to analyze potential social and socio-economic impacts related to the considered mobility scenarios, as well as its application to the case study. A step-by-step method in accordance with the recommendations of ISO 14,040 standards is presented. The global S-LCA framework includes a participatory approach that enables practitioners to account for stakeholders' perception to select the most relevant social and socio-economic impact subcategories for the evaluation step. Mobility technologies are therefore evaluated through reference scale-based social life cycle impact assessment, and a generic database is used to perform the calculation step. To analyze mobility services, a set of social and socio-economic indicators are further developed based on a user-centric vision.

Chapter V: Economic evaluation of electric mobility scenarios through LCC

The chapter starts by introducing key features and phases for LCC and identifies the main challenges within the implementation of LCC. It contributes to the harmonization of LCC method by introducing the key steps for the economic assessment of mobility scenarios by adapting ISO standards for environmental LCA to conventional LCC. Moreover, this chapter focuses on the analysis of the cost effectiveness of mobility scenarios from a users' perspective. In fact, an economic assessment approach is proposed by first conducting a direct cost calculation of vehicle technologies through a Total Cost of Ownership (TCO) and then, a cost calculation of the mobility services.

Chapter VI: Implementation of Conjoint Analysis to LCSA results interpretation: A support for the decision-making process towards sustainable mobility accounting for users' perspective.

This chapter seeks to provide insight on the applicability of the sustainability assessment framework proposed in this PhD thesis, based on LCSA coupled to MCDA, to support decision-making process. To meet this goal, a case study is designed to test how LCSA results can be used by public and private actors within the development of sustainable mobility alternatives, while accounting for users' needs and expectations. The designed case study investigates a specific mobility case study on commuting daily travels of persons between Sophia-Antipolis and Antibes, in the south of France. Hence, the conjoint analysis was selected and implemented in the thesis as an appropriate MCDA approach to integrate users' preferences. This chapter explains how preference analysis is conducted for specific users following a Choice-Based Conjoint (CBC) approach. Weighting factors are obtained for each of the sustainability criteria selected by users to enable their application within the LCSA interpretation of results. The findings are compared to the results of a large-scale survey conducted by local authorities. The comparison aims at pinpointing to what extent the method can be used to guide decision makers.

Chapter VII: General conclusions and recommendations for future research studies are presented. Key features of this present PhD work are discussed with respect to both research questions together with benefits of the implementation of such integrated vision of LCSA to the decision-making process. The main limitations associated with the practical implementation of the developed LCSA framework to the settled mobility scenarios are discussed as well as and the methodological challenges to overcome in the future. This chapter paves the way of future research in terms of MCDA approaches and their coupling to LCSA method. A set of recommendations is proposed to adopt and implement the proposed LCSA framework by targeting other product systems and by including other stakeholders' perspectives.

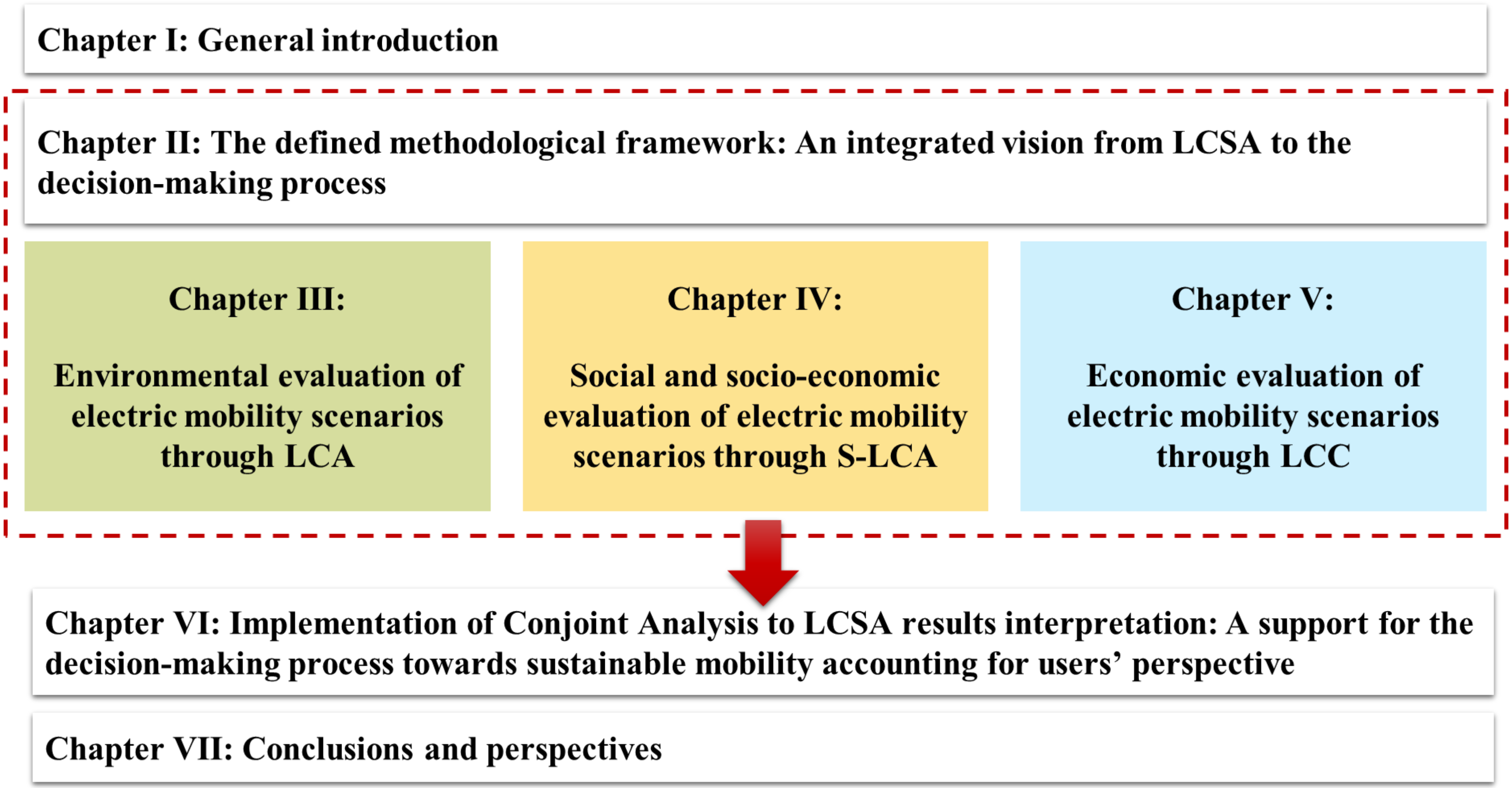

Figure 2 Structure and global outline of this PhD thesis chapter by chapter

5. References

ADEME. (2018). *Définition, sources d'émission et impacts des émissions NOx*. ADEME. https://www.ademe.fr/entreprises-monde-agricole/reduire-impacts/reduire-emissions-polluants/dossier/oxydes-dazote-nox/definition-sources-demission-impacts

Bigo, A. (2020). *Les transports face au défi de la transition énergétique* [PhD Thesis, Ecole Doctorale de l'Institut Polytechnique de Paris (ED IP Paris)]. http://www.chair-energy-prosperity.org/wp-content/uploads/2019/01/These-Aurelien-Bigo.pdf

Bobba, S., Podias, A., Di Persio, F., Messagie, M., Cusenza, M. A., Eynardu, U., Fabrice, M., & Pfrang, A. (2018). *Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB)* (p. 140) [JRC Technical Reports]. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112543/saslab_final_report_2018_2018-08-28.pdf

Bortoli, A. D., & Feraille, A. (2015). *Performance environnementale des modes de transports urbains sur cycle de vie: Quels choix techniques pour le bus à haut niveau de service ?* 17.

Cerdas, F., Egede, P., & Herrmann, C. (2018). LCA of Electromobility. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment* (pp. 669–693). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_27

CGDD. (2019). *Chiffres clés du climat: France, Europe et Monde* (p. 80). Institute ffor climate economics. https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2018-12/datalab-46-chiffres-cles-du-climat-edition-2019-novembre2018_1.pdf

CGEDD, Schmit, P., De Treglode, H., Marques, R., Farniaux, B., & Toulouse, P. (2015). *Urbanisme et mobilité|Rapports publiés du CGEDD* (n° 009796-01; p. 117 p). CGEDD, MTES. https://cgedd.documentation.developpement-durable.gouv.fr/notice?id=Affaires-0008638

CMED. (1987). *Notre avenir à tous (Rapport de Brundtland)*. Commission mondiale sur l'Environnement et le Développenet.

Cox, B. L. (2018). *Mobility and the energy transition: A life cycle assessment of swiss passenger transport technologies including developments until 2050* [ETH Zurich]. https://www.psi.ch/ta/PublicationTab/Thesis_Embargo_free_version.pdf

Datalab- CGDD. (2020, May 1). Chiffres-clés du transport, Édition 2020. *ORT&L Grand Est*. https://www.ortl-grandest.fr/chiffres-cles-du-transport-edition-2020/

De Luca, A. I., Iofrida, N., Leskinen, P., Stillitano, T., Falcone, G., Strano, A., & Gulisano, G. (2017). Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: Insights from a systematic and critical review. *Science of The Total Environment*, *595*, 352–370. https://doi.org/10.1016/j.scitotenv.2017.03.284

Del Duce, A., Gauch, M., & Althaus, H.-J. (2016). Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3. *The International Journal of Life Cycle Assessment*, *21*(9), 1314–1326. https://doi.org/10.1007/s11367-014-0792-4

Dell, R. M., Moseley, P. T., & Rand, D. A. J. (2014a). Unconventional Fuels. In *Towards Sustainable Road Transport* (pp. 86–108). Elsevier. https://doi.org/10.1016/B978-0-12-404616-0.00003-7

Dell, R. M., Moseley, P. T., & Rand, D. A. J. (2014b). Chapter 8—Hydrogen, Fuel Cells and Fuel Cell Vehicles. In R. M. Dell, P. T. Moseley, & D. A. J. Rand (Eds.), *Towards Sustainable Road Transport* (pp. 260–295). Academic Press. https://doi.org/10.1016/B978-0-12-404616-0.00008-6

Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system, (2011). https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:EN:PDF

EC. (2016). *A European Strategy for Low-Emission Mobility* (Communication from the Commission to the European Parliement, the Council, the European Economic and Social Committee and the Committee of the Regions : Europe on the Move - COM(2016) 501 final; p. 13). European Commission. https://ec.europa.eu/transparency/regdoc/rep/1/2016/EN/1-2016-501-EN-F1-1.PDF

EC. (2017a). *An agenda for a socially fair transition towards clean, competitive and connected mobility for all* (Communication from the Commission to the European Parliement, the Council, the European Economic and Social Committee and the Committee of the Regions : Europe on the Move - COM(2017) 283 final). European Commission. https://ec.europa.eu/transport/sites/transport/files/com20170283-europe-on-the-move.pdf

EC. (2017b). *Smart mobility and services: Expert group report.* Publications Office. https://data.europa.eu/doi/10.2777/490085£

EC. (2018). *A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy* (COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK No. 773). European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN

EUR-Lex -On the road to automated mobility: An EU strategy for mobility of the future, (2018). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0283

EC. (2019). *The European Green Deal: Communication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the regions*. European Commission. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

EC. (2020). *Sustainable and Smart Mobility Strategy – putting European transport on track for the future* (Communication from the Commission to the European Parliement, the Council, the European Economic and Social Committee and the Committee of the Regions : Europe on the Move - COM(2020) 789 final). European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

ECA. (2018). *Towards a successful transport sector in the EU: challenges to be addressed* (p. 60) [Landscape review]. European Union. https://www.eca.europa.eu/Lists/ECADocuments/LR_TRANSPORT/LR_TRANSPORT_EN.pdf

EEA. (2016). *Electric vehicles and the energy sector—Impacts on Europe's future emissions—European Environment Agency* [Briefing]. European Environment Agency. https://www.eea.europa.eu/publications/electric-vehicles-and-the-energy

EEA. (2020). *Transport: Increasing oil consumption and greenhouse gas emissions hamper EU progress towards environment and climate objectives*. European Environment Agency. https://www.eea.europa.eu/downloads/2863e38fe827409d97ecf95e8059cae9/1616670582/increasing-oil-consumption-and-ghg.pdf

Field, F. R., Wallington, T. J., Everson, M., & Kirchain, R. E. (2017). Strategic Materials in the Automobile: A Comprehensive Assessment of Strategic and Minor Metals Use in Passenger Cars and Light Trucks. *Environmental Science & Technology*, *51*(24), 14,436–14444. https://doi.org/10.1021/acs.est.6b06063

Finkbeiner, M., Schau, E. M., Lehmann, A., & Traverso, M. (2010). Towards Life Cycle Sustainability Assessment. *Sustainability*, *2*(10), 3309–3322. https://doi.org/10.3390/su2103309

Guignard, S. (2010). *Histoire du développement en France du Véhicule électrique-Rôle de l'ADEME* (p. 52). ADEME.

Harison, P. (2018). *Fueling Europe's Future-How the transition from oil strengthens the economy.pdf* (p. 28). Cambridge Econometrics. https://www.camecon.com/ how/our-work/fuelling-europes-future/

Hu, Y., Cheng, H., & Tao, S. (2017). Retired Electric Vehicle (EV) Batteries: Integrated Waste Management and Research Needs. *Environmental Science & Technology*, *51*(19), 10927–10929. https://doi.org/10.1021/acs.est.7b04207

IEA. (2020). *Global EV Outlook 2020: Entering the decade of electric drive ?* (p. 276) [Technology report]. International Energy Agency. https://www.iea.org/reports/global-ev-outlook-2020

IPCC. (1990). *Climate Change: The IPCC Scientific Assessment* (J. T. Houghton, G.J. Jenkins and J.J Ephraums). Interngorvernmental Panel on Climate Change. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

IRENA. (2017). *Electric Vehicles: Technology Brief* (p. 52). International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/IRENA_Electric_Vehicles_2017.pdf

IRENA. (2018). *Global Energy Transformation: A Roadmap to 2050* (p. 76). International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf

ISO 15686-1. (2011). *ISO 15686-1:2011 Buildings and constructed assets—Service life planning—Part 1: General principles and framework*. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/04/57/45798.html

ISO14044. (2006). *ISO 14044:2006—Management environnemental—Analyse du cycle de vie—Exigences et lignes directrices*. https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:fr

Kloepffer, W. (2008). Life cycle sustainability assessment of products: (With Comments by Helias A. Udo de Haes, p. 95). *The International Journal of Life Cycle Assessment*, *13*(2), 89–95. https://doi.org/10.1065/lca2008.02.376

Kostiainen, J., & Tuominen, A. (2019). Mobility as a Service—Stakeholders' Challenges and Potential Implications. In B. Müller & G. Meyer (Eds.), *Towards User-Centric Transport in Europe: Challenges, Solutions and Collaborations* (pp. 239–254). Springer International Publishing. https://doi.org/10.1007/978-3-319-99756-8_16

LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte (1), Pub. L. No. 2015–992, 2015-992 (2015). https://www.legifrance.gouv.fr/eli/loi/2015/8/17/DEVX1413992L/jo/texte

MaaS Alliance. (2017). *White Paper: Guidelines & Recommendations to create the foundations for a thriving MaaS Ecosystem*. Maas Alliance. https://maas-alliance.eu/wp-content/uploads/sites/7/2017/09/MaaS-WhitePaper_final_040917-2.pdf

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. W. (1972). *The limits to growth: A Report for THE CLUB OF ROME'S Project on the Predicament of Mankind*. Universe Books. http://www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf

Loi-Mobilités-Présentation du projet de loi d'orientation des mobilités, (2018) (testimony of MTES). https://www.ecologique-solidaire.gouv.fr/sites/default/files/18191_DP_LOM_16p_DEF_Web.pdf

MTES. (2020). *La transition écologique et solidaire vers la neutralité carbone* (p. 192). Ministère de la Transition écologique et solidaire. https://www.ecologie.gouv.fr/sites/default/files/2020-03-25_MTES_SNBC2.pdf

Niestadt, M., & Bjornavold, A. (2019). *Electric road vehicles in the European Union*. 11.

Noussan, M., Hafner, M., & Tagliapietra, S. (2020). The Evolution of Transport Across World Regions. In M. Noussan, M. Hafner, & S. Tagliapietra (Eds.), *The Future of Transport Between Digitalization and Decarbonization: Trends, Strategies and Effects on Energy Consumption* (pp. 1–28). Springer International Publishing. https://doi.org/10.1007/978-3-030-37966-7_1

OECD. (2018). *Rethinking Urban Sprawl: Moving Towards Sustainable Cities*. OECD. https://doi.org/10.1787/9789264189881-en

OGL. (2019). *A time of unprecedented change in the transport system*. Government Office for Science. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/780868/future_of_mobility_final.pdf

OPECST. (2019a). *Comment atteindre l'objectif d'un arrêt de commercialisation des véhicules thermiques en 2040*. http://www2.assemblee-nationale.fr/static/15/infographie_1766.pdf

OPECST. (2019b). *Les scénarios technologiques permettant d'atteindre l'objectif d'un arrêt de la commercialisation des véhicules thermiques en 2040* (p. 4) [Synthèse]. Office parlementaire d'évaluation des choix scientifiques et technologiques. http://www2.assemblee-nationale.fr/content/download/78252/801175/version/2/file/4+pages+2040.pdf

Pasquier, M. (2015). *Automotive battery recycling and second life application (ABATTERLIFE)*.

Rodrigue, J.-P. (2020). Chapter 8 – Urban Transportation | The Geography of Transport Systems. In *The Geography of Transport Systems* (5th ed.). https://transportgeography.org/contents/chapter8/

Rodrigue, J.-P., & Notteboom, T. (2020). 3.1 – Transportation and Economic Development | The Geography of Transport Systems. In *The Geography of Transport Systems* (5th ed., p. 456). https://transportgeography.org/contents/chapter3/transportation-and-economic-development/

Sencier, G., & Delasalle, A. (2015). Les automobiles électriques. *Lilliad - Université de Lille - Sciences et technologies*. http://iris.univ-lille1.fr/handle/1908/3214

Tarne, P., Lehmann, A., & Finkbeiner, M. (2019). Introducing weights to life cycle sustainability assessment—How do decision-makers weight sustainability dimensions? *The International Journal of Life Cycle Assessment*, *24*(3), 530–542. https://doi.org/10.1007/s11367-018-1468-2

Regulation (EU) No 333/2014 of the European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO 2 emissions from new passenger cars, Pub. L. No. 32014R0333, 103 OJ L (2014). http://data.europa.eu/eli/reg/2014/333/oj/eng

Tietge, U., Mock, P., Lutsey, N., & Campestrini, A. (2016). *Comparison of leading electric vehicle policy and deployment in Europe* (p. 88) [White paper]. International Council for Clean Transportation. https://theicct.org/sites/default/files/publications/ICCT_EVpolicies-Europe-201605.pdf

UN. (1998). *KYOTO Protocol to the United Nations framework convention on climate change* (p. 24). United Nations. https://unfccc.int/resource/docs/convkp/kpeng.pdf

UN. (2015). *Paris Agreement* (p. 27). United Nations. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Valdivia, S., Backes, J. G., Traverso, M., Sonnemann, G., Cucurachi, S., Guinée, J. B., Schaubroeck, T., Finkbeiner, M., Leroy-Parmentier, N., Ugaya, C., Peña, C., Zamagni, A., Inaba, A., Amaral, M., Berger, M., Dvarioniene, J., Vakhitova, T., Benoit-Norris, C., Prox, M., … Goedkoop, M. (2021). Principles for the application of life cycle sustainability assessment. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-021-01958-2

Valdivia, S., & Lie, C. M. (2012). Towards a life cycle sustainability Assessment-Making informed choices on products. *Sustainability Assessment*, 86.

Chapter II: The defined methodological framework: An integrated vision from LCSA to the decision-making process

Summary (II)

The present chapter aims at contributing to the methodological development of Life Cycle Sustainability Assessment (LCSA) by addressing the research questions established in the introduction of this thesis. Thus, it seeks to propose a comprehensive LCSA framework that enables the combined analysis of the three sustainability dimensions and the integration of key stakeholders' perspectives. It further explores how LCSA results can support public and private decision makers for the design of more sustainable mobility alternatives.

A global overview of sustainability analysis methods and tools is proposed in **section 1**. It introduces LCSA methodological background and focuses on key features and phases for environmental LCA, S-LCA, and LCC.

In **section 2**, LCSA studies dealing with mobility scenarios are reviewed and analyzed. The main methodological issues are thus highlighted in terms of (i) coherence of the scope (ii) compliance with ISO standards and (iii) transparency of the used data and assumptions. To handle these issues, the present thesis first focuses on how to define mobility scenarios. Four elements need to be defined: (i) transportation technologies (ii) mobility services (iii) roads and infrastructure and (iv) energy powering the vehicles. Three mobility scenarios are defined based on this definition: personal, public and shared mobility, and analyzed with a special focus on electric vehicle technologies.

With respect to the goal of this research to support stakeholders in their decision-making process within LCSA, an identification of mobility key actors is required. Transportation users are found to be a key actor within the ongoing shift towards sustainable mobility. Hence, careful attention is to be paid to account for their needs and expectations so to help private and public decision makers better adapt sustainable mobility schemes.

Section 3 entails the design of LCSA framework fitting the research goals. In this section, two methodological pathways are identified and explored; (i) the first one consists of developing a combined sustainability impact assessment approach that accounts for environmental, social and economic dimensions throughout cause-effect chains (ii) the second one, which has been adopted in the present thesis, consists of independently applying the impact assessment approaches to each dimension. Separate applications of impact assessment approaches (following pathway 2), lead to multidimensional results that require handling the induced trade-offs.

Section 4 comprises the main issues on how to make the most of the proposed LCSA and introduces multicriteria decision analysis (MCDA) techniques to solve the challenges linked to trade-off multi-criteria sustainability indicators management. Guidelines based on four stages are thus proposed to support decision makers (public and private mobility actors) in using LCSA results while accounting for users' expectations and needs: (1) definition of the decision scenario, (2) definition of sustainability criteria, (3) selection and application of the relevant MCDA technique, and (4) results interpretation. The selected MCDA technique herein is the conjoint analysis. It calls for the scoring of preferences by the involved actors instead of weighting the criteria directly. It has been selected in view of its ability to fully integrate the users' needs and expectations within the decision-making process.

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1. Methodological background of sustainability assessment and life cycle-based methods

1.1. Sustainability main methodological references and tools

In view of the ever-increasing and wide-ranging environmental problems the world has witnessed in the last century, global ecological awareness gave birth the concept of sustainability. In 1980, the International Union for Conservation of Nature and Natural Resources (IUCN), United Nations Environment Program (UNEP) and World Wildlife Fund (WWF) published "World Conservation Strategy: Living Resource Conservation for Sustainable Development" (IUCN et al., 1980). Major concerns on climate change, biodiversity, and resources overexploitation were underlined and directly linked to the industrial progress. Afterwards, the concept of sustainable development was defined in 1987, in the report "Our Common Future" by the World Commission on Environment and Development (WCED, 1987), as *"the development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. The authors claimed a balance among sustainability inherent pillars, namely, environmental, social, and economic dimensions, to guarantee equity among future generations.

The Earth Summit was held by the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro (UN 1992) to discuss strategies and visions for a sustainable future. Since then, sustainable development has been adopted at the international level as an overarching principle for human well-being and its interest is constantly increasing both in public and private sectors. Efforts have been focusing on its integration to national and international policies and a broad set of normative references fostered its implementation. These references include the Nation's Millennium Development Goals (European Commission & Eurostat, 2017), the Global Reporting Initiative (GRI, 2016), the ISO 26000:2010 standard, introducing the concept of corporate social responsibility (ISO26000, 2010), and the Organization for Economic and Co-operation and Development principles for multinational organizations (OECD, 2011), etc. Figure 3 illustrates the large panorama of sustainability methods, tools and standards and proposes their classification among two different levels. The first level of classification distinguishes four different scales depending on the focus of the sustainability method: national or international scale, organizational scale, local and territorial scale and, finally, individual product or material scale. The second level of the proposed classification identifies sustainability methodologies and tools that have different objectives. The objectives are classified in three categories: i) impacts' evaluation, ii) management and design, and (iii) communication or reporting. Life cycle-based methods are considered as one of the most effective techniques for evaluating impacts throughout their life cycle stages (Blanc, 2015). They were primarily developed for evaluations at the product level, as illustrated in Figure 3. Given the rising interest and need for impacts' evaluation at the various scales, LCA methods have been increasingly adapted to inform decision makers on how to improve products' environmental, social and economic performances.

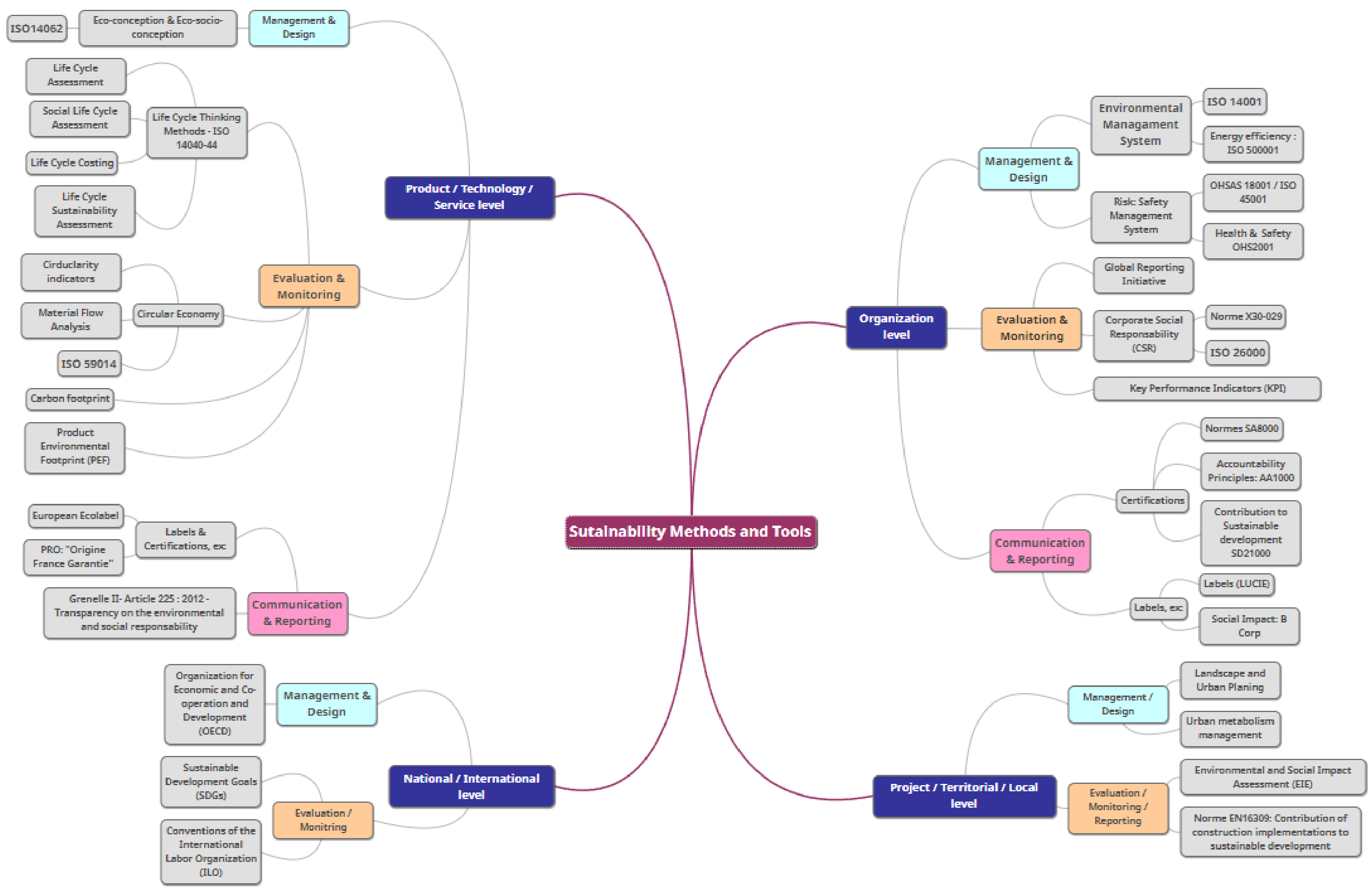

Figure 3 Mind mapping of sustainability evaluation, management and communication methods and tools for the different scales (product, organization, local, national, and international levels), used Mindmap online tool: https://app.mindmup.com/

1.2. Life Cycle Sustainability Assessment (LCSA)

In 2008, Kloepffer (2008) introduced the first formulation for LCSA to allow the identification and assessment of the potential environmental, societal and economic impact categories of product systems. Such model is represented in Equation 1 and Figure 4. LCSA incorporates the life cycle perspective to the three dimensions of sustainable development based on the "triple bottom line" principle. This concept, first defined by Elkington (1998), distinguished three dimensions of sustainability to be integrated within the industrial sector. The aim was to strengthen the vision of organizations in terms of environmental, social, and economic impacts while meeting the constant needs of the industrial progress (Valdivia & Lie, 2012). In this sense, the triple bottom line concept encourages the integration of LCSA to account for the three dimensions simultaneously. Elkington's (1998) definition of "triple bottom line" is in line with the approach known as 3Ps, which stands for Planet, People, Profit and emerged in 2002 (Purvis et al., 2019). Since then, the interest of both public policy-makers and private companies (which constitute the two main groups of decision makers) on LCSA method has drastically increased (Finkbeiner et al., 2010).

[1] LCSA = LCA + S-LCA + LCC

LCSA: Life Cycle Sustainability Assessment
S-LCA: Social Life Cycle Assessment
LCA: environmental Life Cycle Assessment
LCC: Life Cycle Costing

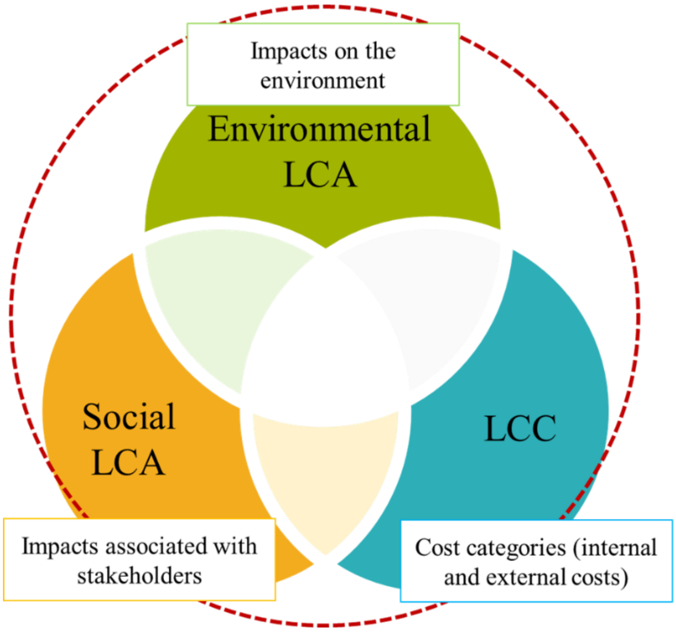

Figure 4 Sustainability pillars and the corresponding LCA methods based on Barbier (1987) proposed model of the three intersecting circles and Kloepffer (2008) first formalized framework for LCSA integrating the TBL to LCT perspective.

Recognizing the need for a global integrated sustainability assessment, the UNEP/SETAC and Life Cycle Initiative published in 2012 global guidance for the implementation of LCSA (Valdivia & Lie, 2012). This document introduced the main features required to conduct a holistic LCSA. These features included specific adjustments for each of the phases of the method.

Valdivia and Lie (2012) also highlighted the interest of integrating the life cycle thinking to sustainability evaluation methods to go beyond the traditional focus on the direct impacts of organizations. A significant number of LCSA studies have further followed (Zamagni 2012; Traverso et al. 2012; Zamagni et al. 2013; Bachmann 2013; Pérez-López 2015; Ekener et al. 2018), seeking to address sustainability of products, technologies, and services and thus, support the decision-making process (De Luca et al., 2017b; N. C. Onat, Kucukvar, Tatari, & Zheng, 2016; Tarne, Lehmann, & Finkbeiner, 2019). Nevertheless, LCSA framework still faces major methodological challenges related to the harmonization between the three dimensions (Valdivia et al., 2021). In order to conceptualize a comprehensive LCSA framework, it is important to understand the key features deriving from each of the environmental LCA, S-LCA and LCC. These features are introduced in the following subsections.

1.2.1. Environmental Life Cycle Assessment (LCA)

Environmental Life Cycle Assessment (LCA) allows the evaluation of the potential environmental impacts related to products (goods and services) throughout their entire life cycle, including raw materials extraction, manufacturing, distribution, use and final disposal at its end of life (ISO 14040 2006). The concept of LCA was first used in the late 1960s to analyze environmental impacts of various packaging options and thus, support the decision-making process for private companies (UNEP/SETAC, 2009). LCA was further applied to other products and technologies contributing, hence, to its methodological development. Over 40 years later, “Guidelines for Life Cycle Assessment: a Code of Practice” (Consoli et al., 1993) was published by SETAC and substantially contributed to a consistent and thorough methodology construction for environmental management.

The ISO 14040-44 standards (ISO 14040 2006; ISO 14044 2006) were later developed and published for the first time in 1997 with the aim of providing more consolidated methodological guidance. LCA was defined as a technique for understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout its life cycle. These international standards established the global framework, which consists of four iterative phases, as presented in Figure 5: (1) Goal and scope definition; (2) Life Cycle Inventory (LCI); (3) Life Cycle Impact Assessment (LCIA); and (4) Life Cycle Interpretation. In addition, the standards provided LCA practitioners with requirements and recommendations for conducting an LCA and thus allow them to i) identify opportunities to improve the environmental performance of products and services, ii) inform decision makers in private and public sectors, and iii) communicate through labels and certifications on the environmental impacts of products.

a. <u>Goal and scope of the study:</u>

This first phase of an LCA consists of defining the objective of the study, the intended application, and the targeted stakeholders. The second element of this step consists of defining the scope of the study. The evaluated product system should be described in detail including the assumptions to be made as well as the functional unit, which serves to represent the function of the evaluated product system according to a measurable reference unit upon which all input and output flows are expressed. The scope of the study should cover the system boundaries within which all the process activities that are accounted in the evaluation are included, as well as the data quality that entails considering the level of precision, variability, completeness and representativeness of the gathered primary and secondary data.

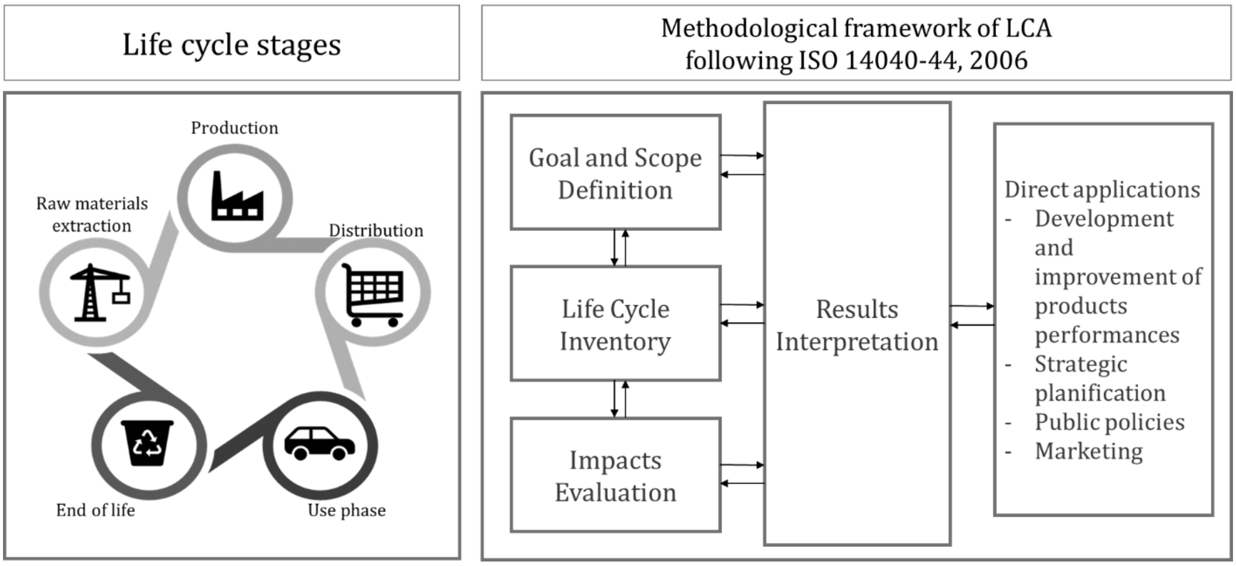

Figure 5 LCA methodological framework adapted from ISO 14040

b. <u>Life Cycle Inventory (LCI):</u>

This second phase consists of collecting qualitative and quantitative data for all input flows (raw materials, energy, water) and output flows (solid waste, emissions to air and water, etc.) in agreement to the considered system boundaries of the study. The collected data should be i) validated following ISO 14040 data quality requirements, ii) related to unit processes and functional unit through an allocation approach if needed. Finally, the system boundaries may be adjusted depending on the selected cut-off criteria.

c. <u>Life Cycle Impact Assessment (LCIA)</u>:

The third phase of LCA entails three mandatory steps:

- Selection of impact categories that should be duly justified according to the goal and scope of the study, environmental indicators and the corresponding characterization models that allow environmental impacts mapping on a cause-effect chain (from environmental inventory indicators to midpoint and endpoint impact categories).

- Classification of LCI results of the substances emitted by the evaluated product system into impact categories, as represented in Figure 6.

- Characterization step, which consists of converting LCI results assigned in the impact categories (step 2) into common units through characterization factors. These characterization factors determine the magnitude of contribution of each input and output flow to the impact category and thus allow the results to be expressed in a uniform reference unit (e.g., kg SO^{-}_2 equivalent for acidification potential).

This phase can also include an additional fourth step depending on the goal and scope of the study, consisting of the normalization of the results, weighting, grouping, and data quality analysis (Finkbeiner et al., 2006).

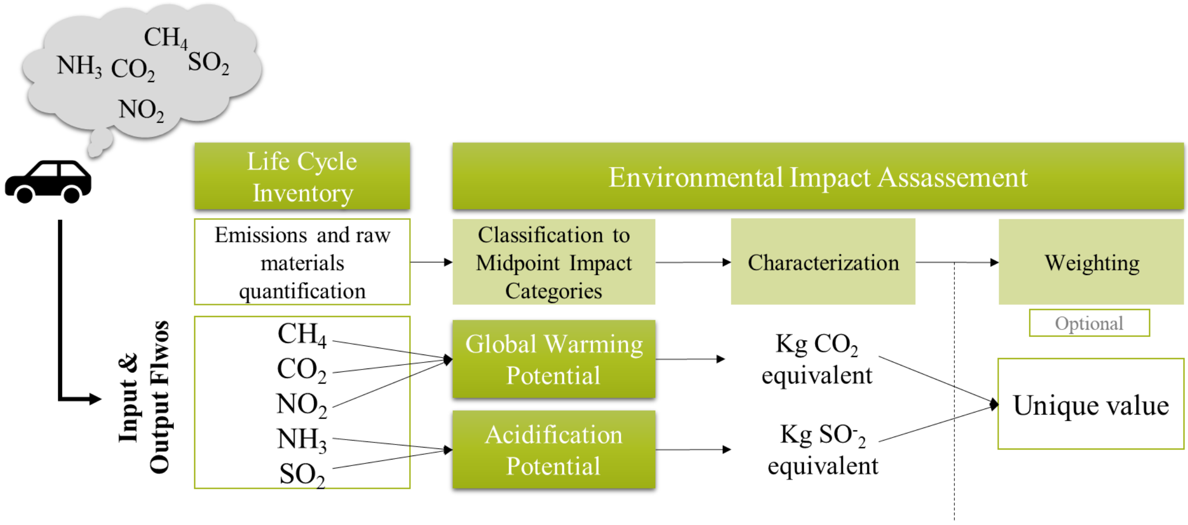

Figure 6 Environmental Life Cycle Impact Assessment: classification and characterization steps

The scope of the evaluated impacts within LCA was gradually extended from energy consumption and solid waste production to other input and output flows. Today, LCA is considered as a multicriteria assessment method that allows various environmental impact categories to be accounted for (JRC, 2010; EC and JRC, 2018), such as global warming potential, acidification potential, resource depletion, to human toxicity, etc. LCA robustness has been significantly enhanced thanks to a wide set of methods and standards developed for the characterization step (EC and JRC, 2018). In fact, recommendations on impact assessment characterization models are regularly published and revised by the European Commission (EC and JRC, 2018; JRC, 2010) to ensure consistent impact assessment results. In addition, methods to analyze uncertainties and variability within LCA are increasingly adopted to support the results interpretation phase.

d. Results interpretation:

The last phase of an LCA consists of analyzing results from both LCI and LCIA phases in line with the goal and scope of the study. This phase also includes a review of the scope, data quality, completeness, sensitivity and consistency of the obtained results related to the product system. The analysis of results should help identify significant environmental impacts and the main contributing process activities for each of the analyzed impact categories.

1.2.2. Social Life Cycle Assessment (S-LCA)

In 1993, a "social welfare impact category" was proposed after the release of the SETAC Workshop report "A Conceptual Framework for Life Cycle Impact Assessment" (Fava et al., 1993). Since then, the debate on how to evaluate social and socio-economic impact categories through LCA methodology is still ongoing (UNEP/SETAC, 2009). Ten years later, the UNEP/SETAC Life Cycle Initiative launched a dedicated task force to work actively on S-LCA development, so as to complete LCA and LCC towards a coherent and integrated sustainability assessment. Social Life Cycle Assessment (S-LCA) methodological framework was developed following the ISO 14040-44 standards (Finkbeiner et al., 2006), originally developed for the environmental LCA. S-LCA is defined as *"a technique that allows social and socio-economic impacts evaluation all along the products and services life cycle stages."* (UNEP, 2020).

The first guidelines for S-LCA of products published by UNEP/SETAC in 2009 (UNEP/SETAC, 2009) introduced five different stakeholder categories, namely workers, value chain actors, local community, consumers and society. A set of impact subcategories was also proposed for each stakeholder group describing the potential impacts that may arise from the product's life cycle stages and the related organization's activities.

Since the publication of S-LCA guidelines (UNEP/SETAC, 2009) and the methodological sheets (Benoît Norris et al., 2013), an increasing number of scientific articles on S-LCA have been published (Dreyer, Hauschild, et Schierbeck 2010; Neugebauer et al. 2014; Zanchi et al. 2018; Arvidsson 2019; Macombe 2019; Mancini et al. 2019). This fact demonstrates the need and interest of this approach to complete the results from the environmental Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) towards a better evaluation of the sustainability of products and services. To further promote the development of S-LCA, the UN Environment Program has published the updated version of the S-LCA guidelines: "Guidelines for Social Life Cycle Assessment of Products and Organizations 2020" (UNEP, 2020). A new stakeholder category "Children" has been introduced and three subcategories are proposed in the guidelines to evaluate potential social and socio-economic impacts affecting this stakeholder category. In addition, the focus has been extended from products to also include an organizational level (UNEP, 2020).

The UNEP S-LCA guidelines for products and organizations (2020) provided guidance for the implementation of S-LCA following the four main iterative phases to be conducted in accordance with the ISO standards (Finkbeiner et al., 2006).

a. <u>Goal and Scope:</u>

This first phase of S-LCA covers the definition of the purpose of the study and the system boundaries under investigation. The goal and scope definition is considered as a key phase of S-LCA (UNEP, 2020). It should describe the main methodological choices adopted such as the functional unit, the cut-off criteria and the impact assessment method together with stakeholder groups and impact subcategories to be considered.

b. <u>Social Life Cycle Inventory (S-LCI):</u>

In this phase, all input and output flows are identified, as well as the social inventory indicators to be evaluated. For each considered product system, data is normalized for a given output process. Input/output flows can then be interlinked through an activity variable. Activity variables were first defined by Norris (2006) to reflect the relevance of social impact subcategories related to the process output. They allow describing the most intensive activities in a unit process and could therefore be used to prioritize data collection and quantify the considered social inventory indicators (UNEP, 2020). The most common activity variable is "working hours" which refers to the number of hours spent to produce 1 USD output of the considered product system (Maister et al., 2020).

The S-LCI covers both quantitative, semi-quantitative and qualitative data collection and validation. Generic databases such as the Production Social Impact Life Cycle Assessment (PSILCA) and Social Hotspots Database (SHDB) can be used as a basis. These make use of economic input/output models for interlinking the process activities and calculate the social inventory indicators based on the working time variable activity.

c. Social Life Cycle Impact Assessment

Social indicators are attributed to the chosen impact subcategories and can then be evaluated according to the chosen S-LCIA approach. Despite providing the main steps and elements to conduct a S-LCA, the framework proposed by these guidelines (UNEP/SETAC, 2009) did not include a clear consensus on the impact assessment method itself. This has led to the development of a large panel of Social Life Cycle Impact Assessment (S-LCIA) approaches. The developed approaches can be classified in two main families as illustrated in Figure 7:

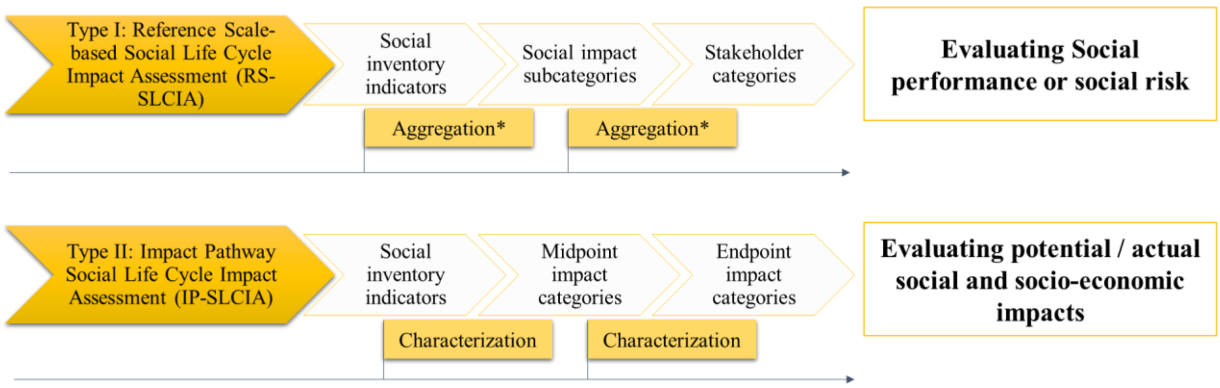

Figure 7 Social Life Cycle Impact Assessment: Type I and Type II approaches, adapted from Neugebauer (2016) and UNEP Guidelines for S-LCA of products and organizations (2020)

- **Reference scale assessment approaches (RS S-LCIA) or "Type I",** which focus on social performance or social risk (Fontes, 2016; Franze, 2011; Goedkoop et al., 2020a; Russo Garrido et al., 2018). The aim is to examine organizations' practices along the entire value chain of the product or service being evaluated. RS-SLCIA approaches compare the life cycle inventory data to Performance Reference Points (PRPs) that represent the expected social performance in terms of each impact subcategory without linking them to endpoint impact categories (representing long-term effects). They therefore estimate the potential social and socio-economic impacts of an activity on a given stakeholder category. Quantitative, qualitative, and semi-quantitative indicators may be defined for each impact subcategory (Benoît Norris et al., 2013), and the data collected can be generic using national and sectorial data or site-specific data. A repository was developed by the "Handbook for Product Social Impact Assessment" (Goedkoop et al., 2020a), which defines performance scales (from -2, -1, 0, +1, to +2) for different indicators associated with impact subcategories for four stakeholder categories; small-scale entrepreneurs, workers, local communities, and consumers.

- **Impact pathway assessment approaches (IP S-LCIA) or “Type II”,** which assess the social and socio-economic potential or actual impacts through characterization models (Dreyer et al., 2010; Jørgensen et al., 2009; Neugebauer et al., 2014; Rugani et al., 2012). The so-called Type II approaches are based, similarly to environmental LCA, on a cause-effect oriented approach (including midpoint and endpoint impact categories). Characterization factors are therefore used to reflect the potential (present or future) social impacts of the entire value chain (Macombe et al., 2013) with a long-term perspective. Despite the connectedness of IP-SLCIA approaches with analogous environmental impact assessment models, their methodological development is slow (Neugebauer et al., 2014). This can be explained by the complexity of identifying and drawing the causal relationships and their translation into appropriate characterization models for all six stakeholder categories proposed by UNEP guidelines.

d. Social Life Cycle Interpretation

The interpretation of results is the final phase of S-LCA. It consists of reviewing all the previous phases and conducting a thorough analysis of S-LCA results. According to requirements of ISO 14044 (ISO 14044 2006), it should cover a completeness check, consistency check, sensitivity and data quality check, a materiality assessment and conclusions, limitations and recommendations (UNEP, 2020). A materiality assessment is a process that selects the most significant social issues regarding their impact on stakeholders or relevance to the business (UNEP, 2020). It has also been defined and recommended by the Global Reporting Initiative (GRI, 2011) and ISO 26000 (ISO26000, 2010) to allow accounting for all relevant topics that might influence the assessment and decision-making process.

1.2.3. Life Cycle Costing (LCC)

Life Cycle Costing (LCC) was first developed by the Defense Department of the United States in mid-1960s for a strictly financial purpose in the military sector (Epstein, 1996). The technique was used to calculate costs related to different life cycle stages of military equipment and thus, analyze the acquisition and operation costs (Asiedu & Gu, 1998). Following this framework, a significant number of LCC tools were developed and used to support purchase decisions and the design of more costs-effective products. In 2011, the first standardized framework for LCC was established to assess building and construction assets following a life cycle perspective that includes operation and end of life stages (ISO 15686-1, 2011). LCC was defined in ISO 15686-1 (2011) as “*a methodology for systematic economic evaluation of life cycle costs over a period of analysis, as defined in the agreed scope”*.

Within sustainability assessment methodologies, an LCC methodology in accordance with environmental LCA was developed by SETAC working group (Hunkeler et al., 2008). The developed method was further used as a basis for the guidelines and a code of practice for LCC published by (Swarr et al., 2011) following ISO 14044 (ISO14044, 2006) standards. Hunkeler et al. (2008) distinguished between three cost categories, namely, direct or internal costs related to the product life cycle, environmental costs and societal costs. These three cost categories can be evaluated respectively through Conventional Life Cycle Costing (Conventional-LCC), Environmental LCC and Societal LCC. While Conventional LCC measures private costs and benefits that are supported by the organization (Figure 8), Environmental and Societal LCC entail a larger scope that includes external costs that may be supported by the society and thus, contribute to better informed decisions.

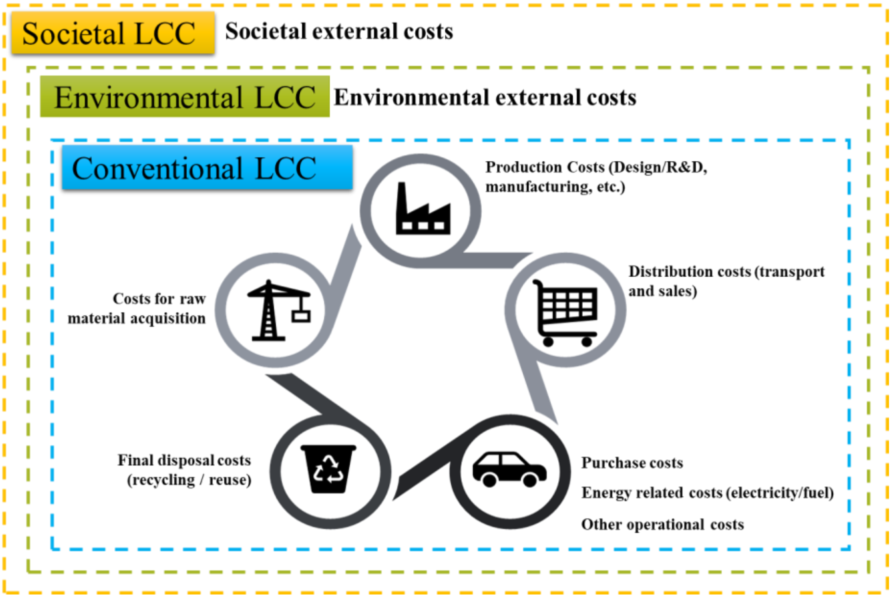

Figure 8 The different scope levels that can be adopted for LCC, adapted from Neugebauer 2016

Although LCC shares the life perspective with LCA and S-LCA, in practice the impact assessment step does not refer to a cause-effect relationship linking cost impact categories to economic "areas of protection" such as value-added, growth, trade, etc. (Neugebauer et al., 2016). Within LCC methodology, impact categories represent aggregated costs that provide a measure of direct impacts (Swarr et al., 2011). In this regard, LCC is often criticized for using merely monetary values through cost categories, which is considered as not sufficient to account for a global economic sustainability.

2. Sustainability assessment of electric mobility integrated to the Life Cycle Thinking

2.1. Literature review of sustainability assessment studies for electric mobility scenarios

As explained in the introduction (chapter 1 of this thesis), electric vehicle alternatives are currently seen as a promising alternative to contribute to sustainable mobility. In this context, sustainability assessment studies have been increasingly adopted to help decision makers (i.e., mobility services providers, technologies manufacturers, etc.) identify the environmental, social and economic potential impacts of future transportation systems. Within this manuscript, a focus has been made on sustainability assessment studies for electric mobility scenarios. The reviewed studies aim to evaluate impact categories on the three sustainability dimensions.

Table 1 presents the identified sustainability assessment studies for mobility including three reviews: methodological publications, literature reviews and case studies. The scopes of the reviewed studies in Table 1 targets both conventional and alternative technologies for passengers' transport and covers, transportation manufacturing and use, energy production, fuel production, transportation infrastructures, mobility services and the. Some of these studies presented a full LCSA with an integrated sustainability interpretation step while others considered each sustainability dimension separately.

As shown in Table 1, sustainability assessment studies that include a life cycle perspective and thus apply a full LCSA are more recent. Wulf et al. (2019) highlighted this aspect and found that the number of LCSA publications is more significant between 2016 and 2018.

The analyzed studies mainly focus on the product and technology level. This can be explained by the barriers that can arise when applying LCSA framework to complex systems. In fact, these systems often require considering a substantial number of components to ensure an exhaustive evaluation. This concept was introduced by Tarne (2019) for the automotive sector, who suggested an application of LCSA per individual component, to overcome this complexity.

Among the different reviewed sustainability studies, only a limited number integrated a life cycle perspective and considered the three sustainability dimensions equally. This finding agrees with the review of sustainability studies in the construction sector by (Backes & Traverso, 2021). **The increasing number of publications tend to focus on case studies rather than methodological aspects** (Wulf et al., 2019). As a result, environmental impacts are the most covered aspect by LCSA studies, while social and economic impacts are often neglected due to several methodological barriers still being identified for S-LCA and LCC.

*Table 1 Summary of the selected 16 sustainability assessment studies in mobility including LCSA studies. The scope of this review covers transportation technologies, mobility services, automotive products and companies, transport infrastructures and related energy systems (in red). *Includes technical/quality social indicators*

Reference	Type	Scale	Scope	LCSA		Objective of the study	Indicators		
				Yes	No		Environmental	Social	Economic
(Tarne, 2019)	Method	Organizational	Automotive – product	**X**		S-LCA targeting data collection MCDA-LCSA weighting factors	**2**	**2**	**2**
(N. C. Onat et al., 2019)	Method and Case study	Product / Technology	Electric vehicle technologies	**X**		Approach for regionalized LCSA of alternative vehicle technologies:	**7**	**4**	**3**
(Traverso et al., 2015)	Method	Product / Technology	Vehicle	**X**		Managing Life Cycle Sustainability Aspects in the Automotive Industry: methodological aspects in LCSA	**--**	**--**	**--**
(Stark et al., 2017)	Method and Case study	Territorial	Urban mobility	**X**		Benefits and obstacles of sustainable product development methods: a case study in the field of urban mobility	**2**	**6***	**1**
(N. C. Onat, Kucukvar, & Tatari, 2016)	Method and Case study	Product / Technology	Alternative vehicle options	**X**		Uncertainty-embedded dynamic life cycle sustainability assessment framework: An ex-ante perspective on the impacts of alternative vehicle options	**1**	**1**	**1**
(Jasinski et al., 2015)	Method	Product / Technology	Vehicle	**X**		A comprehensive framework for automotive sustainability assessment: definition of LCSA impact categories and comprehensive assessment framework	**12**	**8**	**5**
(Günther et al., 2015)	Case study	Product / Technology	Electric vehicles		**X**	Sustainability analysis of electric vehicles supply chain - company specific supply chain models	**1**	**1**	**1**

(Bueno et al., 2015)	Review	Product / Technology	Transport infrastructures		**X**	Literature review of methods and tools for sustainability assessment of transport infrastructure projects	**---**	**---**	**---**
(N. Onat, 2015)	Method and Case study	Product / Technology	Alternative vehicle technologies	**X**		Macro-level sustainability assessment of alternative passenger vehicles. Input-Output analysis coupled with TBL.	**5**	**4**	**3**
(Ben Hnich et al., 2021)	Case study	Product / Technology	Synthetic fuel - palm waste	**X**		Life cycle sustainability assessment of synthetic fuels from date palm waste: application of LCA, S-LCA and LCC	**2**	**2**	**2**
(Hoque et al., 2018)	Review	Product / Technology	Transportation fuels	**X**		Application of Life Cycle Assessment for Sustainability Evaluation of Transportation Fuels	**---**	**--**	**--**
(Ekener et al., 2018)	Method and Case study	Product / Technology	Transportation fuels	**X**		Developing Life Cycle Sustainability Assessment methodology by applying values-based sustainability weighting - Tested on biomass-based and fossil transportation fuels	**4**	**?**	**1**
(Valente et al., 2021)	Case study	Product / Technology	Conventional and renewable hydrogen	**X**		Comparative LCSA of hydrogen fuel	**2**	**2**	**1**
(Santoyo-Castelazo & Azapagic, 2014)	Method and Case study	Product / Technology	Energy systems		**X**	Sustainability assessment of energy systems (coal, oil, natural gas, geothermal, biomass, hydropower, wind turbine, solar, nuclear, wave energy): integrating environmental, economic and social aspects	**10**	**10**	**3**
(Liu, 2014)	Review	Product / Technology	Energy systems		**X**	Development of general sustainability indicators for renewable energy systems	**---**	**---**	**---**

2.2. Definition of electric mobility scenarios: use scenarios and actors' involvement

To enable the development and implementation of an LCSA framework, the work carried out in this thesis first focused on defining the mobility scenarios to be investigated. In fact, mobility is considered as a complex system that can potentially extend over a large geographical scale (local, territorial, national and international) (Gamage, 2011). Such complexity can be explained by the multitude of actors involved in mobility schemes and the very broad system boundaries (vehicles life cycle, fuel or electricity production, transportation infrastructures, etc.). This makes it difficult to establish a methodological framework for sustainability analysis as it involves considering the system life cycle from the three sustainability dimensions. In this regard, mobility scenarios were carefully defined by dissecting all the elements included in.

To serve the goal of the present thesis in informing the private and public mobility decision makers within the shift towards a sustainable mobility, it was necessary to identify the main actors (i.e., involved and affected by the decision-making process) that are involved in mobility schemes and understand the nature of the occurring relationships between them. This reasoning made it possible to identify three key actors that are involved directly within a sustainable mobility transition. They are presented in Figure 9 as well as the connection occurring between them.

- **Public actors** defining actions to meet the requirements of the energy transition law in the transport sector (e.g., local authorities) and guidance for local authorities to implement sustainability action plans and regulations.
- **Industrial actors** who are bringing to market the technologies needed to provide the transport service and develop the necessary infrastructure (infrastructure, fuel, and electricity distribution).
- **Users** choosing among technologies and mobility services those that meet their specific travel needs. They are not decision makers but directly affected by the mobility decision schemes.

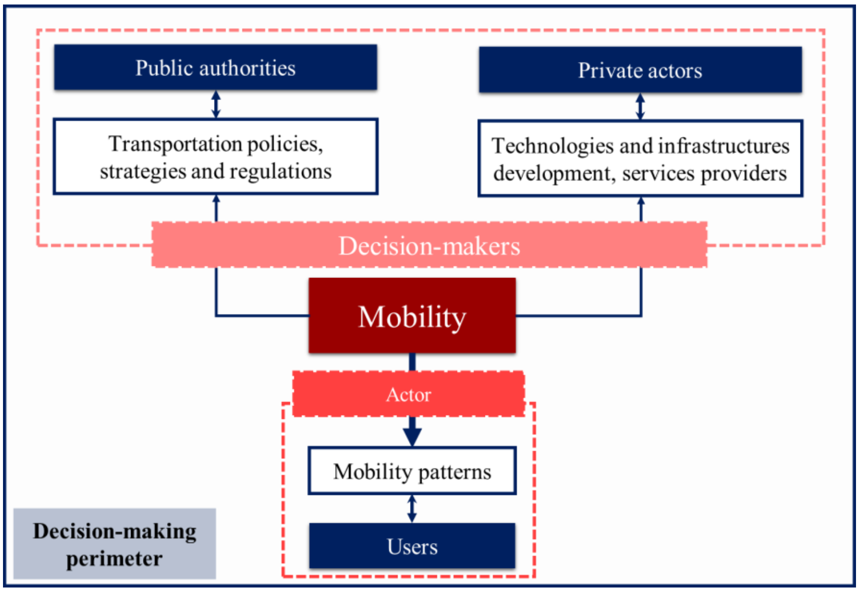

Figure 9 Identified target actors within the sustainability decision-making process of within mobility

Policies and strategies developed by public actors are increasingly oriented towards setting mobility solutions that meet the objectives set in terms of energy transition (Bigo, 2016; *Loi-Mobilités-Présentation du projet de loi d'orientation des mobilités*, 2018). In parallel to these decisions, private actors are adapting their practices to comply with increasingly strict regulations and normative requirements. Thus, to support the ongoing energy transition, new transportation technologies and emerging mobility services have burst into the market. **However, the associated environmental, and particularly social and socio-economic impacts are often unknown and subject to weak regulations.**

As for users, they are increasingly aware of sustainability issues related to their choices, which promotes further the shift towards sustainable mobility patterns. With this regard, private, and public actors are expected to develop mobility alternatives that meet the users' expectations in terms of environmental, social, and economic performances while fulfilling their mobility daily needs. Moreover, the defined measures and policies to meet the transition goals can have substantial effects on users, mainly in terms of their travel patterns (Sierzchula et al., 2014). Hence, if users' expectations and needs in terms of mobility are not understood, several aspects of societal resistance can occur (i.e., habits, data and technophobia, etc.) (Zanchi et al. 2018). **The needs of transport users must, for this purpose, be thoroughly analyzed and their perception must be considered at early stages of the decision-making processes.**

To this end, a new feature is introduced to the sustainability assessment framework proposed in this thesis, which consists of integrating the user's perception into the definition of the assessment method.

Embedding users' perspective will enable the identification of risks and benefits from the deployment of electric mobility scenarios. Moreover, the use of such approach should allow decision makers to account for users' mobility needs and expectations, which is a key factor to achieve sustainable mobility and help decision makers to better size and design future transportation schemes. That being said, users only make a choice based on the availability of transportation alternatives and do not contribute to their design, so they cannot be considered as decision makers but rather as a key actor. Hence, the system boundaries were settled in such a way that can serve the objective of analyzing electric mobility scenarios from a user perspective.

This thesis proposes to define mobility scenarios according to four main elements: (a) **vehicle fleet** (including different technologies), (b) ***transportation energy source*** *(either chemical fuels or electricity)* (c) the **required infrastructures** and (d) the **mobility services** (modes of transport), present on a given geographical area at a territorial, national or international level.

a. Vehicle fleet:

By definition, a vehicle fleet is composed of several vehicles, which can be divided in several segments and powertrains. For personal passenger's transport, the vehicles can be classified as: light vehicle segments (i.e., urban segment A, city cars segment B, mid-range segment C, and high-end segment D)

(IFP Energies Nouvelles, 2018; OIE, 2019), sport utility vehicles (SUV), and bus segments. Buses technologies are in the case of local mobility defined according to two classes of urban areas: class 1 (urban areas with more than 250,000 inhabitants) and class 2 (urban areas with 150,000 to 250,000 inhabitants). It should be noted that electric modes are not present in class 3 (rural areas with fewer than 150,000 inhabitants) (CGEDD et al., 2015). As for the powertrains, they are classified into electric and conventional transportation technologies (Cerdas, Egede, et Herrmann 2018; Del Duce et al. 2016). Conventional vehicles (ICEV) powered by petrol (ICEV-p) or diesel (ICEV-d) and natural gas (ICEV-g) are investigated. Different categories of electric vehicles (EV) can be distinguished depending on the level of electrification: 100% electric vehicles (BEV), hybrid (HEV), plug-in hybrid vehicles (PHEV), and hydrogen vehicles (FCEV).

b. Transportation energy source:

The source of energy powering the vehicle is a determining factor for the environmental impacts. Indeed, emissions during the use phase remain the most significant ones for conventional vehicles over the whole life cycle because of the use of fossil fuels. Despite remarkable improvements in the efficiency of combustion engines over the past decade, and expected ones in the coming years, the energy transition underway imposes exploring other alternatives for non-renewable energy sources. To this end, electrification is proving to be an effective solution for reducing the carbon footprint (Bouter et al., 2020). However, the potential of EVs to reduce the environmental footprint of transportation is conditioned to the use of an electricity mix with low environmental impacts. It is therefore important to account for the environmental impacts linked to the production and consumption of the two types of energy sources powering the vehicles, namely electricity and fuel. Moreover, the impacts, of the broad range of electric vehicle technologies that are gaining importance in the vehicle market, still need to be carefully investigated. The level of electrification (i.e., hybrid, full hybrid, fuel cell, etc.), the size of the vehicles, battery technology, all seem to be important parameters to be considered within LCA of transportation technologies (Sacchi et al., 2021). The energy source can also generate significant social and socio-economic impacts. The extraction of raw materials, often in non-OECD countries, is likely to be a hotspot zone with high social risks for the different stakeholders (i.e., working conditions, healthy and safe living conditions, employment, geopolitical risks, conflicts, etc.) (OECD, 2021). To this end, the shift to electric mobility should be supported by consistent social impact assessment approaches to contribute to better informed decisions.

c. Transportation infrastructures

Transportation infrastructures include road's construction and maintenance, as well as all the related infrastructures for the energy powering sources (i.e., charging infrastructures). Within a massive development of electric mobility, several studies have analyzed their relative impacts on the electricity network from a sustainability perspective (Bueno et al., 2015; RTE, 2015; Arshad et al., 2021; Hosny et al., 2021). Such studies are key to ensure a balance of electricity supply and demand, and to investigate the potential socio-economic impacts in a long-term perspective. Furthermore, an economic analysis can be performed to determine the costs of deployment and use, as well as the generated profits (RTE, 2017a). Nevertheless, charging infrastructures are still poorly addressed within LCA studies and the impacts related to their production and use are thus still unrevealed (Z. Zhang et al., 2019). This aspect should be further analyzed within three-sustainability dimensions.

d. Mobility services

The mobility of people is first and foremost a social need related to the movement of passengers from point A to point B, enabling them to carry out their daily activities (work, leisure, supply, etc.). Users' mobility needs are fulfilled by different mobility services including collective, personal, and shared transportation modes. These services have different characteristics and do not necessarily meet the same criteria that passengers set in terms of cost, comfort, travel time, etc. In this regard, it is necessary to account for mobility services and their synergies with electric vehicle technologies in urban areas.

In view of the four elements defined above, Figure 10 illustrates the three mobility scenarios that were established to be analyzed through the LCSA framework proposed in this thesis, including an assessment from the users' perspective. Three scenarios are analyzed, corresponding to: scenario 1 "collective mobility", scenario 2 "personal mobility", scenario 3 "shared mobility".

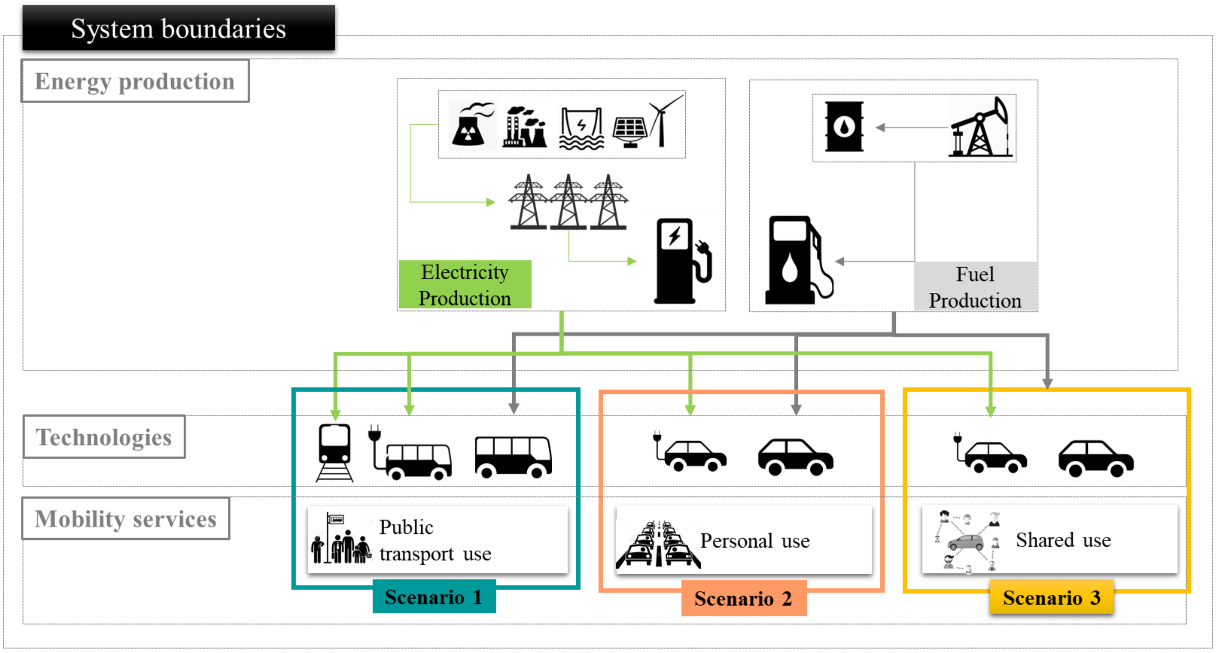

Figure 10: the considered mobility scenarios along the 4 elements (technologies, services, transportation infrastructures and energy sources) defined within this thesis

The three defined scenarios are analyzed for an urban area to enable the investigation of the sustainability of both vehicle technologies and mobility services within the context of a short-distance passenger's transportation. The interest in considering a local mobility scenario can be summarized in the following key points:

- 95% of GHG emissions come from road transport, 56% of which are associated with passenger transport versus 43% for freight transport (CGDD, 2019).
- Individual passenger transport accounts for 80% of road transport and is the main source of transport impacts (CGDD, 2021).
- 98% of French people's trips are short-distance trips (less than 80 km).
- Modal shift combined with electric vehicle technologies may be an opportunity to reduce the environmental footprint of transport, as stated in the existing prospective scenarios (Bigo, 2020).

Within the implementation LCSA framework, it is important to ensure that the covered system boundaries, as well as the geographical and temporal scales, are coherent for all three sustainability dimensions (Valdivia et al., 2021). **Such constraints directly affect the feasibility of the general framework, since the current development of S-LCA and LCC may not allow to cover a similar level of detail as that of the environmental LCA.** To this end, the implementation of the developed approach in this thesis was narrowed down to ensure the coherence of the assessment according to data availability. Hence, the analysis focuses on the French context. Thus, the French electricity mix was considered for powering electric vehicles with respect to the most updated values for the input and output flows. A mid-size vehicle technology is considered for both personal and shared mobility scenarios, as for public transport use, the available generic data was used to model bus technologies. The conducted research does not assess prospective mobility scenarios since the analysis is performed following an attributional LCA model. Hence, the results do not cover the potential evolution of environmental, social and economic impacts over time (e.g., evolution of battery technologies, materials supply, cost projections, geopolitical situations).

3. Designing a comprehensive LCSA methodological framework

With the ambition of designing an LCSA framework, this thesis focuses on how the three LCA approaches could be brought together in a comprehensive method. Such framework should ensure the connectedness between the impact assessment approaches for the three sustainability dimensions. In addition, a thorough interpretation of results is required to provide decision makers with insight on the sustainability performance of products and services. This requires adopting an interdimensional analysis of the environmental, social and economic impact assessment results. Moreover, the present thesis explores the potential of participatory approaches to improve stakeholders' involvement from the sustainability analysis to the decision-making process.

The development of a consistent method for sustainability assessment requires considering a set of key features that can be structured within the four phases recommended in ISO standards (Finkbeiner et al., 2006; Valdivia & Lie, 2012). The following paragraphs describe each of the four phases that need to be considered within LCSA with respect to the three sustainability pillars. Key features to be addressed and the challenges to overcome are thus highlighted in accordance with the defined LCSA principles by Valdivia et al., (2021).

Phase 1: Definition of the objective and scope of the study

The UNEP/SETAC guidelines for LCSA (Valdivia & Lie, 2012) recommend defining a common objective when conducting an LCSA. In fact, LCA, S-LCA, and LCC can have different objectives that could be reflected on the key features of this stage. Hence, the LCSA study should ensure that the models and assumptions are appropriate for the three dimensions:

- **Functional unit:** LCSA requires that characterization factors are linked to life cycle inventories through a common functional unit for all three dimensions. For example, in the case of S-LCA, the functional unit consists of describing both the technical function and the product utility (Traverso et al., 2015) which is not necessarily the case for environmental LCA or LCC.
- **System boundaries:** as stated by Valdivia & Lie (2012), LCSA requires adopting a global vision of the three sustainability dimensions when defining the system boundaries in order to identify the different issues that may represent significant impacts. Each of the three dimensions entails addressing relevant impact categories. As a result, life cycle stages and their corresponding process activities should be carefully selected according to their relevance for the three pillars. For example, the purchase and vehicles' acquisition can be of major importance from a socio-economic point of view, while the link with the relative environmental impacts are not evident to draw. Indeed, factors such as the availability of charging stations or their adaptability to the types of charging required for BEV technologies (type 1, 2, 3) can slow down the development of electric mobility and its social acceptance.
- **Impact categories:** the previous step makes it possible to identify the potential impact categories considering the three dimensions and the different life cycle stages. In addition, identification of stakeholder groups is necessary at this stage to allow the identification of social impact categories to be evaluated through S-LCA. Considering different stakeholders' perceptions is recommended by several studies in this step (Santoyo-Castelazo & Azapagic, 2014; Zamagni et al., 2013).

Phase 2 Life Cycle Inventory (LCI) for LCSA

In this step, it is advisable to consider both the interactions between the different unit processes of the evaluated product system and the organizational aspects (certifications and system management) to achieve consistency among the three techniques (environmental LCA, S-LCA, LCC). Data availability and its accessibility are two limiting factors for S-LCA and consequently for the LCSA. As explained, the existing databases for S-LCA are only compatible with Type I impact assessment approaches and provide generic data following the country specific sector concept. Hence, when choosing to perform a combined LCSA, the current databases for S-LCA are not coherent with LCSA characterization models used within IP S-LCIA and use the reference scales instead. A generic database for LCSA named

"SOCA" is under development since 2018, relying on the "ecoinvent" and "PSILCA" databases and aiming to be usable in OpenLCA (Del Duce et al., 2016b; Eisfeldt et al., 2017; Maister et al., 2020).

Phase 3: Life Cycle Impact Assessment in LCSA

The impact assessment entails the calculation of the input and output flows based on the collected data in phase 2 for the defined environmental, social and economic impact categories. As previously stated, the impact assessment approaches are different from one sustainability dimension to another. Hence, major methodological issues are raised in this step. Two potential pathways to design the impact assessment phase are identified for this purpose. Pathway (1) seeks to establish a combined LCSA methodology by developing coherent life cycle impact assessment (LCIA) approaches. This pathway calls for the development of characterization models for each dimension, in consistency with a cause-effect chain "impact pathway", as it is the case for the environmental dimension. On the other hand, pathway (2) allows an individual application of the three LCIA techniques and integrates other complementary techniques to support the decision-making process in the results' interpretation phase. In this thesis, both pathways were explored, and their respective challenges were identified to define the most appropriate approach to be followed within the development of LCSA framework. Both pathways are thus explained in the coming sections 3.2. and 3.3.

Phase 4: Interpretation of Results in LCSA

This phase involves expanding the view to cover all three dimensions when interpreting the results to identify the life cycle phases that are contributing the most to impacts. Process activities and their corresponding geographical area can also be traced back to allow pathways for sustainability performance improvement to be identified. However, as explained in the introduction chapter, the interpretation step of LCSA is very challenging due to the multitude of impact categories to be considered within the three LCA methods. Such statement was confirmed by the literature review of LCSA studies conducted in this PhD thesis (table 1, section 2.1), which proved that only a limited number of environmental, social, and economic impact categories were usually considered to facilitate the interpretation of the results. They can be selected depending on their relevance for the goal and scope of the study. However, consistent methods for selecting sustainability criteria are still needed. Moreover, combined interpretation of LCSA results often pose trade-off issues, which can be limiting factor for using LCSA to support decision-making. In this regard, the current PhD thesis explores how to tackle the challenges related to the results' interpretation phase of sustainability assessment.

3.1. Pathway (1): A combined life cycle sustainability impact assessment methodology

The first identified pathway comprises, in accordance with ISO standards (Finkbeiner et al., 2006), the classification and characterization of impacts included in a set of analyzed impact categories. Such framework is based on the environmental LCIA phase, which requires converting the environmental input and output flows assigned in midpoint impact categories into common units through characterization factors. Within a sustainability impact assessment, analogous characterization models should be developed for S-LCA and LCC. Such models are illustrated in Figure 11, which highlights the main steps of the impact assessment phase (i.e., classification, characterization, and weighting).

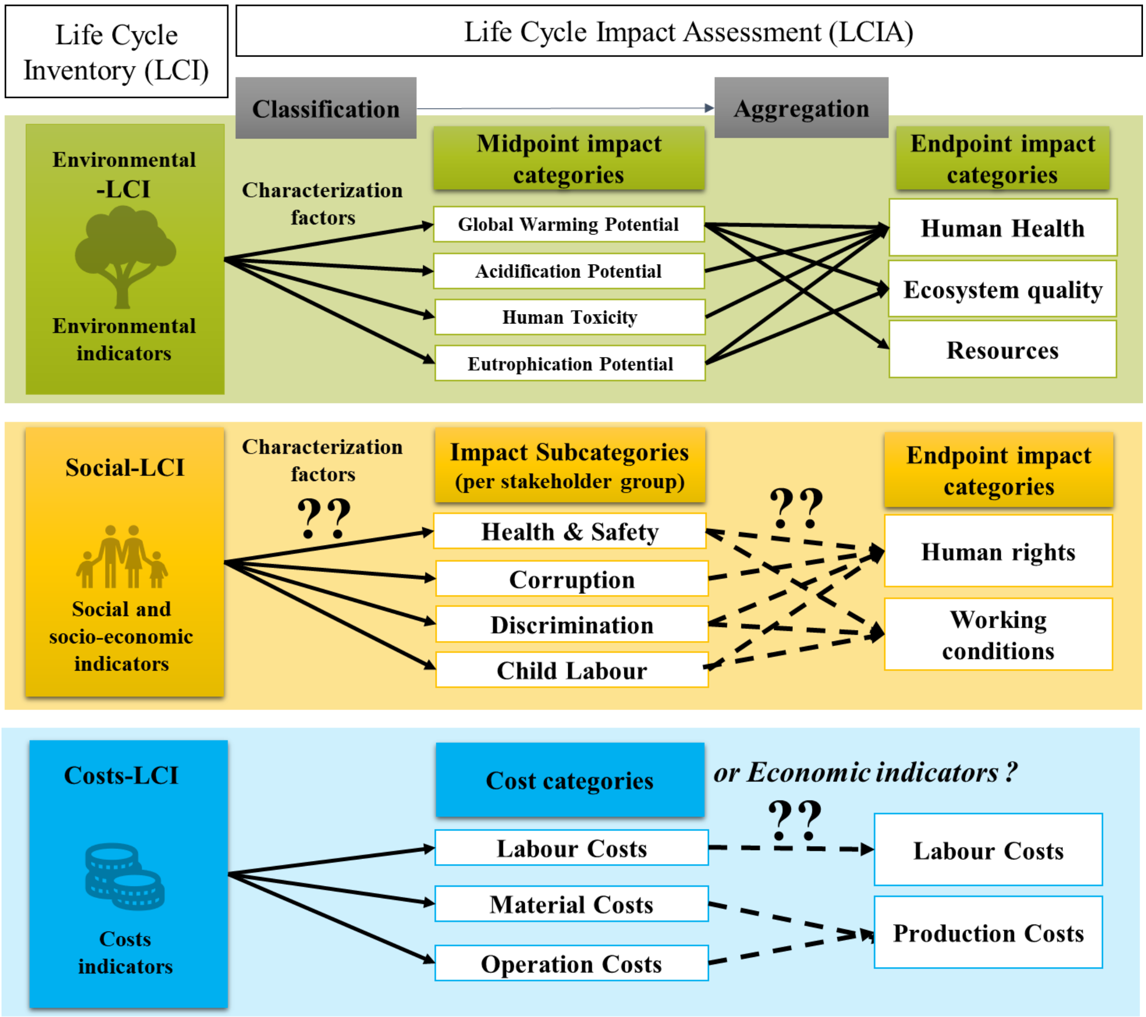

Figure 11 Combined life cycle sustainability impacts assessment: key features and challenges

When choosing the pathway of a combined LCSA method, characterization models for the social and economic dimensions will have to be compatible with the characterization models in the environmental LCA to ensure a consistent method. In this regard, the so-called "Type II" impact assessment approaches appear to be the most appropriate to analyze the social impact subcategories (Valdivia & Lie, 2012; Ekener et al., 2018). However, the use of impact pathway model-based approaches (IP-SLCIA) requires characterization models that are still at an early stage of development. Although several studies have attempted to develop these models, impact subcategories are still far from being totally covered and the stakeholder categories that are fundamental for S-LCA are not all addressed (Neugebauer et al., 2014). Moreover, it should be noted that the impact assessment in LCC follows a different approach than the one in environmental LCA and S-LCA, when accounting solely for direct costs. In case of considering economic indicators such as “value-added indicator”, characterization models for LCC should be developed in accordance with the overall methodology.

The lack of characterization models is associated with the difficulty of defining a common functional unit for different social and socio-economic impact subcategories but also in common with the other sustainability dimensions. In addition, being limited to working hours or wages as an activity variable, only part of the impacts on the category of workers can be reflected (Dreyer et al., 2010). **As a result, other stakeholder groups cannot be evaluated yet, as no correlation exist with the workers' activity variable.** Such evaluation is essential to fulfill the objective of this thesis. In this regard, more maturity is needed for the social impact categories characterization. This requires developing economic indicators to be integrated in a combined impact assessment model for LCSA (Neugebauer et al., 2016).

3.2. The limits of a combined sustainability impact assessment within LCSA

Given the multiple challenges that were identified and discussed in the previous sections, it was concluded that gaining more knowledge on characterization models specific to S-LCA and LCC is crucial to conduct a combined impact assessment in LCSA. This lack of knowledge paved the way to question the whole framework in this PhD thesis. In view of the highlighted methodological issues for developing a combined sustainability impact assessment approach, a question has arisen: **Are S-LCA and LCC characterization models essential to ensure the harmonization of LCSA?**

Although the need for an integrated sustainability assessment is undeniable, it is arguable whether the development of specific characterization models is adequate for each of the three sustainability dimensions or not. In fact, the three sustainability pillars address different types of information corresponding to material and energy flows for the environmental dimension, social sensitive flows related to stakeholder groups for the social dimension and finally monetary flows for the economic dimension. This highly variable nature should be considered to enable a consistent analysis of results and avoid missing significant impact categories due to the lack of a coherent methodological development.

As explained in the previous sections, environmental LCA, S-LCA and LCC have different backgrounds and are not at the same level of development and implementation. So far, efforts have focused on adapting S-LCA and LCC to the existing LCA method for environmental impact evaluation. This can be explained by the fact that primary audience and practitioners for these techniques were environmental LCA experts (UNEP, 2020). Hence, careful attention should be accorded when adopting the same matrix to analyze social and socio-economic impact categories. In fact, this can lead to some serious shortages while evaluating sustainability, which usually requires considering indicators that cannot be quantified and projected on cause-effect relationships. As a result, the present thesis explores an alternative methodological pathway to allow the design of a comprehensive LCSA method implemented to electric mobility scenarios.

3.3. Pathway (2): the proposed LCSA framework: environmental, social, and economic LCIA approaches

The identified pathway (2) adopted in this PhD thesis aims to design a global sustainability method using a separate assessment of LCIA approaches for each of the three dimensions. Such structure is illustrated in Figure 12. The aim is to use approaches that fit the nature of each sustainability dimension thus, allowing the evaluation of all significant impact categories. For this purpose, the main methodological aspects related to the three-life cycle-based methods are addressed, as well as requirements for conducting a coherent LCSA framework regarding the system boundaries and the functional unit.

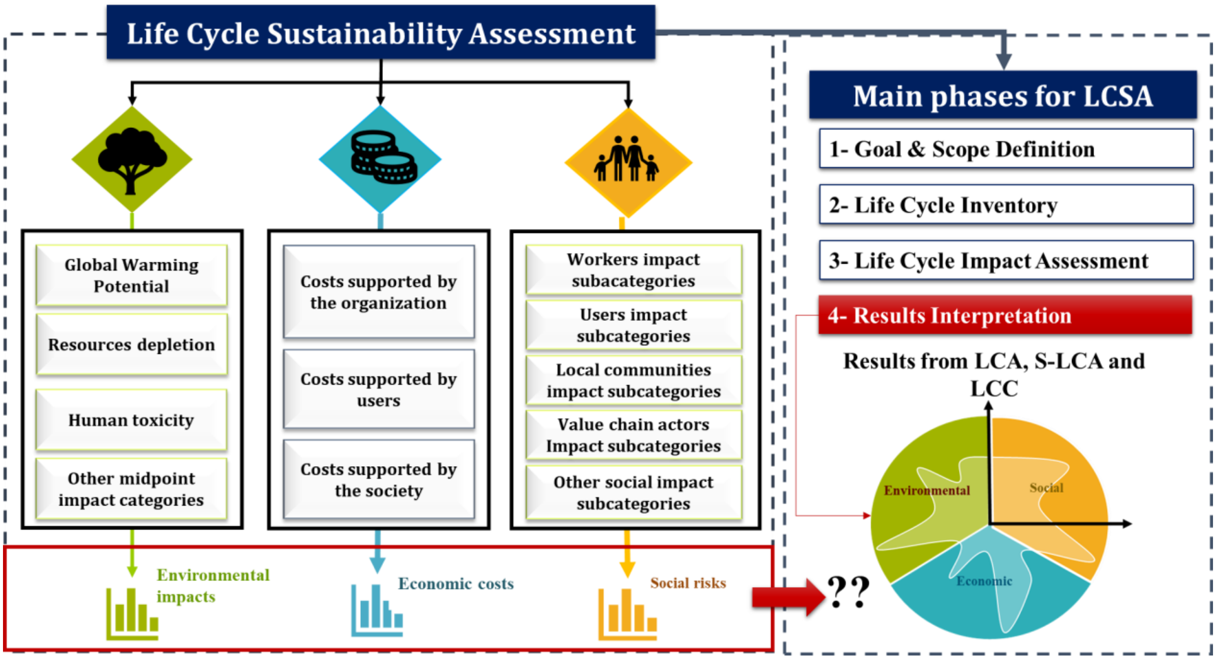

Figure 12 The designed LCSA framework: key features and challenges to be addressed

As reflected in the first research question of this thesis, limitations related to S-LCA and LCC implementation should be solved to allow the design of a comprehensive sustainability evaluation method. Results for each sustainability dimension should be sufficiently consistent and representative to support the decision-making process. Although environmental LCA has been widely implemented to analyze different mobility scenarios, a global S-LCA framework that addresses both mobility technologies and services is still lacking. In addition, LCC is implemented at the technologies' level yet, the mobility services are still not clearly addressed. To overcome these limitations, the following sub-targets have been fixed:

- **Environmental dimension:** Based on the defined mobility scenarios, a systematic approach is proposed to integrate a parametrized LCA model for mobility technologies allowing thus to enhance representativeness of the multiple technological aspects that may influence the results. The main influent parameters on the environmental impacts are identified as well as the potential environmental impacts of the three considered electric mobility scenarios.

- **Social dimension:** A step-by-step S-LCA framework is proposed ensuring a consistent social and socio-economic evaluation of electric mobility scenarios. Reference Scale-based Social Life Cycle Impact Assessment (RS-SLCIA) approaches are adopted to allow accounting for the different stakeholder groups that could be involved or affected from the value chain of the evaluated product system. The adapted framework for S-LCA includes a novel participatory approach that allows stakeholders' perception to be accounted for in order to select the most relevant social and socio-economic subcategories for the evaluation. In addition, a set of specific indicators are defined in accordance with a user-centric vision adopted in this thesis. Specific social and socio-economic indicators and their calculation methods are therefore developed for electric mobility scenarios to enhance potential impacts' assessment for users' stakeholder group. This additional step in the impact assessment phase allows thus mobility services (i.e., personal, public and shared transportation) to be analyzed from a user's perspective.
- **Economic dimension**: several techniques are studied in terms of their relevance with respect to the defined methodological framework for sustainability evaluation including conventional Life Cycle Costing (LCC), environmental LCC and societal LCC. In line with the goal of the study, this chapter suggests the key steps to be conducted in accordance with ISO standards when performing an economic assessment of mobility scenarios. To enable the user-centric vision within LCC, a Total Cost of Ownership (TCO) technique is adopted and applied to different transportation technologies from the users' point of view. The evaluation phase is, thus, complemented by a service costs calculation for each of the mobility services through a user-centric approach.

4. Tackling trade-off management challenges in LCSA through MCDA approaches

Following the separate application of impact assessment approaches, an important question rises regarding the interpretation phase, which is also the main challenge associated to this second pathway. In fact, the three LCA techniques deliver **separate multidimensional results** (potential environmental impacts, social risk or performance and cost categories), as presented in Figure 13, which induce trade-offs' management. A straightforward interpretation of LCSA results is insufficient to guide decisions in view of the complexity of the systems studied on the one hand, and the divergence of sustainability dimensions on the other. Results from environmental, social, and economic pillars can present heterogenous and sometimes contradictory performances.

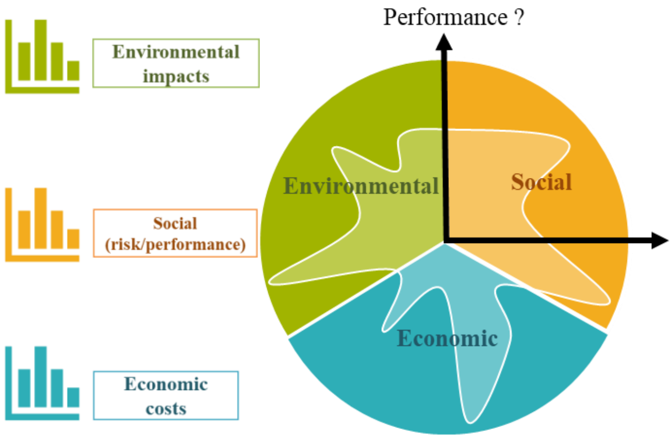

Figure 13 Illustration of trade-off management within LCSA interpretation step

Regarding this type of multi-criteria problem, LCSA outcomes can only set compromises between impact categories and among the sustainability dimensions. Hence, guiding the choice of decision-makers turns out to be complex. Further techniques are necessary to go beyond a simple or even partial representation of sustainability. This issue is directly connected to the second research question seeking to inform the decision-making process in the ongoing shift of the transport sector. This requires handling the induced compromises from LCSA results. In this regard, multicriteria decision analysis (MCDA) approaches for a thorough interpretation of LCSA results within a comprehensive LCSA framework. In fact, MCDA approaches are recognized as the most effective decision-making tools to handle the induced compromises from multicriteria problems. Moreover, they were used in a substantial number of studies dealing with transportation sustainability (Macharis et al., 2009; Barfod, 2018; R. Zhang & Zhao, 2018; Nalmpantis et al., 2019; Brusselaers et al., 2021; Gompf et al., 2021).

MCDA includes a set of approaches that seek to support decision-making problems that call for trade-offs' management. To this end, MCDA enables accounting for multiple criteria, decision scenarios and involved actors in the decision-making scheme, with the aim to compare and/or select the most appropriate alternatives (Cinelli et al., 2014). These can be very relevant within the context of sustainability analysis allowing thus to tackle the challenges that are likely to raise during the interpretation of results phase.

Within the current thesis, the design of a comprehensive LCSA framework is conducted through an individual application of LCIA approaches of the three sustainability dimensions. Thus, to support the results' interpretation phase, MCDA approaches are explored and introduced to support the decision-making process while accounting for a given actor's perspective. To serve this end, the following sub-targets have been settled:

- ✓ **Identification of the different multicriteria decision analysis (MCDA) approaches to allow an effective interpretation of LCSA results.**

- ✓ **Establishment of a step-by-step procedure that covers the definition of the decision scenario, the selection of sustainability criteria and the involvement of stakeholders in the overall framework.**
- ✓ **Implementation of the proposed methodological framework integrating MCDA with LCSA is applied to a specific case study of electric mobility scenarios from a user's perspective. This section application seeks to check the consistency of the overall proposed framework by narrowing down the scope to a specific geographical context and mobility commuting travel. Later on, a discussion is provided on the generalization and application of the method to embed other actors' perspectives and other mobility scenarios.**

4.1. MCDA approaches to support the LCSA Interpretation of results

Despite the undeniable progress of research in this field, most of the authors still highlight the difficulties to define "the most appropriate" MCDA approach (Guitouni & Martel, 1998; Cinelli et al., 2014; Wątróbski et al., 2019). Such statement is also reflected within studies that attempted to integrate MCDA approaches to LCSA (He-Hua et al., 2018; Tarne, Lehmann, & Finkbeiner, 2019; Arshad et al., 2021). In fact, these studies have used different MCDA techniques, yet no clear reporting of the actual reasons and motivations for the choices were given. Hence, two questions were raised in the thesis at this stage:

- ✓ What are the different MCDA approaches that can be used to support LCSA framework?
- ✓ What is the most appropriate technique to support the decision-making process within LCSA of electric mobility scenarios while accounting for users' needs and expectations?

In accordance with Cinelli et al. (2014), the literature review reveals a consensus on three categories of MCDA approaches. These three categories have been summarized in the following paragraphs by describing the corresponding approaches:

a. <u>Utility-based approaches</u>

This first type regroups the most widely used MCDA approaches to handle decision-making issues from sustainability analysis studies (Macharis et al., 2009; Cinelli et al., 2014; Mohd Safian & Nawawi, 2011; Garrido Fernández, 2018; Gompf et al., 2021). They consist of aggregating a set of criteria by directly converting them into a single criterion. Such approaches usually call for participatory methods that involve decision makers to perform the weighting of criteria through a scoring system that expresses the levels of performance. There is a broad range of approaches that use this utility-based theory, namely analytical hierarchy process (AHP), method of the weighted sum (Rowley et al., 2012; Majumder, 2015), multi-attribute utility theory , etc.

Analytic Hierarchy Process (AHP), since its development by R. W. Saaty, (1987), has been widely adopted in view of its easiness of implementation (Cinelli et al., 2014). In addition, it was supported by several tools and software that have fostered its application (Goepel, 2018). Such approach uses a pairwise comparison of criteria and their sub-criteria in a hierarchical manner to evaluate the different alternatives that arise by comparing the alternatives in pairs (T. L. Saaty, 1989). First, sub-criteria are reduced to a single criterion based on a set of weighting factors. Subsequently, the weights of each criterion and alternative are calculated. For n =3 criteria, a binary comparison of (C_1/C_2) (C_1/C_3) (C_2/C_3) allows us to develop weighting factors relative to each of the criteria (w_c). We thus constitute the following matrix (Table 2):

Table 2 Decision criteria matrix and weighting factors calculation (R. W. Saaty, 1987)

	C_1	C_2	C_3	Weighting factors
C_1	1	w_{12}	w_{13}	$\frac{w_{12} * w_{13}}{n}$
C_2	w_{21}	1	w_{23}	$\frac{w_{21} * w_{23}}{n}$
C_3	w_{31}	w_{32}	1	$\frac{w_{31} * w_{32}}{n}$

b. <u>Outranking-based methods</u>

The second type of MCDA approaches identified from the literature corresponds to methods that use preference aggregations and focus on the alternatives. They can also use pairwise comparisons that considers over-ranking through an actor value choice. For example, ELECTRE approach which stands for “elimination and choice expressing the reality” is structured over four elements determining the preference score of the alternatives (i.e., elementary binary relations, indifference, preference, weak) (Roy & Vanderpooten, 1996; Kaya & Kahraman, 2011). This type of approach is relevant for cases where the decision criteria cannot be aggregated in a single criterion. In fact, they allow accounting for criteria with exogenous nature by assessing the preference models from a set of proposed alternatives and avoid direct aggregation of the criteria (Jacquet-Lagrèze & Siskos, 2001). Similarly to ELECTRE approaches, the preference ranking organization method for the enrichment of evaluation (PROMETHEE) also uses the outranking method to calculate the relative importance.

c. <u>Decision-making utility methods</u>

The third type of MCDA approaches that were identified are “data oriented” approaches. These techniques allow the assessment of a set of decision scenarios through decision-making units (Cooper et al., 2004). Data Envelopment analysis (DEA) calls for multiple scenarios’ analysis to identify those who meet the maximum number of settled decision criteria with a satisfying level of performance. Vázquez-Rowe & Iribarren, (2015) have coupled such technique with environmental LCA to identify the most environmentally performant scenarios. However, it should be noted that these approaches are based on empirical observations and do not integrate the different actors' perspectives into the overall decision-making framework. It seemed for this reason that it is not the most appropriate option in the present thesis as the goal is to consider users' perspective in terms of their needs and expectations. Moreover, a significant amount of information is needed to support the data analysis as the method requires accounting for a high number of scenarios to enable an exhaustive assessment.

4.2. The designed framework for the introduction of MCDA to LCSA

To answer the defined sub-targets, this section entails the introduction of an MCDA technique to the overall proposed LCSA framework. Such methodological contribution seeks to support the interpretation of LCSA results, individually obtained for each dimension, and thus help inform decision makers on the sustainability issues while accounting for users' needs and expectations. The designed framework includes four main steps, illustrated in Figure 14 and further explained step-by-step in the subsequent paragraphs.

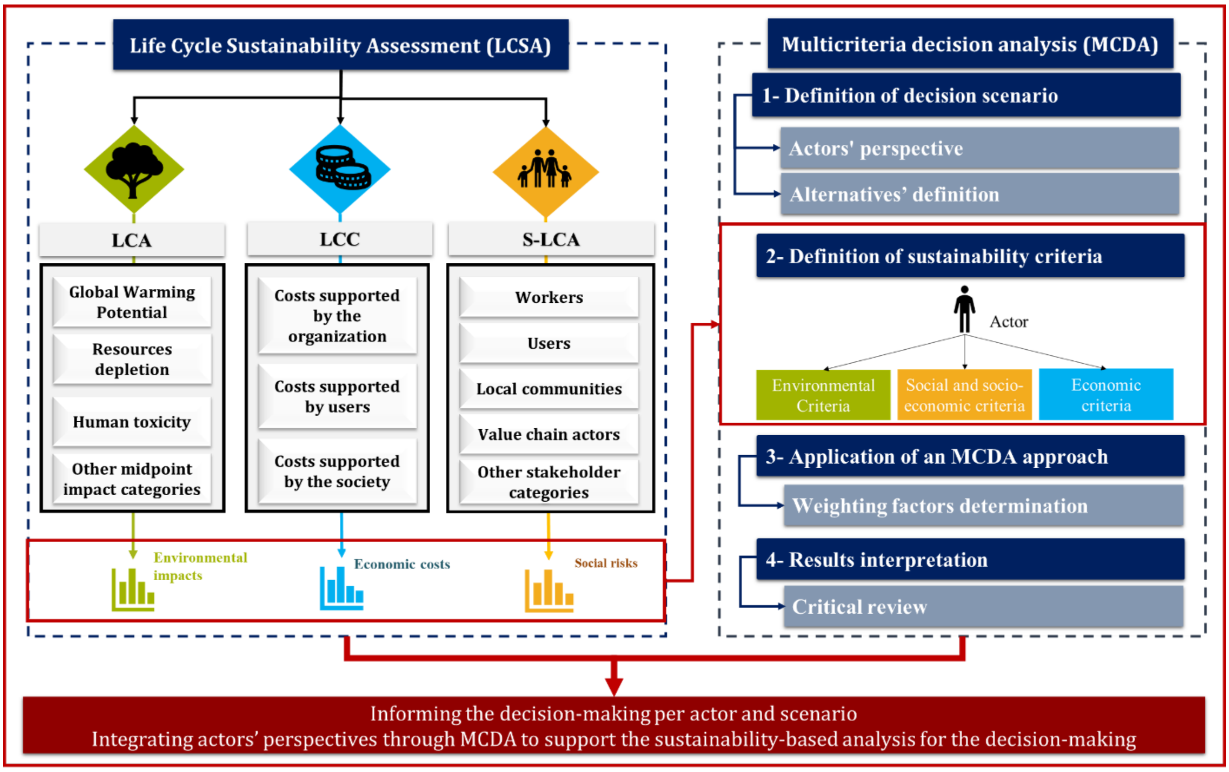

Figure 14 The main steps for the application of an MCDA technique to LCSA global framework

4.2.1. Definition of the decision-making scenario

This first step includes the definition of the alternatives and the concerned actors within the specific decision-making scenario. The alternatives represent here the scenarios evaluated through LCSA for which the results need to be analyzed from a sustainability perspective. The geographical, social and political context also need to be defined.

Target actors could be identified depending on the nature of their involvement in the decision scenarios and their relevance for the goal and scope of the study.

4.2.2. Definition of sustainability decision-making criteria

In this second step, decision-making criteria are identified and selected to perform the MCDA. Three main steps are proposed in this thesis.

a. **Definition of sustainability decision-making criteria**: an approach is proposed for actors' involvement within this step, in order to identify relevant criteria. The criteria considered when applying MCDA should also reflect the needs and the expectations together with sustainability impact categories to enable better representativeness of the actual decision-making scenario. In this regard, different consultation methods can be used to collect the needed information. In this thesis, a direct citation method, based on a focus group is used, allowing the actors to express their needs. Actors are therefore asked to generate the largest possible number of environmental, social and economic criteria that could affect their decisions and thus, guide their preferences and choices in terms of the considered scenarios. The brainstorming is conducted for each sustainability criterion individually and classified into three main categories.

b. **Hierarchization of actors' priority for decision criteria**: the involved actors are asked, in the second part of the focus group, to prioritize the established list in step (a) for each sustainability dimension. The aim is to select a limited number of decision criteria that would allow the implementation of the MCDA technique.

a. **Normalization and definition of sustainability performance scales:** The final step of the decision-criteria definition consists of the attribution of the performance scales in order to prepare data for the conjoint analysis. Impact categories that were previously evaluated through environmental LCA, S-LCA and LCC are used to compare the different alternatives through sustainability performance scales. The application of CA requires two main elements: the attributes that correspond to sustainability criteria in the considered use case, and their variation levels. In this thesis three levels of performance are defined (favorable performance to unfavorable performance). These scales are determined according with the geographical context of the study, the regulation level for each of the impact categories used, and the specific characteristics of the considered decision scenario. It is also important to note that other types of scales could be used depending on the objective of the study (e.g., risk levels).

4.2.3. Selection and application of the MCDA approach to LCSA

In this section, the advantages and disadvantages of the identified three categories of MCDA approaches presented in section 4.1 are discussed. The aim is to select the most relevant MCDA approach to deal with different LCSA impact categories and to involve stakeholders' views, namely users' needs and expectations in terms of mobility, within the framework. Prior studies have provided guidance on how to select the most appropriate MCDA technique depending on the specific features investigated and can, thus, be used to support this step (Guarini et al., 2018; Wątróbski et al., 2019).

One of the key features of MCDA approaches rely on the value choices introduced to determine the weighting factors of the considered decision criteria. Although this participatory nature of MCDA approaches is likely to be the most accurate for simulating real-world decision-making scenarios, it may also involve a number of limitations. In fact, depending on the type of MCDA approach used in the study, the involved actors and decision-makers might be expected to have a knowledge of the criteria under study and the issues that may be involved. This is the case for pairwise comparison studies, where the actors are asked to directly rank/compare and/or select the most representative criteria and aggregate them into a single criterion. Such approach can lead to compensation among the sustainability dimensions thus, misleading of the actual performance of each of the decision criteria, especially when considering the three pillars.

One of the main challenges of these approaches is to define the decision-making factors that may vary from one actor to another and that are not necessarily homogeneous. **It is therefore necessary to identify these factors through an analysis of needs and interests for each category of actor.**

The chosen method is based on the scoring of preferences by the involved actor perspective instead of weighting the criteria directly. This makes it possible to create different combinations of the selected criteria based on their scales of variations. In fact, such approach can be very relevant to avoid a pairwise comparison of the different sustainability criteria which often requires high knowledge of the magnitude of impacts and induce a high uncertainty. Hence, no direct scoring is requested from the decision makers for criteria that they sometimes do not fully master, but simply exposes the different existing possibilities reflecting sustainability performances of the underlying product or service. This method seems to be relevant in the context of sustainability analysis in view of the variable nature of the impact categories and the various compromises that are likely to occur. However, a high number of criteria will lead to a very high number of combinations. Thus, it is required to reduce the number of criteria to ensure the feasibility of the method. The following section describes the chosen MCDA approach adapted to the LCSA framework developed in this research, together with its relative features and key steps.

Conjoint Analysis based on a preference analysis

The Conjoint Analysis (CA) method is based on a statistical approach of preference analysis used to develop weighting factors and to identify the relative importance of the constituent attributes (the criteria). It is recognized for its ability to address trade-off issues where the choice is complex because each criterion or attribute is characterized by variable specifications (v_1, v_2, ..., v_n). It therefore calls for combinations of these variants which the actors can rank according to their preferences.

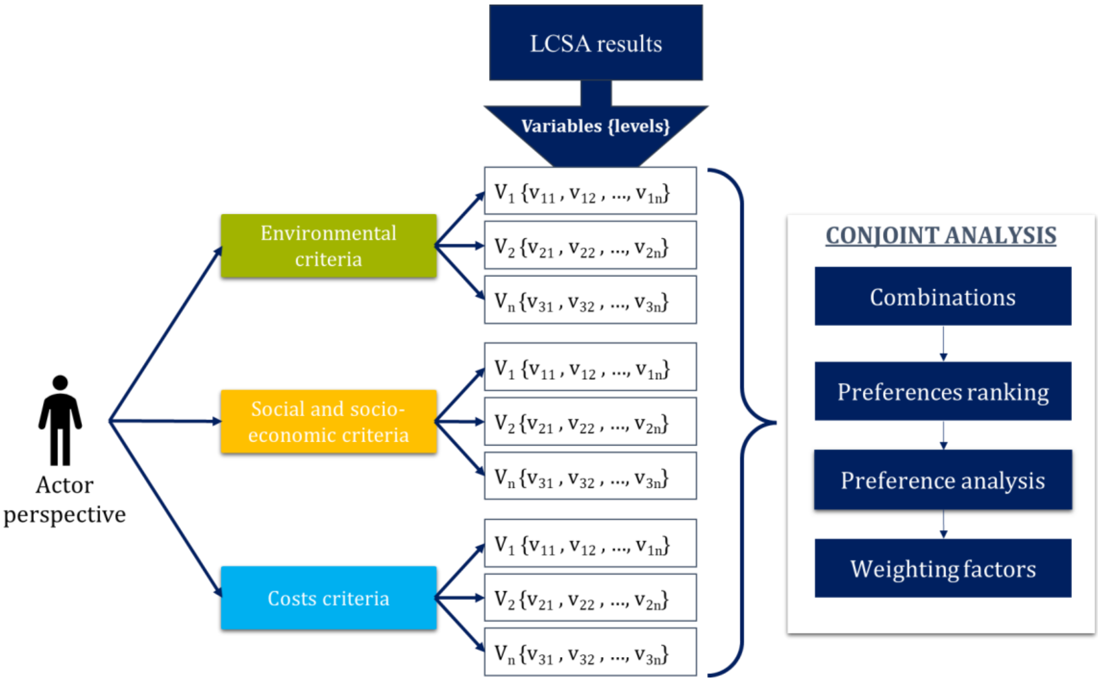

Figure 15 Representation of conjoint analysis method in the case of sustainability trade-offs management: environmental, social and socio-economic and costs decision criteria

As illustrated in Figure15**Erreur ! Source du renvoi introuvable.**, the conjoint analysis entails the implementation of the following steps:

a. **Development of combinations (or profiles):** it consists of building up a whole set of possible profiles based on the defined decision criteria and their corresponding variants. The total number of combinations thus, depends on the fixed number of decision criteria and the number of variants associated to each criterion.

b. **Preference ranking:** consists of determining the rating value to be assigned to each of the combinations according to the preferences of the considered actor's perspective.

c. **Preference analysis:** allows the determination of the weighting factors according to the chosen method, either through a ranking of the different combinations or through a choice-based conjoint. A preference analysis based on the scoring-order method consists of a ranking of the defined combinations according to the considered actor's perspective, namely users in this study. One of the problems of this approach is the high number of possible combinations, which calls into question the practicality and ease of the method. As an alternative, the choice-based conjoint method can be used. CBC allows the reduction of the number of defined combinations by eliminating those who are not accurate for the real-world scenarios (either too weak performance or excessively high performance). Thus, CBC analysis enables the development of weighting factors expressing the relative importance of each decision criterion through a more restricted selection of combinations or profiles. In fact, the concerned actor is here asked to choose between a selection of profiles representing variable performances of the defined decision criteria.

The Conjoint Analysis (CA) has been used in the transport sector, since the very beginning of its application. Louviere, (1988) reviewed the existing literature on this subject. Indeed, several researchers were interested in the potential of this approach to study users' mobility patterns and better understand the drivers of their purchase decisions. Based on realistic models, these approaches allow the experimental design of a set of alternatives compiled from combinations of different criteria (travel cost, travel time, etc.).

Since Louviere's publication (1988), several studies sought to apply conjoint analysis to improve the decision-making process. Table 2 provides brief insight on the case studies, the geographical scope, the sampling size together with the used approach for the data collection and the selected decision criteria, called attributes within the CA framework. (K. Lebeau et al., 2012a) investigated the market potential for plug-in hybrids and all-electric vehicles in Flanders. The data were derived from a large survey conducted in 2011. The explored approach was the "Choice Based-Conjoint" (CBC) technique, which uses discrete choice models to collect users' preferences. Respondents were asked to select a product (based on defined combinations of features) that best meets their needs. This increases the representativeness of the sample by getting closer to the real-world situations. Among several decision criteria (purchase cost, recharging time, availability of recharging infrastructure, autonomy) identified through the bibliography, the authors selected three major criteria (purchase price, maximum speed, and autonomy). (P. Lebeau et al., 2016) also used the CBC approach to investigate the potential of electric vehicles to support sustainability in logistics. The selection of attributes was considered one of the most critical steps. In a study carried out by Tarne, Lehmann, & Finkbeiner (2019) weighting factors were defined for three different sustainability criteria through the Conjoint Analysis method. This work was carried out on electric motors to support manufacturers in the decision-making process.

References	Themes & objective of the case study	Sampling & geographical area	Method & considered criteria
K. Lebeau et al. (2012)	Market for electric vehicles (BEV) and plug-in hybrids (HEV, PHEV): **User preferences for purchasing vehicles** (speed, charging time, cost, etc.)	Flanders, Belgium 2037 persons (over 18 years old) of which 1197 provided complete responses. Data from a national survey in 2011.	Face-to-face interviews for attributes selection, 8 attributes (purchase cost, annual cost/year, trip cost/100 km, recharge time, range (km), average speed (km/h), brand image quality. Surveys: options to rank
P. Lebeau, Macharis et Van Mierlo (2016)	Exploring the EV market for **logistics**: identification of the main factors/barriers for the development of electric mobility	Belgium Transport companies located in the capital Brussels Sample 427 of which 128 accepted to answer, of which only 45 were usable	CBC Approach 10 questions 6 attributes (range, charging time, environmental performance, vehicle type, purchase price, operating cost)

(Tarne, Lehmann, & Finkbeiner, 2019)	GMP: Automotive manufacturers' preferences in terms of environmental, social and economic performance of products	Germany 54 transportation users (industrial managers)	3 attributes (3 levels of specifications: risks) 27 combinations → Preferences analysis: ranking Definition of KO criteria by respondents Individual interviews (20/30 min)
(Li et al., 2020)	Public preferences for government-initiated EV incentives.	China: Beijing, Shanghai, Nanjing, Guangzhou, Hangzhou, and Hefei 1039 people	3 main issues: knowledge of incentives, preferences, individuals' data (profiles, social class) 4 attributes (purchase costs, registration, operation, recharge).

Table 2 Identified case studies implementing the Conjoint Analysis with a focus on mobility scenarios

4.2.4. Interpretation of results

This last stage of the defined framework entails the use of the defined weighting factors in the previous step to analyze the different decision scenarios from a sustainability perspective. The aim is to determine the alternatives that are most respectful for the settled sustainability performance scales and those that are ranked as the most important alternatives by the users. This stage can also include a validation of the used data and techniques through a critical review which analyzes the accuracy of the developed and implemented framework to decision-making process.

5. Conclusions of the chapter

Sustainability analysis has been widely covered in the literature review. Different methods and tools are proposed and experimented. These are targeting objects with variable natures and scales. In particular, LCA approaches are widely recognized as the most effective techniques allowing the evaluation of impacts from the extraction of raw materials to the end of life of products and services.

Although LCA has been adapted to each sustainability dimension, there is still a significant research gap in S-LCA and LCC as they raise substantial methodological challenges, whereas environmental LCA has a higher level of maturity. Such challenges are reflected in the impact assessment phase, which calls for the consideration of different features, namely stakeholder categories, in S-LCA and monetary values in LCC. This is even more important to be considered when a sustainability analysis is conducted through LCSA. Herein, the coherence of the three impact assessment approaches may be a critical issue. When conducting an LCSA, other issues are to be solved, mainly in the results interpretation phase. The heterogenous nature of the three LCA techniques induce variable results, namely environmental quantitative impacts for LCA, social performance or social risks for S-LCA, and monetary values for LCC. Such multidimensional results can induce trade-offs problems and require multicriteria analysis to support decision makers compare the scenarios in terms of sustainability and select the most appropriate ones. Moreover, despite the important role stakeholders play in sustainability decision-making process, few studies have attempted to address their involvement within early stages of the design of LCSA.

The current thesis focuses on evaluating sustainable electric mobility scenarios. Two research questions were formalized in the introduction chapter; **RQ1** targeting the design of sustainability analysis through LCSA and **RQ2** exploring how LCSA results can support the decision-making in the context of electric mobility while integrating the users' perspective.

To provide insight into these two research questions, a comprehensive methodological framework for LCSA was proposed. Such framework relies on a separate assessment of the environmental, social and economic dimension through LCA, S-LCA and LCC. With respect to the objective of this thesis, the present chapter settled three mobility scenarios to be analyzed for passengers' transportation, namely personal, public and shared mobility scenarios with a special focus on electric vehicle technologies. These scenarios aim to analyze not only the effectiveness of electric mobility – by covering transportation technologies – but also the mobility services. Such vision is expected to better address user-related impacts in the context of mobility and thus contribute to the ongoing shift towards sustainable mobility while accounting for their needs and expectations.

To address the above-mentioned methodological challenges, a comprehensive LCSA framework has been proposed in this chapter. It relies on the use of a separate application of impact assessment approaches of environmental LCA, S-LCA and LCC to the defined scenarios and on the interpretation of LCSA results using MCDA techniques. The developed framework enables thus the heterogeneous nature of each sustainability dimension to be considered by selecting the most appropriate impact assessment approach depending on the goal and scope of the study. Hence, the main four phases of LCSA are defined with respect to the key features of each sustainability dimension. The implementation of the framework for the environmental, social and economic dimensions is addressed separately in the next chapters.

Regarding the implementation of MCDA, this chapter has settled four steps guiding LCSA practitioners in: (1) the definition of the decision scenarios, (2) the definition of sustainability decision criteria, (3) the selection and application of a relevant MCDA technique and (4) the interpretation of LCSA results. These steps are further implemented in a case study (Chapter 6) to analyze the obtained results from each sustainability evaluation.

The Conjoint Analysis method is selected among different other MCDA techniques due to its ability to deal with results of attributes rather than a direct weighting of sustainability criteria. Moreover, such technique is also relevant to address the users' perspective by proposing a set of different profiles (scenarios) that are most accurate to the real-world scenario.

The overall framework is implemented (chapter 6 of this thesis), on a case study for daily commuting travels. Users' preferences are integrated to the defined LCSA framework to select the most relevant sustainability criteria and their preferences are analyzed through the conjoint analysis. The applicability of the comprehensive LCSA framework coupling MCDA to results interpretation is further investigated.

6. References

Aparcana, S., & Salhofer, S. (2013). Application of a methodology for the social life cycle assessment of recycling systems in low income countries: Three Peruvian case studies. *The International Journal of Life Cycle Assessment*, *18*(5), 1116–1128. https://doi.org/10.1007/s11367-013-0559-3

Arshad, H., Thaheem, M. J., Bakhtawar, B., & Shrestha, A. (2021). Evaluation of Road Infrastructure Projects: A Life Cycle Sustainability-Based Decision-Making Approach. *Sustainability*, *13*(7), 3743. https://doi.org/10.3390/su13073743

Arvidsson, R. (2019). On the use of ordinal scoring scales in social life cycle assessment. *The International Journal of Life Cycle Assessment*, *24*(3), 604–606. https://doi.org/10.1007/s11367-018-1557-2

Asiedu, Y., & Gu, P. (1998). Product life cycle cost analysis: State of the art review. *International Journal of Production Research*, *36*(4), 883–908. https://doi.org/10.1080/002075498193444

Bachmann, T. M. (2013). Towards life cycle sustainability assessment: Drawing on the NEEDS project's total cost and multi-criteria decision analysis ranking methods. *The International Journal of Life Cycle Assessment*, *18*(9), 1698–1709. https://doi.org/10.1007/s11367-012-0535-3

Backes, J. G., & Traverso, M. (2021). Application of Life Cycle Sustainability Assessment in the Construction Sector: A Systematic Literature Review. *Processes*, *9*(7), 1248. https://doi.org/10.3390/pr9071248

Barbier, E. B. (1987). The Concept of Sustainable Economic Development. *Environmental Conservation*, *14*(2), 101–110. https://doi.org/10.1017/S0376892900011449

Barfod, M. B. (2018). Supporting sustainable transport appraisals using stakeholder involvement and MCDA. *Transport*, *33*(4), 1052–1066. https://doi.org/10.3846/transport.2018.6596

Ben Hnich, K., Martín-Gamboa, M., Khila, Z., Hajjaji, N., Dufour, J., & Iribarren, D. (2021). Life cycle sustainability assessment of synthetic fuels from date palm waste. *Science of The Total Environment*, *796*, 148961. https://doi.org/10.1016/j.scitotenv.2021.148961

Benoît Norris, C., Franze, J., Valdivia, S., Traverso, M., Vickery, G., & Siddharth, P. (2013). *The methodological sheets for subcategories in social life cycle assessment (SLCA)*. https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf

Bigo, A. (2016). *Comment atteindre le facteur 4 dans les transports ?* (p. 159). Chaire énergie et prospérité. http://www.chair-energy-prosperity.org/wp-content/uploads/2018/02/publication2016-facteur-4-dans-les-transports-aurelien-bigo.pdf

Bigo, A. (2020). *Les transports face au défi de la transition énergétique* [PhD Thesis, Ecole Doctorale de l'Institut Polytechnique de Paris (ED IP Paris)]. http://www.chair-energy-prosperity.org/wp-content/uploads/2019/01/These-Aurelien-Bigo.pdf

Blanc, I. (2015). *Comment calculer l'impact environnemental des énergies renouvelables ?* https://hal-mines-paristech.archives-ouvertes.fr/hal-01248286

Bouter, A., Hache, E., Ternel, C., & Beauchet, S. (2020). Comparative environmental life cycle assessment of several powertrain types for cars and buses in France for two driving cycles: "Worldwide harmonized light vehicle test procedure" cycle and urban cycle. *The International Journal of Life Cycle Assessment*, *25*(8), 1545–1565. https://doi.org/10.1007/s11367-020-01756-2

Brusselaers, N., Mommens, K., & Macharis, C. (2021). Building Bridges: A Participatory Stakeholder Framework for Sustainable Urban Construction Logistics. *Sustainability*, *13*(5), 2678.

Bueno, P. C., Vassallo, J. M., & Cheung, K. (2015). Sustainability Assessment of Transport Infrastructure Projects: A Review of Existing Tools and Methods. *Transport Reviews*, *35*(5), 622–649. https://doi.org/10.1080/01441647.2015.1041435

Cerdas, F., Egede, P., & Herrmann, C. (2018). LCA of Electromobility. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment* (pp. 669–693). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_27

CGDD. (2019). *Chiffres clés du climat: France, Europe et Monde* (p. 80). Institute ffor climate economics. https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2018-12/datalab-46-chiffres-cles-du-climat-edition-2019-novembre2018_1.pdf

CGDD. (2021). *Chiffres clés du transport—Edition 2021* (p. 92). Commissariat Général au Développement Durable, Ministère de la transition écologique. https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-transport-2021/livre.php

CGEDD, Schmit, P., De Treglode, H., Marques, R., Farniaux, B., & Toulouse, P. (2015). *Urbanisme et mobilité|Rapports publiés du CGEDD* (n° 009796-01; p. 117 p). CGEDD, MTES. https://cgedd.documentation.developpement-durable.gouv.fr/notice?id=Affaires-0008638

Cinelli, M., Coles, S. R., & Kirwan, K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators*, *46*, 138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A. A., De Oude, N., Parrish, R., Perriman, R., Postlethwaite, D., Quay, B., Séguin, J., & Vigon, B. (1993). *Guidelines for Life Cycle Assessment: A "Code of Practice"* (SETAC Workshop Report No. 1; p. 85). Society of Environmental Toxicology and Chemistry and SETAC Foundation for Environmental Education, Inc. https://cdn.ymaws.com/www.setac.org/resource/resmgr/books/lca_archive/guidelines_for_life_cycle.pdf

Cooper, W. W., Seiford, L. M., & Zhu, J. (2004). Data Envelopment Analysis. In W. W. Cooper, L. M. Seiford, & J. Zhu (Eds.), *Handbook on Data Envelopment Analysis* (Vol. 71, pp. 1–39). Kluwer Academic Publishers. https://doi.org/10.1007/1-4020-7798-X_1

De Luca, A. I., Iofrida, N., Leskinen, P., Stillitano, T., Falcone, G., Strano, A., & Gulisano, G. (2017). Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: Insights from a systematic and critical review. *Science of The Total Environment*, *595*, 352–370. https://doi.org/10.1016/j.scitotenv.2017.03.284

Del Duce, A., Gauch, M., & Althaus, H.-J. (2016). Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3. *The International Journal of Life Cycle Assessment*, *21*(9), 1314–1326. https://doi.org/10.1007/s11367-014-0792-4

Dreyer, L. C., Hauschild, M. Z., & Schierbeck, J. (2010). Characterisation of social impacts in LCA. *The International Journal of Life Cycle Assessment*, *15*(3), 247–259. https://doi.org/10.1007/s11367-009-0148-7

EC and JRC. (2018). *Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods: New methods and differences with ILCD.* Publications Office. https://data.europa.eu/doi/10.2760/671368

Eisfeldt, F., Rodriguez, C., & Ciroth, A. (2017). *SOCA- A database add-on for Life Cycle Sustainability Assessment*. CILCA, by Greendelta, Medellin.

Ekener, E., Hansson, J., Larsson, A., & Peck, P. (2018). Developing Life Cycle Sustainability Assessment methodology by applying values-based sustainability weighting—Tested on biomass-based and fossil transportation fuels. *Journal of Cleaner Production*, *181*, 337–351. https://doi.org/10.1016/j.jclepro.2018.01.211

Elkington, J. (1998). Accounting for the triple bottom line. *Measuring Business Excellence*, *2*(3), 18–22. https://doi.org/10.1108/eb025539

Epstein, M. J. (1996). *Measuring corporate environmental performance: Best practices for costing and managing an effective environmental strategy*. Irwin Professional Pub.

European Commission & Eurostat. (2017). *Sustainable development in the European Union: Monitoring report on progress towards the SDGs in an EU context : 2017 edition*. Publications Office of the European Union.

Fava, J., Weston, R. F., Consoli, F., Denison, R., Dickson, K., Mohin, T., & Vigon, B. (1993). *A Conceptual Framework for Life Cycle Impact Assessment* (Workshop Report; p. 192). Society of Environmental Toxicology and Chemistry and SETAC Foundation for Environmental Education, Inc. https://cdn.ymaws.com/www.setac.org/resource/resmgr/books/lca_archive/impact_assessment.pdf

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment*, *11*(2), 80–85. https://doi.org/10.1065/lca2006.02.002

Finkbeiner, M., Schau, E. M., Lehmann, A., & Traverso, M. (2010). Towards Life Cycle Sustainability Assessment. *Sustainability*, *2*(10), 3309–3322. https://doi.org/10.3390/su2103309

Fontes, J. (2016). *Handbook for product social impact assessment-version3.0-*. PréSustainability.

Franze, J. (2011). *Lca of an ecolabeled notebook—Consideration of social and environmental.* Lulu Com.

Gamage, G. B. (2011). *A New Model for Assessing Sustainability of Complex Systems* [University of Auckland]. https://researchspace.auckland.ac.nz/bitstream/handle/2292/8348/02whole.pdf?sequence=2

Garrido Fernández, A. (2018). *Towards transport futures using mobile data analytics: Stakeholder identification in the city of Stockholm* [KTH, School of Architecture and the Built Environment (ABE), Sustainable development, Environmental science and Engineering.]. urn:nbn:se:kth:diva-240604

Goedkoop, M., De Beer, I., Harmens, R., Saling, P., Morris, D., Florea, A., Hettinger, A. L., Indrane, D., Visser, D., Morao, A., Musoke-Flores, E., Alvarado, C., Rawat, I., Schenker, U., Head, M., Collotta, M., Andro, T., Viot, J.-F., & Whatelet, A. (2020). *Product Social Impact Assessment Handbook 2020*. https://product-social-impact-assessment.com/wp-content/uploads/2020/12/20-01-Handbook-2020_10.pdf

Goepel, K. D. (2018). Implementation of an Online Software Tool for the Analytic Hierarchy Process (AHP-OS). *International Journal of the Analytic Hierarchy Process*, *10*(3). https://doi.org/10.13033/ijahp.v10i3.590

Gompf, K., Traverso, M., & Hetterich, J. (2021). Using Analytical Hierarchy Process (AHP) to Introduce Weights to Social Life Cycle Assessment of Mobility Services. *Sustainability*, *13*(3), 1258. https://doi.org/10.3390/su13031258

GRI. (2011). *G3-Sustainaability Reporting Guidelines* (3.1; p. 195). Global Reporting Initiative. https://www.globalreporting.org/

GRI. (2016). *GRI-2016-Consolidated set of GRI sustainability Reporting Standards*. Global Reporting Initiative. https://www.globalreporting.org/

Guarini, M. R., Battisti, F., & Chiovitti, A. (2018). A Methodology for the Selection of Multi-Criteria Decision Analysis Methods in Real Estate and Land Management Processes. *Sustainability*, *10*(2), 507. https://doi.org/10.3390/su10020507

Guitouni, A., & Martel, J.-M. (1998). Tentative guidelines to help choosing an appropriate MCDA method. *European Journal of Operational Research*, *109*(2), 501–521. https://doi.org/10.1016/S0377-2217(98)00073-3

Günther, H.-O., Kannegiesser, M., & Autenrieb, N. (2015). The role of electric vehicles for supply chain sustainability in the automotive industry. *Journal of Cleaner Production*, *90*, 220–233. https://doi.org/10.1016/j.jclepro.2014.11.058

He-Hua, W., Jian-Jun, Z., Xiao-Yan, G., & Ye, C. (2018). *A Multiple Criteria Decision Analysis Method for Alternative Assessment Results Obeying a Particular Distribution and Application* [Research Article]. Mathematical Problems in Engineering. https://doi.org/10.1155/2018/2108726

Hoque, N., Mazhar, I., & Biswas, W. (2018). Application of Life Cycle Assessment for Sustainability Evaluation of Transportation Fuels. In *Reference Module in Materials Science and Materials Engineering*. Elsevier. https://doi.org/10.1016/B978-0-12-803581-8.10792-1

Hosny, H. E., Ibrahim, A. H., & Eldars, E. A. (2021). Development of infrastructure projects sustainability assessment model. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-021-01791-5

Hunkeler, D., Lichtenvort, K., & Rebitzer, G. (2008). *Environmental Life Cycle Costing*. CRC Press.

IFP Energies Nouvelles. (2018). *Bilan transversal de l'impact de l'électrification par segment* (p. 21). PROJET E4T. ADEME. www.ademe.fr/mediatheque

ISO 14040. (2006). *Management environnemental—Analyse du cycle de vie—Principes et cadre* (p. : 23). Internationanl Standardization Organization. https://www.iso.org/cms/render/live/fr/sites/isoorg/contents/data/standard/03/74/37456.html

ISO 15686-1. (2011). *ISO 15686-1:2011 Buildings and constructed assets—Service life planning—Part 1: General principles and framework*. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/04/57/45798.html

ISO14044. (2006). *ISO 14044:2006—Management environnemental—Analyse du cycle de vie—Exigences et lignes directrices*. https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:fr

ISO26000. (2010). *ISO 26000:2010(en), Guidance on social responsibility*. https://www.iso.org/obp/ui/#iso:std:iso:26000:ed-1:v1:en

IUCN, UNEP, WWF, FAO, & Unesco (Eds.). (1980). *World conservation strategy: Living resource conservation for sustainable development* (International Union for Conservation of Nature and Natural Resources, United Nations Environment Programme, World Wildlife Fund, Food and Agriculture Organization of the United Nations). IUCN.

Jacquet-Lagrèze, E., & Siskos, Y. (2001). Preference disaggregation: 20 years of MCDA experience. *European Journal of Operational Research*, *130*(2), 233–245. https://doi.org/10.1016/S0377-2217(00)00035-7

Jasinski, D., Meredith, J., & Kirwan, K. (2015). A comprehensive review of full cost accounting methods and their applicability to the automotive industry. *Journal of Cleaner Production*, *108*, 1123–1139. https://doi.org/10.1016/j.jclepro.2015.06.040

Jørgensen, A., Lai, L. C. H., & Hauschild, M. Z. (2009). Assessing the validity of impact pathways for child labour and well-being in social life cycle assessment. *The International Journal of Life Cycle Assessment*, *15*(1), 5. https://doi.org/10.1007/s11367-009-0131-3

JRC. (2010). *ILCD Handbook: Analysis of existing Environmental Impact Assessment methodologies for use in life cycle Assessment* (1st ed.).

Kaya, T., & Kahraman, C. (2011). An integrated fuzzy AHP–ELECTRE methodology for environmental impact assessment. *Expert Systems with Applications*, *38*(7), 8553–8562. https://doi.org/10.1016/j.eswa.2011.01.057

Kloepffer, W. (2008). Life cycle sustainability assessment of products: (With Comments by Helias A. Udo de Haes, p. 95). *The International Journal of Life Cycle Assessment*, *13*(2), 89–95. https://doi.org/10.1065/lca2008.02.376

Lebeau, K., Van Mierlo, J., Lebeau, P., Mairesse, O., & Macharis, C. (2012). The market potential for plug-in hybrid and battery electric vehicles in Flanders: A choice-based conjoint analysis. *Transportation Research Part D: Transport and Environment*, *17*(8), 592–597. https://doi.org/10.1016/j.trd.2012.07.004

Lebeau, P., Macharis, C., & Van Mierlo, J. (2016). Exploring the choice of battery electric vehicles in city logistics: A conjoint-based choice analysis. *Transportation Research Part E: Logistics and Transportation Review*, *91*, 245–258. https://doi.org/10.1016/j.tre.2016.04.004

Li, W., Long, R., Chen, H., Dou, B., Chen, F., Zheng, X., & He, Z. (2020). Public Preference for Electric Vehicle Incentive Policies in China: A Conjoint Analysis. *International Journal of Environmental Research and Public Health*, *17*(1), 318. https://doi.org/10.3390/ijerph17010318

Liu, G. (2014). Development of a general sustainability indicator for renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*, *31*, 611–621. https://doi.org/10.1016/j.rser.2013.12.038

Louviere, J. J. (1988). Conjoint Analysis Modelling of Stated Preferences: A Review of Theory, Methods, Recent Developments and External Validity. *Journal of Transport Economics and Policy*, *22*(1), 93–119. JSTOR. https://www.jstor.org/stable/20052837

Macharis, C., Witte, A. de, & Ampe, J. (2009). The multi-actor, multi-criteria analysis methodology (MAMCA) for the evaluation of transport projects: Theory and practice. *Journal of Advanced Transportation*, *43*(2), 183–202. https://doi.org/10.1002/atr.5670430206

Macombe, C. (2019). *Social Life Cycle Assessment for Industrial Biotechnology*. Springer Berlin Heidelberg. https://doi.org/10.1007/10_2019_99

Macombe, C., Leskinen, P., Feschet, P., & Antikainen, R. (2013). Social life cycle assessment of biodiesel production at three levels: A literature review and development needs. *Journal of Cleaner Production*, *52*, 205–216. https://doi.org/10.1016/j.jclepro.2013.03.026

Maister, K., Di Noi, C., Ciroth, A., & Srocka, M. (2020). *Product Social Impact Life Cycle Assessment (PSILCA) Database v.3 Documentation* (Databse Documentation version 1.0; p. 124). GreenDelta. https://www.openlca.org/wp-content/uploads/2020/06/PSILCA_V3_manual.pdf

Majumder, M. (2015). Multi Criteria Decision Making. In M. Majumder, *Impact of Urbanization on Water Shortage in Face of Climatic Aberrations* (pp. 35–47). Springer Singapore. https://doi.org/10.1007/978-981-4560-73-3_2

Mancini, L., Eynard, U., Eisfeldt, F., Ciroth, A., Blengini, G., & Pennington, D. (2019). *Social assessment of raw materials supply chains. A life cycle-based analysis*. https://doi.org/10.2760/470881

Mohd Safian, E. E., & Nawawi, A. (2011). *The Evolution of Analytical Hierarchy Process (AHP) as a Decision Making Tool in Property Sectors*.

Loi-Mobilités-Présentation du projet de loi d'orientation des mobilités, (2018) (testimony of MTES). https://www.ecologique-solidaire.gouv.fr/sites/default/files/18191_DP_LOM_16p_DEF_Web.pdf

Nalmpantis, D., Roukouni, A., Genitsaris, E., Stamelou, A., & Naniopoulos, A. (2019). Evaluation of innovative ideas for Public Transport proposed by citizens using Multi-Criteria Decision Analysis (MCDA). *European Transport Research Review*, *11*(1), 22. https://doi.org/10.1186/s12544-019-0356-6

Neugebauer, S. (2016). *Enhancing Life Cycle Sustainability Assessment—Tiered Approach and new Characterization Models for Social Life Cycle Assessment and Life Cycle Costing* [Thèse de doctorat, Prozesswissenschaftender Technischen Universität Berlin]. http://dx.doi.org/10.14279/depositonce-5644

Neugebauer, S., Forin, S., & Finkbeiner, M. (2016). From Life Cycle Costing to Economic Life Cycle Assessment—Introducing an Economic Impact Pathway. *Sustainability*, *8*(5), 428. https://doi.org/10.3390/su8050428

Neugebauer, S., Traverso, M., Scheumann, R., Chang, Y.-J., Wolf, K., & Finkbeiner, M. (2014). Impact Pathways to Address Social Well-Being and Social Justice in SLCA—Fair Wage and Level of Education. *Sustainability*, *6*(8), 4839–4857. https://doi.org/10.3390/su6084839

Norris, G. A. (2006). Social Impacts in Product Life Cycles—Towards Life Cycle Attribute Assessment. *The International Journal of Life Cycle Assessment*, *11*(1), 97–104. https://doi.org/10.1065/lca2006.04.017

OECD. (2011). *Les principes directeurs de l'OCDE à l'intention des entreprises multinationales.* OCDE Pub. http://public.eblib.com/choice/publicfullrecord.aspx?p=3026431

OECD. (2021). *Trends in Stakeholder Reporting: Mineral Supply Chains* (p. 39). OECD. https://mneguidelines.oecd.org/trends-in-stakeholder-reporting-mineral-supply-chains.pdf

OIE. (2019). *Chiffres des marchés de l'électromobilité*. Observatoire de l'industrie électrique. EV

Onat, N. (2015). *A macro-level sustainability assessment framework for optimal distribution of alternative passenger vehicles*.

Onat, N. C., Kucukvar, M., Aboushaqrah, N. N. M., & Jabbar, R. (2019). How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar. *Applied Energy*, *250*, 461–477. https://doi.org/10.1016/j.apenergy.2019.05.076

Onat, N. C., Kucukvar, M., & Tatari, O. (2016). Uncertainty-embedded dynamic life cycle sustainability assessment framework: An ex-ante perspective on the impacts of alternative vehicle options. *Energy*, *112*, 715–728. https://doi.org/10.1016/j.energy.2016.06.129

Onat, N. C., Kucukvar, M., Tatari, O., & Zheng, Q. P. (2016). Combined application of multi-criteria optimization and life cycle sustainability assessment for optimal distribution of alternative passenger cars in U.S. *Journal of Cleaner Production*, *112*, 291–307. https://doi.org/10.1016/j.jclepro.2015.09.021

Osorio-Tejada, J. L., Llera-Sastresa, E., Scarpellini, S., & Hashim, A. H. (2020). An integrated social life cycle assessment of freight transport systems. *The International Journal of Life Cycle Assessment*, *25*(6), 1088–1105. https://doi.org/10.1007/s11367-019-01692-w

Pérez López, P. (2015). *Environmental sustainability of bioactive molecules from marine organisms*. https://minerva.usc.es/xmlui/handle/10347/13778

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: In search of conceptual origins. *Sustainability Science*, *14*(3), 681–695. https://doi.org/10.1007/s11625-018-0627-5

Rowley, H. V., Peters, G. M., Lundie, S., & Moore, S. J. (2012). Aggregating sustainability indicators: Beyond the weighted sum. *Journal of Environmental Management*, *111*, 24–33. https://doi.org/10.1016/j.jenvman.2012.05.004

Roy, B., & Vanderpooten, D. (1996). The European school of MCDA: Emergence, basic features and current works. *Journal of Multi-Criteria Decision Analysis*, *5*(1), 22–38. https://doi.org/10.1002/(SICI)1099-1360(199603)5:1<22::AID-MCDA93>3.0.CO;2-F

RTE. (2015). *Valorisation socio-économique des réseaux électriques intelligents-Méthodologie et premiers résultats* (p. 232) [Rapport d'étude]. Réseau de transport d'électricité-ademe. https://www.rte-france.com/sites/default/files/rei_bd_1.pdf

RTE. (2017). *Réseaux électriques intelligents: Valeur économique, environnementale et déploiement d'ensemble* (Synthèse; p. 12). Réseau transport électrifié. https://www.rte-france.com/sites/default/files/rei_synthese_2017.pdf

Rugani, B., Panasiuk, D., & Benetto, E. (2012). An input–output based framework to evaluate human labour in life cycle assessment. *The International Journal of Life Cycle Assessment*, *17*(6), 795–812. https://doi.org/10.1007/s11367-012-0403-1

Russo Garrido, S., Parent, J., Beaulieu, L., & Revéret, J.-P. (2018). A literature review of type I SLCA—making the logic underlying methodological choices explicit. *The International Journal of Life Cycle Assessment*, *23*(3), 432–444. https://doi.org/10.1007/s11367-016-1067-z

Saaty, R. W. (1987). The analytic hierarchy process—What it is and how it is used. *Mathematical Modelling*, *9*(3), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Saaty, T. L. (1989). Group Decision Making and the AHP. In B. L. Golden, E. A. Wasil, & P. T. Harker (Eds.), *The Analytic Hierarchy Process: Applications and Studies* (pp. 59–67). Springer. https://doi.org/10.1007/978-3-642-50244-6_4

Sacchi, R., Bauer, C., & Cox, B. L. (2021). Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium- and Heavy-Duty Vehicles. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.0c07773

Santoyo-Castelazo, E., & Azapagic, A. (2014). Sustainability assessment of energy systems: Integrating environmental, economic and social aspects. *Journal of Cleaner Production*, *80*, 119–138. https://doi.org/10.1016/j.jclepro.2014.05.061

Sierzchula, W., Bakker, S., Maat, K., & van Wee, B. (2014). The influence of financial incentives and other socio-economic factors on electric vehicle adoption. *Energy Policy*, *68*, 183–194. https://doi.org/10.1016/j.enpol.2014.01.043

Stark, R., Buchert, T., Neugebauer, S., Bonvoisin, J., & Finkbeiner, M. (2017). Benefits and obstacles of sustainable product development methods: A case study in the field of urban mobility. *Design Science*, *3*. https://doi.org/10.1017/dsj.2017.20

Swarr, T. E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A. C., & Pagan, R. (2011). Environmental life cycle costing: A code of practice. *Int J Life Cycle Assess*, 3. https://doi.org/DOI 10.1007/s11367-011-0287-5

Tarne, P. (2019). *Life cycle sustainability assessment at an automotive company*. https://doi.org/10.14279/depositonce-7920

Tarne, P., Lehmann, A., & Finkbeiner, M. (2019). Introducing weights to life cycle sustainability assessment—How do decision-makers weight sustainability dimensions? *The International Journal of Life Cycle Assessment*, *24*(3), 530–542. https://doi.org/10.1007/s11367-018-1468-2

Traverso, M., Asdrubali, F., Francia, A., & Finkbeiner, M. (2012). Towards life cycle sustainability assessment: An implementation to photovoltaic modules. *The International Journal of Life Cycle Assessment*, *17*(8), 1068–1079. https://doi.org/10.1007/s11367-012-0433-8

Traverso, M., Kim, P., Brattig, S., & Wagner, V. (2015). Managing Life Cycle Sustainability Aspects in the Automotive Industry. In G. Sonnemann & M. Margni (Eds.), *Life Cycle Management* (pp. 331–339). Springer Netherlands. https://doi.org/10.1007/978-94-017-7221-1_24

UN. (1992). *Report of the United Nations Conference on Environment and Development: Resolutions adopted by the Conference* (A/CONF.151/26/Rev.l (Vol. I); p. 492). United Nations. https://undocs.org/pdf?symbol=en/A/CONF.151/26/Rev.1(vol.I)

UNEP. (2020). *Guidelines for Social Life Cycle Assessment of Products and Organizations* (C. Benoît Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A. Lehmann, M. Finkbeiner, & G. Arcesse, Eds.). United Nations Environment Programme (UNEP). https://www.lifecycleinitiative.org/wp-content/uploads/2020/12/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-sml.pdf

UNEP/SETAC. (2009). *Guidelines for social life cycle assessment of products* (C. Benoît, B. Mazijn, CIRAIG, & P. and S. Interuniversity Research Centre for the Life Cycle of Producs, Eds.). United Nations Environment Programme. http://ra.ocls.ca/ra/login.aspx?inst=centennial&url=https://www.deslibris.ca/ID/236529

Valdivia, S., Backes, J. G., Traverso, M., Sonnemann, G., Cucurachi, S., Guinée, J. B., Schaubroeck, T., Finkbeiner, M., Leroy-Parmentier, N., Ugaya, C., Peña, C., Zamagni, A., Inaba, A., Amaral, M., Berger, M., Dvarioniene, J., Vakhitova, T., Benoit-Norris, C., Prox, M., … Goedkoop, M. (2021). Principles for the application of life cycle sustainability assessment. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-021-01958-2

Valdivia, S., & Lie, C. M. (2012). Towards a life cycle sustainability Assessment-Making informed choices on products. *Sustainability Assessment*, 86.

Valente, A., Iribarren, D., & Dufour, J. (2021). Comparative life cycle sustainability assessment of renewable and conventional hydrogen. *Science of The Total Environment*, *756*, 144132. https://doi.org/10.1016/j.scitotenv.2020.144132

Vázquez-Rowe, I., & Iribarren, D. (2015). Review of Life Cycle Approaches Coupled with Data Envelopment Analysis: Launching the CFP + DEA Method for Energy Policy Making. *The Scientific World Journal*, *2015*, e813921. https://doi.org/10.1155/2015/813921

Wątróbski, J., Jankowski, J., Ziemba, P., Karczmarczyk, A., & Zioło, M. (2019). Generalised framework for multi-criteria method selection. *Omega*, *86*, 107–124. https://doi.org/10.1016/j.omega.2018.07.004

WCED. (1987). *Report of the World Commission on Environment and Development: Our Common Future* (Oxford ; New York : Oxford University Press, 1987.). World Commission on Environment and Development. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf

Wulf, C., Werker, J., Ball, C., Zapp, P., & Kuckshinrichs, W. (2019). Review of Sustainability Assessment Approaches Based on Life Cycles. *Sustainability*, *11*(20), 5717. https://doi.org/10.3390/su11205717

Zamagni, A. (2012). Life cycle sustainability assessment. *The International Journal of Life Cycle Assessment*, *17*(4), 373–376. https://doi.org/10.1007/s11367-012-0389-8

Zamagni, A., Pesonen, H.-L., & Swarr, T. (2013). From LCA to Life Cycle Sustainability Assessment: Concept, practice and future directions. *The International Journal of Life Cycle Assessment*, *18*(9), 1637–1641. https://doi.org/10.1007/s11367-013-0648-3

Zanchi, L., Delogu, M., Zamagni, A., & Pierini, M. (2018). Analysis of the main elements affecting social LCA applications: Challenges for the automotive sector. *The International Journal of Life Cycle Assessment*, *23*(3), 519–535. https://doi.org/10.1007/s11367-016-1176-8

Zhang, R., & Zhao, B. (2018). Research on Location Selection of Shared Vehicle Charging Station Based on Analytic Hierarchy Process and Fuzzy Evaluation Method. *OALib*, *05*(09), 1–6. https://doi.org/10.4236/oalib.1104899

Zhang, Z., Sun, X., Ding, N., & Yang, J. (2019). Life cycle environmental assessment of charging infrastructure for electric vehicles in China. *Journal of Cleaner Production, 227*, 932–941. https://doi.org/10.1016/j.jclepro.2019.04.167

Chapter III: Environmental evaluation of electric mobility scenarios through LCA

Summary (III)

The aim of this chapter is to provide a systematic analysis of the environmental sustainability dimension through LCA. The chapter underlines the key environmental issues related to the considered mobility scenarios covering personal, collective, and shared use, with a special focus on electric vehicle technologies.

LCA method is introduced in **section 1**, as well as the objective of this chapter. In **section 2**, an extensive literature review on LCA studies is conducted to allow the identification of the main impact categories (e.g., Global Warming Potential, Resources Depletion, and Air Quality) and life cycle stages (e.g., manufacturing stage, vehicles' operation stage and final disposal) for mobility scenarios. This latter step enables the definition, in **section 3**, of key input parameters (driving cycles, fuel pathways and electricity mix, etc.) and assumptions to be integrated in the analysis. Several drawbacks are identified within the most current LCA datasets that could lead to a poor representation of the environmental impacts. A strategy based on the development and the use of parametrized LCA models is proposed and encouraged to define key input parameters and to update LCA datasets fitted to the considered mobility scenarios. Such approach is presented in **section 4**. Finally, the environmental midpoint indicators together with the obtained results are discussed for the three considered scenarios.

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1. Introduction

Life Cycle Assessment (LCA) has been widely adopted for the evaluation of potential environmental impacts in the mobility sector at various scales (e.g., automotive components, vehicles technologies, vehicle fleets, etc.). LCA allows basic "Cradle to Gate" impact evaluation of raw materials extraction and equipment production to be extended to a broader scope including the end of life of the vehicles according to a **"Cradle to Grave"** perspective, and energy power sources used for the vehicle's operation with a **"Well to Wheel"** perspective. Moreover, LCA aims at assessing a wide range of environmental impact categories that are supposed to represent the most relevant ones for the scope and objective of the study. LCA is generally used for two main purposes: (1) identifying most significant environmental impacts and investigating the most contributing processes together with the potential improvements to be made for the design of the product systems and services (2) comparing products, technologies and services that share the same functional unit (e.g., vehicle technologies, mobility services, etc.) towards more informed decision-making.

Within the rise of electric mobility, a large number of transportation technologies and mobility services have gained the market whose impacts are still unknown. The need of analyzing the potential environmental impacts that are directly and indirectly related to these emergent technologies as well as the infrastructures they require is therefore essential to gain insights on the consequences on human health, ecosystem quality, resources availability and climate change, etc.

This chapter aims at investigating through LCA the environmental impacts associated with three mobility scenarios with a focus on electric vehicle alternatives. The results of the environmental evaluation are further used conjointly with S-LCA and LCC results within the LCSA developed framework integrating the MCDA approach.

This chapter starts by analyzing the existing LCA studies and existing models to identify the main impact categories and life cycle stages (section 2) and thus, define a set of key input parameters to be entailed in the modeling (section 3). The environmental analysis is performed through parametrized LCA models which have been adjusted to cover the electric mobility scenarios settled within this thesis. Such models enhance representativeness of the existing datasets by including the multiple technological advances that may occur over time. The defined approach together with the steps to be followed for the establishment of the parametrized models are detailed in section 4 all along the four iterative LCA phases.

2. Environmental evaluation of electric mobility: State of the art

The aim of this section is to investigate environmental evaluation studies in the context of mobility. The focus is made on LCA of mobility services, vehicle technologies, powertrains, batteries as well as transportation fuels. A thorough analysis of the existing LCA studies is presented allowing the most significant impact categories and key life cycle stages to be identified and understood. As a result, the main assumptions and input parameters are identified to be integrated further into the LCA model developed for the defined mobility scenarios (detailed in section 2.2. of chapter 2).

2.1.The main covered environmental impact categories in the LCA literature

Given the intensive use of petroleum products, road transport is one of the largest contributor to greenhouse gas emissions (GHG) (EEA, 2019) and thus, Global Warming Potential (GWP) has been widely covered in LCA studies. Nevertheless, it is by no means the only relevant impact category for mobility scenarios. Indeed, as highlighted by a study from the European Commission (2020a), most studies focus also on energy consumption, air quality, toxicity and resources depletion. Other impact subcategories, such as noise emissions have been often neglected despite their relevance for transportation technologies and especially within the fleet electrification. In the following paragraphs the main impact categories for mobility scenarios are discussed as well as their relevance for a comprehensive within LCA framework.

2.1.1. Contribution to climate change

In France, 31% of the total GHG emissions are produced by the transport sector (CGDD, 2021). These GHG emissions are closely related to fuel combustion in the use phase. Such emissions cause extreme and irreversible consequences on the planet. According to the most recently published report by the Intergovernmental Panel on Climate Change (IPCC, 2021), widespread and rapid changes have occurred in the last decades on the atmosphere, ocean and land. CO_2 12-month global mean atmospheric concentration reached 415 ppm in 2021 (Dlugokencky & Tans, 2021). As a result, GHG emissions have modified the Earth's energy budget, leading to an accumulation of energy within the earth system, which is at the origin of the observed climate changes.

The global heating of the climate system caused a 20-cm rise of the global sea level over the last century due to ice loss on land and thermal expansion through ocean warming. Indeed, the global ocean has warmed since 1871, including depths below 2000 meters since 1992 (Arias et al. 2021). and the rate of ice sheet loss has increased by a factor of four between 1992-1999 and 2010-2019 (IPCC, 2021). Furthermore, a portion of the CO_2 emitted is also absorbed by the oceans causing ocean acidification which results in consequential damages in the marine eco-system (IPCC, 2021).

The five presented scenarios in the IPCC report, seeking to explore consequences of climate change over the 21st century, have stated that the best estimates for the period 2081-2100 are ranging from 1.9°C for the $SSP_{1\text{-}1.9}$ to 4.4°C for the $SSP_{5\text{-}8.5}$. These consequences are also apparent in terms of precipitations frequency and soil moisture with variable regional effects.

The unequivocal consequences caused by the anthropogenic activities, more likely due to fossil fuels combustion, call for unprecedented actions to limit the forecasted climate system variations below the low-CO_2 emissions scenarios. Accordingly with the Paris agreement (UN, 2015), appropriate responses should be developed to foster climate resilience and limit the temperature increase within the coming years. Although electric mobility is the most promising technological solution to substitute the use of fossil fuels by conventional vehicles, it is wrong to claim zero CO_2 emissions. In fact, electric vehicle technologies emit indirectly CO_2 emissions through their production and through the electricity production used for their operation. In contrast, the impacts associated with the production of electric vehicles are greater than their thermal counterparts due to the electric powertrain and batteries production (European Commission, 2020a). It is therefore highly relevant to consider this impact category within the environmental evaluation of mobility scenarios.

2.1.2. Impacts on the ecosystem quality

Transport sector is responsible of significant drawbacks on the environment associated with water and soils acidification, their eutrophication, and the decrease of agricultural yields. Emissions from transport and related infrastructures contribute directly to the ecosystem alteration.

The IPBES report (2019) have underlined the importance of designing nature-sensitive road networks and developing low impact infrastructures and transportation systems to meet SDGs related to sustainable production and consumption patterns as well as sustainable cities.

The rapid expansion of road transport and especially individual passenger vehicles has fostered the urban sprawl which in turn has resulted in vast and complex transportation infrastructures network. The need for road and transport infrastructures has been growing since then, driven by additional environmental concerns for communities and governments. In fact, 1.5% to 2.0% of the world's total land surface is devoted to road infrastructures and parking lots (Rodrigue, 2020b). As a result, it is becoming increasingly challenging to afford sustainable and cost-effective mobility services that fit users' needs in the urban, sub-urban and rural areas.

There are numerous effects associated with land use transformation. The outward expansion of cities and suburbanization contributes further to the heat island effect (Rodrigue, 2020b). Urban surfaces absorb more significant portions of the heat during the days which induces higher temperatures during the nights. Such phenomena create unbalances in the local climate. Moreover, land use change is the main driver for negative impacts on terrestrial and freshwater ecosystems quality. After agriculture, infrastructures' development associated with the growing population in urban areas since 1992 has come at the expense of forests, wetlands and grasslands (IPBES, 2019).

Climate change, which is direct result of road transport emissions, has been exacerbating negative effects of the ecosystem quality through the increase of the frequency and intensity of extreme weather events. These have notably increased in the past 50 years, driving by more fires, floods and droughts. Profound and widespread changes have consequently occurred in the marine, terrestrial and freshwater ecosystems and disabled nature's ability to sustain its main ecological functions and processes. About 1 million species are threatened and facing extinction as substantial losses are demonstrated in the biodiversity (IPBES, 2019). If no serious actions are taken, these effects are expected to accelerate in the coming years driving by more complex and negative effects on agriculture, aquaculture, fisheries and in general nature's functions to people.

2.1.3. Impacts on human health and toxicity

Transport sector contributes to a wide range of gaseous air pollutants (e.g., O_3, SO_2, NO_x, CO and COVs) and suspended particulate matter ($PM_{2.5}$, PM_{10}) of different sizes and composition. These Pollutant emissions come either from direct fuel combustion in the case of conventional vehicles operation (exhaust emissions), or from indirect emissions (non-exhaust emissions) linked to the friction of the tires and the road. These emissions play a major role in the deterioration of local air quality, resulting in substantial drawbacks for human health and the environment. Accordingly, 60% of cities in Europe exceed the World Health Organization (WHO) thresholds for particulate matter (Arseni & Racioppi, 2018) and 91% of the world population is exposed to low air quality risks (Anenberg, 2017). These overshoots are even more worrisome as transport demand is constantly increasing and individual mobility continues to grow.

Health effects can be of short or long term and can range from minor ailments (fatigue, nausea, eye and skin irritation) to serious illnesses (asthma, allergies) and even life-threatening effects (cancer, cardiovascular disease) (WHO, 2015). About 100.000 premature adult deaths related to air quality occur each year in Europe (Arseni & Racioppi, 2018). Health concerns are prominent in dense urban areas where the road traffic is more concentrated which increases the exposure of the local population to emissions. Although significant improvements in the diesel powertrains efficiency and reductions in tailpipe emissions have occurred (Del Duce et al., 2016a; IEA, 2020a), fuels combustion for ICEV operation accounted for 60% $PM_{2.5}$ emissions, in 2015, in Europe (Anenberg, 2017). These PM emissions comprise a broad range of toxic micro particles that penetrate easily and lastingly into the organism. In addition, Nitrogen dioxide (NO_x) emissions are mostly resulting from transport sector. Tailpipe emissions such as NO_x and PM have been targeted by the EU 2016/2284 directive (2018) and emissions stringent standards for commercialized passenger cars and vans (currently Euro 6). As a result, these have significantly declined between 2000 and 2019 in France; PM_{10} emissions have decreased by 51%, $PM_{2.5}$ by 61% and NOx emissions have decreased by 56% (CGDD, 2020a). Nevertheless, NO_2, PM_{10} and O_3 emissions still exceed the European recommendations. The annual average concentrations have to be reduced for NO_2 by 10% compared to 2018, to meet the European thresholds (CGDD, 2020a). More tightening of the existing limits is therefore expected in the future through the development of EURO 7.

Human toxicity from local air quality degradation is an important impact category to consider within LCA of mobility scenarios. A holistic evaluation of this impact category should enable the quantification of potential adverse effects of conventional vehicle technologies but also evaluate electric mobility technologies in the sense of their benefits in urban areas. Vehicles fleet electrification can yield significant local air quality improvements in dense urban areas and thus, reduce the societal costs related to human health damages. In fact, the total cost of air pollution in France, based on transport-related health damages estimations (although these are complex and utmost uncertain) are between 68 to 97 billion euros, each year (Sénat, 2015). Nevertheless, it is important to note that electric vehicles also emit particulate matter through tire abrasion that should be quantified. In this regard, several studies (Buekers et al., 2014; Ke et al., 2017; Pan et al., 2021) have focused on this impact category to analyze the benefits from the development of electric vehicles in the future. Although real-time measurement of the exhaust and non-exhaust emissions is the best way to improve the representativeness of the results, these can be quantified based on the driving cycles profile and thus EURO standards are commonly used to determine their values.

2.1.4. Noise emissions

Noise emissions are a major environmental health concern commonly associated to transport, as a large part of the world population is exposed to exceeded noise threshold. More than 100 million Europeans are exposed to road-traffic noise (Lden) ≥ 55 dB against 40 dB WHO recommended level and 32 million are exposed to very high levels (above 65 dB) (EEA, 2021). The WHO has identified noise emissions as the second most pressing problems in European dense urban areas after the air pollution (Arseni & Racioppi, 2018). In fact, excessive noise levels affect the organs of hearing (physiological dimension), but can also disrupt the body in general, including sleep or behavior (psychological dimension).

In an attempt to reduce this nuisance, since the law n° 92-1444 (1992), relating to the fight against noise, the French government has implemented a set of policy measures that target noise risks through both preventive and curative requirements. This has been reinforced by the application of the directive 2002/49/EC (2002) on the assessment and management of environmental noise. Emitted noise from electric and hybrid vehicles has also been a source of concern at the European level. In fact, despite the benefits electric vehicles might generate for the environment in terms of lower noise pollution compared to the combustion engine transportation systems, their quietness can be dangerous to road users and cyclists (European Commission, 2019). Hence, the acoustic vehicle alerting system (AVAS) has introduced a set of rules for exterior and interior noise levels following various driving profiles (Fortino et al., 2016). All these measures are expected to reduce transport-related noise effects on human health and the environment in accordance with Sustainable Development Goals (SDGs).

Although measuring noise emissions is highly recommended when evaluating mobility scenarios (Del Duce et al., 2013), especially when comparing conventional and electric vehicle technologies through LCA these have been often neglected (Cucurachi et al., 2019). Moreover, noise emissions are still not included in the set of impact categories covered by the ILCD recommendations handbook (European Commission & JRC, 2010). Hence, noise emissions models should be added for a comprehensive environmental analysis of mobility scenarios. In a recent publication by Cucurachi et al. (2019), noise calculation models are introduced to LCA allowing the characterization of noise potential impacts associated the use of private and public road transport. Furthermore, Sacchi et al., (2021) have integrated these models to “carculator”, a python library tool that allows computing noise impact category among a numerous other categories, for various driving profiles and vehicle technologies within LCA.

2.1.5. Impacts on natural resources depletion

The rapid expansion of the automotive market since the early half of the 20th century, was driven by petroleum low-cost extraction which fostered people's accessibility to the market and thus increased transportations demand. This growth hit a hard wall in 1973 when the oil prices rose to an all-time high due to the geopolitical situation in the Middle East. As a result, dependency of western countries on oil products has since been questioned, yet not entirely addressed. In fact, oil extraction has never stopped growing despite the constantly increasing awareness on the declining reserves around the globe. Such statement can apply to any non-renewable resource, especially when accounting the huge automotive energy supply demand.

Transport manufacturing supply chain involves increasingly complex and diverse mineral resources to produce automotive components (e.g., catalytic converters, powertrains, batteries, etc.). Some of these used for electric motors and automotive electronics are particularly vulnerable for future disruption (e.g., rhodium, dysprosium, neodymium, terbium, europium and praseodymium) (Zimmermann et al., 2018). In fact, if conventional transport rises oil dependency questions and the limited supplies in the future, several studies have discussed the new demand for critical raw materials related to the low-carbon mobility transition (Ortego et al., 2018; Zimmermann et al., 2018; IEA, 2020a; Schmid, 2020).

The fast-evolving energy transition, including electric mobility and renewable energies sectors, still count on the oil and gas industry to fulfill the shift from conventional transportation fleet to electric alternatives. In addition, raw materials scarcity is expected to increase within the fleet electrification due to the significant amounts of critical raw materials used.

The expansion of Battery Electric Vehicles (BEV) market should increase the production of lithium-ion batteries and therefore, the demand of lithium and other minerals such as cobalt, neodymium, and praseodymium (Ortego et al., 2018). In fact, the main materials that are used in commercial lithium-ion batteries figure on the EU's (European Commission, 2020b) list of critical raw materials (i.e. lithium, cobalt and natural graphite). In this regard, a more sustainable and efficient management of resources supply is of utmost importance to guarantee a secure and effective energy transition. Correspondingly, materials criticality has been increasingly introduced in the recent years within the automotive sector to analyze the system resource supply and the related risk for its disruption (Hache et al., 2018; Knobloch et al., 2018; Lapko & Trucco, 2018). However, within LCA methods, criticality assessment is still an on-going research subject as for the most part it requires the use of economic modeling (J. Zhang et al., 2016) and thus, consequential LCA seems to be more suitable than attributional LCA studies.

The present analysis from LCA studies highlights the importance of clearly presenting the choice of impact categories to be included as well as the assumptions and data sources when reporting results. It also has implications for understanding the environmental burden of different vehicles life cycle stages by covering the various powertrains, vehicle and batteries technologies, together with the fuel types and electricity generation as discussed in the following section.

2.2. Identification of key life cycle stages and processes

There are numerous environmental LCA studies that have been identified (Cerdas et al., 2018; Hawkins et al., 2013; Van Mierlo et al., 2017; Cox, 2018; Sacchi et al., 2021) that addressed the environmental issues of electric mobility scenarios. Depending on their objectives, these studies considered different system boundaries.

2.2.1. Manufacturing stage: main contributing processes and parameters

There's a significant number of LCA studies that focus on the extraction of raw materials or the production of some key components such as batteries (Notter et al., 2010; Oliveira et al., 2015; De Sutter et al., 2019) or vehicle powertrains (Edwards et al., 2004; Dell et al., 2014b; Cox & Mutel, 2018). In fact, the automotive sector depends on a substantial number of materials (e.g., steel, copper, aluminum, plastics, platinum, gold, lithium, etc.) that are used in different amounts and can lead to very different environmental impacts. Consequently, the identification of **key processes, components and sub-components** involved in the manufacturing stage is essential to ensure representativeness of the potential impacts and the main contributing processes. **The geographical scope** of the extraction and production activities is also important for determining impacts related to the energy pathway for the foreground and background processes. In addition, decarbonization of the industry sector is occurring at a different pace in separate locations which induces a major source of uncertainty in the current production trends of automotive materials and components depending on the region of manufacturing and the origin of these materials.

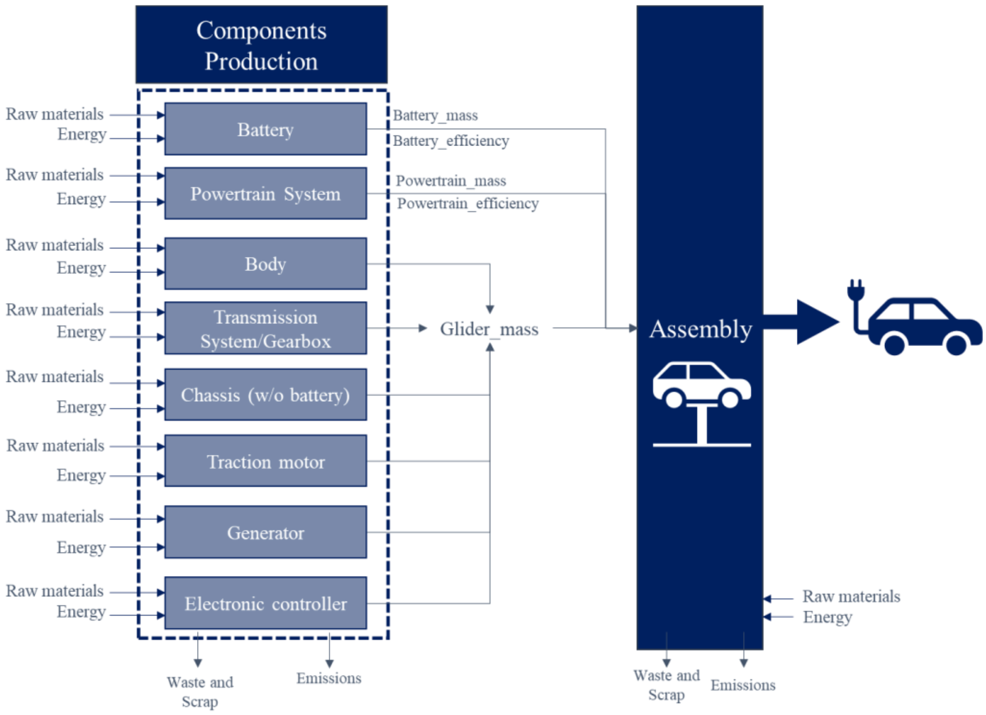


Figure 16 Definition of the background systems: vehicle's components manufacturing and vehicle's assembly

Depending on the considered vehicle's equipment, the environmental impacts resulting from the extraction of raw materials and components production could vary significantly (Nordelöf et al., 2014). The inventory should therefore cover input materials for each investigated process in detail. Background processes for the manufacturing stage include the **production of components**, such as the battery, and **sub-components**, such as, for batteries, the electrolyte, the separator, and the electrodes. Batteries' production for BEV has been identified as a major source of impacts, up to 35-41% of total GHG impacts (Hawkins et al., 2012), 7-8% from the electric motor and 16-18% from other powertrain components. The intensive use of copper to manufacture some batteries, driven by its conductivity properties, could lead to acidifying emissions and sulfidic tailings generated by mining activities (Del Duce et al., 2013). As presented in Figure 16, this also applies to other vehicle's components that may involve the use of potentially critical raw materials (e.g., platinum, gold, silver, copper, etc.) for components such as power electronic devices and, in the case of electric vehicles, the non-propulsion electrical system. The powertrain technology under investigation, plays an important role due to the use of some critical raw materials or ferrite permanent magnets (e.g., neodymium) (Hernandez et al., 2017).

The automotive sector has experienced the integration of more lightweight materials for the glider production which has significantly decreased the vehicle's final weight and thus, the energy consumption for the vehicle's operation. In fact, the use of steel is replaced by aluminum, plastics and carbon fiber, which results in a significant decrease in the vehicle's total weight, i.e., the steel weight share goes from 60% of the vehicle's total weight to 30.75% when shifting from ICEV conventional to lightweight materials and Appendix 1: Input conventional and lightweight materials share (%) for Internal Combustion Engine Vehicles (GREET, 2020).). Nonetheless, these lightweight materials are not devoid of environmental impacts due to their extraction and production. Hence, environmental impact mitigation that may result from the introduction of lightweight materials can be negligible especially when vehicles are operated with a low environmental footprint energy mix (Del Duce et al., 2013).

2.2.2. Vehicle's operation phase: main contributing processes and parameters

When modeling the vehicle's operational phase, it is important to consider exhaustive emissions from the fuel combustion, non-exhaustive emissions, maintenance, transportation infrastructure and indirect emissions from the life cycle of fuel or electricity production. To do so, the following elements need to be investigated:

Energy consumption

The energy consumption represents the specific energy required by a vehicle for its operation. It can be determined from measurements of actual values of a vehicle or a fleet of vehicles, or through estimation from mathematical models/formulas (Del Duce et al., 2013). Total energy consumption, expressed in [Wh/km] for EV or [L/km] for ICEV, depends on the driving cycle and the weather conditions as well as standardized comfort values (heating, air conditioning), equipment efficiency (powertrain, battery) and charging characteristics.

The energy required by the vehicle is defined based on a set of input parameters also identified for the production phase modeling (such as the mass of the vehicle, the battery, the power of the GMP, its efficiency, etc.), but also on other parameters specific to the operation phase such as the driving cycle, the powertrain and battery efficiencies. These are illustrated in Figure 17.

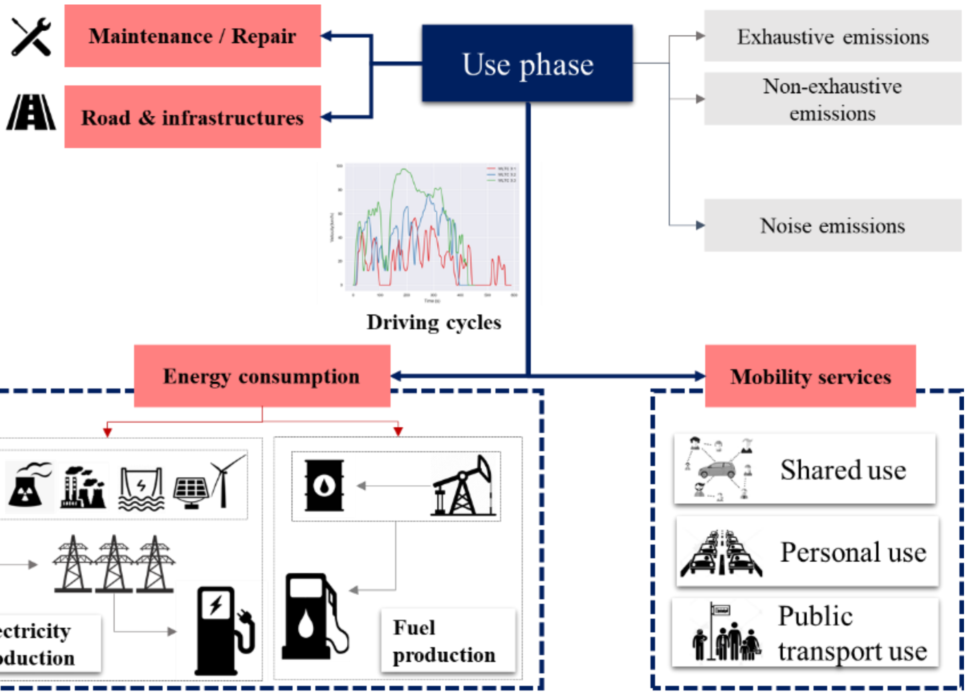


Figure 17 Vehicles' use phase and the main elements to be covered: energy consumption, driving cycles, fuel/electricity generation, maintenance and roads infrastructures

Fuel pathways and electricity mixes

The energy mix powering the vehicle (e.g., electricity or fuel) is a key determinant factor for the vehicle's environmental impacts. In fact, previous LCA studies have demonstrated that the operation phase contributes the most significantly to the environmental impacts of conventional vehicles due to fuel combustion (Bouter et al., 2020; Cerdas et al., 2018; European Commission, 2020a). In contrast, electric mobility offers the opportunity for substantially reducing the environmental footprint of the operation phase, especially when using of low-impact energy sources.

The European strategy for carbon-neutrality by 2050 (MTES, 2020) calls for significant reductions of the GHG emissions arising from the different sectors (e.g., industry, energy, residential, transport, etc.). In this context, various prospective scenarios have been developed to identify key pathways for achieving an effective energy transition at different temporal horizons (ADEME, 2015; Bigo, 2020; IEA, 2020b; RTE, 2021), or their associated impacts (Volkart et al., 2018; Catalan & Cornelus, 2019; Besseau, 2019). These scenarios have focused on the massive integration of renewable energies to substitute fossil resources in the long-term. Given the high dependence of transport sector on petroleum-based products (91% of the total final energy consumed in 2019), more specific scenarios were established to tackle the challenges that may occur particularly for this sector. Bigo (2020) studied 5 key evolution factors, namely transport demand, modal shift, occupation rate, energy efficiency, and carbon intensity, to achieve energy transition in the transport sector based on 18 different prospective passengers transport scenarios.

The shift from petrol-based fuels and non-renewable energy sources to low-impact energy pathways is essential to achieve sustainability in future mobility schemes. Hence, renewable energy sources, such as photovoltaics, wind energy systems and other bio-energy sources, can be favored for EVs charging (Longo et al., 2019) enabling thus a better environmental performance. The evolution of the electricity mix following a scenario from the IRENA (2018) revealed that the share of renewable energies is expected to increase by 61% between 2015 and 2050. Moreover, Hoarau & Perez (2018) have identified the underlying synergies between the joint development of PV-powered EVS. The most disruptive synergies reside in the environmental benefits that EV massive development could use from such renewable energy source and, in return, the bi-directional flexibility of EV batteries to maximize the PV's self-consumption. The IEA' sustainable development scenario "Scenario EV30@30" has also pointed out the importance of an accelerated deployment of EV fleet coupled with decarbonized power generation allowing thus to reduce up to 50% the GHG emissions of WTW perspective from an equivalent conventional fleet.

When analyzing the environmental benefits or burdens related to the integration of renewables to electric mobility scenarios, various electricity pathways are to be considered within LCA studies. Such multicriteria assessments are needed to provide consistent information on all the environmental impact categories rather than a narrow focus on the GHG emissions and thus, guide the public and industrial actors towards more informed decision-making.

Definition of the vehicles' driving cycles

The vehicle speed and acceleration needed to compute the required motive energy depend on the driving cycles performed by the vehicle. The New European Driving Cycle (NEDC), the worldwide harmonized Light vehicles Test Conditions (WLTC) and the Common Artemis Driving Cycle (CADC) illustrated in Figure 1818 are three of the most common approval cycles. They are most often used to define the energy consumption according to standardized test conditions (e.g., temperature, wind speed, etc.).

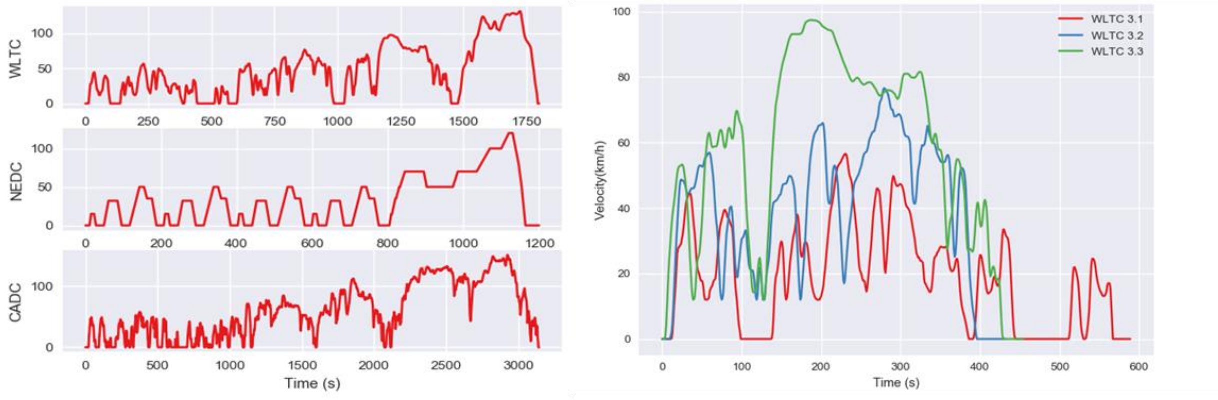


Figure 18 Driving cycles velocity and time for CADC, NEDC, and WLTC. In the right is presented the WLTC 3 covering the urban profil driving characterisitics

The WLTC and NADC cycles are more representative of real-world use than NEDC one thanks to the consideration of 4 driving profiles (congested urban use, free-flowing urban use, extra-urban use and motorway use) and measurements made in real time on the daily operation of vehicles in European countries. In contrast, the NEDC cycle, used by the ecoinvent database, considers only 2 types of driving profiles (urban and highway) and seems to underestimate the real energy consumption because of the use of optimal conditions used during the test (temperature, wind speed, etc.) and the limited driving profiles. Moreover, the driving cycles also play an important role in determining the exhaust emissions and noise emissions as discussed in Sacchi et al. (2021).

Roads and infrastructures

The evaluation of transportation technologies requires the integration of road infrastructure and all activities related to its maintenance, but also technology-specific infrastructure such as charging stations for electric vehicles.

Two types of loads exist (RTE, 2017b; UFE, 2019): (1) a normal, slow charge, most often performed, through which the battery is recharged by means of the on-board charger in the vehicle and lasts on average from 6 to 8 hours. (2) an accelerated charge requiring a much more powerful charger (43 kW) to reduce the charging time to less than one hour. This type of charging is only applicable to a limited number of vehicle models and requires a specific connection to the charging stations provided for this purpose.

Depending on the type of transport, the type of charge (normal or accelerated) may differ. Indeed, given the high capacity of electric bus batteries, and in order not to weigh them down with large on-board chargers, slow charging, using external chargers, is more efficient by organizing it in depots during the night. Normal charging delivers 50kW while for fast charging, sometimes organized in line terminus, can reach a power of the order of 300 to 600kW (RTE, 2019).

Maintenance and repair

It includes all activities related to maintaining the vehicle in good working order and replacing certain components (wheels, batteries, fluids, etc.) during its use. Battery replacement has been considered crucial for EVs by the "Electric Car LCA (eLCAr)" guidelines (Del Duce et al., 2013) due to the presence of batteries that could be replaced during the use phase of the vehicle. Indeed, the life of a battery is expressed in terms of the number of complete charge/discharge cycles performed to fulfill its function. The number of cycles is in the order of 650 cycles for a battery of 11kWh capacity and can go up to 1000 cycles for batteries of 25kWh (Cox, 2018). Given, that the ecoinvent database considers the presence of a single battery for a 10-year life of a vehicle (Del Duce et al., 2016b), the variation of this parameter depending on the type of transport will be estimated in order to evaluate its impact on the results.

Mobility services: shared, personal and collective transport

Three main categories of mobility services can be distinguished:

Personal mobility: consists of individual use of transportation technologies. In France, it represents 80% of total traveled kilometers in 2020 (CGDD, 2021). The use of private cars is the most contributing to carbon footprint with 56% of total GHG emissions.

Collective mobility: consists of public transportation services, can be distinguished by the traveled distance; long-distance transportation such as trains, ships, aircraft, and short-distance transportation in urban cities such as buses, tramways, subways, etc.

Shared mobility: consists of the shared use of transportation technologies, i.e., vehicles, bicycles, motorcycles, etc. Often calls for a digital service to make the link between the service provider and the end-user possible.

One of the key drivers for future energy transition within mobility relies on the modal shift. Since 1960, collective transport modes have declined by 11% giving way to the expansion of individual passenger vehicles (CGDD, 2021). As a result the GHG emissions have increased by 22% between 1960 and 2016 (Bigo, 2016). Personal mobility involves the concept of “ownership” by which the users’ relationship with vehicles involve issues of convenience, independence, safety and social status (Lawler et al., 2013). Hence, promoting the modal shift directly affect users’ mobility patterns as it requires changing their habits, sometimes, with public or shared transportation offers that do not fully meet their needs.

Exhaust and non-exhaust emissions

Exhaust emissions arise from conventional vehicles and can be grouped into two types (Del Duce et al., 2016b): (1) emissions that are directly related to fuel combustion and depend on the nature of the fuel (e.g., diesel, petroleum, etc.) and the amount consumed fuel per km. (2) emissions that depend on EURO standards (3, 4, 5, and 6) representing standardized emissions according to the class of the vehicle. The EURO 6-d standard is seen as the most challenging for emissions reduction, especially in terms of particulate matter affecting human health (European Commission 2012).

Non-exhaust emissions related to the vehicle's braking system include particulate matter from vehicle tires and road abrasion (Del Duce et al., 2016b). These emissions are proportionally related to the vehicle size and are prevalent for both conventional and electric vehicles and they depend on the nature of the road tires and the driving patterns.

2.2.3. Vehicle's end of life: main contributing processes and parameters

The European directive has set the rate of reuse of vehicles at the end of their lifecycle at 95% in 2015 (MTES, 2018). The vehicles end of life involves a set of processes allowing the reuse and recycling of raw materials or components. A depollution is carried out after the separation of liquid and solid hazardous waste (battery, cooling and braking fluid, etc.). All the extracted parts are redirected to a specialized center for reuse, recovery or final disposal as illustrated in figure 19.

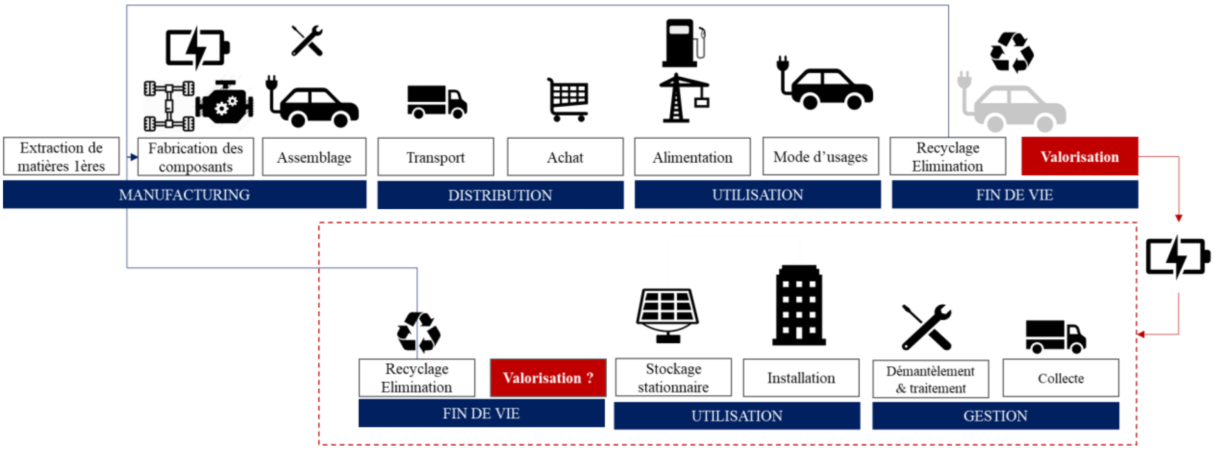


Figure 19 "Cradle to Grave" perspective: accounting for the vehicle's End of Life through a second application of the battery

After a regular automotive use, corresponding to a specific number of charge/discharge cycles, batteries lose 20 to 30% of their initial capacity and the driving range is thus affected. The battery reaches end-of-life conditions at 80% of its initial capacity (De Sutter et al., 2019). Secondary applications can be envisaged. For example, stationary storage to support the production of self-consumption renewable energies such as photovoltaic and wind power (Bobba et al., 2018). In this thesis, such accounting of the battery second life application was not possible due to the complexity of impacts allocation with respect to the sustainability assessment. Such allocations models are still not sufficiently developed within the social dimension. Nonetheless, it is important to note that from the environmental perspective, it can be very relevant to consider this within LCSA studies to allow a full representation of the environmental impacts.

3. Key assumptions and input parameters for LCA of electric mobility scenarios

In this section, the most significant parameters that have been identified from the previous literature review are established. These parameters enable comparing between the three mobility scenarios that are under investigation and are later used in section 3 for the construction of the parameterized LCA model. The parameters that have been chosen as variable are not exhaustive and should be adapted following the objective of the study. In fact, there's a substantial number of parameters that could have an influence on the final results which can vary according to the considered scope of the study. For instance, total number of travels operated by a vehicle within a shared use and the average traveled distance is a key parameter when analyzing solely shared mobility services while for collective use the operation duration and heating and cooling systems can have a significant influence on the generated impacts. In this study, those parameters are identified from previous studies and their values are fixed to reflect the average use case. The defined parameters are therefore adapted for this purpose. Vehicles' modeling, whether for individual, shared or collective transport, depends on a high number of key input parameters. These parameters have been determined according to their influence on the results.

Vehicle lifetime [years]: represents the total number of years or traveled kilometers for the vehicle's operation, expressed in driven km or in yrs. This is a key factor for determining the overall impacts of the vehicles. This parameter is lower in the case of shared mobility use (4 years) because of the intensive use of the vehicle. However, the total traveled distance is more significant than individual mobility use.

Vehicle lifetime kilometers [km]: represents the total number of traveled kilometers during the vehicle's operation, expressed in driven kilometers. This is a key factor for determining the overall impacts of the vehicles.

Battery lifetime kilometers [km]: corresponds to total number of the battery's years of operation and given number of charge and discharge cycles. It is expressed in total traveled kilometers. This parameter allows determining the battery's replacement number.

Total driving mass [kg]: The total mass of the vehicle is the sum of the battery mass, powertrain mass and the glider mass. Within this thesis midsize passenger vehicles are evaluated.

Energy consumption [Wh/km] or [L/km]: represents the total energy consumption, expressed in [Wh/km] for EV or [L/km] for ICEV, depends on total driving mass, the driving cycle chosen for the study. Such parameter is directly linked to the weather conditions as well as standardized comfort values (heating, air conditioning), equipment efficiency (powertrain, battery) and charging characteristics, etc.

Average passengers (unit): this parameter corresponds to the percentage of the passenger mass on the total mass of the vehicle, thus expressing the number of passengers that use a vehicle during a trip. Being different according to the type of transport evaluated, this parameter is very significant for the comparison between the types of uses. In the ADEME-IFPEN 2018 study, it is 1.3 for an individual use, about 17.4 for collective use and 2.6 for a shared free-floating use (IFP Energies Nouvelles, 2018).

Driving cycle: Urban driving conditions are considered to allow the calculations of the energy required for the vehicles' operation and thus the evaluation of the considered scenarios.

Very high temporal and technological variability is found for all of these parameters due to significant research and development advances in the automotive sector (Tamayao et al., 2015; Cox, 2018). In addition, the modeling of the parameters as well as the corresponding values in the ecoinvent 3.6

database are derived from the Habermarcher (2011) study. Hence, the included information could be outdated and lead to erroneous representation of the actual environmental impacts. In order to take into account, the technological advancements, these data are updated to improve the representativeness of the evaluation results through the use of parameterized models.

Systematic approach for the environmental-impact analysis: integrating parametrized LCA models and its application to electric mobility scenarios. Built on the analysis of LCAs related to electric mobility scenarios, the current thesis proposes a four-step approach for establishing an LCA parametrized model and its implementation for mobility scenarios:

a) Selection of the input variables. This step is conducted according to the previous literature review where the key input parameters are defined.
b) Modeling of mobility scenarios or product system under investigation. In this thesis, various external models and tools are identified and adjusted to integrate the key input parameters.
c) Selection of appropriate background inventory data for the settled scenarios. The ecoinvent database or other data sources can be used depending on their relevancy for the study and the data quality they provide.
d) Definition impact categories and characterization models to perform the impacts analysis.

Such model is further implemented by specifying the input parameters corresponding to the three electric mobility scenarios considered within this thesis.

4. Systematic approach for the environmental impacts analysis: integrating parametrized LCA models and its application to electric mobility scenarios

4.1.Goal and Scope

The goal of this study is to analyze two key aspects of passenger mobility: electric mobility and urban transport modes. It therefore seeks to identify the environmental impacts associated with mobility scenarios that cover three different mobility services and various vehicles technologies with different electrification levels. The study focuses on the case of urban mobility. The most representative vehicles' segments corresponding to urban transport for personal, collective, and shared mobility is therefore analyzed. To achieve this goal, five different powertrains (BEV, PHEV-p, HEV-p, ICEV-p, ICEV-d) corresponding to passenger midsize vehicles are analyzed over the WLTC driving cycle in the French context. The national electricity mix is therefore used for performing the analysis of electric vehicles. In a second part, the environmental impacts of buses for the collective transport mode scenario are analyzed. Urban public transport modes depend on 2 classes of agglomerations: class 1 (agglomerations of more than 250,000 inhabitants) and class 2 (agglomeration of 150,000 to 250,000 inhabitants). Electric modes are not present on class 3 (agglomerations of fewer than 150,000 inhabitants), which are more accurate for a rural area representation (CGEDD et al., 2015).

Within the definition of the goal and scope of the study, and according to the ISO standards (ISO 14,040, 2006) the functional unit is key for analyzing the impacts of the different mobility scenarios considered within this thesis. The function of the evaluated product systems should also be coherent for the three-sustainability dimensions considered within this thesis (Traverso et al., 2015). Hence, the transportation of people for similar driving condition is expressed as passengers per traveled kilometer.

The lifetime of the analyzed transportation systems depends on the mobility services. In fact, different values should be considered for the type of the technology and the mobility services. The assumptions made for the lifetime of passenger vehicles are based on the literature (Bouter et al. 2020, Guyon 2021). For a personal use, the vehicle lifetime in kilometers is 150,000 km corresponding to 10 years of a personal vehicle operation and 480.000km corresponding to 12-year operation is taken for buses. For a shared use, the life span is shorter compared to a personal use as the operation phase accounts for 4 years corresponding to 138,500 km. This assumption is based on Guyon (2021) study for carpooling service LCA modeling.

The system boundaries covered in this study, and shown in Figure 20 System boundaries of the current study: the integration of the Well to Wheel perspective to account for the impacts from the fuel/electricity production and use within the vehicle's operationaddress the environmental impacts stemming from the entire life cycles, i.e., the production of the transportation technologies, including different powertrains for electric and conventional vehicles, the WTW perspective accounting for the energy pathway used (electricity generation and fuel pathways) as well as their use within a TTW perspective in the French context.

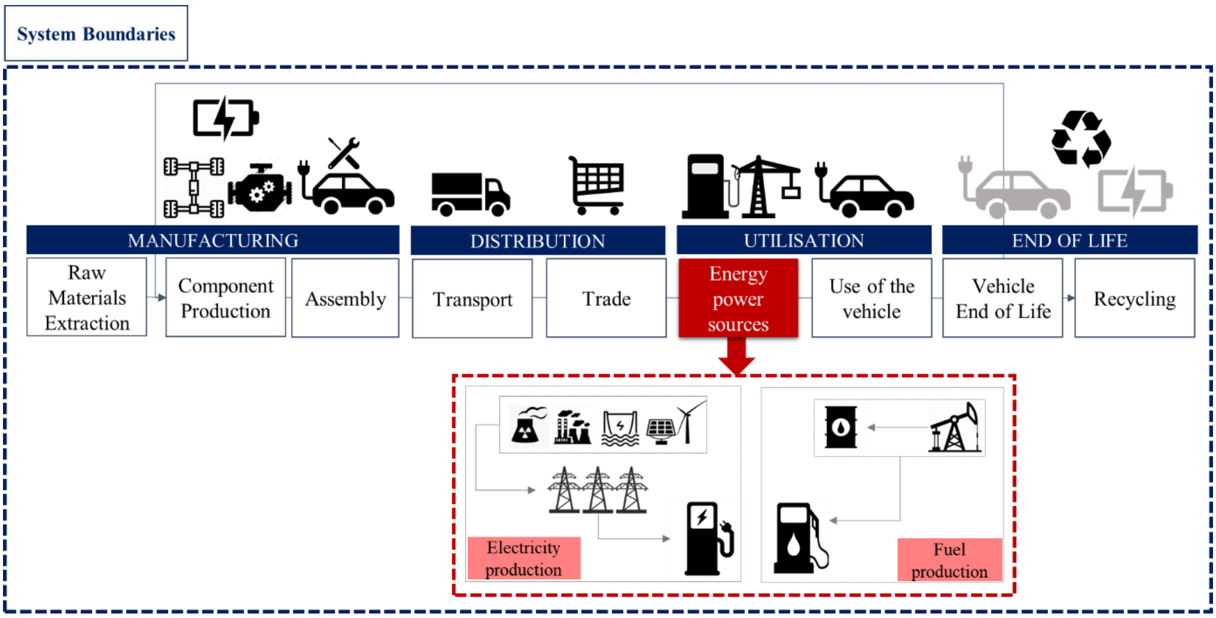


Figure 20 System boundaries of the current study: the integration of the Well to Wheel perspective to account for the impacts from the fuel/electricity production and use within the vehicle's operation

The LCA is performed following ISO standards (ISO 14040-44, 2006), using brightway2 library (Mutel, 2017) in python language to allow integrating the identified key parameters within the life cycle inventory suggested by the ecoinvent database 3.6 (Del Duce et al., 2016b). The brightway2 library allows loading the existing datasets in ecoinvent or creating new updated ones and thus, advanced impacts calculations can be performed. As mentioned above, the identified key parameters could substantially influence the results and the existing vehicles' datasets could include outdated information. Moreover, this thesis makes use of a second open-source Python library "carculator" dedicated to adjusting passenger vehicles' inventories by covering the production, use and disposal stages (Sacchi et al., 2021). Such tool allows the integration of the most significant parameters through parametrized inventories to LCA and consequently enhance the representativeness of the obtained results. The impact assessment of the three mobility scenarios considered within this study covers the ILCD midpoint indicators (European Commission. Joint Research Centre., 2018b) corresponding to the most significant impact categories identified from the literature.

4.2.Life Cycle Inventory definition

According to the ISO 14040-44 standards, the LCI should include all input and output flows from the various processes covered by the study. This entails data collection for the foreground and background systems. In addition, data validation is also required in this phase to ensure compliance with the standards requirements. The quantification of input and output flows as well as their units of measurement should be utmost representative of the current situation.

This thesis uses the cut-off version of the provided datasets by the ecoinvent database v3.6 for passenger vehicles and buses (Del Duce et al., 2016b) as a basis of the modeling. The first step that was conducted within the LCI phase consists of analyzing the ecoinvent datasets for four covered vehicle technologies corresponding to passenger electric and conventional vehicles, i.e., petrol-ICEV, diesel-ICEV, natural gas-ICEV and BEV. This analysis was performed for the 19-midpoint ILCD indicators and provided in Appendix 2: Inventory analysis with brightway 2 Python library, ecoinvent 3.6, ILCD midpoint indicators 20 and noise emissions. The same analysis was conducted for two existing inventories for buses corresponding to electric (trolley bus) and conventional (diesel bus) technologies, presented in Appendix 3: Analysis of the variations of the parameters depending on the EURO emissions standards (3.4 and 5), the location (GLO, RER and RoW), size (large, medium, small) and the powertrain (diesel, petrol, natural gas and electric) Moreover, the variability of the environmental impacts was analyzed for the different existing systems following four elements, the size (small, medium, large), the powertrain (ICEV-d, ICEV-p), the EURO standards (3, 4 and 5) and location (GLO, RER and RoW). These are presented in Appendix 3: Analysis of the variations of the parameters depending on the EURO emissions standards (3.4 and 5), the location (GLO, RER and RoW), size (large, medium, small) and the powertrain (diesel, petrol, natural gas and electric). Following this step, we have identified several shortcomings for the datasets that could lead to a poor representation of the actual impacts mainly for the following reasons:

- The existing inventories for vehicles and batteries do not reflect the technological advances that have occurred over time in the automotive industry.
- The NEDC cycle, used by the ecoinvent database, considers only 2 types of driving profiles (urban and highway) and seems to underestimate the real energy consumption because of the conditions used during the test (temperature, wind speed, etc.) and the limited driving profiles. As discussed in section 1.2 more recent driving cycles exist, such as the WLTC and CADC driving cycle and are more accurate for a realistic use.
- EURO5 standards are used for modeling the exhaust emissions instead of the updated version EURO 6-d (the updated EURO 6).
- Noise emissions are not included
- The electricity pathway corresponds to the year of the vehicle production rather than a time-distributed electricity mix for the year of the analysis.

Several previous studies dealing with energy systems have pointed these drawbacks and developed specific parametrized models and tools to allow the integration of the important parameters (Padey et al., 2012; Besseau, 2019; Sacchi et al., 2019; Douziech et al., 2021). Such studies provide parametrized models for LCA to perform advanced environmental impacts or uncertainties calculations based on updated inventories of the systems under investigation. In the same line, Cox (2018) has developed these parametrized models for different vehicle powertrains and thus enabled more representativeness of the energy, materials flows used through more updated life cycle inventories. Sacchi & Mutel (2019) have designed the "carculator" model that includes more updated information on various key parameters for passenger vehicles. This model is developed with Python programming language to assess the environmental and economic life cycle footprint for a wide range of vehicle technologies based on the work of Cox (2018). All required information is provided in Sacchi & Mutel (2019) study and the library is open-source and available in (Sacchi, 2019/2021).

The use of parametrized models within LCA in the present chapter would enable to consider the key input parameters listed above, including energy mix modeling, noise emissions modeling, vehicle powertrains modeling. This should enhance the representativeness of the findings by accounting for more specific inventories compatible with the analyzed technologies. With respect to the previous statements, the current environmental study makes use of carculator tool by integrating the identified key parameters within the literature review (section 2) to perform the impacts evaluation phase for personal passenger vehicles.

To build the carculator model (Sacchi, 2019/2021), numerous databases and models were used for calculating the parameters including (mass module, auxiliary energy, motive energy, noise emissions and exhaust emissions). Figure 21 21 illustrates a snapshot of the calculated energy consumption model, as an example, of the performed modeling. Hence, input parameters that are used by the carculator (in yellow circles) for its calculation together with those adjusted in the current study (represented in red circles). Carculator model provides more than 300 input parameters that can be accounted for and processed within the modeling. The relative values and their range of variations can be found directly in the published vehicle inventories and associated publication that analyzes the uncertainties for the some of the parameters such as the mass modules, energy modules and noise emissions (Sacchi & Mutel, 2019; Sacchi, 2019/2021).

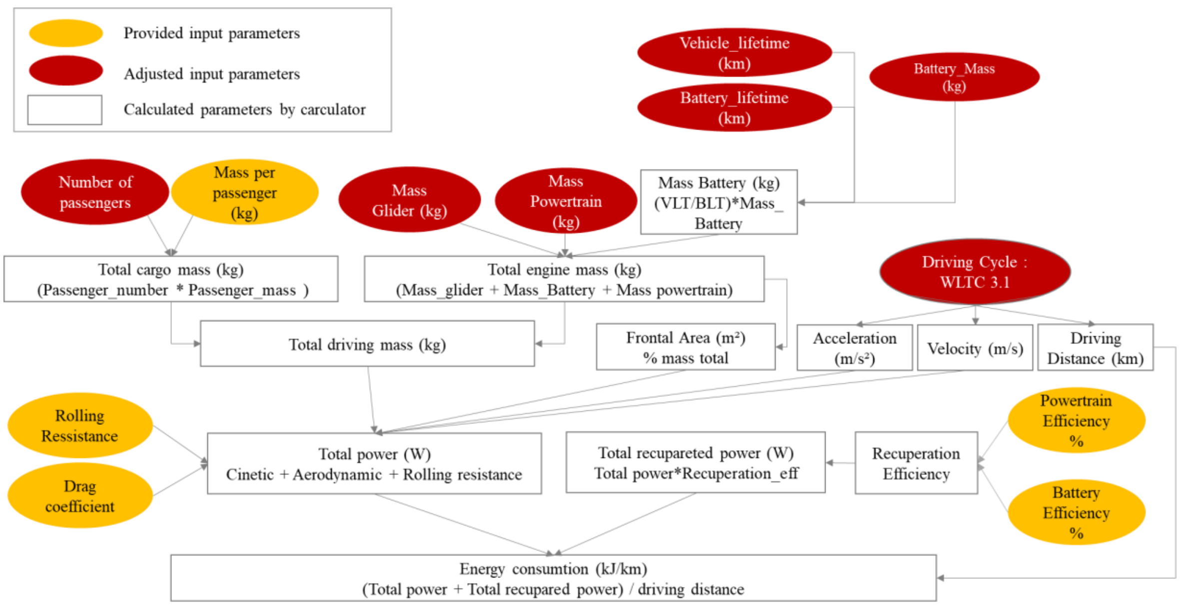


Figure 21 Snapshot of the defined variable parameters (in red) to calculate the vehicle's energy consumption and those who were fixed during this study (yellow)

Within this research, the provided inventories in carculator for passenger cars and buses are used within the environmental analysis. Seven parameters were adjusted to enable the analysis of the three considered scenarios. Table 3 presents all the key adjusted parameters and assumptions for the three considered mobility scenarios and their corresponding values (illustrated in red in).

Table 3 Key input parameters adjusted from carculator for each mobility scenario considered in this thesis

Parameters	**Scenario 1: personal mobility**	**Scenario 2: Public transportation**	**Scenario 3: Shared mobility**
Technologies	5 powertrains (BEV, HEV-p, PHEV-p, ICEV-d, ICEV-p)	4 powertrains (BEV, ICEV-d, PHEV-p, ICEV-g)	5 powertrains (BEV, HEV-p, PHEV-p, ICEV-d, ICEV-p)

Vehicle size: total driving mass*	Medium size (Depends on specific powertrains parameter)	13m city bus (Depends on specific powertrains parameter)	Medium size (Depends on specific powertrains parameter)
Vehicle lifetime in years	10 [10-16]	12 [12-14] ; -20 for BEV]	4 [2-4]
Vehicle lifetime in km	150,000 [120,000-200,000]	480,000 [480,000-700,000]	138,500 [66,200-138,500]
Number of passengers	1.6 (Sacchi & Mutel 2019)	17.4 (ADEME & IFPEN 2018 ; Bouter 2020)	2 (Guyon 2021)
Electricity mix used for EV technologies	France (Assumption)	France (Assumption)	France (Assumption)
Driving cycle	WLTC 3.1	WLTC 3.1	WLTC 3.1
Energy consumption**	Variable (Depends on specific powertrains parameter)	Variable (Depends on specific powertrains parameter)	Variable (Depends on specific powertrains parameter)

** and ** depends on each of the powertrain technologies considered in the study.*

The analysis is conducted for a medium size vehicle for scenario 1 and 3 (personal and shared mobility use case) and for a 13m city bus for the scenario 2 (public transportation use case). Within each of these three scenarios a set of different powertrains are considered as represented in table 4 covering electric (BEV, HEV-p, PHEV-p) and conventional (ICEV-p, ICEV-d, and ICEV-g for public transportation).

The total driving mass is calculated by considering the powertrain mass, glider mass, battery mass and passengers' mass are thus specific for each of the evaluated vehicle powertrains. As for the energy consumption (tank to wheel energy), it is determined by using both the total driving mass and the considered driving cycle, namely urban cycle WLTC3.1 in this study. The energy consumption also depends on other parameters, such as the battery charge and discharge efficiency (%), the average passenger mass considered, powertrain and recuperation efficiency (%). These are fixed and their values are based on those provided by inventories in carculator. Table 4 presents an example of both the total driving mass and the energy consumption for each of the five vehicle technologies analyzed.

Table 4 Fixed input parameters and those calculated for five vehicle technologies considered within a personal mobility use case

	BEV	**HEV-p**	**ICEV-p**	**ICEV-d**	**PHEV-p**
Driving mass (kg)	2049	1783	1719	1894	1857
Powertrain mass (kg)	95	126	123	131	189
Average passenger mass (kg)	75	75	75	75	75

Battery charge efficiency (%)	0.85	--	--	--	0.85
Battery discharge efficiency (%)	0.88	--	--	--	0.58
Recuperation efficiency (%)	0.73	0.73	0.69	0.69	0.69
Powertrain efficiency (%)	0.89	0.30	0.28	0.35	--
TTW energy (kWh)	785.78	2001.08	2409.86	2055.48	1284.27

Exhaust emissions module uses the Handbook Emissions Factors for Road Transport (HBEFA) database v4.1 (INFRAS, 2019) that provide emission factors following each level of speed. The driving cycle chosen for the study influences thus the emissions factors. Moreover, the amounts of pollutants are calculated with respect to the EURO 6-d standards (Commission Regulation (EU) 2016/427, 2016). Noise emissions model uses Cucurachi et al. (2019) study where noise profiles are suggested based on various driving conditions. The WLTC 3 urban driving cycle is also used to calculate these emissions.

4.3.Life Cycle Impact Assessment

In this phase the impact categories and their corresponding indicators are defined, and the analysis is performed through the characterization of the emitted substances and the extracted materials and energy sources (both for renewables and non-renewables). To perform the analysis of the relevant impact categories identified, this thesis uses midpoint impact categories that arise from the ILCD handbook recommended indicators (EC and JRC, 2018b). These impact categories concern various environmental related effects such as climate change, ecosystem deterioration, human health, resources depletion. Table 5 presents a summary of the impact categories and their corresponding indicators used in this evaluation phase. As explained previously, emissions factors for noise impact categories are not covered by the ILCA handbook. In the present work, this category is quantified based on (Sacchi, 2019/2021) parametrized models based on the chosen driving cycle, i.e., urban driving cycles (WLTC) in this study both for passenger vehicles and buses models. These are calculated within the calculator model as direct-exhaust emissions from the vehicle's operation.

Table 5 Impact categories and their corresponding midpoint indicators from ILCD 2018 used within the conducted analysis in this thesis from European Commission and JRC (2018) handbook on ILCD Midpoint indicators.

Impact category	Indicator	Unit	Recommended LCIA model
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq	Baseline model of 100 years of the IPCC
Ozone depletion Ozone	Depletion Potential (ODP)	kg CFC-11eq	Steady-state ODPs
Human toxicity, cancer effects	Comparative Toxic Unit for humans (CTU_h)	CTU_h	USEtox model
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans (CTU_h)	CTU_h	USEtox model
Particulate matter / respiratory inorganic	Human health effects associated with exposure to $PM_{2.5}$	Disease incidences	PM model recommended by UNEP
Ionizing radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}	Human health effect model
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS as applied in ReCiPe
Acidification	Accumulated Exceedance (AE)	Mol H+ eq	Accumulated Exceedance
Eutrophication terrestrial	Accumulated Exceedance	Mol N eq	Accumulated Exceedance
Eutrophication aquatic freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model
Eutrophication aquatic marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND
Ecotoxicity (freshwater)	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model
Land use	Soil quality index (Biotic production, Erosion resistance, Mechanical filtration, and Groundwater replenishment	Dimensionless*	Soil quality index based on LANCA
Water scarcity	User deprivation potential (deprivation-weighted water consumption)	kg world eq. deprived	Available Water REmainning
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML Guinée et al. 2002
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML

*: aggregated index of kg biotic production/(m^2*a)[7] kg soil/(m^2*a); m^3*a; m^3 water/(m^2*a); m^3g.water/(m^2*a)

4.4. Life Cycle Interpretation

A multicriteria environmental analysis is presented for the three mobility scenarios analyzed within this thesis with a focus on electric vehicle technologies. These results are analyzed per each mobility use corresponding to personal use, collective use and shared use mobility.

The obtained results will later be used conjointly with S-LCA results and LCC results through an MCDA approach aiming to improve the overall interpretation phase of the proposed LCSA framework.

4.4.1. Personal use mobility scenario

Figure 22 Environmental Impacts calculation for personal passenger midsize vehicles in France 2020 for each powertrain technologyillustrates impacts calculation for midsize passenger vehicles with respect to the WLTC driving cycle corresponding to an urban driving profile in France. The environmental impacts are performed for conventional diesel (ICEV-d), petrol (ICEV-p) fueled vehicles and are compared with electric powertrains with different electrification levels (BEV, HEV-p, PHEV-p). These results were obtained following the adjustment of a set of input parameters (section 3) using carculator model and performed through brightway2 python library and ecoinvent v3.6 database as a basis for the datasets.

As it can be observed on Figure 22 Environmental Impacts calculation for personal passenger midsize vehicles in France 2020 for each powertrain technology22, the main factors associated to the calculated impact categories are highlighted, i.e., vehicle production, energy chain (fuel or electricity generation), road, exhaust-direct emissions and non-exhaust emission as well as the energy storage (battery technology NMC produced in China).

The overall impacts analysis for the 20 environmental indicators is quite complex as the different powertrains show different environmental impacts. Within the current study, electric powertrains, especially in the case of BEV technologies, show enhanced performance for climate change and fossil depletion thanks to the use of France low-carbon electricity mix. As represented in figure 22, climate change impacts are directly linked to the electrification level where the direct exhaust emissions stemming from the liquid fossil-fuel combustion are the most significant in the case of ICEV-p and ICEV-d. In contrast, electric powered vehicle technologies present higher environmental impacts for resources depletion (i.e., water and metal depletion) and the impacts on the ecosystem quality (i.e., ionizing radiation, freshwater ecotoxicity and marine eutrophication, etc.). Such environmental impacts for BEV are mainly derived from the battery production, while PHEV showed better environmental performance as lower energy storage capacity required and thus fewer environmental impacts from the battery production. The electricity mix in France used for the vehicles’ battery powering is mostly responsible for the significant impacts on ionizing radiation due to high share of nuclear sources that amounts to 67% in France in 2020 (CGDD, 2021), but can also present impacts on human toxicity and metals depletion as discussed in (Besseau, 2019).

A study from Bouter et al. (2020) have already discussed the significant influence of the electrification level on the generated environmental impacts and discussed the double-edged effects of the PHEV technologies. In fact, if these technologies show better environmental performance than their counterparts BEV, the use of fossil fuel as the only energy source for the WTW stage can lead to more significant environmental impacts that are comparable with those associated with ICEV-p.

The same study has pointed out the fact that conventional vehicles could present better performance for some impacts categories compared to electric powertrains (Bouter et al., 2020). Although such observation can also be highlighted by the present work, it is important to note that a classification of resources depletion impact category could lead to partial conclusions. In fact, the updated list of ILCD midpoint indicators (European Commission. Joint Research Centre., 2018b) distinguish between the metal, fossil and water depletion which in this study demonstrated different results for electric vehicles. When considering the vehicle's production (without batteries), the different powertrains perform similar results for most of the evaluated impact categories. As for noise emissions, electric vehicles have better environmental performance on this impact category compared to the conventional ones.

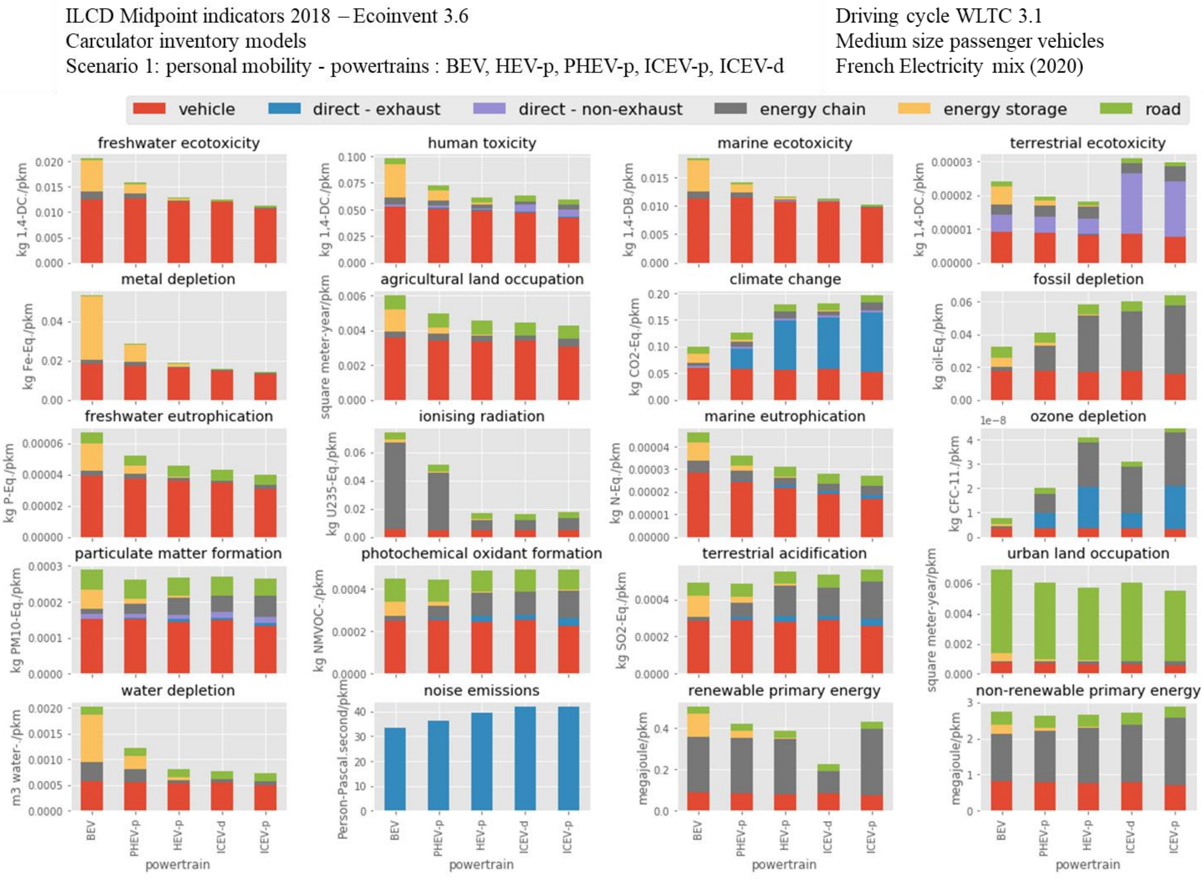


Figure 22 Environmental Impacts calculation for personal passenger midsize vehicles in France 2020 for each powertrain technology

Impacts on local air quality are showing variable environmental performance between BEV and PHEV but also compared to conventional vehicles. Indeed, the associated impacts to ozone depletion showed better performance for BEV while for other indicators, i.e., photochemical oxidant formation, human toxicity and particulate matter formation, HEV and PHEV demonstrated better environmental performance compared to ICEV technologies. This can be explained by the use of nickel for batteries production which is the main contributor to the impacts on air quality in the case of BEV technologies.

4.4.2. Collective use mobility scenario

This section presents the performed impacts calculation for four different buses' powertrains corresponding to full BEV technology (BEV-depot), hybrid electric buses (HEV), natural gas powered (ICEV-g) and diesel fuel powered buses (ICEV-d). The analysis is performed for a use case in France in 2020 following an urban driving profile. Input data for the used life cycle inventories in bus_carculator (Sacchi, 2020/2021) are mostly based on data from the European Commission for heavy-duty vehicles. The results are illustrated in figure 23 for the fourth analyzed technologies.

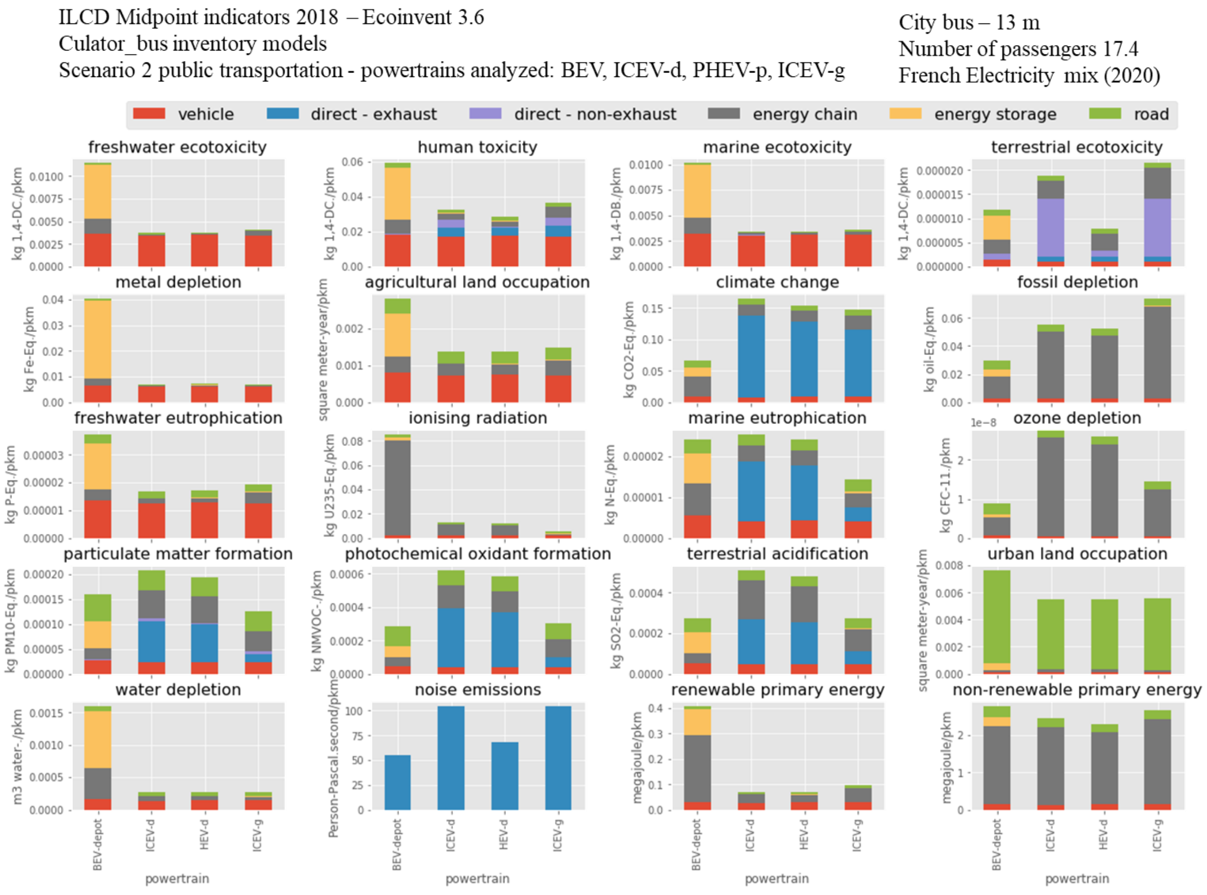


Figure 23 illustrate impacts calculation results for four powertrains of buses (13m city bus) with urban driving use scenario in France 2020

The results show significantly higher environmental impacts for BEV buses technologies compared to other technologies regarding the ecosystem quality, metals depletion and water depletion, human toxicity and ionizing radiation. These impacts are directly associated to the important battery life cycle while ionizing radiation is mainly associated with the electricity generation in France.

Better environmental performance is observed for climate change, fossil-resource depletion, noise emissions, particulate matter formation, terrestrial acidification and ozone layer depletion. If such results are favorable to the current massive fleet electrification within the transport sector decarbonization and the objective settled for air quality improvements in dense urban areas, questions should be raised on the environmental burdens these technologies can generate on other impact categories.

4.4.3. Shared use mobility scenario

The third mobility use scenario analyzed within this thesis corresponds to a shared mobility use of midsize passenger vehicles within an urban driving profile in France. Results are illustrated in figure 24 for the five analyzed technologies.

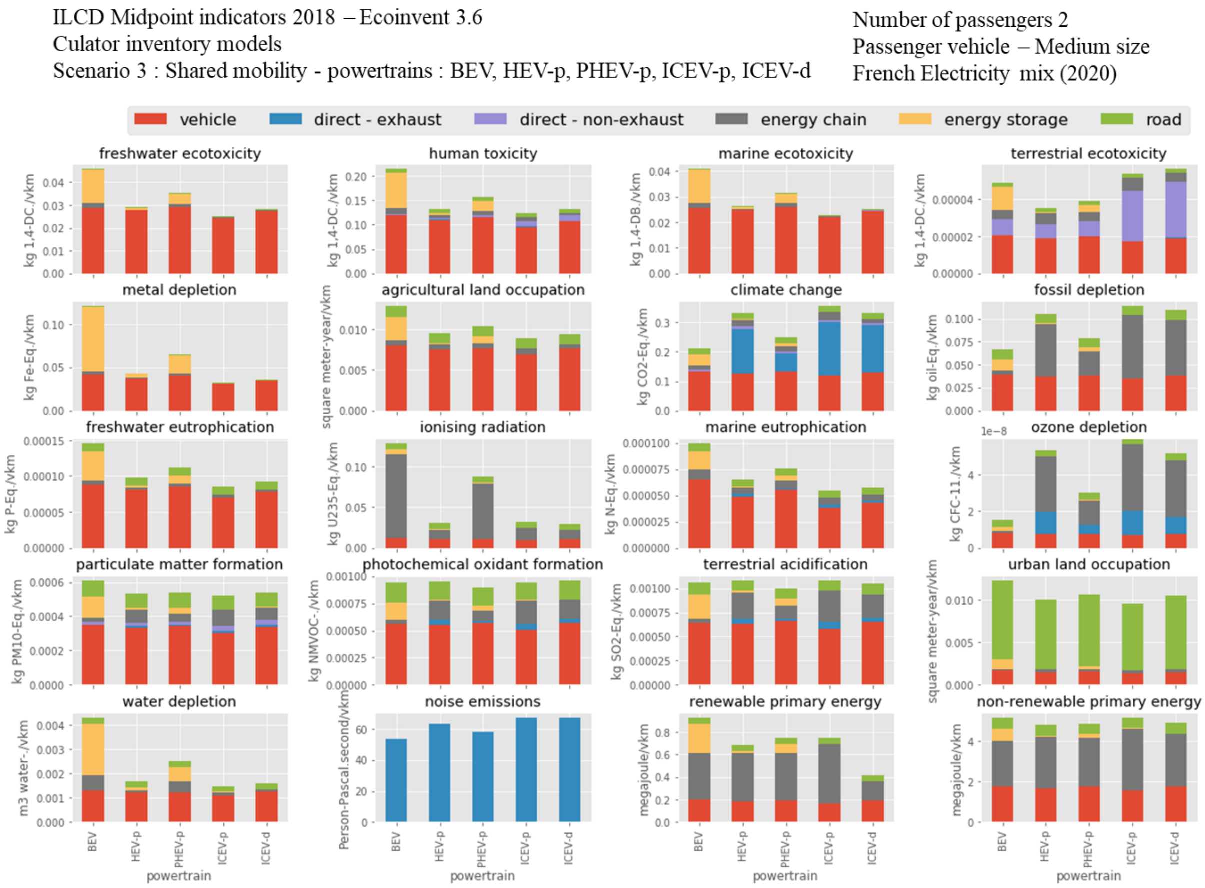


Figure 24 Environmental Impacts calculation for shared passenger midsize vehicles in France 2020 by powertrain

The overall environmental multicriteria analysis demonstrates similar tendance of the environmental impacts compared to those obtained within the personal use mobility. Nonetheless, the environmental performance seems to be slightly lower than a personal mobility use scenario, as the impacts are allocated to a reduced vehicle lifetime, i.e., 4 years instead of 10 years in the case of personal passenger vehicles. It is important to note that the service end of life does not correspond to the vehicle's final disposal. Hence, some studies suggest allocating the impacts for the vehicle's total lifetime operation with battery's replacement to enhance representativeness of the final impacts.

4.4.4. Discussions of the results

The interpretation of results for the environmental impact categories did not show a clear clustering for the environmental performance as the different powertrains considered induced a large variability of the environmental impact results. Electric vehicles exhibited a low contribution to climate change, to a large extent linked to the French electricity mix, which is relatively dominated by nuclear energy source. In contrast, higher environmental impacts were recorded by electric vehicles compared to their conventional counterparts for resources depletion (i.e., use of water and metal resources use) and ecosystem quality (i.e., ionizing radiation, freshwater ecotoxicity and marine eutrophication). These impacts mainly derived from the electric batteries' production which led to higher impacts in the case of full BEV than in the case of PHEV. Public transportation has shown the best environmental performance compared to other analyzed scenarios, namely personal and shared mobility. Such improved environmental performance is observed for most of the environmental impacts except for noise emissions. In contrast, full-electric transportation buses illustrated significant environmental impacts in comparison with their conventional counterparts and the hybrid vehicles due to the significant weight of batteries. As for the shared transportation vehicle, although the number of passengers considered within this scenario was higher than the case of personal mobility, it was not reflected in the environmental impacts. This can be explained by the missing allocation of the impacts on the total duration of the vehicle lifetime, as only four years was considered within the LCA modeling. It is worth to note that results associated with the shared mobility scenario showed a number of issues to be solved in the future within LCA studies. Indeed, data availability is an issue as well as the modeling of the shared mobility that implies variable travel characteristics (i.e., distance, duration, number of trips per day, etc.) that need to be accounted for within the assessment to fully account for the environmental impacts.

Overall, the results of the analysis of this environmental dimension show that modal shift can be very beneficial for reducing the environmental impacts. Electric transportation technologies can also be an opportunity for reducing the carbon footprint within the context of low-carbon electricity mix. Other impact categories highly depend on the level of electrification involving battery production, which generally contributed the most to the environmental impacts. Massive development of electric mobility, especially for long-distance travels where significant battery autonomy is required, involves heavier batteries and thus impacts. Several solutions are under development to solve this issue. For example, battery swapping technologies appears to be an interesting alternative by reducing the battery size and also to better manage the potential imbalance in the electricity network due to its massive development (Vallera et al., 2021). Other alternatives, especially for long-distance travels are being explored such as electrified highways (Fragnol, 2017), highways with fast charging infrastructures (Mowry &

Mallapragada, 2021), and tenders (Gonzalez Venegas et al., 2019). All these technologies still need thorough environmental, social and economic analysis to investigate their potential impacts throughout a life cycle perspective.

5. Conclusions of the chapter

The concept of environmental LCA is considered mature enough prior to this thesis, so research has focused on (a) formalizing a systematic protocol to generate parametrized LCAs fitting mobility scenarios and on (b) S-LCA development and LCC adaptation for the overall sustainability evaluation method. The results are discussed from an environmental perspective for the three considered scenarios (i.e., personal, public and shared transportation).

This chapter starts by analyzing the existing LCA studies for electric mobility scenarios to identify the main impact categories and life cycle stages. As a result, a set of key input parameters has been identified to be entailed in LCA modeling, e.g., the driving cycles, fuel pathways and electricity mixes.

The environmental evaluation is performed for the considered set of mobility scenarios covering five different conventional and electric powertrains as well as three mobility services, namely personal, public and shared mobility use.

This chapter highlights the main drawbacks related to the available LCA Datasets. A systematic approach for the implementation of parametrized LCA models has been proposed to cover and fit at best all scenarios under study. Such approach is used to integrate different LCA models from the literature and to adjust them with the key input parameters for the defined mobility scenarios in this thesis. LCA is thus performed by running parametrized LCA models fitting these electric mobility scenarios. Such parametrized LCA models clearly enhance the representativeness of the existing datasets by including the multiple technological advances that may occur over time. The defined approach together with the steps to be followed for the establishment of the parametrized models are detailed in section 4 all along the four iterative LCA phases for the case study.

6. References

ADEME. (2015). Un mix électrique 100% renouvelable? Analyses et optimisation- Un travail d'exploration des limites du développement des énergies renouvelables dans le mix électrique métroppolitain à un horizon 2050 [Rapport d'étude]. https://www.ademe.fr/sites/default/files/assets/documents/mix-electrique-rapport-2015.pdf

Anenberg, S. (2017). A global snapshot of the air pollution-related health impacts of transportation sector emissions in 2010 and 2015 (p. 55). International Council for Clean Transportation. https://theicct.org/sites/default/files/publications/Global_health_impacts_transport_emissions_2010-2015_20190226.pdf

Arseni, O., & Racioppi, F. (2018). Making the transport, health and environment link—Transport, Health and Environment Pan-European Programme and the Sustainable Development Goals (p. 60). World Health Organization: Europe. https://www.euro.who.int/__data/assets/pdf_file/0004/375511/9789289053334-eng.pdf

Besseau, R. (2019). Analyse de cycle de vie de scénarios énergétiques intégrant la contrainte d'adéquation temporelle production-consommation [Phdthesis, Université Paris sciences et lettres]. https://pastel.archives-ouvertes.fr/tel-02732972

Bigo, A. (2016). Comment atteindre le facteur 4 dans les transports ? (p. 159). Chaire énergie et prospérité. http://www.chair-energy-prosperity.org/wp-content/uploads/2018/02/publication2016-facteur-4-dans-les-transports-aurelien-bigo.pdf

Bigo, A. (2020). Les transports face au défi de la transition énergétique [PhD Thesis, Ecole Doctorale de l'Institut Polytechnique de Paris (ED IP Paris)]. http://www.chair-energy-prosperity.org/wp-content/uploads/2019/01/These-Aurelien-Bigo.pdf

Bobba, S., Podias, A., Di Persio, F., Messagie, M., Cusenza, M. A., Eynardu, U., Fabrice, M., & Pfrang, A. (2018). Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB) (p. 140) [JRC Technical Reports]. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112543/saslab_final_report_2018_2018-08-28.pdf

Bouter, A., Hache, E., Ternel, C., & Beauchet, S. (2020). Comparative environmental life cycle assessment of several powertrain types for cars and buses in France for two driving cycles: "Worldwide harmonized light vehicle test procedure" cycle and urban cycle. The International Journal of Life Cycle Assessment, 25(8), 1545–1565. https://doi.org/10.1007/s11367-020-01756-2

Buekers, J., Van Holderbeke, M., Bierkens, J., & Int Panis, L. (2014). Health and environmental benefits related to electric vehicle introduction in EU countries. Transportation Research Part D: Transport and Environment, 33, 26–38. https://doi.org/10.1016/j.trd.2014.09.002

Catalan, C., & Cornelus, M. (2019, March). Energy Transition scenarios: Strengths and weakness of LCA in a resource-limited context. Séminaire-SCORE LCA.

Cerdas, F., Egede, P., & Herrmann, C. (2018). LCA of Electromobility. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), Life Cycle Assessment (pp. 669–693). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_27

CGDD. (2020). Bilan de la qualité de l'air extérieur en France en 2019 (p. 36). Commissariat Général au Développement Durable, Ministère de la transition écologique. https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2020-09/datalab_71_bilan_qualite_air_france_2019_septembre2020.pdf

CGDD. (2021). Chiffres clés du transport—Edition 2021 (p. 92). Commissariat Général au Développement Durable, Ministère de la transition écologique. https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-transport-2021/livre.php

CGEDD, Schmit, P., De Treglode, H., Marques, R., Farniaux, B., & Toulouse, P. (2015). Urbanisme et mobilité|Rapports publiés du CGEDD (n° 009796-01; p. 117 p). CGEDD, MTES. https://cgedd.documentation.developpement-durable.gouv.fr/notice?id=Affaires-0008638

Cox, B. L. (2018). Mobility and the energy transition: A life cycle assessment of swiss passenger transport technologies including developments until 2050 [ETH Zurich]. https://www.psi.ch/ta/PublicationTab/Thesis_Embargo_free_version.pdf

Cox, B. L., & Mutel, C. L. (2018). The environmental and cost performance of current and future motorcycles. Applied Energy, 212, 1013–1024. https://doi.org/10.1016/j.apenergy.2017.12.100

Cucurachi, S., Schiess, S., Froemelt, A., & Hellweg, S. (2019). Noise footprint from personal land-based mobility. Journal of Industrial Ecology, 23(5), 1028–1038. https://doi.org/10.1111/jiec.12837

De Sutter, L., Firouz, Y., De Hoog, J., Omar, N., & Van Mierlo, J. (2019). Battery aging assessment and parametric study of lithium-ion batteries by means of a fractional differential model. Electrochimica Acta, 305, 24–36. https://doi.org/10.1016/j.electacta.2019.02.104

Del Duce, A., Egede, P., Öhlschläger, G., Dettmer, T., Althaus, H.-J., Bütler, T., & Szczechowicz, E. (2013). E-Mobility Life Cycle Assessment Recommendations (No. 285571; p. 150). EMPA. http://www.elcar-project.eu/uploads/media/eLCAr_guidelines.pdf

Del Duce, A., Gauch, M., & Althaus, H.-J. (2016a). Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3. The International Journal of Life Cycle Assessment, 21(9), 1314–1326. https://doi.org/10.1007/s11367-014-0792-4

Del Duce, A., Gauch, M., & Althaus, H.-J. (2016b). Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3. The International Journal of Life Cycle Assessment, 21(9), 1314–1326. https://doi.org/10.1007/s11367-014-0792-4

Dell, R. M., Moseley, P. T., & Rand, D. A. J. (2014). Chapter 8—Hydrogen, Fuel Cells and Fuel Cell Vehicles. In R. M. Dell, P. T. Moseley, & D. A. J. Rand (Eds.), Towards Sustainable Road Transport (pp. 260–295). Academic Press. https://doi.org/10.1016/B978-0-12-404616-0.00008-6

Dlugokencky, E., & Tans, P. (2021). Global Monitoring Laboratory—Carbon Cycle Greenhouse Gases. https://gml.noaa.gov/ccgg/trends/gl_data.html

Douziech, M., Ravier, G., Jolivet, R., Pérez-López, P., & Blanc, I. (2021). How Far Can Life Cycle Assessment Be Simplified? A Protocol to Generate Simple and Accurate Models for the Assessment of Energy Systems and Its Application to Heat Production from Enhanced Geothermal Systems. Environmental Science & Technology, 55(11), 7571–7582. https://doi.org/10.1021/acs.est.0c06751

Edwards, R., Mahieu, V., Griesemann, J.-C., Larivé, J.-F., & Rickeard, D. J. (2004). Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. 2004-01–1924. https://doi.org/10.4271/2004-01-1924

EEA. (2019). Greenhouse gas emissions by aggregated sector—European Environment Agency [Data Visualization]. https://www.eea.europa.eu/data-and-maps/daviz/ghg-emissions-by-aggregated-sector-5#tab-dashboard-02

EEA. (2021). Exposure of Europe's population to environmental noise—European Environment Agency [Indicator Assessment]. https://www.eea.europa.eu/data-and-maps/indicators/exposure-to-and-annoyance-by-2/assessment-4

Directive (EU) 2016/2284 du Parlement européen et du Conseil du 14 décembre 2016 concernant la réduction des émissions nationales de certains polluants atmosphériques, modifiant la directive 2003/35/CE et abrogeant la directive 2001/81/CE (Texte présentant de l'intérêt pour l'EEE)—Légifrance, 01-07–2018 L. 222-9 (2018). https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000035464615

Directive 2002/49/CE du Parlement européen et du Conseil du 25 juin 2002 relative à l'évaluation et à la gestion du bruit dans l'environnement—Déclaration de la Commission au sein du comité de conciliation concernant la directive relative à l'évaluation et à la gestion du bruit ambiant—Légifrance, 2002/49/CE (2002). https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000000337482

Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6) (Text with EEA relevance), Pub. L. No. 32016R0427, 082 OJ L (2016). http://data.europa.eu/eli/reg/2016/427/oj/eng

Electric and hybrid cars: New rules on noise emitting to protect vulnerable road users, (2019). https://ec.europa.eu/growth/content/electric-and-hybrid-cars-new-rules-noise-emitting-protect-vulnerable-road-users_en

European Commission. (2020a). Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA (p. 456) [Final report for the EC, DG Climate Action]. Directorate-General for Climate Policy -European Commission. https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/2020_study_main_report_en.pdf

European Commission. (2020b). Study on the EU's list of Critical Raw Materials (2020) (p. 157) [Final report]. European Commission. https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Report_Final.pdf

European Commission. Joint Research Centre. (2018). Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods: New methods and differences with ILCD. Publications Office. https://data.europa.eu/doi/10.2760/671368

European Commission, & JRC. (2010). ILCD-Handbook-Framework and requirements for Life Cycle Impact Assessment (LCIA) models and indicators (First Edition). Publications Office of the European Union.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. The International Journal of Life Cycle Assessment, 11(2), 80–85. https://doi.org/10.1065/lca2006.02.002

Fortino, A., Eckstein, L., Viehöfer, J., & Pampel, J. (2016). Acoustic Vehicle Alerting Systems (AVAS)—Regulations, Realization and Sound Design Challenges. SAE International Journal of Passenger Cars - Mechanical Systems, 9(3), 995–1003. https://doi.org/10.4271/2016-01-1784

Fragnol, L. (2017). Concept de l'autoroute électrique: Évaluation socio-économique. Ministère de l'Environnement, de l'énergie et de la mer, en charge des relations internationales sur le climat. https://www.ecologie.gouv.fr/sites/default/files/Th%C3%A9ma%20-%20Concept%20autoroute%20%C3%A9lectrique.pdf

Gonzalez Venegas, F., Petit, M., & Perez, Y. (2019). Can DERs fully participate in emerging local flexibility tenders? 2019 16th International Conference on the European Energy Market (EEM), 1–5. https://doi.org/10.1109/EEM.2019.8916343

Habermarcher, F. (2011). Modeling Material Inventories and Environmental Imapcts of Electric Passenger Car. Department of environmental science, ETH Zurich.

Hache, E., Simoën, M., & Seck, G. S. (2018). Electrification du parc automobile mondial et criticité du Lithium à l'horizon 2050 (p. 71). ADEME et IFP Energies Nouvelles. https://librairie.ademe.fr/mobilite-et-transport/3803-electrification-du-parc-automobile-mondial-et-criticite-du-lithium-a-l-horizon-2050.html

Hawkins, T. R., Gausen, O. M., & Strømman, A. H. (2012). Environmental impacts of hybrid and electric vehicles—A review. The International Journal of Life Cycle Assessment, 17(8), 997–1014. https://doi.org/10.1007/s11367-012-0440-9

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles: LCA of Conventional and Electric Vehicles. Journal of Industrial Ecology, 17(1), 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

Hernandez, M., Messagie, M., De Gennaro, M., & Van Mierlo, J. (2017). Resource depletion in an electric vehicle powertrain using different LCA impact methods. Resources, Conservation and Recycling, 120, 119–130. https://doi.org/10.1016/j.resconrec.2016.11.005

Hoarau, Q., & Perez, Y. (2018). Interactions between electric mobility and photovoltaic generation: A review. Renewable and Sustainable Energy Reviews, 94, 510–522. https://doi.org/10.1016/j.rser.2018.06.039

IEA. (2020a). Global EV Outlook 2020: Entering the decade of electric drive ? (p. 276) [Technology report]. International Energy Agency. https://www.iea.org/reports/global-ev-outlook-2020

IEA. (2020b). World Energy Balances: 2020 Edition (Database documentation). https://iea.blob.core.windows.net/assets/4f314df4-8c60-4e48-9f36-bfea3d2b7fd5/WorldBAL_2020_Documentation.pdf

IFP Energies Nouvelles. (2018). Bilan transversal de l'impact de l'électrification par segment (p. 21). PROJET E4T. ADEME. www.ademe.fr/mediatheque

INFRAS. (2019). Handbook emission factors for road transport 4.1. IFRAS. https://www.hbefa.net/e/help/HBEFA41_help_en.pdf

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science—Policy Platform on Biodiversity and Ecosystem Services (p. 39). IPBES. https://www.dropbox.com/sh/yd8l2v0u4jqptp3/AACpraYjOYWpTxAFv5H-2vrKa/1%20Global%20Assessment%20Summary%20for%20Policymakers?dl=0&preview=Summary+for+Policymakers+IPBES+Global+Assessment.pdf&subfolder_nav_tracking=1

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (p. 3949). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf

IRENA. (2018). Global Energy Transformation: A Roadmap to 2050 (p. 76). International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf

ISO 14040. (2006). Management environnemental—Analyse du cycle de vie—Principes et cadre (p. : 23). Internationanl Standardization Organization. https://www.iso.org/cms/render/live/fr/sites/isoorg/contents/data/standard/03/74/37456.html

Ke, W., Zhang, S., Wu, Y., Zhao, B., Wang, S., & Hao, J. (2017). Assessing the Future Vehicle Fleet Electrification: The Impacts on Regional and Urban Air Quality. Environmental Science & Technology, 51(2), 1007–1016. https://doi.org/10.1021/acs.est.6b04253

Knobloch, V., Zimmermann, T., & Gößling-Reisemann, S. (2018). From criticality to vulnerability of resource supply: The case of the automobile industry. Resources, Conservation and Recycling, 138, 272–282. https://doi.org/10.1016/j.resconrec.2018.05.027

Lapko, Y., & Trucco, P. (2018). Influence of power regimes on identification and mitigation of material criticality: The case of platinum group metals in the automotive sector. Resources Policy, 59, 360–370. https://doi.org/10.1016/j.resourpol.2018.08.008

Lawler, J. J., Spencer, B., Olden, J. D., Kim, S.-H., Lowe, C., Bolton, S., Beamon, B. M., Thompson, L., & Voss, J. G. (2013). 4.25—Mitigation and Adaptation Strategies to Reduce Climate Vulnerabilities and Maintain Ecosystem Services. In R. A. Pielke (Ed.), Climate Vulnerability (pp. 315–335). Academic Press. https://doi.org/10.1016/B978-0-12-384703-4.00436-6

LOI n° 92-1444 du 31 décembre 1992 relative à la lutte contre le bruit (1), 92-1444 (1992).

Longo, M., Foiadelli, F., & Yaïci, W. (2019). Electric Vehicles Integrated with Renewable Energy Sources for Sustainable Mobility. In L. Romeral Martínez & M. Delgado Prieto (Eds.), New Trends in Electrical Vehicle Powertrains. IntechOpen. https://doi.org/10.5772/intechopen.76788

Mowry, A. M., & Mallapragada, D. S. (2021). Grid impacts of highway electric vehicle charging and role for mitigation via energy storage. Energy Policy, 157, 112508. https://doi.org/10.1016/j.enpol.2021.112508

MTES. (2018). Véhicules hors d'usage. Ministère de la Transition écologique et solidaire. https://www.ecologique-solidaire.gouv.fr/vehicules-hors-dusage

MTES. (2020). La transition écologique et solidaire vers la neutralité carbone (p. 192). Ministère de la Transition écologique et solidaire. https://www.ecologie.gouv.fr/sites/default/files/2020-03-25_MTES_SNBC2.pdf

Mutel, C. (2017). Brightway: An open source framework for Life Cycle Assessment. Journal of Open Source Software, 2(12), 236. https://doi.org/10.21105/joss.00236

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—What can we learn from life cycle assessment? The International Journal of Life Cycle Assessment, 19(11), 1866–1890. https://doi.org/10.1007/s11367-014-0788-0

Notter, D. A., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., & Althaus, H.-J. (2010). Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles. Environmental Science & Technology, 44(17), 6550–6556. https://doi.org/10.1021/es903729a

Oliveira, L., Messagie, M., Rangaraju, S., Sanfelix, J., Hernandez Rivas, M., & Van Mierlo, J. (2015). Key issues of lithium-ion batteries – from resource depletion to environmental performance indicators. Journal of Cleaner Production, 108, 354–362. https://doi.org/10.1016/j.jclepro.2015.06.021

Ortego, A., Valero, A., Valero, A., & Restrepo, E. (2018). Vehicles and Critical Raw Materials: A Sustainability Assessment Using Thermodynamic Rarity. Journal of Industrial Ecology, 22. https://doi.org/10.1111/jiec.12737

Padey, P., Blanc, I., Le Boulch, D., & Xiusheng, Z. (2012). A Simplified Life Cycle Approach for Assessing Greenhouse Gas Emissions of Wind Electricity. Journal of Industrial Ecology, 16(s1), S28–S38. https://doi.org/10.1111/j.1530-9290.2012.00466.x

Pan, S., Fulton, L. M., Roy, A., Jung, J., Choi, Y., & Gao, H. O. (2021). Shared use of electric autonomous vehicles: Air quality and health impacts of future mobility in the United States. Renewable and Sustainable Energy Reviews, 149, 111380.

Rodrigue, J.-P. (2020). The Geography of Transport Systems—Chapter 4 – Transport, Energy and Environment ‣ 4.3 – The Environmental Footprint of Transportation (5th Edition, p. 456). https://transportgeography.org/contents/chapter4/environmental-footprint-of-transportation/

romainsacchi. (2021). Carculator_bus [Jupyter Notebook]. https://github.com/romainsacchi/carculator_bus/blob/9749b2a6fa931b30fee015b0b1a543e3495b766b/examples/buses.ipynb (Original work published 2020)

RTE. (2017). Valorisation socio-économique des réseaux électriques intelligents-Synthèse commune des contributions [Synthèse]. https://www.ademe.fr/sites/default/files/assets/documents/valorisation-socio-economique-reseaux-electriques-intelligents_synthese.pdf

RTE. (2019). Enjeux du développement de l’électromobilité pour le système électrique (p. 82) [Principaux résultats]. https://www.rte-france.com/sites/default/files/electromobilite_synthese_9.pdf

RTE. (2021). Futurs énergétiques 2050: Les scénarios de mix de production à l’étude permettant d’atteindre la neutralité carbone à l’horizon 2050. https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques

Sacchi, R. (2021). Carculator [Python]. https://github.com/romainsacchi/carculator (Original work published 2019)

Sacchi, R., Bauer, C., & Cox, B. L. (2021). Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium- and Heavy-Duty Vehicles. Environmental Science & Technology. https://doi.org/10.1021/acs.est.0c07773

Sacchi, R., Besseau, R., Pérez-López, P., & Blanc, I. (2019). Exploring technologically, temporally and geographically-sensitive life cycle inventories for wind turbines: A parameterized model for Denmark. Renewable Energy, 132, 1238–1250. https://doi.org/10.1016/j.renene.2018.09.020

Sacchi, R., & Mutel, C. (2019). Carculator: Prospective environmental and economic life cycle assessment of vehicles. Zenodo. https://doi.org/10.5281/zenodo.3778259

Schmid, M. (2020). Challenges to the European automotive industry in securing critical raw materials for electric mobility: The case of rare earths. Mineralogical Magazine, 84(1), 5–17. https://doi.org/10.1180/mgm.2020.9

Sénat. (2015). Rapport fait au nom de la commission d'enquête sur le coût économique et financier de la pollution de l'air. [N° 610 TOME i]. Mme Leila AÏCHI. http://www.senat.fr/rap/r14-610-1/r14-610-11.pdf

Tamayao, M.-A. M., Michalek, J. J., Hendrickson, C., & Azevedo, I. M. L. (2015). Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO $_2$ Emissions across the United States. Environmental Science & Technology, 49(14), 8844–8855. https://doi.org/10.1021/acs.est.5b00815

Traverso, M., Kim, P., Brattig, S., & Wagner, V. (2015). Managing Life Cycle Sustainability Aspects in the Automotive Industry. In G. Sonnemann & M. Margni (Eds.), Life Cycle Management (pp. 331–339). Springer Netherlands. https://doi.org/10.1007/978-94-017-7221-1_24

UFE. (2019). Développement de l'électromobilité: Démystifier les questions de faisabilité pour faire apparaître les opportunités pour le système électrique. http://ufe-electricite.fr/IMG/pdf/ufe-developpement_de_l_electromobilite-2.pdf

UN. (2015). Paris Agreement (p. 27). United Nations. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Vallera, A. M., Nunes, P. M., & Brito, M. C. (2021). Why we need battery swapping technology. Energy Policy, 157, 112481. https://doi.org/10.1016/j.enpol.2021.112481

Van Mierlo, J., Messagie, M., & Rangaraju, S. (2017). Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment. Transportation Research Procedia, 25, 3435–3445. https://doi.org/10.1016/j.trpro.2017.05.244

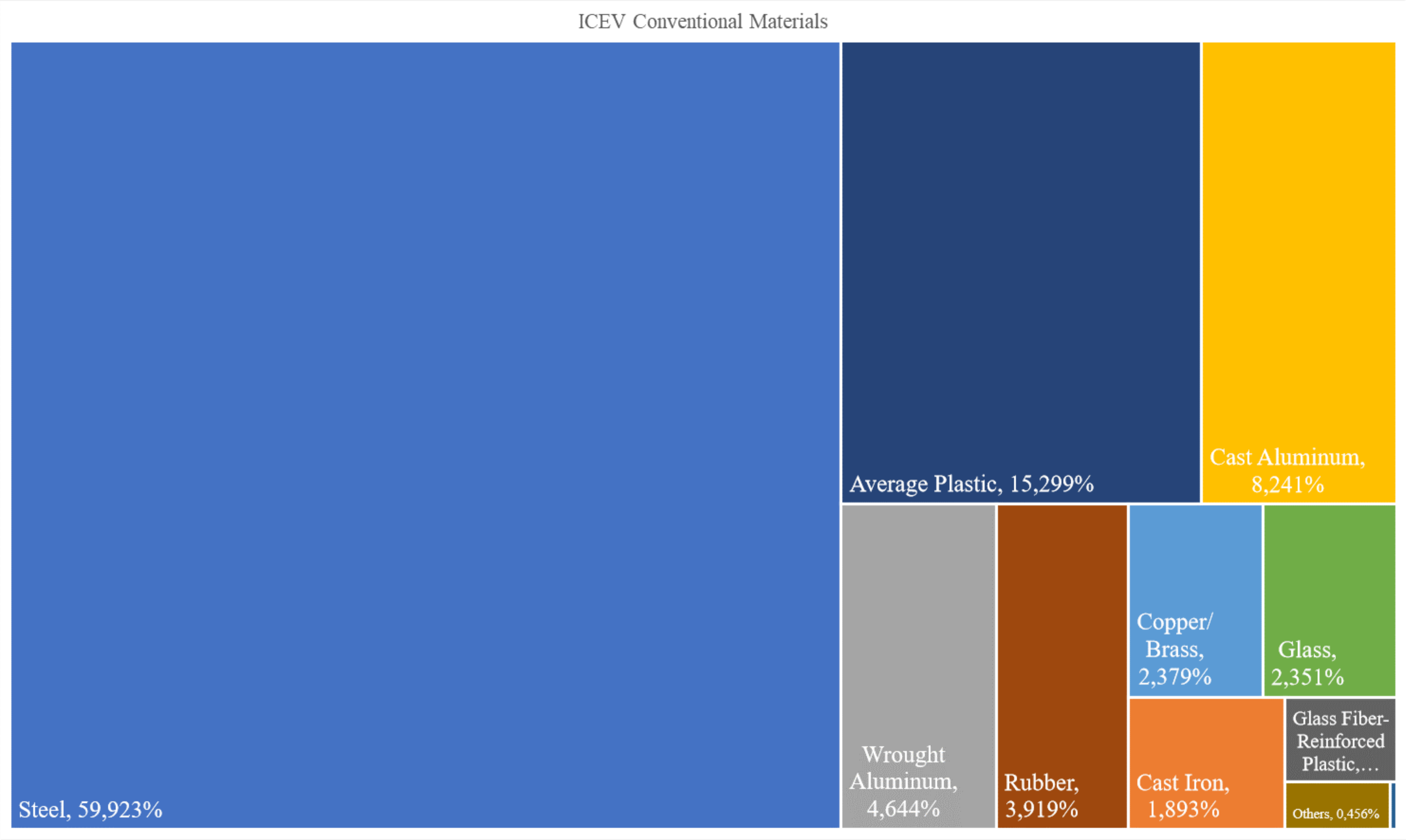
Volkart, K., Mutel, C. L., & Panos, E. (2018). Integrating life cycle assessment and energy system modelling: Methodology and application to the world energy scenarios. Sustainable Production and Consumption, 16, 121–133. https://doi.org/10.1016/j.spc.2018.07.001

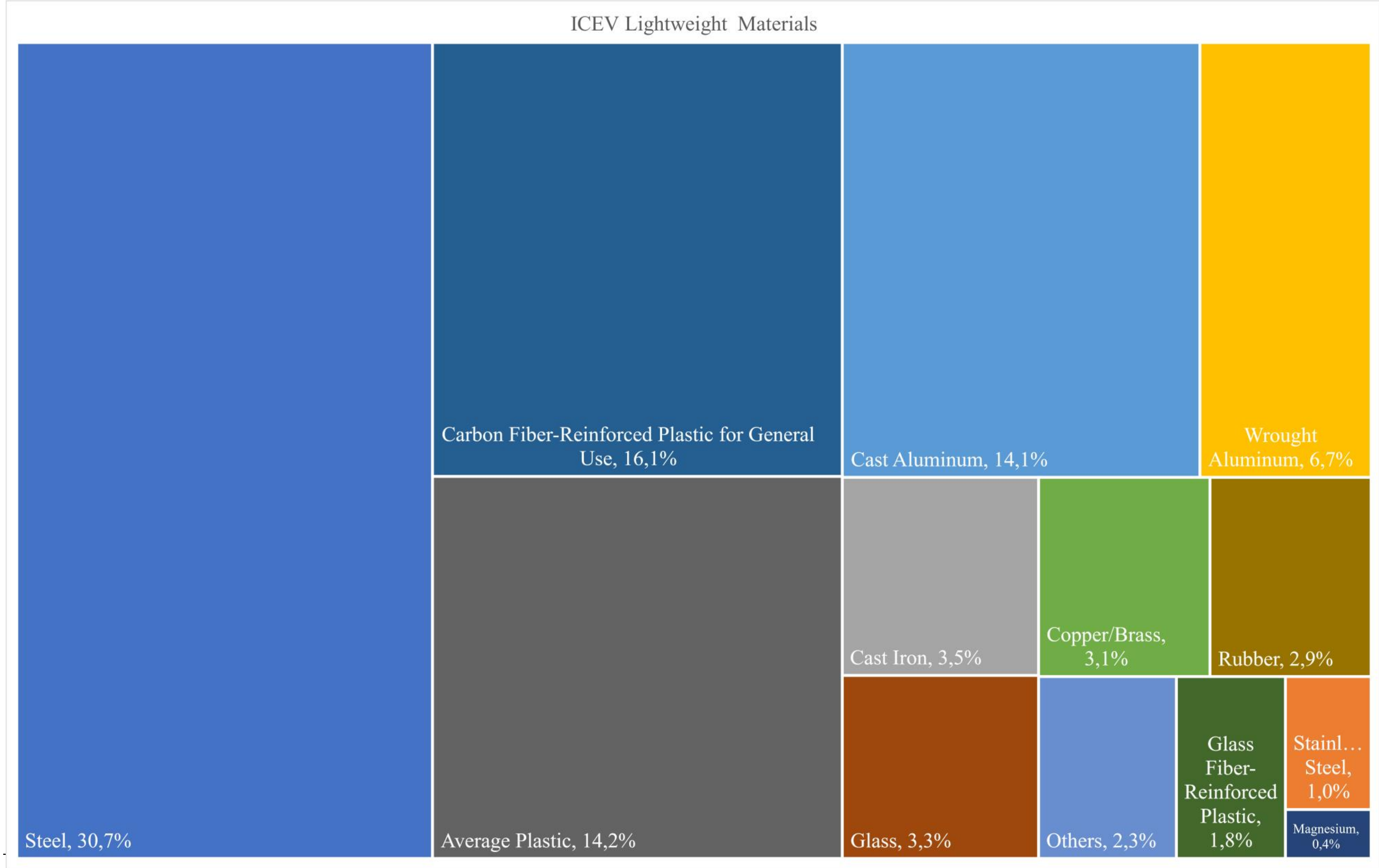
WHO. (2015). Health 2020: Transport and health. World Health Organization: Europe. https://www.euro.who.int/__data/assets/pdf_file/0005/286421/Transport_E.pdf

Zhang, J., Everson, M. P., Wallington, T. J., Field, F. R., Roth, R., & Kirchain, R. E. (2016). Assessing Economic Modulation of Future Critical Materials Use: The Case of Automotive-Related Platinum Group Metals. Environmental Science & Technology, 50(14), 7687–7695. https://doi.org/10.1021/acs.est.5b04654

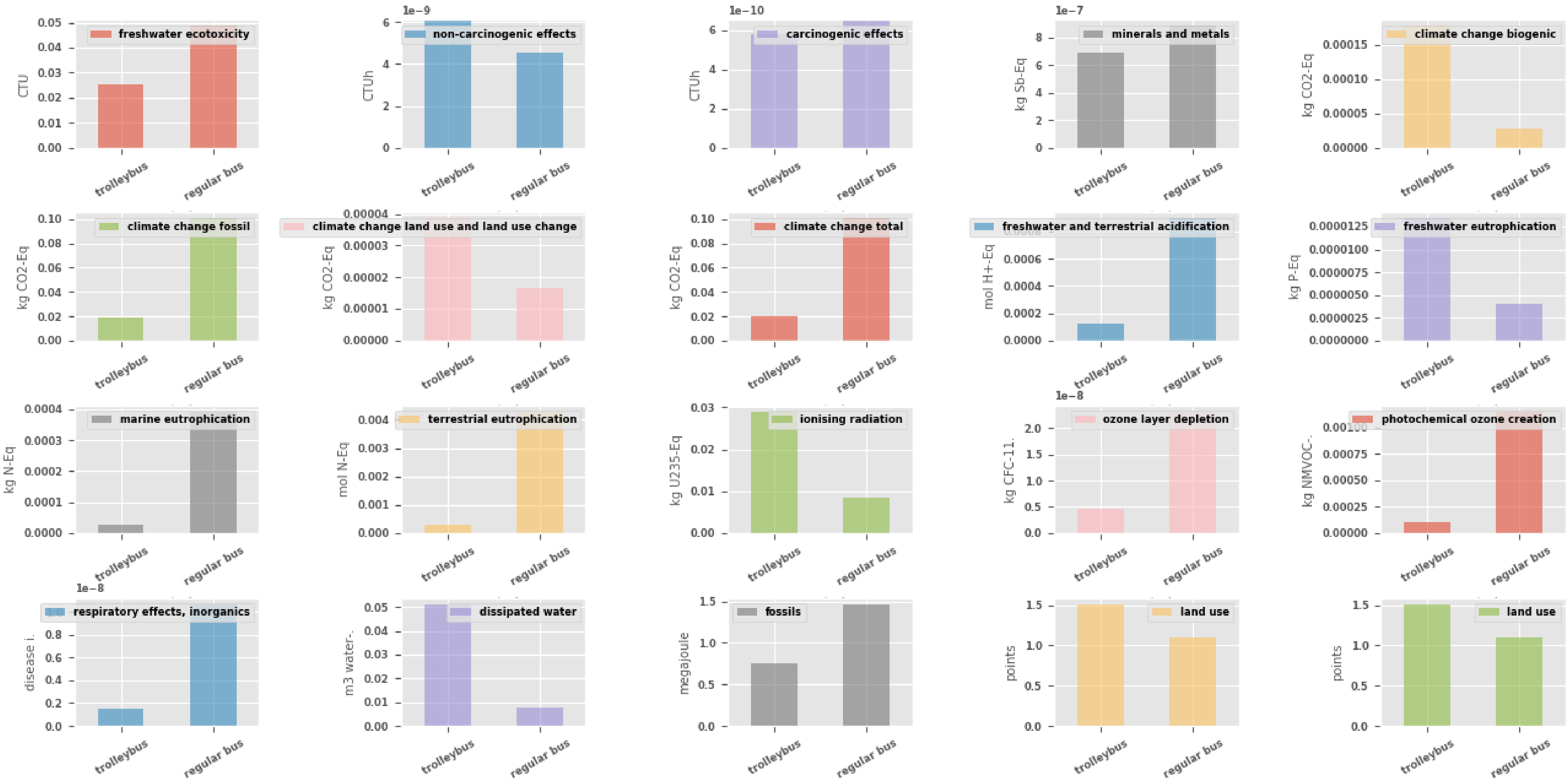
Zimmermann, T., Knobloch, V., & Goessling-Reisemann, S. (2018). From criticality to vulnerability of resource supply: The case of the automobile industry. Resources Conservation and Recycling, 138, 272–282. https://doi.org/10.1016/j.resconrec.2018.05.027

Appendix 1: Input conventional and lightweight materials share (%) for Internal Combustion Engine Vehicles (GREET, 2020).



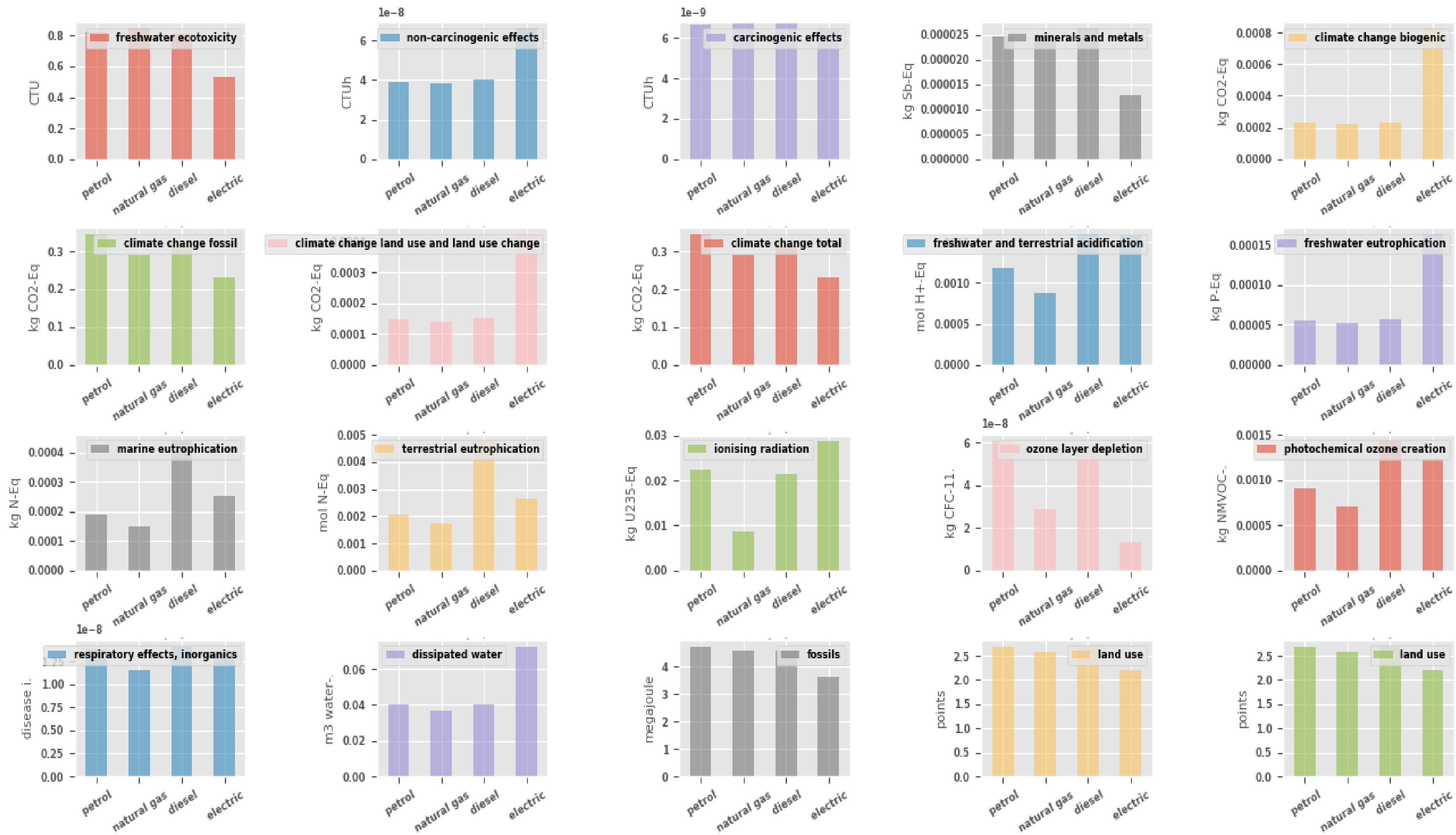

ICEV Lightweight Materials
Steel, 30,7%
Carbon Fiber-Reinforced Plastic for General Use, 16,1%
Average Plastic, 14,2%
Cast Aluminum, 14,1%
Wrought Aluminum, 6,7%
Cast Iron, 3,5%
Copper/Brass, 3,1%
Rubber, 2,9%
Glass, 3,3%
Others, 2,3%
Glass Fiber-Reinforced Plastic, 1,8%
Stainl… Steel, 1,0%
Magnesium, 0,4%

Appendix 2: Inventory analysis with brightway 2 Python library, ecoinvent 3.6, ILCD midpoint indicators 20



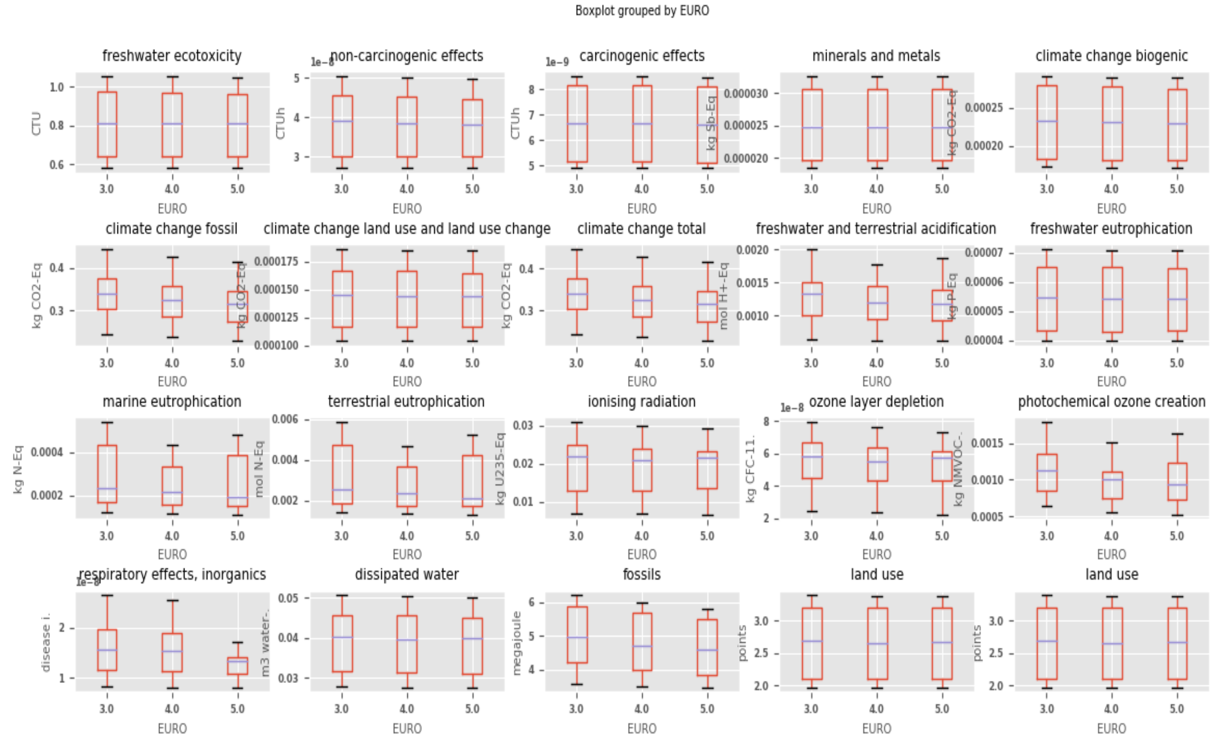
Results from the inventory analysis of the existing buses datasets in the ecoinvent 3.6 datasets and using the brightway2 Python library.

Two technologies are analyzed (trolley and electric buses)

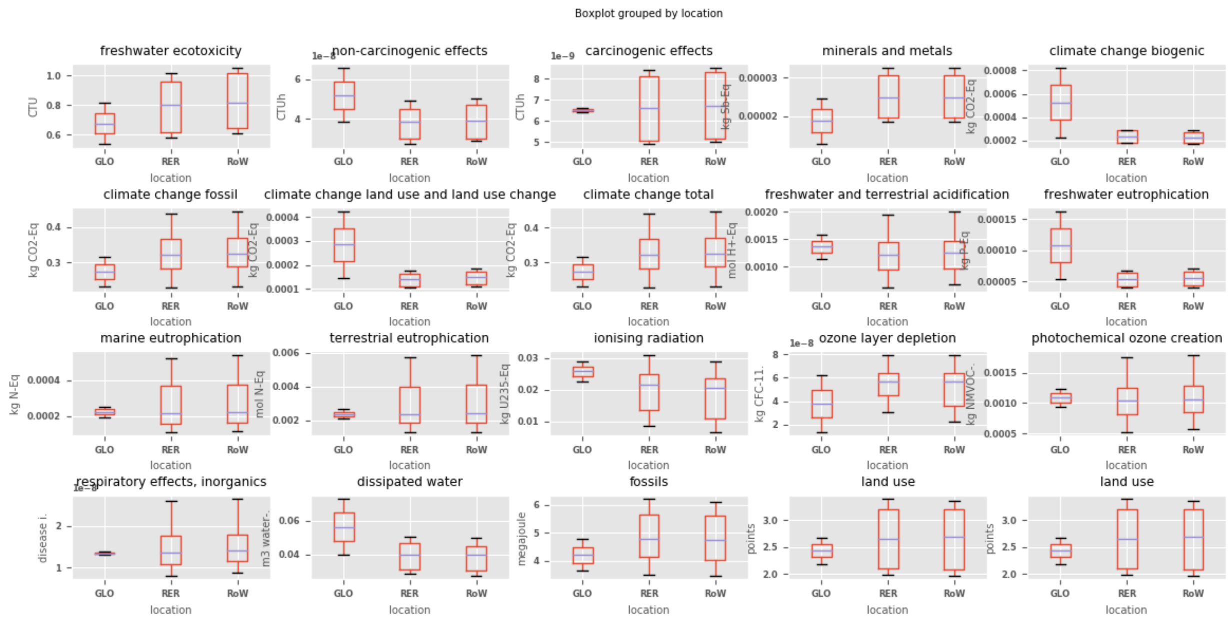


Results of inventory analysis of passenger vehicles inventories provided by the ecoinvent 3.6 datasets using the brightway2 Python library. Four different vehicle's powertrains (medium size, NEDC driving cycle, EURO 5 standards, RER)

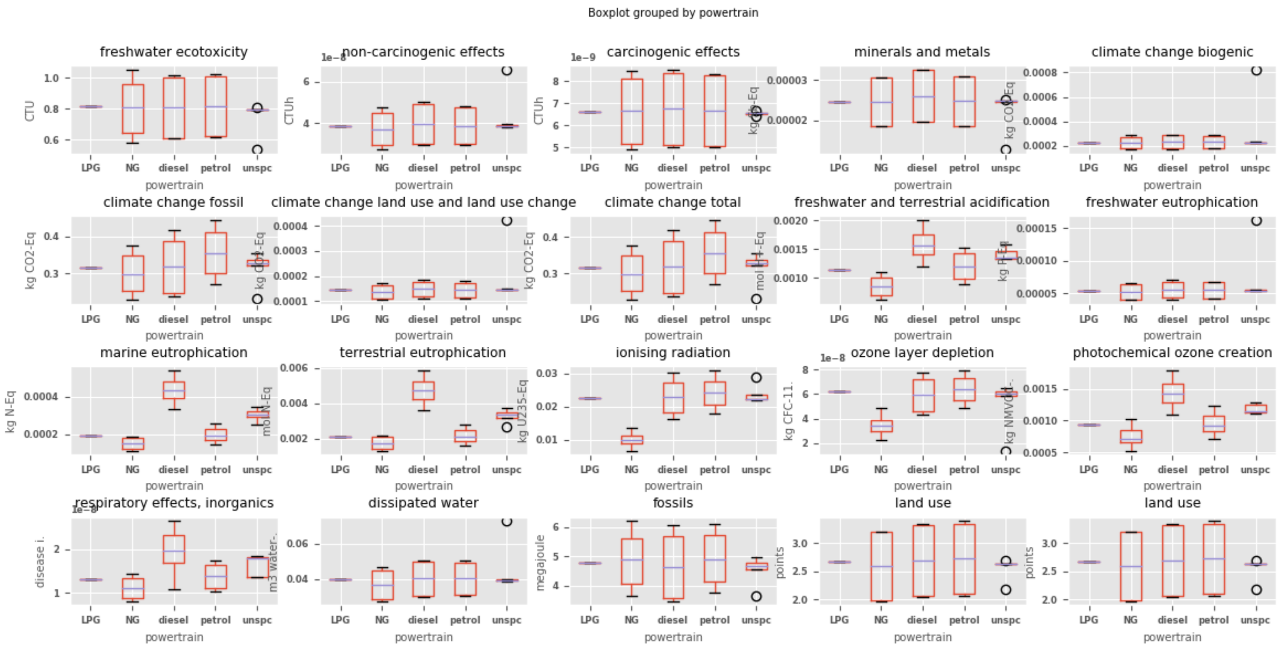
Appendix 3: Analysis of the variations of the parameters depending on the EURO emissions standards (3.4 and 5), the location (GLO, RER and RoW), size (large, medium, small) and the powertrain (diesel, petrol, natural gas and electric)



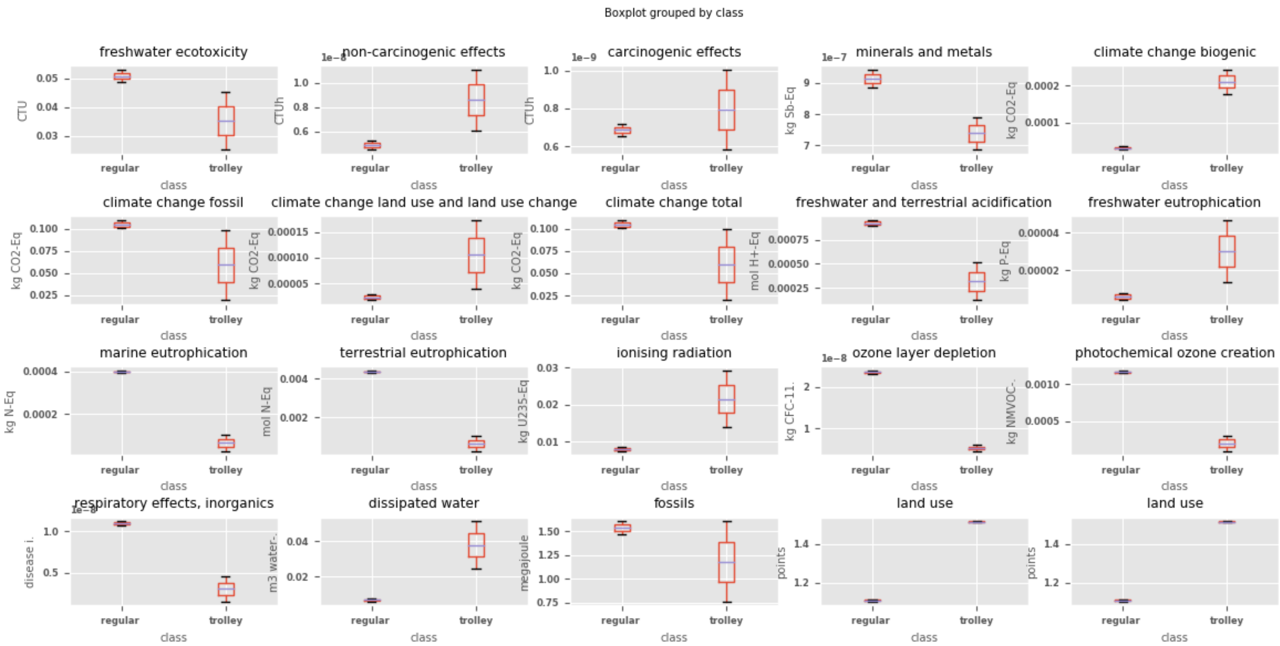
LCI Analysis (ecoinvent 3.6 – brightway 2) depending on EURO 3, 4 and 5



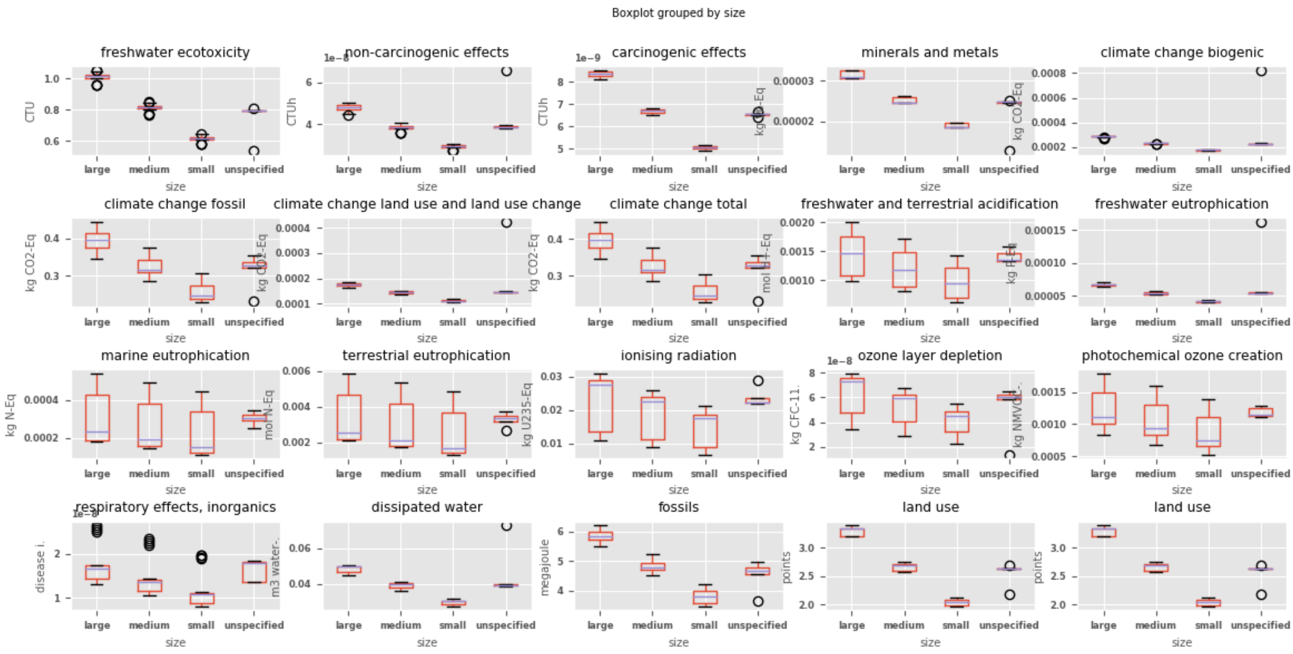
LCI Analysis (ecoinvent 3.6 – brightway 2) depending on Location GLO, RER and RoW



LCI Analysis (ecoinvent 3.6 – brightway 2) depending on different powertrains (LPG, NG, diesel, petrol)



LCI Analysis (ecoinvent 3.6 – brightway 2) for buses depending on powertrains (regular and trolley)



LCI Analysis (ecoinvent 3.6 – brightway 2) depending on size of the vehicles (large, medium, small)

Chapter IV: Social evaluation of electric mobility scenarios through Social Life Cycle Assessment

Summary (IV)

The current thesis gives particular attention to the methodological development of Social-LCA (S-LCA) by proposing a step-by-step S-LCA framework in accordance with the recommendations of ISO 14040-44 standards. Such framework includes two innovative features: (1) a participatory approach for the selection of impact subcategories and (2) a user-centric social impact assessment. It is implemented to investigate potential social and socio-economic impacts associated with the three mobility scenarios considered within this thesis.

Section 0 starts by identifying the main methodological issues and present limitations within S-LCA studies for the mobility sector and thus introduces the challenges to be addressed in the present research work.

Section 2 presents the key identified specific social topics for mobility scenarios by expanding the scope of the current published studies to be able to cover different stakeholder groups, life cycle stages, existing vehicle technologies and current and emerging mobility services.

Section 3 describes the comprehensive step-by-step S-LCA framework proposed in this work with two new features: (1). A participatory approach for the selection of relevant impact subcategories and (2). A specific social impact assessment to support S-LCA evaluation phase through a user-centric approach. These two novelties are detailed in two toolboxes to enable their adaptation and application to other product systems and sectors.

Section 4 entails the implementation of the proposed framework to the considered electric mobility scenarios, conventional and electric vehicle technologies and mobility services. Hence, it describes the four phases of ISO standards and specifications that were added. The evaluation phase is performed through a reference scale-based Social Life Cycle Impact assessment (RS S-LCIA). It is carried out in two steps: first, a generic assessment is used to perform the impacts calculation of vehicle technologies and then, the assessment is complemented by a specific analysis of mobility services from a user point of view.

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1. S-LCA for mobility scenarios: State of the art and the main limitations

Social Life Cycle Assessment (S-LCA) allows the analysis of potential social and socio-economic impacts all along the products and services life cycles (UNEP, 2020). Potential social impacts are defined by UNEP guidelines (2020) as: "*the likely presence of a social impact, resulting from the activities/behaviors of organizations linked to the life cycle of the product or service and from the use of the product itself*".

The updated version of S-LCA guidelines by UNEP (2020) for products and organizations introduced six different stakeholder categories, as represented in figure 25 (i.e., society, workers, local communities, value chain actors, consumers, and children). By definition, *stakeholder categories* include one or a group of persons that are involved in the product system value chain (i.e., involved stakeholders) or susceptible of being affected by its related activities (i.e., affected stakeholders) all through life cycle stages. For each of the stakeholder groups, a set of impact subcategories is recommended. *Impact subcategories* are social and socio-economic items or attributes that describe how each stakeholder category can be affected by the potential social and socio-economic impacts of the product system. These impact categories are analyzed using quantitative, semi-quantitative and qualitative indicators for which generic and specific data is collected.

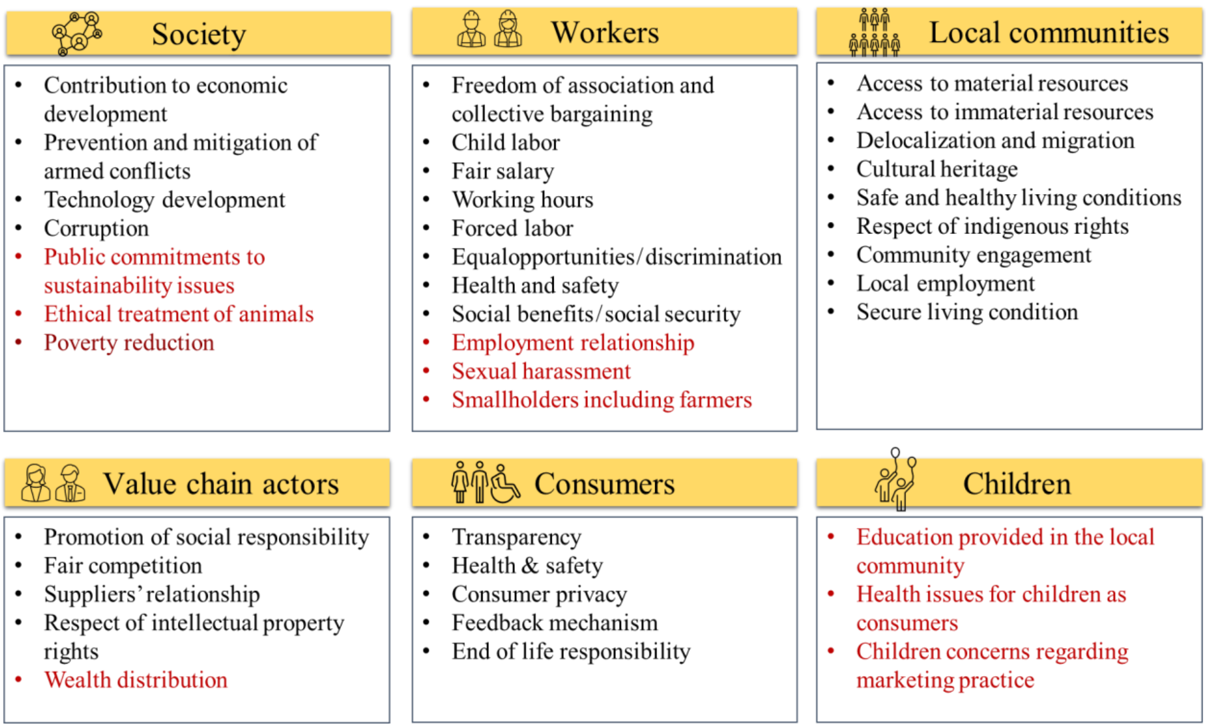


Figure 25 Stakeholder categories and their associated social and socio-economic impact subcategories following the new updated S-LCA guidelines (in red the added stakeholder impact subcategories in UNEP Guidelines 2020)

Studies that tackle the challenges of S-LCA in the automotive sector have been recently increasing (Zimmer et al., 2017; Zanchi et al., 2018; Karlewski et al., 2019; Zanchi et al., 2020; Osorio-Tejada et al., 2020b; Gompf et al., 2020).

The main methodological issues that were identified from the literature review covering S-LCA studies in the mobility sector and would require further development are:

- The focus is mainly made on the development of social impact subcategories and inventory indicators based on a literature review analysis (Gompf et al., 2020; Karlewski et al., 2019; Pastor et al., 2018), the domain of applicability and the main barriers for practical application of S-LCA (Zamagni et al., 2013; Zanchi et al., 2018).
- The selection of impact subcategories is often missing, not sufficiently justified, or based solely on a literature review. Participatory approaches are rarely applied for this purpose, despite their promising ability to introduce further stakeholders' opinions to S-LCA and thus increase the local relevancy of the results (UNEP, 2020).
- Most studies adopt the companies and designers' perspectives within the assessment while the users' point of view and other concerned stakeholders are rarely included in the assessment (Zanchi et al., 2018).
- Most studies do not include the user stakeholder group in the evaluation phase and do not analyze the use phase of mobility scenarios due to its complexity (Petti et al., 2016; Osorio-Tejada et al., 2020b).
- The evaluation phase is challenging as very few studies consider a complete product system in S-LCA but rather focus on a specific component or lifecycle stage to simplify the modeling, e.g., notably the production and manufacturing stages (Karlewski et al., 2019; Osorio-Tejada et al., 2020b; Zimmer et al., 2017). On the other hand, the first study to introduce a core set of mobility services evaluation is Gompf et al. (2020) still, no application of the proposed indicators to assess the impacts of a specific case study is available.

To overcome the above-mentioned limitations, this thesis seeks to support the development of S-LCA methodology by introducing two novelties:

- ✓ **Definition of a participatory approach to enable the selection of impact subcategories from all concerned stakeholders' perspectives**
- ✓ **Introduction of a user-centric impact assessment approach to S-LCA**

These two features are integrated to an S-LCA method and explained step-by-step in accordance with the four recommended phases in ISO standards (ISO 14040-44, 2006). The new proposed framework, applicable to various product systems and sectors, is implemented in this thesis to assess the three electric mobility scenarios under study. Hence, the results of the S-LCA obtained within this chapter are meant to feed the development of LCSA framework and provide science-based information to the decision makers within the context of electric mobility scenarios.

2. Key social topics for mobility scenarios: A first screening of the literature

This section comprises the five stakeholder groups proposed by UNEP guidelines and investigates the key social topics to be considered within S-LCA for the different life cycle stages of transportation systems and mobility services. The aim is to identify main social topics to be further considered in the evaluation and explores the existing social assessment studies, main references and key locations or process activities that may substantially contribute to positive or negative social impacts.

2.1. Social and socio-economic impacts on workers

Workers are generally involved in the different life cycle stages of products, technologies, and services. In the case of mobility, these stages cover the extraction activities and manufacturing of the vehicle technologies to their final disposal, but also include workers involved in the vehicle's operation (purchase, repair and maintenance activities together with drivers and road infrastructure's workers).

The working conditions can substantially vary depending on the geographical context, thus the social and political context of the country under consideration but can also be linked to the organization practices and its social management system efficiency. Although the transport sector is a major source of employment (CGDD, 2021), it is essential to verify the conditions under which the workers carry out their activities. Consequently, the so-called "sustainable" mobility requires compliance with workers' rights all along transportation systems life cycle stages.

Transportation supply chain, especially for electric transportation systems, raises several concerns about the **working condition**s due to the intensive use of metals and minerals. In fact, e**xtractive activities** are more likely to be a hotspot linked to several key social risks, i.e.**, human rights abuses, conflict financing and crimes** (OECD, 2021). Although social risks underlined by the extractive industry are increasingly being reported within social risk assessment studies, there is still a significant lack of transparency and socially responsible mineral sourcing is still scarce. A recent publication from the OECD (2021) has demonstrated the need of more transparent information to support policy-makers in enforcing sustainability practices and due diligence process. The mining industry is generally insufficiently controlled by regulations as the most majority of activities are located in non-OECD countries with less restrictive policies. Hence, men and women workers without basic protection equipment are directly exposed to severe pollution aspects driving by serious short—and **long-term health threats.** Workers in cobalt and copper mines, which are primary sources of materials for the automotive sector among others, suffer from diverse health effects such as respiratory diseases, urinary tract infections and can also face birth defect problems (Amnesty International, 2021). It is important to note that, until now, most studies rely on direct measure of given emitted substances whereas long-term characterization of the pollution effects on workers and local communities is not adequately informed (Amnesty International, 2020).

Moreover, **child and forced labor** are very common in the mining sector (OECD, 2021). The list of goods produced by child labor or forced labor was published by The Bureau of International Labor Affairs (2020). **Cobalt has been identified a high-risk input product** which is generally mined in Central Africa by child laborers before being refined and integrated to electric vehicles batteries in factories in China (ILAB, 2020). There are several other social and socio-economic impact subcategories included in the UNEP guidelines (UNEP, 2020) that are of high importance to the transportation sector.

The likelihood of social risks can be different in the case of OECD countries. In fact, by considering mobility use scenarios in France, child labor, forced labor and other concerns related to working conditions are less likely due to the stricter regulation.

It is important to highlight that **social performance also depends on mobility services** that take place in the use phase. In fact, a wide range of mobility services have become widespread in recent years, but their associated social and socio-economic impacts are not fully characterized and are still poorly controlled and regulated. This raises the **need for transparent information** which S-LCA can provide. More often the emergence of certain mobility services, such as shared mobility, is hampered by the lack of social security coverage for the employees, in the **absence of mature regulatory measures** (European Commission. Joint Research Centre, 2018). For instance, the French social security authority (URSSAF) has taken legal action against the UBER company due to the fact that the workers are mostly independent contractors and are not recognized as "employees" (Alix, 2017). The UBER company, claiming to be only a provider of a digital facilitating platform for mobility end-users, has strongly disputed the proceedings. In response, the European court of justice classified in 2017 UBER as a "transport company" and not only a digital service provider (Ingber, 2018). Such gaps in the regulatory coverage might substantially undermine t**he social security of workers** and result in significant societal costs. These concerns are even more worrisome within the current digitalization and shared economy promoted by the European Commission (2016). The social and socio-economic impacts from such emergent mobility services are still ambivalent and require careful investigations and measurements to avoid **precarious working conditions** and ensure a successful transition towards sustainable mobility alternatives. In the same line, bus drivers, which are also workers in the use phase, can be significantly affected from the organization practices (service provider), but also from the direct use of the buses.

The recommended impact subcategories in S-LCA for workers by the methodological sheets (Benoît Norris et al., 2013) derive from the International Labor Organization (ILO) on workers' conventions. The ILO (2018) has established a set of conventions that countries have ratified (or not) describing the areas of concern facing workers in the course of their activities.

Social and socio-economic topics related to workers are in the core of interest of S-LCA method and have been considered so far in most S-LCA studies (Macombe et al., 2013; Holger et al., 2017; Zanchi et al., 2020). However, these studies merely consider the workers in the manufacturing stages and up to date no previous study has considered workers in the use phase within mobility S-LCA studies. This raises a real methodological issue; to distinguish between both workers in the manufacturing stages and workers in the use phase (that can also be considered as secondary users).

2.2. Social and socio-economic impacts on local communities

Local communities can be defined as a group of people that are organized around a common value and living in a common region. These people are thus likely to be directly affected by the activities of the organization providing the product or service under investigation. Organizations involved in the entire value chain are therefore expected to ensure that the rights of these local communities are respected, mainly through the improvement of their living conditions: job creation, willingness of the organizations to take their concerns into account when making decisions, etc. Hence, it is of utmost importance to identify, analyze and measure the magnitude of potential negative and positive social and socio-economic impacts related to the system under investigation.

Within the transportation value chain, the local population is highly susceptible of being affected by the extraction and manufacturing activities. Automotive materials' extraction is a major source of **soil and water pollution** (e.g., toxic liquid discharges due to the use of acid in metal processing) and **air pollution** threatening the **quality of local resources** and in consequence the s**afety and health conditions of the population**. Moreover, **access to local resources**, particularly for water resources, may be restricted in the event of conflict between the organization and the local community. Such conflicts may be the result of a disagreement over ownership of the resources or of material or immaterial damage caused by the activity. In fact, serious concerns and challenges have been pointed out at the international level due to the observed conflict issues in countries such as Congo, Peru or Chile for the four main primary material supplies for automotive batteries (lithium, cobalt, nickel and copper) (International Energy Agency, 2019).

A large share of the refining of automotive primary materials takes place in China, i.e., more than 50% for lithium refining, 40% for copper, 60% for cobalt and 30% for nickel (International Energy Agency, 2019). In addition, since the financial crisis of 2008, the contrast between the decline of vehicle manufacturing in the United States, Europe and Japan, and the rapid growth of emerging markets, particularly in Asia, has become even more striking (Pardi, 2017). Such reversal of the geopolitical and economic balance has more significant consequences at a local scale. The mutation of the automotive market can be responsible of **workers' delocalization and migration**, thus, undermining the social and economic balance of the local population that should be strictly organized.

The emergence of vehicle manufacturing in non-OECD countries can be seen as an opportunity for **local employment**, which is of significant added value for the **economic development** of local communities. On the other hand, the decline of automotive manufacturing activities in the OECD countries is of significant concern due to **low employment security**. For example, in France, about 65,000 jobs are expected to be at risk by 2030 due to the expanding market of electric transportation, which is 25% less demanding in terms of employment than conventional transportation(Soula, 2021). The employment security has also been identified as one of the main factors for **societal resistance** deriving from the fear of job loss associated with future transportation schemes (L'Hostis et al., 2016). Hence, social acceptability should be considered carefully to measure local communities' ability to adopt emergent mobility solutions. Community engagement is therefore increasingly encouraged to **include the local population concerns** and potential societal resistance within the decision-making process (i.e., opening/operation of a mine, installation of a nuclear power plant/charging infrastructure).

It is also to note that 50% of global Cobalt demand derives from the automotive sector and particularly for batteries production (International Energy Agency, 2019). Despite the current production surplus, cobalt demand—as well as for other minerals—is expected to rise in the coming years within the growth of EV market. It is therefore important to ensure that the environmental benefits from EV technologies due to low direct emissions in the use phase does not undermine decent living conditions of local communities in other parts of the world.

2.3. Social and socio-economic Impact on the users

In this study the term "users" refers to "consumers," "customers," or "passengers." The users can be significantly affected and in various ways, i.e., by the use of conventional and electric technologies, by the different mobility services but also by the regulation and taxation of fuel or electricity consumption. It is to note that, two categories of users can be distinguished; primary users are the passengers and represent the entities for which the product utility has been described, and secondary users, which represent the workers (i.e., bus drivers, taxi drivers).

A major issue for mobility solutions during the use phase is related to **passengers' safety**. Special attention should indeed be paid to road accidents. Personal transportation is the mode of travel most frequently involved in **road accidents,** which amounted in 2018 to 50% of total number of road accidents in France (ONISR, 2019). Electric vehicle technologies also recorded accidents related to their quietness, resulting in casualties among road users, such as impaired people and cyclists, but also among domestic animals sheltering under the cars. To resolve this issue, the acoustic vehicle alerting system (AVAS) has been introduced by the European Commission in 2019 (Electric and Hybrid Cars: New Rules on Noise Emitting to Protect Vulnerable Road Users, 2019).

Users' safety can also be associated to **harassment and sexual assaults,** which are of major concern in public transportation. In fact, nearly one in five robberies took place in public transport in 2019 on the French territory (Interstat, 2021). Such acts affect women and men differently: 56% of women are victims of nonviolent theft and 95% for sexual-based violence while 63% of men are victims of intentional assault and 85% for violence against public officials (Interstat, 2021). In general, women tend to take more public transport, walking and cycling than men, which increases their risk to suffer gender-based harassment (European Commission. Joint Research Centre., 2019). The new trends in the transport sector regarding the innovative digital solutions for mobility usher new challenges in terms of potential threats for users of shared mobility. It is therefore important to account for users' needs and especially for women's safety risks when developing new mobility services (ITF, 2018).

One of the key drivers of users' mobility choices is th**e travel comfort** (İmre & Çelebi, 2017). Despite the lack of a standardized definition of comfort, it has been recognized as a quality indicator for mobility services and especially for public transportation (Shen et al., 2016). It has also been covered by some International standards such as the EN 13,816 (AFNOR, 2002) for public transportation quality of service and ISO 2631-1 (2010) which is generally included in the design phase of the buses, relative to vibrations and shocks.

Comfort is an aspect that can relate to the health of users and their well-being but other social topics, such as urban congestion, are also significant in dense urban areas and can result in substantial social and economic externalities (Levy et al., 2010). **Traffic congestion** not only increases pollutant emissions, fuel consumption and travel costs, but also has a direct impact on travel time, speed, delay, and affects consequently the quality of the mobility service (ATC, 2017). When conducting social assessment studies of mobility scenarios, it is important to account for the various **health aspects related to users, i.e., comfort, congestion, noise, etc**. These can involve negative effects, but positive effects can also be identified, especially when investigating the benefits of walking and cycling as alternative transportation solutions. The French Active Mobility Plan, established by the French Environmental Agency (ADEME, 2020), has the ambitious objective of achieving 24% of cycling modal share by 2030 in accordance with the WHO recommendations. Although most studies are mainly based on economic indicators to measure the benefits of walking and cycling for the society (Rutter et al., 2013), a review by Kelly et al. (2014) showed how all 21 analyzed studies demonstrated that walking and cycling tend to reduce the risk of all-cause mortality.

To guarantee a sustainable mobility in the future, **inclusiveness** has been targeted as one of the most priority goals at the European level ensuring equal access for everyone to transportation alternatives (Gallez & Motte-Baumvol, 2017). In addition, target 11.2 of the sustainable development goals (DGDs) (World Bank, 2015) highlights the need to provide, by 2030, safe, affordable, accessible, and sustainable transport systems for all citizens. The Orienting Mobility Law introduced by the French government (*Loi-Mobilités-Présentation du projet de loi d'orientation des mobilités*, 2018) set inclusiveness as a key factor for achieving sustainable future mobility schemes. In fact, accessibility to transportation is a human basic right giving each person the ability to move geographically and thus extending job opportunities (Holzwarth, 2015). **Accessibility** can be measured through the availability of the transportation services, interoperability of infrastructures, but also through the affordability of the transportation vehicles and the services to guarantee the inclusiveness of all people, especially with those in vulnerable situations, i.e., women, children, persons with disabilities and older persons.

In the context of personal mobility, the ownership of a car sometimes involves a cost exceeding the average purchase power in the country. This can affect the **affordability** of the vehicle's transportation and to mobility services. In order to encourage the conversion towards electric transport technologies, measures such as conversion incentives, battery leasing systems, etc. have been introduced in France. On the other hand, other measures are being adopted to change users' behavior, such as carbon taxation or emission reduction zones that can affect accessibility to transportation solutions, especially in rural areas.

In the previous paragraphs, the discussed social and socio-economic topics are related to the direct use of mobility services and transportation technologies either conventional or electric ones. However, there is also a wide range of social impacts that can derive from organizations' practices, either vehicle manufacturers or mobility service operators. Western users are becoming increasingly aware of the social and socio-economic impacts associated with their daily mobility choices. Transportation value chain actors are therefore expected to enhance their social management system and provide more transparent information on their social performance.

The communication system plays here an important role allowing the users to make informed and unbiased choices and can even improve the quality of the mobility service (Limon et al., 2018). In fact, an effective communication system is a key factor for public and shared mobility services allowing passengers to explore, for example, all the possible combinations to reach their destination and to access information related to their journey (timetables, points served, etc.). Most of the digital mobility platforms promoted within the growing "mobility as a service" (Kostiainen & Tuominen, 2019) rely on these communication tools to facilitate the accessibility of end-users to variable transportation alternatives. In addition, several mobility platforms have been developed to allow an effective communication on warranty systems, insurance and product return policies, but also to allow users' feedback to be taken into account so as to improve the ability of such platform to respond to their needs (Silva et al., 2018). With respect to the ongoing digitalization in the transport sector, several challenges need to be highlighted and considered carefully to avoid a rebound effect.

One of the main concerns associated with such communication tools is the **users' data privacy**. This subject is getting particular attention at the European level due to non-compliance with users' rights and the abuse of personal data use for commercial purposes. A French person spends an average of 7 hours per week traveling, mainly by personal car (ADEME, 2019). In the case of connected vehicle use, the personal data privacy raises more concerns regarding the significant amount of information that goes through mobile applications. A "connected vehicle" compliance pack was launched in 2016 by the National Commission for Information Technology and Civil Liberties (CNIL), in consultation with stakeholders in the automotive industry and public authorities, to propose a sector-based reference framework for the responsible use of personal data of transport users (CNIL, 2016). The aim is to integrate the privacy dimension in the design phase and to define measures for handling personal data in compliance with the General Data Protection Regulation (RGPD | CNIL, 2018).

The social risks related to passenger data use also applies to shared transport as it requires access to users' personal data for its operation, including their identifiers, personal addresses, journeys made, etc. In 2018, a penalty of €400,000 following a breach of user data safety was imposed to the company UBER (CNIL, 2018). The conducted investigation revealed the lack of security of personal data that led to the breach of 57 million users, 1.4 million of whom are located in France (CNIL, 2018).

Within S-LCA studies, users are the less considered among the other stakeholder categories. Several studies (Petti et al., 2016; Zanchi et al., 2018; Gompf et al., 2020; Osorio-Tejada et al., 2020b) have also confirmed this statement. Four potential reasons for the **insufficient representation of users' stakeholder group** were identified from the literature review:

a. The product system does not have a direct relationship with the clients/consumers or users' category and it could be evaluated only through the organization performance (Osorio-Tejada et al., 2020b).
b. The consumer category is not correlated with the most frequent activity variable used "working hours".
c. There is a lack of data or accessibility issues, and inventory indicators for users and consumers are still not covered by generic databases such as PSILCA (Eisfeldt et al., 2017; Maister et al., 2020).
d. The use phase is underrepresented or excluded from the system boundaries (Blom & Solmar, 2009; Foolmaun & Ramjeeawon, 2013; Mancini & Sala, 2018; Petti et al., 2016).

Social performance of a transportation option depends, not only on the technology, but also the type of use (personal, shared, and public transportation). As stated by Gompf et al. (2020) in their work, the use phase is elementary for the assessment of mobility services. They have therefore defined a core set of indicators to evaluate mobility services including all stakeholder groups. In this thesis, users' stakeholder category is carefully considered to allow a thorough evaluation of the social and socio-economic impacts within S-LCA method. Based on the identified key potential social and socio-economic impacts on users, a set of social indicators have been defined and evaluated. A specific analysis for mobility services is therefore introduced within the global S-LCA framework developed in this work and presented in the next sections.

2.4. Social and socio-economic impacts on value chain actors

Manufacturers, suppliers, partners and all the actors involved in the extraction, manufacturing, distribution, repair, or recycling processes are today held responsible for their environmental and social management policies. Organizations are thus expected to consider the potential impacts or unintended consequences of their purchasing and procurement decisions on other organizations and to be careful to avoid or minimize any negative impact (ISO26000, 2010).

Transportation supply chains generate direct and indirect impacts on users (through the products or services they offer), on workers (through the industrial activity itself), on local communities (through their interaction with local resources) and on society in general, when we consider the contribution in a broader sense to socio-economic, cultural, technological and sustainable development.

In the automotive sector, there are various aspects linked to the **strongly competitive after-sale market**: increase in the price of individual repair services for users leading to a direct impact on public health and the environment (poorly maintained cars), **dominance of car manufacturers** on the aftersales market (repairers approved by the manufacturers) limiting the offers for suppliers of materials and components as well as **independent repairers.**

The attractive prices offered by some suppliers could override the quality of the environmental and social conditions under which these materials, components, goods, or services have been designed.

Another aspect related to the **lack of communication** between the manufacturer and its suppliers could undermine the trust between both parties and **lead to unfair decisions.**

Impact subcategories for value chain actors were poorly assessed within previous S-LCA of mobility scenarios (Gompf et al., 2020). This can be explained by the lack of data accessibility, which here can include very sensitive information.

2.5. Social and socio-economic impacts on society

The social issues described here illustrate global aspects that can relate to mobility scenarios with a special focus on electric mobility. This category of stakeholders includes governmental institutions, non-governmental organizations, and all entities that could be affected by the impacts of the transportation sector in a global scale.

In France, transport is a very important sector in terms of **employment**, with 1.4 million employees, excluding temporary workers (CGDD, 2021), but also in terms of income, since it generates 386 billion euros which is equivalent to 17.3% of gross domestic product (INSEE, 2017). The penetration of the electric fleet in the transport market will consequently have impacts on job creation (or their suppression), e**ducation and training and public investments,** both for the deployment of services and development of charging stations and infrastructure and for the contribution to the **development of research** in the field. The need for more sustainable mobility alternatives paves the way for developing more carpooling, car sharing and other shared mobility services that interest users due to the **technological ease** they offer. Such emergent mobility alternatives **foster the technological development,** which in turn enhances mobility users' comfort and also optimizes the use through maximization of the functionalities.

Due to the opposing financial interests of different organizations, the integrity of the economic system should be questioned. In fact, the price of minerals more than doubled on average between 2000 and 2009 and continues to grow (Soula, 2021). The minerals' booming demand has been supported by new emergent powers such as China and India where most of the refining activities are located (International Energy Agency, 2019). The energy transition in its "sustainable" perspective requires the consideration of the potential evolution of **geopolitical situations (or conflicts)** and **economic markets** related to heavy metals (or rare earths) in order to foresee the imbalance that this transition could generate (Pardi, 2021). It is therefore important to ensure that the organization and the entire value chain of a product are not involved in the **creation of a conflict** and, instead, they make efforts to prevent it.

3. Development of S-LCA methodological framework with two novel features

With the aim of contributing to an operational S-LCA method, the present thesis focuses on two innovative features and their consistent integration to S-LCA method. A step-by-step S-LCA framework is therefore proposed based on the four main iterative phases as defined in the guidelines (UNEP, 2020) and in consistency with ISO 14,040 (Finkbeiner et al. 2006). Such framework is presented in Figure 26 and emphasizes the novel steps that are introduced in the main phases recommended in the S-LCA guidelines, together with the interactions between steps.

The first feature introduced by this thesis consists of developing a systematic participatory approach for the selection of relevant impact subcategories within the goal and scope phase, as shown in Figure 26. The impact subcategories that were perceived as the most relevant by the different stakeholders are used to perform the evaluation phase and thus contribute to a comprehensive analysis of results. The designed participatory approach enables S-LCA practitioners to account for stakeholders' perceptions in order to select the most relevant social and socio-economic subcategories as suggested by the updated version of S-LCA guidelines (UNEP, 2020).

The second feature focuses on improving the evaluation phase by introducing a user perspective to S-LCA to analyze mobility services. As previously stated within the identification of key social topics, the analysis of mobility services is key to ensure a comprehensive social assessment of mobility scenarios. In this regard, the present thesis focuses on addressing this issue by introducing a user-centric social impact assessment. Hence, the evaluation phase is conducted in two steps through RS S-LCIA: (1) generic assessment for transportation technologies and (2) specific assessment with a user-centric social impact assessment for mobility services. Such specific analysis is based on a set of identified user-related impact subcategories for which performance indicators, performance scales and calculation methods are defined.

The coming subsections entail the methodological description of the four phases of S-LCA by including these two features. The required guidance and steps to be conducted are explained to enable the implementation of the suggested framework to other product systems and sectors. It is worth to note that such novel participatory approach applied to transportation technologies has been already published into the International Journal of Life Cycle Assessment. Two boxes are presented to help S-LCA practitioners with box (1) the design of the consultation process and box (2) the implementation of a specific social impact assessment within S-LCA. Section 4 entails the application of the proposed S-LCA comprehensive framework to the three mobility scenarios considered within this thesis: covering both electric and conventional technologies as well as mobility services, i.e., personal use, public transport use and shared use.

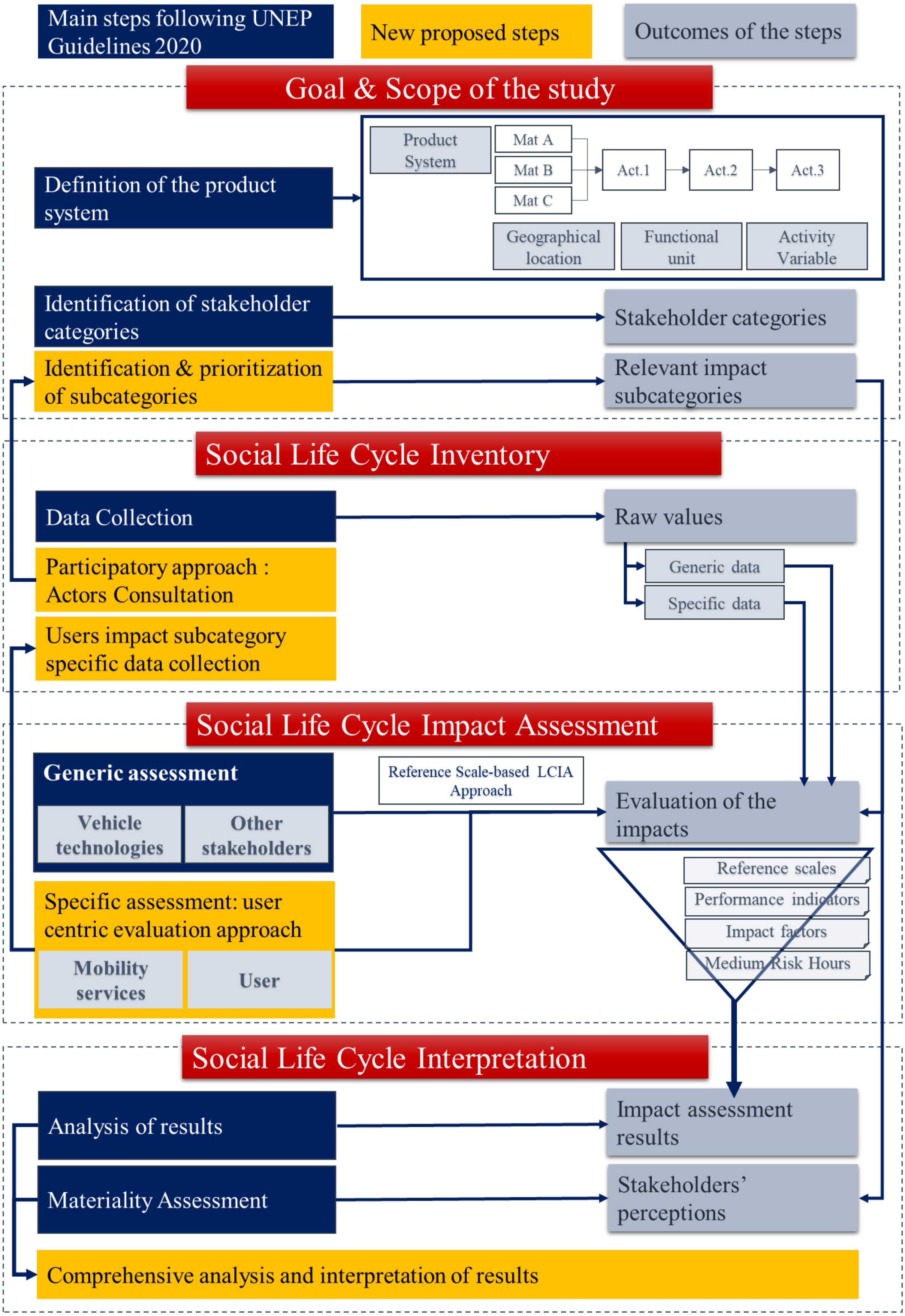


Figure 26 Step-by-step comprehensive S-LCA framework within this thesis adapted from Bouillass et al. (2021)

3.1.Goal and scope definition

The first phase of S-LCA defines the purpose of the study, the intended use, the system boundaries, as well as the considered stakeholders and social impact subcategories. It describes the main methodological pathways adopted such as the functional unit, the cut-off criteria and the impact assessment method (UNEP, 2020). In this study, elementary flows and process activities are used to identify directly and indirectly related stakeholders. The listed stakeholder categories can be then prioritized following different criteria, i.e., legitimacy, impact and completeness (UNEP, 2020).

As shown in Figure 26, one of the key features provided by this work is the introduction of specific steps in the first phase of S-LCA for the identification and prioritization of social and socio-economic impact subcategories. This approach can be used to select the most relevant topics for the evaluation and interpretation phases. It is generic enough to be applied to different product systems and sectors.

3.1.1. Design of a participatory approach for the selection of impact categories

Within the definition of the goal and scope of the study, the impact categories to be analyzed should be defined. There is a broad range of studies that aimed to define subcategories and their relative social indicators (Kühnen & Hahn, 2017; Mancini & Sala, 2018; Sureau et al., 2018; Gompf et al., 2020). Such studies have focused on the literature review to identify relevant impact categories and indicators.

To this end, S-LCA studies introduce a selection step to choose among the recommended subcategories in the UNEP Guidelines those who should be considered. Such selection often lacks transparency and solely use the literature review. Moreover, studies tend to choose the "easiest" impact subcategories for which data is available and impact assessment models are known. Hence, there is a significant imbalance within the different impact categories and stakeholder groups that were analyzed in previous S-LCA studies, e.g., workers and local communities' subcategories are often analyzed while users, value chain actors and society are often let out of the scope (Petti et al., 2016; Gompf et al., 2020). In addition, this selection introduces a value choice that needs to be transparent.

The selection of impact subcategories is a critical step in S-LCA and can substantially affect the results of the assessment and thus, the decisions made on that basis. It is therefore highly recommended to duly justify the use of impact subcategories to prevent a partial representation of the impacts on stakeholders. The UNEP guidelines (2020) suggest the use of materiality assessment within S-LCA to focus on significant impact categories. The concept of materiality, illustrated in Figure 27, has also been included in the Global Reporting Initiative (GRI, 2016) and ISO standards (ISO 26000, 2010) to allow the selection of material topics that are of importance and interest for the organization's business and can be of significant impacts on stakeholders. However, such process can be limited for three main reasons: i) not systematically covering a life cycle perspective, ii) not covering the needs and expectations of all the affected and involved stakeholders, iii) lacks transparency as no clear selection criteria and guidance are provided for its implementation.

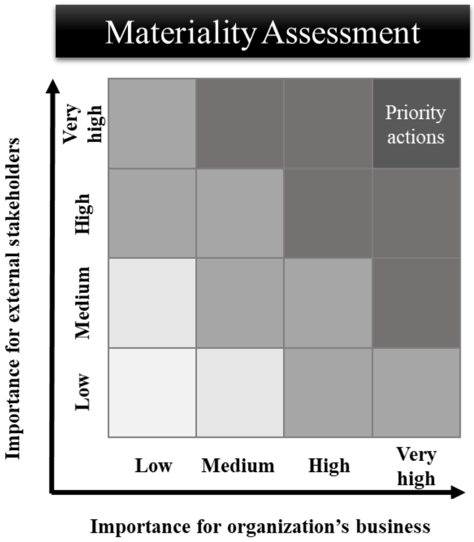


Figure 27 Materiality Assessment based on the importance for the organization's business and according to external stakeholders (GRI 2014).

Social significance of the impact subcategories can substantially vary depending on the perspective of the considered actor. The organization and the other concerned stakeholders involved in a given sector (here the mobility sector) through complex networks are likely to have different interests, concerns, and influence on the decision-making. To date, studies have mainly focused on the perceptions of designers and companies while other stakeholders' perceptions are still not integrated into the evaluation methods (Zanchi et al. 2018).

The need to extend the scope of materiality assessments by involving all concerned stakeholders when prioritizing and evaluating social impact subcategories was also pointed by Karlewski et al. (2019). Following S-LCA guidelines (UNEP, 2020), participatory approaches can be used to select the final set of indicators according to stakeholders' values, thus contributing to legitimate the assessment and justify the chosen impact subcategories for the evaluation.

The proposed participatory approach, illustrated in Figure 28, covers two main stages: stage (1) identification of social and socio-economic impact subcategories through a sectorial risk analysis and stage (2) prioritization of the impact subcategories following a multi-actor consultation process. Such approach can help duly justify the need of the used indicators in S-LCIA phase and increase the local relevance of S-LCA results. Moreover, embedding the perception of all concerned stakeholders, as introduced by this approach, for the selection of relevant impact subcategories is expected to improve their representativeness and inclusiveness, compared to a materiality assessment that solely reflects the perception of designers and companies.

This part of the work has been published to the International Journal of Life Cycle Assessment. The submitted paper explains step-by-step how the proposed S-LCA framework can be adapted to other product systems for the selection of impact subcategories.

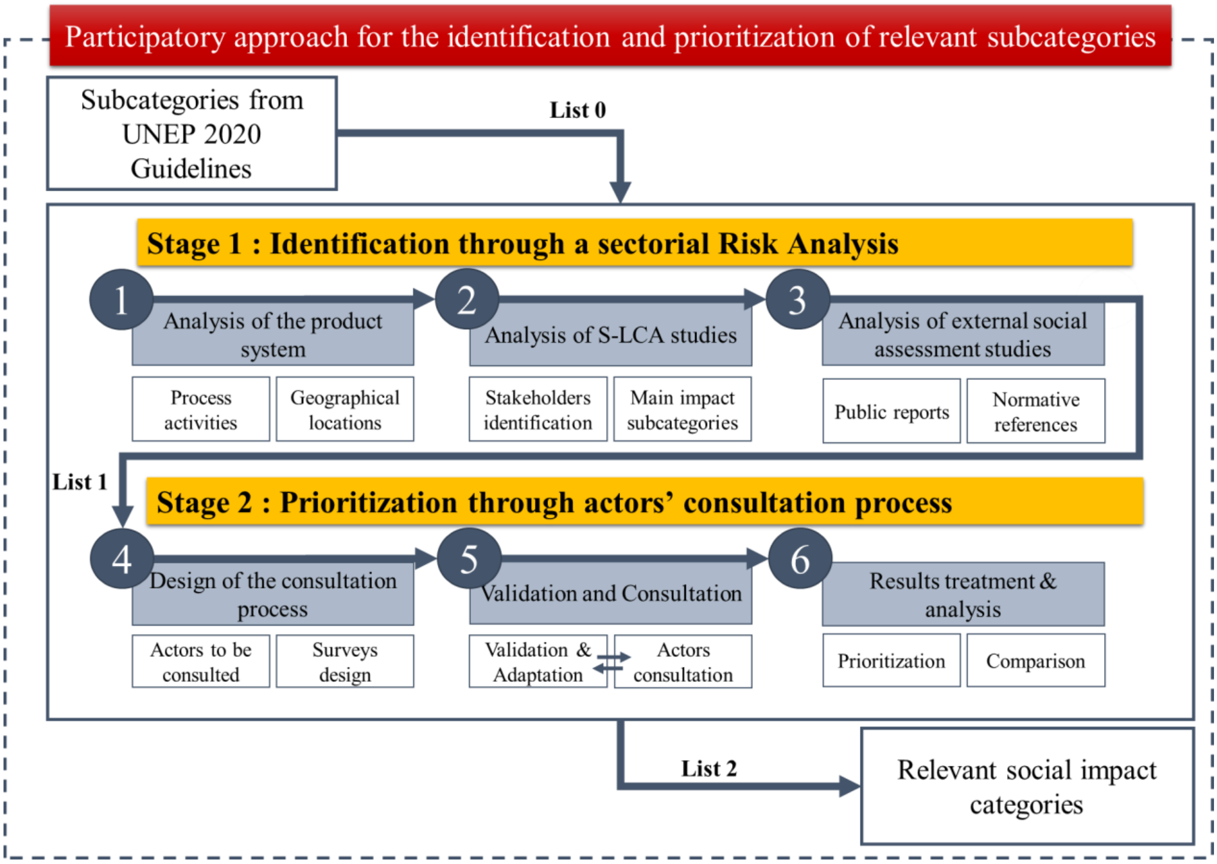


Figure 28 Main steps of the defined participatory approach for the selection of impact subcategories within S-LCA, adapted from (Bouillass et al. 2021)

Stage 1: Identification of sector-specific impact subcategories through a sectorial risk analysis

This step is conducted with respect to the first phase of S-LCA, the goal and scope of the study. The definition of impact subcategories is performed with respect to the considered system boundaries, main process activities and their related geographical locations.

The recommended stakeholder groups and their related impact subcategories in S-LCA guidelines (UNEP, 2020) — list 0 in Figure 28 *Main steps of the defined participatory approach for the selection of impact subcategories within S-LCA, adapted from (Bouillass et al. 2021)* — are adapted with regard to the sector under investigation. To do so, S-LCA studies, together with external social assessment reports, regulations, and normative references can be used to identify topics of interest to the defined product system.

Stage 2: Prioritization of impact subcategories through a multi-actor consultation process

The established list 1 from the identification stage, as represented in Figure 28, is here used for the prioritization stage. To allow a full representation of stakeholders, the design of the consultation process should start by defining the actors that can be consulted to collect their perception on the social significance of each impact subcategory. Following the definition of actors to be consulted, the surveys are to be designed to serve the objective of the consultation and the targeted stakeholders.

The design of the survey can be tested by third parties to validate its practical implementation. According to this step, adjustments can be made before proceeding the survey. Finally, the collected answers should be processed in transparent manner to analyze the perspective of the different involved actors. To enable the design of a multi-consultation process, this thesis proposes the following box 1 with the main features that should be considered.

BOX 1: DESIGN OF THE CONSULTATION PROCESS

The design of the consultation process should include the actors to be consulted, survey tools, the type of questions, and the data collection.

a. What actors to be consulted?

Directly affected and involved stakeholders whenever they can be consulted and external concerned stakeholders for all other cases. The external concerned stakeholders do not have a direct relation with the product system but can provide relevant information on the social significance of impact subcategories. The relevance of stakeholders can be determined based on their level of concern, likeliness of representativeness of affected and or involved stakeholder interests, awareness, and level of influence on decision-making.

For example, it can be difficult to access information from some of the directly affected and involved stakeholders, i.e., workers in the extraction, local communities, suppliers, etc. As a solution, other external concerned stakeholders can be consulted depending on their relevance to the product system.

b. What are the available tools?

There are many different tools that can be used to conduct the survey either, through online semi-structured surveys or individual interviews, focus groups, etc. The choice is to be made based on the specific needs and the goal of the study. Sometimes it can be relevant to use different tools as they are often in complementarity. In fact, individual interviews can be very beneficial for collecting qualitative information while online semi-structured surveys are easier in terms of the logistics and allow gathering greater information for the specific need of the study.

For example, the prioritization of impact subcategories in this work is conducted based on the outcome of the identification step. In this regard, the consulted actors are asked to rank a suggested list of impact subcategories. Online semi-structured surveys are here the most adequate to enable such exercise. However, the online survey was complemented whenever it was possible with individual interviews allowing to gather information on how the respondents understood and analyzed each question.

c. Type of questions?

Once the data collection method has been chosen, the step after consists of defining the questions and the most

- The questionnaires should address the different impact subcategories that have been identified. To perform the prioritization, online surveys can be useful to order the list of impact subcategories according to the importance assigned by each stakeholder.
- It can be helpful to consider distinctive characteristics of life cycle stages and the corresponding geographical areas in the questions to analyze the variability of the perceived importance.

d. What adjustments should be made?

The adjustments can be made to cover special features of the product system under investigation. It is recommended to validate the surveys after a first trial of the consultation. Supplementary adjustments can be made to custom-made the surveys following the stakeholders needs. However, it should be noted that, such configuration can affect the duration of the consultation step.

The above established participatory approach is implemented subsequently to select the impact subcategories intended to the analysis in S-LCIA phase. A set of specifications was included to allow its application to the defined scenarios in this thesis; personal, public and shared mobility. These specifications are explained in section 4, which entails the implementation of the defined S-LCA comprehensive framework.

The three considered scenarios are analyzed following a user perspective which allows to focus the social assessment on the most relevant impact subcategories. Results from the prioritization enable the selection of impact subcategories, but also the comparison of the perceived importance variability per each considered mobility use scenario.

3.2. Definition and structure of the Social Life Cycle Inventory (S-LCI)

This phase aims at collecting generic and specific data to perform the evaluation phase. Modeling product systems from an S-LCA perspective requires the use of multiple data sources that could be either generic or specific. Primary data is needed to determine amounts of input flows, social inventory indicators and corresponding risk or opportunities levels and finally the activity variables that allow interlinking data for various product systems.

Generic databases can be used to gather information on the evaluated product system. In this study, the Product Social Impact Life Cycle Assessment (PSILCA) database is used to allow the modeling of the input and output flows of the different vehicle technologies by covering four different stakeholder groups. The use of the database is explained in section 4.2. and implemented to the considered vehicle technologies in this study as was illustrated in Figure 26.

Although site-specific data accessibility is often a limiting factor when conducting the S-LCI phase, it is highly recommended in this phase (UNEP, 2020) to cover social and socio-economic aspects related to a specific production site or a case study that cannot be fully measured with generic databases. Specific data is therefore needed to complete the results of generic databases and thus enhance their representativeness.

In this research, specific data is collected to feed the prioritization stage of the proposed participatory approach as illustrated in Figure 26. It should be noted that the use of the participatory approach has been classified by the UNEP (2020) S-LCA guidelines as an “evidence-based” method for collecting data, which ensures a higher reliability of statements compared to “emotionally convincing” methods (i.e., anecdotal evidence, case studies, photo and video documentation).

The S-LCI phase is considered as a preparatory stage for S-LCIA phase. In the case of using generic databases, these provide predetermined reference scales and performance reference points (PRP). To ensure specific assessment of users’, the impact subcategories should be prior established. With this regard, specific data is also collected to enable the analysis of the defined users' impact subcategories. Various data sources can be used depending on the geographical and political contexts. This phase is implemented for the whole set of impact subcategories that were defined within this thesis and are further analyzed in the S-LCIA phase. The following toolbox (box 2) is providing the main key features to be considered when conducting a specific social impact assessment.

BOX 2: SPECIFIC SOCIAL IMPACT ASSESSMENT

To allow the **specific impact assessment to define impact subcategories**, the following questions are suggested:

a. What is measurable?

This first question seeks to identify which aspects are measurable for each of the impact subcategories. For example, for affordability, the price, purchasing power, user perception, incentives, and taxation seem all to have a direct relationship with this subcategory.

b. What are the main references?

This question addresses whether the topic in question is subject to any regulatory requirement in the considered geographical context. If so, the regulatory thresholds are identified and used to feed the definition of the reference scales and the PRPs.

c. What if no regulatory thresholds are identified for a given impact subcategory?

Among the various identified subcategories, there may be some that do not benefit from a specific regulatory structure. In this case, the focus lies on identifying existing voluntary standards, statistical studies, case studies, etc. For example, affordability is not subject to specific regulations. However, there are some regulatory measures, such as carbon taxation, and some incentives, such as the conversion incentive for the purchase of electric vehicles, that can be used to inform the analysis.

d. What are the reference scales used in other social impact assessment studies?

The aim here is to identify the reference scales used for other social impact analysis references such as the PSIA Handbook (Goedkoop et al., 2020a, 2020b). For example, the PSIA handbook proposes five reference scales to analyze the affordability that can be adjusted to the considered product system.

e. What data is needed?

Based on the identified measurable aspects and the reference scales to be used, the type of data to be collected is determined, i.e., quantitative, semi-quantitative or qualitative as well as performance indicators. The methodological sheets (Benoît Norris et al., 2013) and the PSIA handbook (Goedkoop et al., 2020b) can be used for this purpose.

3.3. Social Life Cycle Impact Assessment (S-LCIA) definition

Social Life Cycle Impact Assessment (S-LCIA) aims at calculating, understanding and analyzing the magnitude of social impacts for the defined impact subcategories along the life cycle of the product system (UNEP, 2020). The S-LCIA phase is conducted in this study according to "Type I" impact assessment approaches, namely “Reference Scale-based Social Impact Assessment” (RS S-LCIA). In fact, the current development of characterization models within the “Impact Pathway Social Life Cycle Impact Assessment” (IP SLCIA) is limited to potential social and socio-economic impacts for a single stakeholder category, the workers, and for a very restricted number of impact subcategories. RS S-LCIA approaches enable the assessment of all stakeholder groups and their related impact subcategories, which makes them more compatible with the multi-actor perspective introduced in this work. Moreover, the main S-LCA databases are in line with RS S-LCIA, which is also a key support for this study. Indeed, S-LCA generic databases measure social risks at country and sector data levels. Besides the methodological sheets, the handbook for Product Social Impact Assessment (PSIA) (Fontes et al., 2016; Goedkoop et al., 2020a, 2020b) is an important basis for Type I assessment approaches.

Reference scales established within the inventory phase are used in the S-LCIA phase to perform the calculation of social and socio-economic impacts. These describe for each inventory indicator ordinal scales that comprise a set of PRP corresponding to different levels of social performance or social risks. For example, the employed reference scales in PSILCA database distinguish risk levels that vary from “very low risk” to “very high risk,” and opportunities levels that vary from “low opportunity” to “high opportunity” that allow S-LCA practitioners to account for the positive aspects. Within each impact subcategory, social and opportunity levels are translated in a quantitative metric through an impact factor (Maister et al., 2020). All subcategories and their corresponding inventory indicators, together with the equivalencies between quantitative metrics and risk levels can be found in PSILCA database documentation (Maister et al., 2020).

Performance Reference Points (PRP) are also determined to allow estimating social risk or performance levels based on context-dependent references, i.e., international standards, local legislations, and organizations best practices. According to the framework defined in this work, social and socio-economic impact subcategories that are perceived as the most relevant following the prioritization are used to perform the S-LCIA phase. Social inventory indicators, performance scales and PRP are attributed to the selected social and socio-economic subcategories. The calculation is performed following the characterization method chosen for the study. We further explain how this phase was conducted using PSILCA generic database with an application to transportation technologies.

3.3.1. Introducing a user-centric perspective to S-LCA

Since users’ impact subcategories are not covered in the existing S-LCA databases, the reference scales for impact assessment should be defined as well as the inventory indicators and their related PRP. The inclusion of these specific impact categories is intended to complement the evaluation of the scenarios by providing insight into the mobility services for a local use case in France. This will enable a comparison of the three considered scenarios based on a user-centric approach with respect to the objective of this thesis.

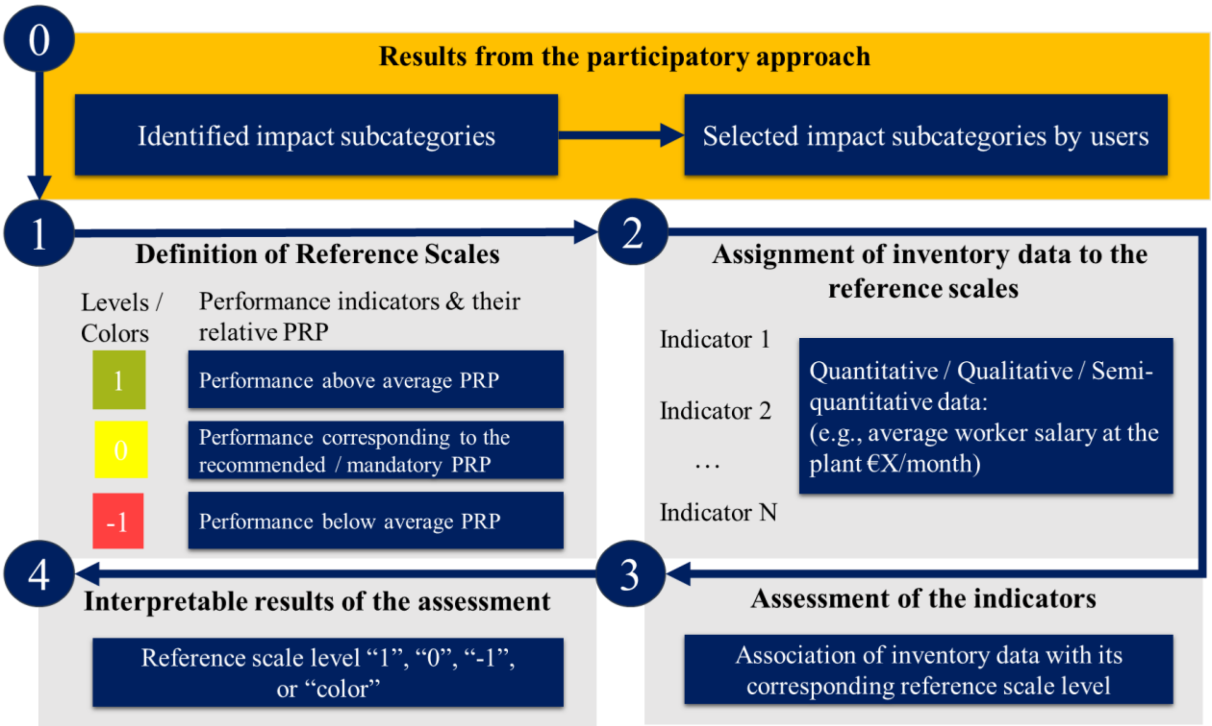


Figure 29 Representation of S-LCIA phase through a specific analysis following the establishment of reference scales and the collected inventory data, adapted from UNEP 2020 S-LCA guidelines with the introduction of the participatory approach.

The establishment of reference scales is conducted following the suggested steps in UNEP (2020) guidelines. Figure 29 illustrates the adjustments that are brought to the process by integrating the results of the participatory approach, notably the identified and the selected impacts subcategories by users following the consultation. The representation of S-LCIA process presented in Figure 29 requires the selection of the impact subcategories to be considered in the assessment, the definition of reference scales (either performance, risk scales, opportunity scales, etc.), the Performance Reference Points (PRP) determining the reference values of performance indicators and inventory data collection. These can be qualified as preparatory steps for S-LCIA phase and are illustrated in Figure 29 as step 0, 1 and step 2. The assessment entails the association of the inventory data to each of the reference scales, thus linking steps 1 and 2 for each of the selected impact subcategories in step 0. In step 4, the results are expressed in risk or performance levels.

The S-LCIA phase can also include an aggregation or weighting step and can be introduced at different states of the advancement of the process. Weighting consists of attributing weights that rely on value choices to indicators, to impact subcategories, or to stakeholder groups.

In the current work, the assessment of inventory data is aggregated by each stakeholder group and impact subcategory. An implicit equal weighting is performed as no specific weighting factors are applied to S-LCIA results. Impact assessment results are thus considered individually equal for each impact subcategory. However, it is important to mention that the focus is made on the prioritized impact subcategories from the participatory approach. Hence, the approach uses explicit weighting in the upstream process and involves all concerned stakeholders.

There is a wide range of weighting techniques, i.e., equal weighting, most robust indicators prioritized, expert or stakeholder values and worst performance prioritized. The description of these techniques and their integration to S-LCA is explained in S-LCA guidelines (UNEP, 2020). It is important to note that, the ISO standards do not support the use of weighting for publishing comparative assertions in LCA (Roesch et al., 2020). The UNEP guidelines (2020) have also highlighted the need of transparency when using a weighting technique to avoid confusion and questioning of the interpretation of S-LCIA results. The participatory approach introduced in this thesis provides an opportunity to integrate stakeholders' opinions to determine the relative importance of impact subcategories escaping from a simple implicit weighting approach. However, the determined relative importance is only used to focus the assessment on some impact subcategories that are perceived as relevant and does not apply the relative importance values to the assessment results. The assessment of the other impact subcategories and their relative indicators are provided to support a more in-depth analysis.

The implementation of the established steps of S-LCIA to users' impact subcategories is explained in section 4 within the implementation of the overall S-LCA framework defined in this work to analyze electric mobility scenarios.

3.4. A comprehensive analysis for Social Life Cycle interpretation

To ensure a comprehensiveness analysis of the results, this study integrates a participatory approach to Social Life Cycle Interpretation (see *Figure 26*). Involving variously affected and concerned stakeholders should help to enhance the materiality assessment by extending the scope to fully consider the divergence of interests and objectives that can occur between the various stakeholders. Such work should improve the representativeness of the materiality assessment that usually reflects solely the organization's perspective and does not take into consideration the points of view of other stakeholders about the economic, environmental, and social topics that could substantially affect them.

Throughout this study, we aim at overcoming this limitation by using a qualitative ranking to prioritize social and socio-economic impact subcategories according to various actors' perceptions. Results from the consultation process could therefore be used to discuss the social significance of the social and socio-economic impact subcategories and to compare the different points of view. Such approach enables to extend the scope of the interpretation phase and consider stakeholders' expectations and their increasing concern on social and socio-economic topics. Moreover, the S-LCIA is complemented by a specific analysis of mobility services by considering the impact subcategories that were perceived as the most relevant.

4. Application of the developed S-LCA methodological framework to electric mobility scenarios.

4.1.Goal and Scope definition

The goal of the implementation of the S-LCA framework in this work is to evaluate the social risks associated with three mobility scenarios corresponding to personal, collective and shared transport use, with a special focus on electric vehicle technologies. The function of the evaluated system is to ensure the transport of passengers in France for a midsize vehicle. This study considers USD 1 output of the product system for the input processes modeling. The system boundaries in this study are illustrated in **Erreur ! Source du renvoi introuvable.** 30. The analyzed impact subcategories are related to the manufacturing, distribution, use and end of life of the vehicles. For both electric and conventional vehicles, the main components and raw materials are identified (e.g., batteries production and powertrains) together with the raw materials and their corresponding geographical location (e.g., Lithium, Cobalt, Steel, etc.) from previous sustainability assessment studies (Bobba et al., 2018; Hosseinijou et al., 2014; Mancini et al., 2019). In addition, two energy production pathways are assessed in this study for the vehicles' power sources, namely electricity and fuel production in France. In fact, the analysis of transport energy sources is increasingly required to complete environmental and economic assessments due to high use of fossil fuels and their associated risks on resources depletion and as a result the degradation of safe and healthy living conditions (Hoque et al., 2020). The use phase entails three mobility use scenarios, corresponding to personal use, public transport use and shared use.

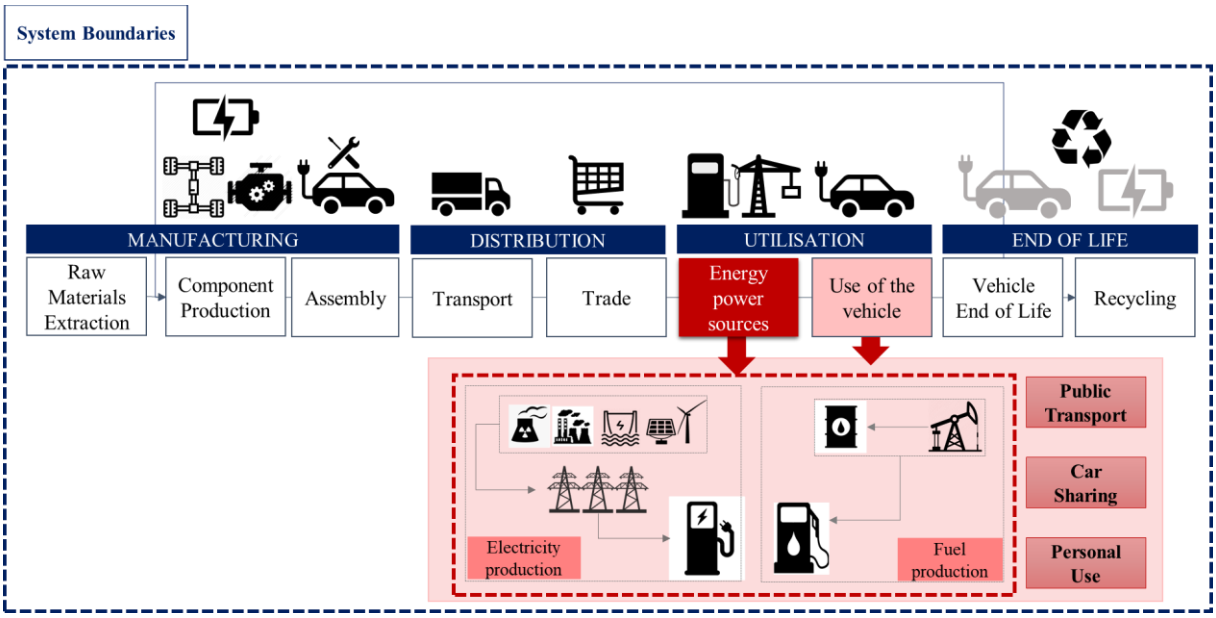


Figure 30 System boundaries of the study according to a "cradle to grave", including mobility use scenarios, e.g., three mobility services, and energy production systems; conventional and electric transportation technologies

The defined life cycle stages are assessed following the sector/country social risks; therefore, the input-output flows are identified to reflect the share of each process activity into the final product output rather than physical flows connections, as done in environmental LCA. Geographical locations of each process activity are identified to allow a representative coverage of the associated impact subcategories considered in the assessment.

For the identification of stakeholders, the UNEP (2020) revised S-LCA guidelines were considered. However, the children stakeholder category is excluded from this work as no mature definitions are currently available for the subcategories suggested in the guidelines and are still not covered in existing S-LCA databases. In this regard, this study focused on five stakeholder categories, namely, workers, consumers, local communities, value chain actors, society.

Mobility-related stakeholders are identified through the analysis of several studies that targeted stakeholders' identification and mapping in mobility (Dobrzyński et al., 2015; Garrido Fernández, 2018; Harrington et al., 2016; Imre Keseru et al., 2018; Jones et al., 2015; Le Pira et al., 2016; Mancini & Sala, 2018; Zambre, 2015). These have addressed direct relations occurring between stakeholders and the studied product system and indirect relations resulting from interactions with other related sectors such as mineral extraction (Mancini & Sala, 2018; OECD, 2021), manufacturing activities, use phase (Eskerod & Huemann, 2013; Spickermann et al., 2014; Lindenau & Böhler-Baedeker, 2014; Kostiainen & Tuominen, 2019; Esztergár-Kiss & Tettamanti, 2019; Kougias et al., 2020; Ludovico et al., 2020; Bjørgen et al., 2021) and final disposal of transportation technologies as defined within the system boundaries. The list of identified stakeholders, their definition together with the type of the occurring interaction is provided table 6.

Table 6 Identified stakeholders, sub-stakeholders, their definition and the nature of their relationship with the product system

Stakeholders' categories	Sub-Stakeholders	Definition	Type of the relation
Workers	Employees	All employees (males and females) in the extraction of raw materials (minerals' extraction) and manufacturing of components (batteries, powertrains, etc.) and final products (internal combustion engine vehicles and electric vehicles)	**Affected** by the organization practices and decisions.
	Migrant employees	The share of migrant employees/total number of employees in the sector Changes following the regulatory context	**Affected** by the organization practices and decisions.
	Child laborers	The share of child labor in the sector (males and females) Changes following the regulatory context	**Affected** by the organization practices and decisions.
	Worker unions	Representative entities for employees in the organization and or the sector.	**Concerned** about the social and socio-economic risks generated by specific activities on the workers. **Could influence** the decision-

			making to protect workers' rights in the organization.
Value Chain Actors	Manufacturer	Designer of and developer of the final product/technology	**Directly involved** in the decision-making process
	Suppliers/Creditors and Contractors	Industrial actors and private entities that are linked to the supply chain of the product/technology	**Involved** in the decision-making process/supply chain of the product/technology
	Shareholders	Particular partner, who is an investor in capital, the owner of a given share of the activity that gives him the prerogatives in the functioning of the company and its decisions.	**Directly involved** in the decision-making process and could have significant influence/control
Society	Government	Define regulation and transportation/manufacturing policies on the national scale	**Concerned** by the environmental and social and socio-economic performance of organizations. And have great **influence** on the decision-making process.
	NGOs	Local organization for environmental protection/air quality and a local scale/noise, biodiversity, etc. data privacy of users, etc.	**Concerned** by the environmental and social and socio-economic performance of organizations. And have great **influence** on the decision-making process.
Local Community	Local Authority	Local authorities that define the local politics and regulations to be respected by the organizations	**Concerned** by the environmental and social and socio-economic performance of available products/technologies in the market. **Define local actions** and plans to manage products/organization's impacts on a local scale.
	Local community	Local residents at a given geographical area where extraction/manufacturing activities take place	**Directly and indirectly affected** by the products/technologies and activities related to the manufacturing
Workers	Workers	Employees in the distribution and purchase stages (male and female)	**Affected** by the organization practices/local/national transportation policies
Users	Users	Person or group of people that would buy the vehicle technology	**Directly affected** by
Society	Governments	Actors' decision makers at the national level for mobility policy and regulations and objectives (reduction of GHG emissions)	**Directly involved** in the decision-making: subvention policies for EV/Incentive taxes related to petroleum products
Users	Users	Primary users of transportation technologies (Bikes, EV, Buses) and mobility services (personal, public, and shared transport)	**Directly affected** by the product (vehicle technology and mobility services) and practices of the: Operators of the mobility service/providers of the technology and insurance and other mobility services/also affected by the local/national policies (ZER)
Local community	Local community	Local residents at a given geographical area characterized by x types of transportation vehicles/and y mobility services/z mobility infrastructures	**Affected** by environmental, social and socio-economic aspects related to technologies/mobility services (noise, local air quality, local employment, accessibility to

			mobility services and infrastructure for EV)
Society	Government's	decision makers at the national level for mobility policy and regulations and objectives (reduction of GHG emissions)	**Directly involved** in the decision-making: subvention policies for EV/Incentive taxes related to petroleum products
	NGOs	Local organization for environmental protection/air quality and a local scale/noise, biodiversity, etc. data privacy of users, etc.	**Concerned** by the environmental and social and socio-economic performance of organizations. And have great **influence** on the decision-making process.
Value chain actors	Constructors	Road's infrastructures, charging infrastructures and other mobility infrastructures	**Involved** in the decision-making and concerned by the local and national mobility policies—subventions for charging infrastructures
	Insurance	Providers of insurance services to the different users (primary and secondary: workers)	**Involved** in the decision-making process (private actors) could have directly affected on users
	Service operators	Providers of mobility platforms (MaaS)/mobility services providers	**Involved** in the decision-making process. Could have direct impacts on users. Concerned by the national/local mobility policies.
Workers (secondary users)	Workers	Independent repairmen or those affiliated to the producers' organizations. Bus drivers, taxi drivers, and other workers in the operating stage of the vehicle (deliveries included)	**Affected** by the organization's practices and local and national regulatory context
Value Chain Actors	Batteries Collectors	Actors involved in the secondary use/application of the battery.	**Involved** in the decision-making process. Concerned by the local and national
	Other materials collectors	Actors involved in the recycling of the vehicles	**Involved** in the supply chain, concerned by the national/local regulatory context
	Manufacturer	Actors involved in the recycling of vehicles and related components and raw materials. "Filière REP"	**Involved** in the supply chain, concerned by the national/local regulatory context
User	Users of the secondary products	Users of second life of vehicles, batteries for energy storage	**Affected** by the technology/component and local/national regulations
Local Community	Local Authority	Local regulations and actions for the final disposal of vehicle technologies and components circularity.	**Involved** in the decision-making process, promotion of circular economy of the materials and vehicles components at the local scale
Society	NGOs	Local organization for environmental protection/air quality and a local scale/noise, biodiversity, etc.	**Concerned** by the local policies and impacts on the various stakeholders

As explained above, users' stakeholder category is the least represented stakeholder category in S-LCA studies related to mobility sector (Osorio-Tejada et al., 2020a; Petti et al., 2016), as social risks are usually evaluated directly through organization's performance. In this study, the users are considered as a key stakeholder due to their significant impact on social acceptability of the final transportation technology (Chalkia et al., 2017; L'Hostis et al., 2016). A new set of social and socio-economic impact subcategories is therefore proposed related to users' stakeholder category particularly suitable for the mobility sector. The users' perception is also introduced in the prioritization stage to identify relevant impact subcategories and thus their expectations and concerns in terms of sustainable mobility alternatives. However, the evaluation of user-related social inventory indicators was not possible through the generic database as no correlation can be made with the activity variable and no social inventory indicators are available in generic databases (Goedkoop et al., 2020b).

In this thesis, a set of social and socio-economic indicators to evaluate the social performance of the mobility services with a user-centric perspective is presented in this thesis. This add-on imposes the adaptation of the different S-LCA phases notably, the S-LCI phase to enable specific data collection and S-LCIA phase to perform the assessment of social and socio-economic impacts through a specific analysis. In order to identify relevant impact subcategories, the designed participatory approach—described in section 3.1.—is applied here to the mobility scenarios considered within this thesis.

Stage 1: Identification of impact subcategories following a sectorial social risk analysis applied to mobility scenarios

To perform the identification stage, UNEP/SETAC methodological sheets (Benoît Norris et al., 2013) and the PSIA handbook (Goedkoop et al., 2020b) were used as a basis. As explained in section 3.1, the first step involves analyzing the considered product system, the main process activities and their corresponding geographical locations to focus the social risk analysis on specific processes or countries and to generate a first draft of the major risks. A thorough literature review was conducted within studies on social externalities, transportation regulations and standards to identify potential social and socio-economic topics as well as scientific publications dealing with these issues. The scope of the review covered 68 scientific publications addressing social and socio-economic impacts of mobility-related supply chains and underlined the different life cycle stages and stakeholders. These publications addressed two scales; micro level covering different technologies, materials, and components such as batteries and powertrains production (Leurent & Windisch, 2015; Lopez-Arboleda et al., 2019; Noel et al., 2018; Omahne et al., 2021; N. C. Onat, Kucukvar, Tatari, & Egilmez, 2016; Patil & Khairnar, 2021; Smaragdakis et al., 2020) and macro level addressing global social impacts of market electrification, of policies, and other sectors that are related to transport (Azapagic, 2004; Aznar-Sánchez et al., 2019; Kamenopoulos et al., 2016; Litmanen et al., 2016; Mancini & Sala, 2018; Orozco, 2018; Pastor et al., 2018; Schlör et al., 2018; Zambrano-Gutiérrez et al., 2018; A. Zhang et al., 2015; Zimmer et al., 2017). Moreover, 155 social assessment reports, transportation regulations and standards were collected from the International Labor Office (ILO), OECD, World Bank and the JRC reports, etc. An iterative approach was followed to identify stakeholders and the associated social and socio-economic topics covered by these studies. The scope was extended to cover raw materials extraction and mining activities (OECD, 2016, 2019b, 2019a, 2021), World Bank (World Bank, 2006, 2010, 2015, 2020).

Among 91 different ILO studies, 46 didn't concern the scope of our research (e.g., railway transport, aviation, etc.). The selected 45 studies focused on "road transport" and "transport equipment manufacturing" (International Labour Office, 2010, 2015b, 2015a, 2016, 2018, 2020; Turnbull, 2013), "road infrastructures" (Johannessen, 2009; World Bank, 2010), "basic metals production" (International Labour Office, 2001, 2005), "oil and gas industry" (Graham, 2010; International Labour Office, 2015c), "mining activities" (Coderre-Proulx et al., 2016; Hilson & Maconachie, 2020; ILO, 2002; International Labour Office, 2019a, 2019b, 2021; Loayza & Rigolini, 2016; McQuilken & Perks, 2021; Walle, 2001). These studies were analyzed to identify relevant positive and negative social and socio-economic topics for transport. The most discussed social and socio-economic issues were identified, such as "health and safety," "decent working conditions," "employment," "child labor," "gender equity—women's employment," and "migrant workers." These described mostly topics related to workers and local communities. Furthermore, Russo-Spena et al. (2018) study was used to analyze the most discussed social and socio-economic topics in 19 different automotive CSR reports.

To cover user-related social and socio-economic impact subcategories, we have considered the UNEP (2020) guidelines list of impact subcategories. However, this list does not cover all the social and socio-economic topics that are related to transport technologies, mobility services and transport infrastructures. A set of new mobility-related impact subcategories for users' stakeholder were defined. The key social hotspots for mobility in section 2.3 were used to inform this step. In order to produce this analysis, normative references and regulations at the European scale were gathered for different social transport topics (CNIL, 2016; CNIL, 2018; European Commission, 2019; RGPD | CNIL, 2018) as well as 27 different scientific publications that focused mainly on users' stakeholder category. Moreover, a project from the European commission (European Commission, 2020c) came up with the definition of a core set of 14 different sustainable urban mobility indicators for users. These indicators were used to support the definition of users' impact subcategories allowing the comparison of the defined mobility scenarios and more representativeness of the actual social and socio-economic impacts. Table 7 presents the core set of impact subcategories, their definitions and the main social and socio-economic aspects that can be measured. These include safety issues (e.g., road accidents, sexual harassment, and insecurity feelings), health and comfort (e.g., vibrations, noises, thermal comfort), users' privacy (consumers personal data uses and privacy management by vehicles' manufacturers and mobility operators), communication system (including transparency, end of life responsibility, mobility service information quality, etc.), availability and interoperability of infrastructures (e.g., geographical coverage of transportation infrastructures such as collective transport station and charging infrastructures, etc.), and affordability (e.g., economic accessibility to the vehicle technology or mobility service).

Table 7 Definition of user's impact subcategories to feed up the S-LCIA phase of mobility scenarios

Subcategories	Definition	Attributed social and socio-economic aspects	Sources
Safety	Covers social risks associated to different types of transportation technologies as well as mobility services. Beside the traffic accidents that are largely covered by social transport externalities studies, other aspects, such as security of infrastructures, insecurity and sexual harassment are also covered by this impact subcategory.	Road accidents and security of infrastructures and transport equipment	(Bondaz et al., 2014; CGDD, 2020b; Newman, 2015; ONISR, 2019)
		Sexual harassment and insecurity.	(CIVITAS, 2010; INSEE-ONDRP-SSMSI, 2019; Noble, 2015)
Health and comfort	Includes various social aspects to transportation technologies or mobility services that could affect the health of the users.	Comfort (vibration)	(Brand et al., 2015; Goedkoop et al., 2020b)
Privacy	Covers social aspects related to web services and mobility platforms (personal, shared, public transportation) in which users' personal data could be affected. Mobility services' operators are expected to respect the OECD privacy guidelines and regulations related to data privacy (RGPD in Europe)	Users' data privacy related to vehicle technologies and mobility online platforms	(Benoît Norris et al., 2013; EU, 2020; Goedkoop et al., 2020a; Ostojski, 2018; le règlement général sur la protection des données — RGPD | CNIL, 2018)
Communication system	Regroups different types of communication relations that could occur between users and organizations. Quality of mobility services is significantly dependent on the efficiency and the strength of the communication system. Aspects such as the end-of-life responsibility and transparency related to environmental a social performance of an organization is also covered by this impact subcategory.	End of life responsibility	(Benoît Norris et al., 2013; Véhicules hors d'usage : Directive 2000/53/ CE, 2000)
		Performance of communication system (technologies and mobility services)	(CIVITAS, 2010; Goedkoop et al., 2020a; Peron, 2010)
		Transparency (social and environmental responsibility)	(ISO 26,000 2010; UNEP 2018)
		Feedback mechanism	(Benoît Norris et al., 2013; Silva et al., 2018)
Availability and interoperability of infrastructures	Covers social aspects related to accessibility of users to mobility services through the evaluation of public transportation coverage, affordability or the ability of purchase and access to a mobility service, as well as the charging infrastructures in case of a massive development of electric mobility.	Accessibility: geographical coverage	(Folcher & Lompré, 2012; Gompf et al., 2020)
		Interoperability of infrastructures	(OIE, 2017; RTE, 2015, 2019)

Affordability	Measures the economic accessibility of vehicle technologies and mobility services. The affordability can be evaluated through actual supported costs by users related to the operation of technologies and services, as well as tax incentives and mobility grants such as conversion incentives.	Affordability of mobility services and transportation technologies	(Tseng et al., 2013)

Stage 2: Actors' consultation process for the prioritization of relevant impact subcategories applied to mobility scenarios—comprise the data collection method (S-LCA iterative aspect)

According to the designed participatory approach in this work, three sets of surveys were developed according to three different types of consulted actors: users (survey 1), worker unions (survey 2) and industrial, academic, and public actors (survey 3). Table 8 presents the consulted actors and the affected and/or involved stakeholders for which impact subcategories describe the positive and negative potential social topics to prioritize. As stated before, multiple adjustments might be required to the designed consultation process. In the current case study, a focus was made on potential social and socio-economic impacts related to the electro-mobility shift *(i.e., "In the context of an electric mobility transition, what would be the social and socio-economic issues that you are most concerned about?").* The questions mainly addressed three different aspects, which can also be considered as part of the assumptions fixed in this work:

- **The geographical location:** two cases for the geographical location were considered, namely, outside Europe and inside France.
- **Transportation technologies:** both electric and conventional transportation technologies were considered to allow the comparison of social significance of impact subcategories in both cases.
- **The type of mobility service:** survey 1 distinguishes between personal, shared mobility and public transportation use. Indeed, users were asked to prioritize social and socio-economic topics following these three types of transportation modes enabling to cover mobility services from a user-centric vision.

All the asked questions in the three online surveys are available in the Appendix 4. A total number of 70 different respondents were consulted in France to gather the information on impact subcategories prioritization. Survey (1) covered in total eight questions that addressed three main elements according to a user perspective: (1) identification of the most relevant impact subcategories affecting users directly by both electric and conventional transportation technologies, (2) identification of the most relevant impact subcategories for each mobility service (personal, collective and shared transportation use), (3) identification of the most important impact subcategories related to workers and local communities' stakeholder categories in the manufacturing stage. The aim was to understand potential effects of social and socio-economic topics on their choices in terms of mobility and their concern related to social sustainability aspects of emergent electric vehicles technologies and mobility services.

Survey (2) described potential impact subcategories for workers according to worker union's perspective. Direct consultation of workers appeared to be quite challenging; worker unions were therefore selected regarding their relevancy for representing the workers' stakeholder category. They represented three types of entities, namely, worker unions in the vehicle's production sites in France, worker unions from VTC (the French abbreviation for chauffeur-driven private cars) and worker unions from public transportation services in France. These actors were asked to prioritize the direct social and socio-economic topics associated to workers in France through online survey and were complemented through individual interviews. The survey covered seven main questions. They were also asked to describe, for each subcategory, the risk level according to the geographical area where the activity is located.

Survey (3) was addressed to public authorities, academic and industrial actors according to their roles, respectively as decision makers, researchers, experts, and developers of products and technologies. The online survey entailed thirteen questions describing social and socio-economic topics associated to all involved and/or affected stakeholders (users, workers, local communities, value chain actors, and society). The aim was to understand how each impact subcategory was perceived in terms of its significance in the assessment, relevance to business and its importance in the decision-making process.

Table 8 The designed multi-actor consultation process for the electric mobility case study and the defined actors

	Consulted actors (affected and/or involved stakeholders + external concerned stakeholders)				
Involved and/or affected stakeholders (recommended by UNEP guidelines)	**Users**	**Worker unions**	**Public actors**	**Industrial actors**	**Academic actors**
Users	X		X	X	X
Workers	X	X	X	X	X
Local communities	X		X	X	X
Value chain actors			X	X	X
Society			X	X	X
	Survey 1	**Survey 2**	**Survey 3**		

The prioritization was performed by computing an importance score, "S", for each impact subcategory, "x". Such score was determined based on the position that the actors assigned for a given impact subcategory within the proposed lists of impact subcategories. For a total number "P" of participants, "I" representing the number of impact subcategories considered by each stakeholder, and "i" rank that was attributed by the consulted actors for each impact subcategory. The importance score "S_i" for each impact subcategory "x" can be obtained as:

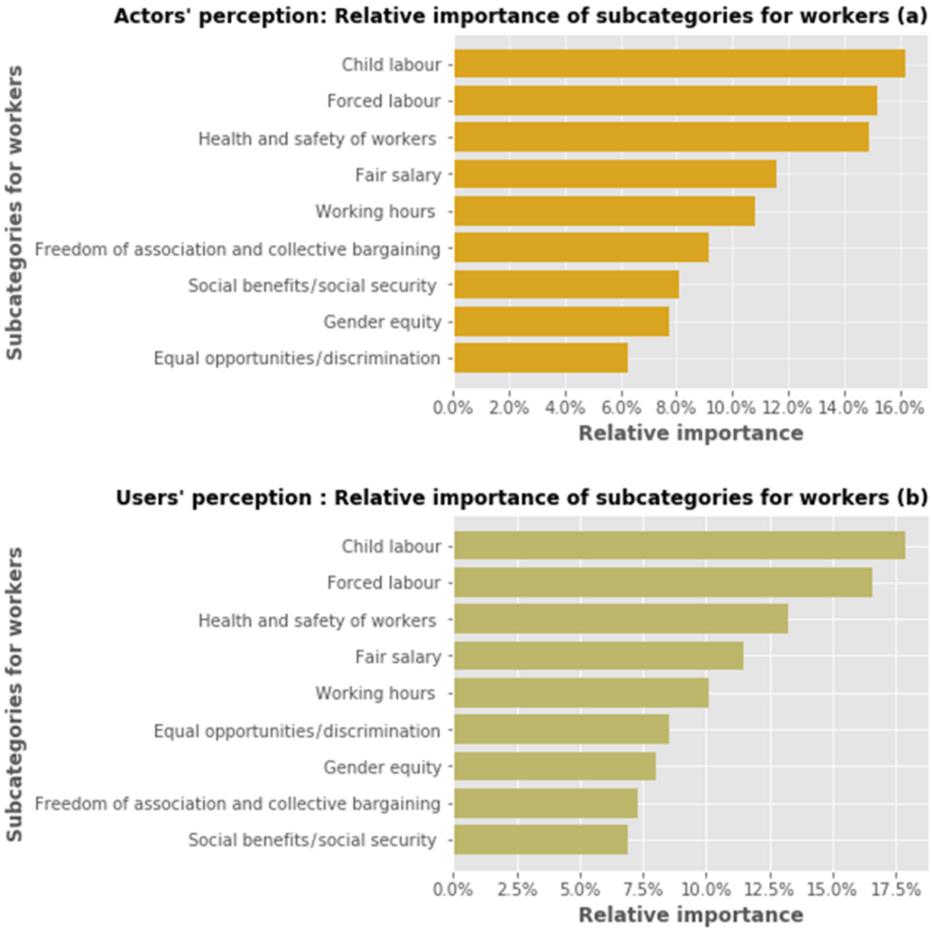
$$S(x) = \sum_{i=0}^{P} S_i \qquad [1]$$

With $$S_i = (I + 1) - i_x \qquad [2]$$

To perform the analysis of results and data treatment, Python programming language was used. Results of the prioritized social and socio-economic impact subcategories for five stakeholder categories are discussed in the following paragraphs from two different actors' perspectives.

The following paragraphs present the obtained results of the consultation process, accounting for both industrial actors' and users' perspectives. The prioritization is discussed for each stakeholder group:

- **Workers' impact subcategories:** in Figure 31



- *Figure 31 Relative importance of workers' impact subcategories from users (b) and other consulted actors (a) (public, industrial and academic) perspectives.*(a) and (b), results of the prioritization from both industrial and user perceptions for workers subcategories outside Europe show that "Child labor," "forced labor," "health and safety of workers" are perceived by the consulted actors as the most relevant ones. These prioritized impact subcategories were assessed using the PSILCA database.

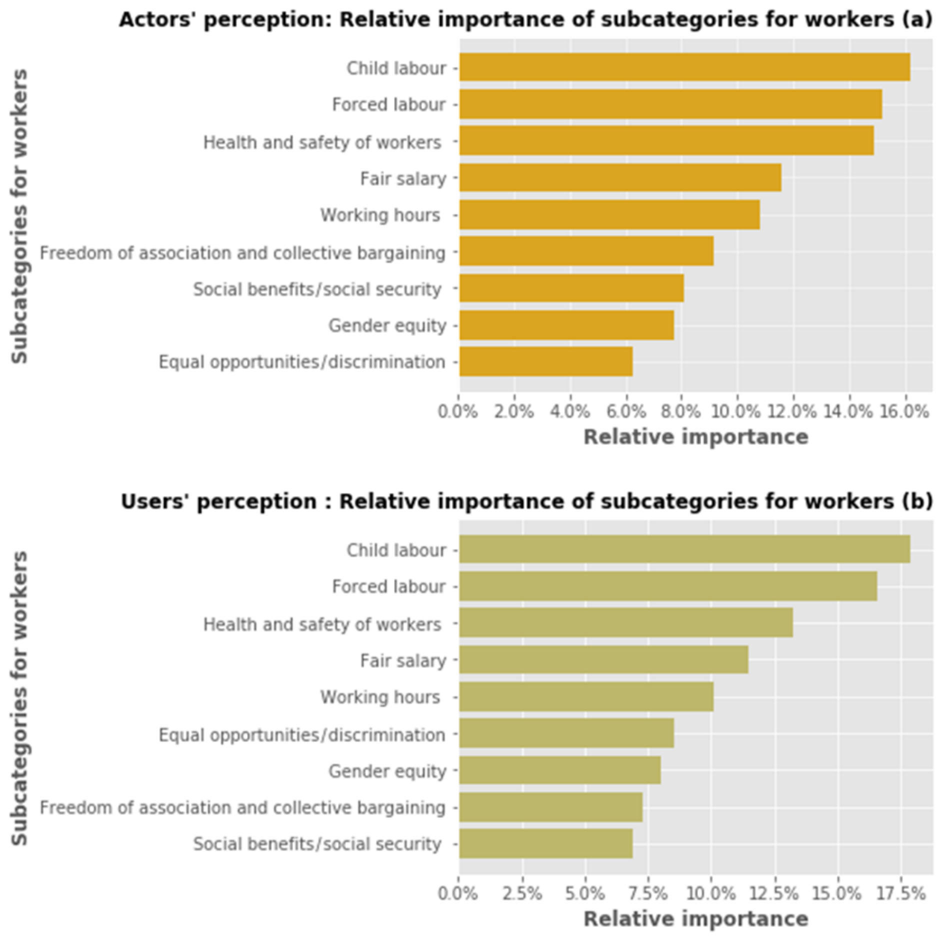


Figure 31 Relative importance of workers' impact subcategories from users (b) and other consulted actors (a) (public, industrial and academic) perspectives.

For workers' impact subcategories in France, the prioritization reveals that "working hours," "fair salary," "health and safety living conditions" and "freedom of association and collective bargaining" are classified with the highest priority by the consulted actors, including industrial actors, users, and worker unions. As an initial observation, such prioritization highlights the influence of the geographical context on the point of view of the consulted actors. Indeed, these actors showed more concern for certain aspects or others depending on the considered geographical location. Given the regulation context in France, no social risk is perceived for "child labor" or "forced labor" and the subcategories are, consequently, not relevant for the evaluation of subcategories for workers' in France compared to other impact subcategories such as "fair salary" or "worker hours." The conducted individual interviews confirm this statement as several respondents justify their answers by referring to "the pyramid of needs" allowing them to rank the different impact subcategories according to the likely presence of social risks and the level of development and performance of the associated regulations in each country.

- **Local communities' impact subcategories:** the relevance of impact subcategories is perceived differently depending on the consulted actors, as shown in Figure 32 *Relative importance of local* *community's impact subcategories according to different consulted actors (c) (public, industrial, and academic) and users (d) perspectives.* (c) and (d).

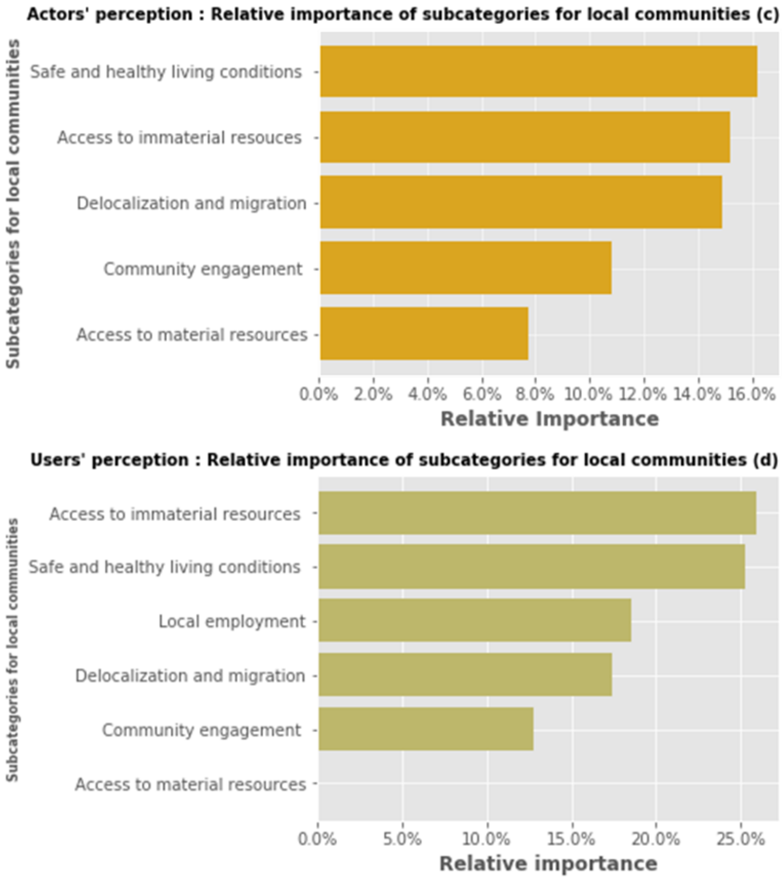


Figure 32 Relative importance of local community's impact subcategories according to different consulted actors (c) (public, industrial, and academic) and users (d) perspectives.

The industrial actors consider "safe and healthy living conditions," "community engagement," and "delocalization and migration" as the most relevant impact subcategories for the evaluation. On the other hand, as represented in Figure 32 (d), "safe and healthy living conditions," "access to immaterial resources" and "local employment" are perceived as the most relevant by users. Following these results, the most prioritized impact subcategories by all the consulted actors were selected to perform the S-LCIA phase. They can be listed as follows: "safe and healthy living conditions," "local employment," and "delocalization and migration". Table 10 (later presented) lists the selected impact subcategories from the prioritization and the attributed indicators for their assessment. The consulted industrial actors and users emphasized the importance of the considered scope when ranking the different impact subcategories, given the variable regulatory context. Thus, the most relevant impact subcategories for local communities outside Europe are different from those located in France.

- **Users' impact subcategories:** Figure 33 (e) and (f) show results of the prioritization of impact subcategories for users' stakeholder category according to industrial actors' and users' perceptions.

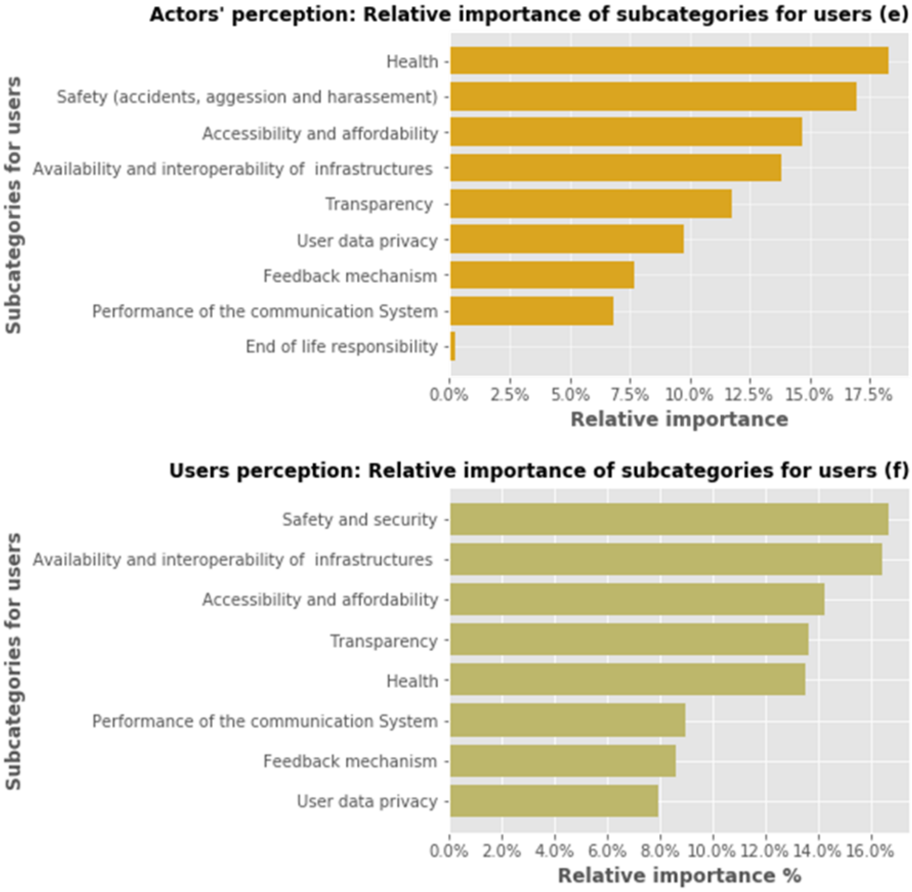


Figure 33 Relative importance of users' impact subcategories according to different consulted actors (e) (public, industrial and academic) and users (f) perspectives.

The impact subcategories "health," "safety," and "accessibility and affordability" are the most relevant impact subcategories from the industrial actors' point of view, while the results from the consulted users show that "safety," "health" and "transparency" are the most important. According to industrial actors, "transparency" appears in the fifth position after "the availability and operability of infrastructures." The observed difference in ranking "transparency" confirms the uprising concern of users about the delivered information on social and environmental performance of organizations related to transportation technologies. This should be analyzed in depth in future assessments.

The second feature that was investigated within users' impact subcategories is the relative importance of social and socio-economic impacts for each of the considered mobility services namely, public, personal and shared transport use. In fact, users were asked to rank the impact subcategories depending on a given type of mobility service in order to verify the variability of the results. The score of the relative importance was therefore calculated as shown in Table 9.

Table 9 Calculated relative importance of users' impact subcategories per each mobility service

	Public transport	**Personal transport**	**Shared mobility**
Transparency	108	116	100

Health	107	121	111
User data privacy	63	64	97
Performance of the communication System	71	84	83
Safety and security	132	146	147
Availability and interoperability of infrastructures	130	91	67
Accessibility and affordability	113	92	115
Feedback mechanism	68	78	72

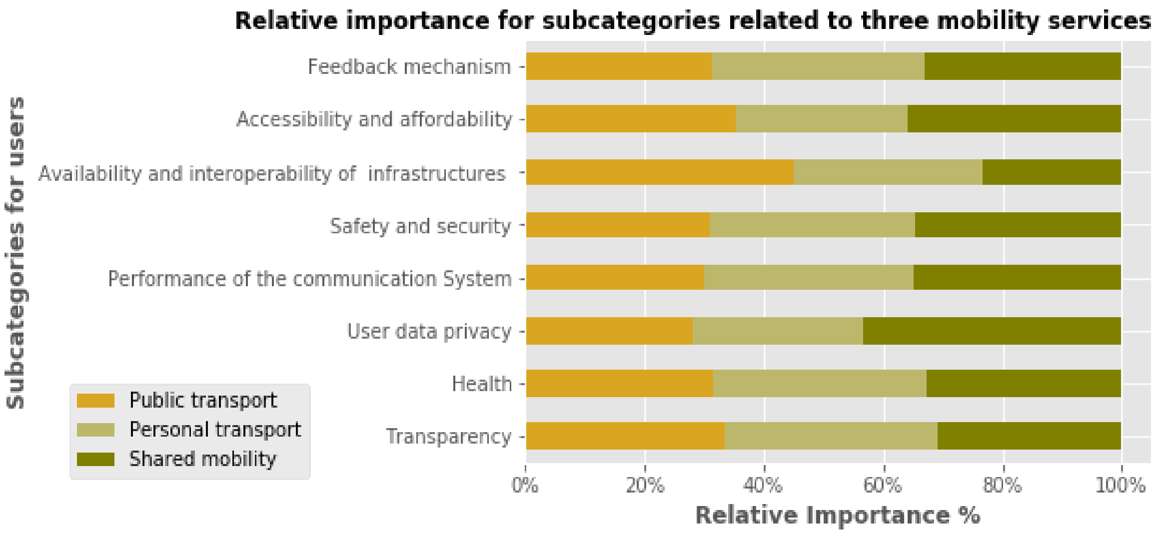


Figure 34 Comparison of the relative importance assigned by users to the different impact subcategories per each type of mobility service

Figure 34 illustrates the results comparing the three types of mobility services. The importance of the impact subcategories was perceived differently according to the users. As shown by figure 34, “the availability and interoperability of infrastructures” is perceived as the most important for public transportation, followed by “safety and security” and “accessibility and affordability”. Shared transportation shows the higher relative importance score of “users’ data privacy” compared to the other considered mobility services. This impact subcategory is followed by “safety and health and “accessibility and affordability”. Finally, personal transportation use shows the higher share of relative importance score related to “health and comfort”. Based on these results, it is worth noting the variable nature of the relative importance of impacts subcategories even when the assessment is conducted from the same perspective. It is thus important to split up the investigated system in order to get the most out of the information on the social relevance of the impact subcategories.

- **Value chain actors’ impact subcategories:** results illustrated in figure 35 show that “promotion of social responsibility” is the most relevant considering the consulted actors’ perspectives, followed by “fair competition” and “respect of intellectual property rights” and finally “supplier relationships”.

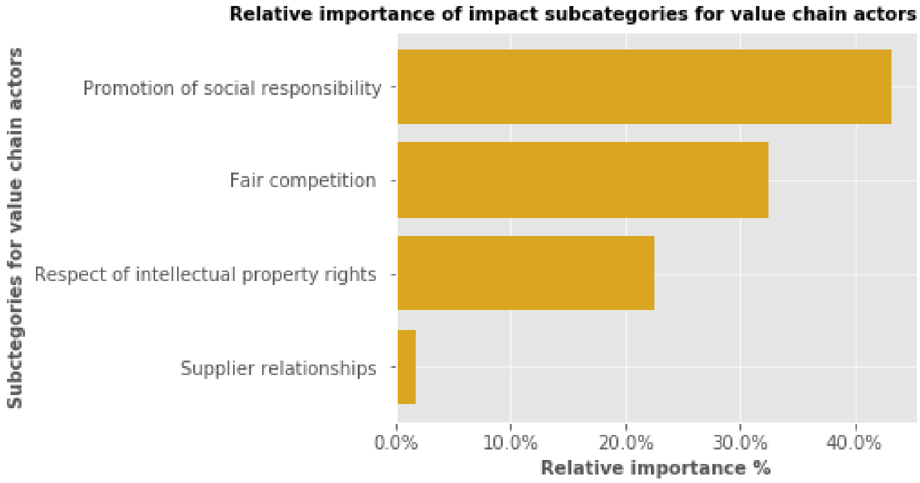


Figure 35 Prioritized impact subcategories for value chain actors according to the consulted actors

To perform S-LCIA phase, both "promotion of social responsibility" and "fair competition" are analyzed. These have been selected to perform the S-LCIA phase as PSILCA database did not cover other impact subcategories that were prioritized.

- **Society's impact subcategories:** results, presented in figure 36,, show that "corruption", "contribution to socio-economic development", "technology development", and, finally, "prevention and mitigation of armed conflicts" are perceived as the most relevant for the evaluation of electric and conventional technologies.

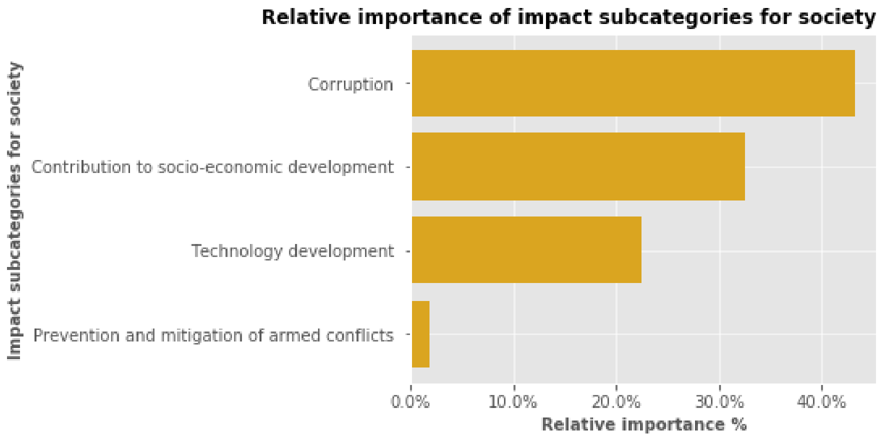


Figure 36 Prioritized impact subcategories for society according to the consulted actors

The provided indicators in PSILCA database only account for two impact subcategories "contribution to economic development" and "health and safety". The "contribution to economic development" was therefore analyzed in the S-LCIA phase as it represents the priority impact subcategory for the different consulted actor while "health and safety" impact subcategory was excluded from the prioritization step.

Comparison of the social relevance of impact subcategories for EV and ICEV technologies

In a second step, the consulted actors were asked to compare the relevance of the different social and socio-economic impact subcategories depending on the type of the transportation technology:

conventional or electric vehicles. As an outcome, relevant impact subcategories were identified when comparing electric and conventional mobility. Figures 37, 38 and 39 **Erreur ! Source du renvoi introuvable.**show the results for users, workers, and local communities from the different consulted actors. Some of the impact subcategories appear to be more important in case of electric mobility evaluation compared to conventional technologies evaluation.

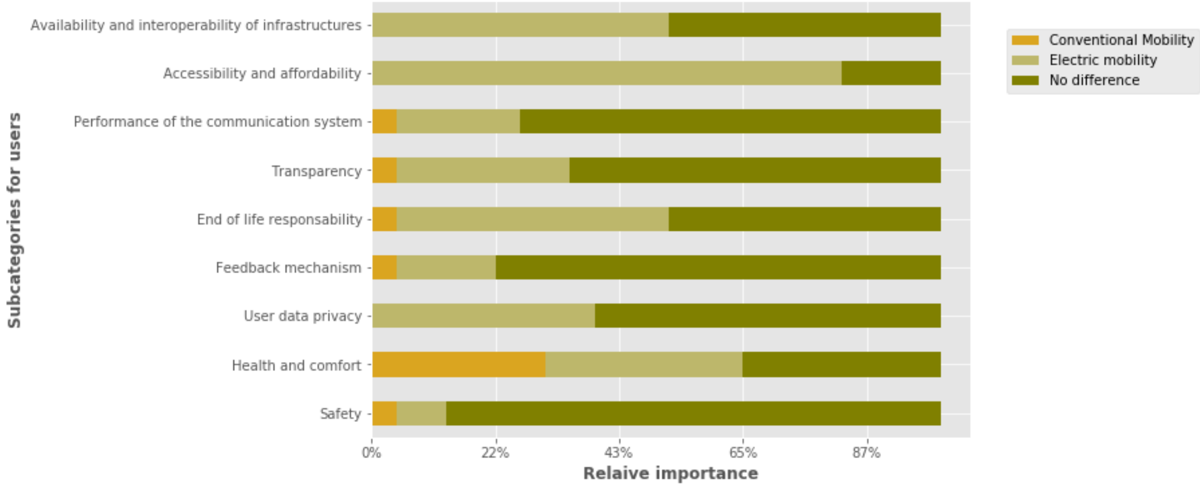


Figure 37 Comparison of electric and conventional vehicle technologies according to the consulted actors: impact subcategories for users

Figure 37 demonstrates that for users' impact subcategories, "accessibility and affordability", "availability and interoperability of infrastructures" and "end of life responsibility" are perceived particularly important in the case of electric technologies. These results are consistent with the identified social hotspots related to the current development of electro-mobility such as the management of the batteries' end of life (Bobba et al., 2018), high initial costs of electric vehicles technologies and complex grid capacity management in case of a mass-market uptake (Tietge et al., 2016).

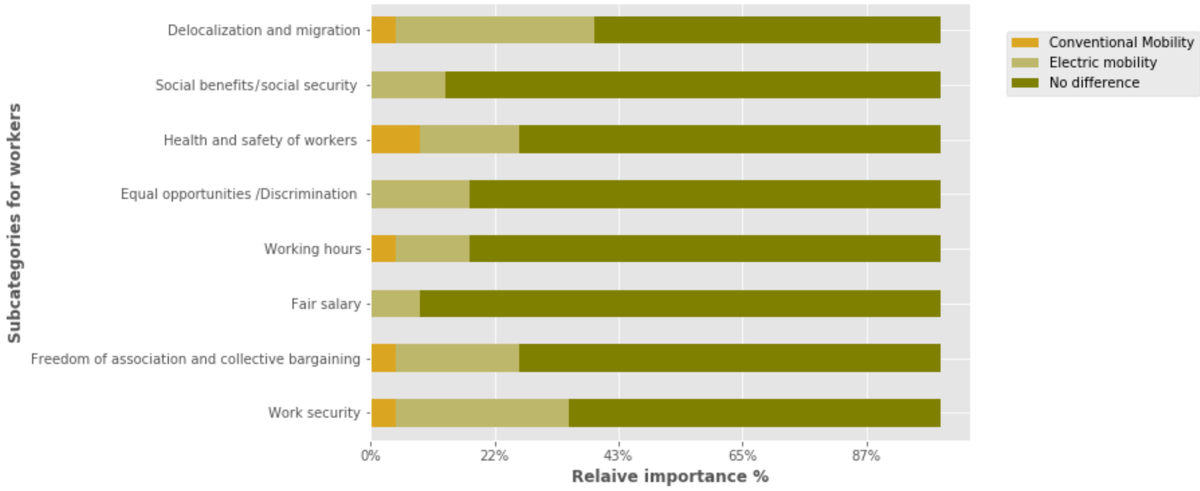


Figure 38 Comparison of electric and conventional vehicle technologies according to the consulted actors: impact subcategories for workers.

For workers-related impact subcategories, presented in figure 38, "delocalization and migration" and "work security" are prioritized for electric mobility and ranked as more relevant than in the case of conventional one which can highlight the need of a consequential assessment of social and socio-economic aspects related to a massive development of electro-mobility. It is also important to note that individual interviews with worker unions have emphasized that electro-mobility requires 25% less workforce and it is therefore crucial to account for the work security-related indicators.

A study from the European Climate Foundation (2018), analyzed several social and socio-economic indicators for mobility prospective scenarios in 2030 and 2050. Such assessment revealed that employment in the automotive manufacturing sector is expected to decrease in Europe, regardless of the low-carbon transition. This is explained by the fact that Battery Electric Vehicles are less labor intensive compared to conventional vehicles, meanwhile Hybrid and plug-in hybrid electric vehicles are expected to be more labor intensive (ECF, 2018). On the other hand, a net increase in employment is expected for the electricity production, hydrogen-related supply chain.

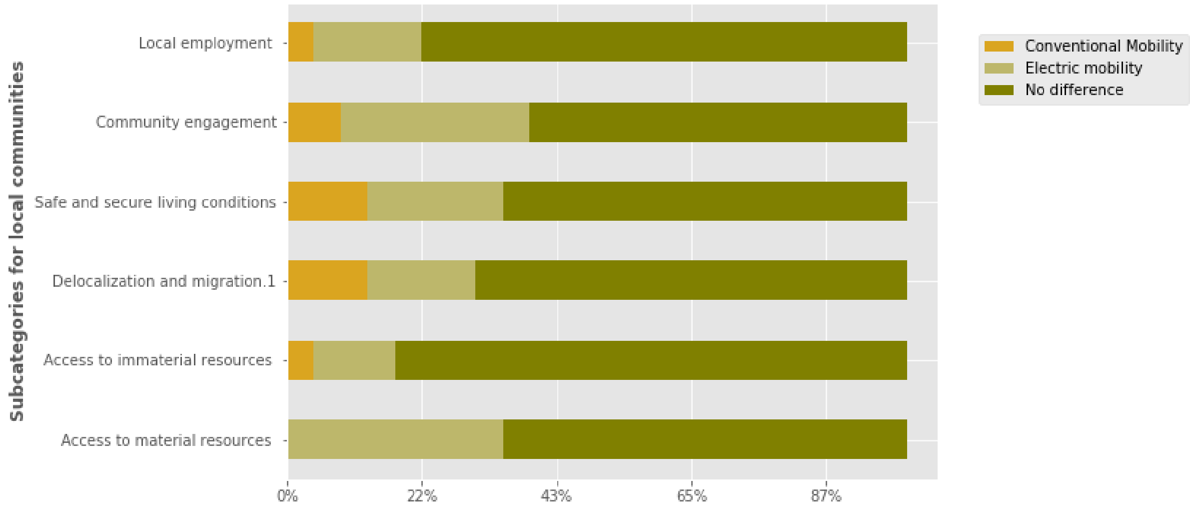


Figure 39 Comparison of electric and conventional vehicle technologies according to the consulted actors: Impact subcategories for local communities

Figure 39 shows the obtained results for the comparison of local communities' subcategories relevance between electric and conventional technologies. According to the consulted actors, there is no significant difference in terms of the importance of subcategories between EV and ICEV. However, it can be observed that subcategories "access to material resources" and "community engagement" were slightly more ranked than the other subcategories.

Despite the potential of this approach, the consultation process was time-consuming and restricted to a limited number of relevant impact subcategories. This could be a potential limitation for its practical application and should be further developed in future studies. As no similar study has been conducted before, to the best of our knowledge, the sample size used might be questioned, yet the analysis of our results shows that the sample is homogeneous and sufficiently representative for the consulted actors and the considered transportation technologies. It is recommended, for future studies, to broaden the sample size, if possible, and confirm its consistency to enhance results representativeness.

4.2. Definition and structure of the Social Life Cycle Inventory (S-LCI) for electric mobility scenarios

4.2.1. Generic data collection through PSILCA database

In this study, PSILCA database was used to obtain data on social inventory indicators. PSILCA database uses a Multi-Regional Input/Output (MRIO) (Mattila, 2018) model from the EORA database (Lenzen et al., 2013). EORA covers economy of global supply chains on an industrial sector basis and uses monetary flows to link different sectors and processes. PSILCA is a Country-Specific Sector (CSS) database. It covers 189 different countries for which a wide range of sectors are attributed (around 15,000 different sectors in total). Both inputs (materials and products provided by other sectors) and outputs (generated products) of a CSS are expressed in USD (Maister et al., 2020). The version 2 of PSILCA database, used in this work, provides 65 qualitative and quantitative social indicators that address a set of 19 impact subcategories classified into four stakeholders, namely, workers, value chain actors, local communities, and society. The selected impact categories and their relative indicators are listed in Table 10.

In this study, inputs of each evaluated process were identified based on the defined system boundaries. To do so, the entailed processes in PSILCA corresponding to the vehicle life cycle stages were investigated as defined in Figure 30. Input materials of the evaluated products and their amounts were collected from ecoinvent database (Del Duce et al., 2016b) and *GREET_2: vehicle_Inputs* (Keoleian et al., 2012). The input processes were connected through monetary values (in USD) corresponding to their contributions into the output of the evaluated product system. In case of lacking data, amounts of input process activities were estimated through other similar existing processes in PSILCA database.

The activity variable used in this study to measure process output and reflect the impact share (relative significance) of each unit process related to the product system was "working time". Worker hours are related to USD 1 of process (or sector) output and are calculated in PSILCA through the following equations [3] and [4] (Maister et al., 2020):

[3] $$\text{Worker hours} = \frac{\text{Unit labor costs}}{\text{Mean hourly labor cost (per employee)}}$$

With:

[4] $$\text{Unit labor costs} = \frac{\text{Compensation of employees (in USD per country–specific sector and year)}}{\text{Gross output (in USD per country–sector and year)}}$$

However, the provided values of the worker hours were calculated for PSILCA database and cannot be sourced on external published references. The numbers of worker hours have been selected for corresponding processes used in this study to calculate the working time activity variable, following equation [5], for both evaluated transportation technologies:

[5] $$\text{working time} = \text{worker hours per USD 1 product output} * \text{total price of the product} * \text{share of labor costs}$$

Vehicles labor costs are uncertain and dependent on the considered technology. Hybrid Electric Vehicles (HEV) seem to have higher labor costs than Battery Electric Vehicles (BEV), while no clear distinctions between BEV and Internal Combustion Engine Vehicles (ICEV) are found. A share of labor costs of 10% of the total cost of vehicles manufacturing was used based on König et al. (2021). Total prices of vehicles were taken for the most adopted urban Electric Vehicles (EV) and ICEV technologies in France, corresponding respectively to USD 39,120.99 (Renault, 2020) and USD 19,229.92 (Peugeot, 2020). The worker hours for USD 1 product output provided for "manufacture of motor vehicles" in France by PSILCA is 0.002481 hours/USD. This value was used to perform the calculation of the working time. Hence, the working time for both scenarios is 9.71 hours for EV and 4.77 hours for ICEV.

These values are attributed to each of the selected social inventory indicators in the S-LCIA phase. The working time activity variable originally refers to the workers' stakeholder category group and is less compatible with other stakeholder groups. Other activity variables, such as the value added that consists of the amount of the added value created in each process activity, and other paths allowing direct quantification of inventory indicators without need of activity variables are currently under development to cover the various stakeholder groups (Ciroth et al., 2019).

Table 10 Inventory indicators from PSILCA database aggregated by impact subcategories and stakeholders' groups.

Stakeholder categories	**Selected impact subcategories**	**Inventory indicators used through PSILCA database**	**Definition of the indicators and units of measurement**
Workers	Child labor	Children employment, total **[CE medium risk h**]	Percentage of all children ages 7–14
	Forced labor	Goods produced by forced labor **[GFL medium risk h]**	Number of goods produced by forced labor in the sector
	Health and safety	Rate of fatal accidents at workplace **[FA medium risk h]** Rate of non-fatal accidents at workplace **[NFA medium risk h]**	Number of fatal accidents per 100,000 employees and year Number of non-fatal accidents per 100,000 employees and year
Local communities	Safe and healthy living conditions	Drinking water coverage **[DW medium risk h]** Pollution level of the country **[P medium risk h]**	Percentage of the population with access to drinking water Pollution Index based on perceptions
	Local employment	Unemployment rate in the country **[LC medium risk h]**	Percentage of the population
	Delocalization and migration	Net migration rate **[NM medium risk h]**	Difference between the number of emigrants and immigrants during a given year per 1,000 inhabitants
Value chain actors	Promotion of social responsibility	Membership in an initiative that promotes social responsibility along the supply chain **[PSR medium risk h]**	number of companies involved in CSR along the supply chain.
	Fair competition	Anti-competitive behavior or violation of anti-trust and monopoly legislation **[AC medium risk h]**	Number of violations per 10,000 employees in the sector

Society	Contribution to economic development	Contribution of the sector to the economic development **[CED medium risk h]**	Shares of breakdown of GDP/Value Added at current prices in percent; if value is derived from the Mining contribution index, it expresses the Metallic mineral and coal production value 2014 (as % of GDP).

4.2.2. Specific data collection for the participatory approach and specific analysis of impacts

In this study, with respect to the iterative nature of S-LCA method, specific data was introduced since the first phase of the definition of the Goal and Scope. In fact, the identification and prioritization stages as suggested by the participatory approach call for specific data collection through different tools. The gathered information is covering a specific sector and geographical context. This was described in the previous section 4.1. by presenting the data collection methods and tools that were used.

To perform the specific analysis as suggested by the proposed S-LCA framework, section 3.2. entails methodological information that was used to gather information on the defined users' impact subcategories. This includes, the reference scales, performance indicators, the PRPs, and available data sources. Figure 40 illustrates the main elements to be defined within the S-LCI phase for each of the impact subcategories by covering, the reference scales, the performance indicators and the PRPs to estimate the level of social performance or social risk.

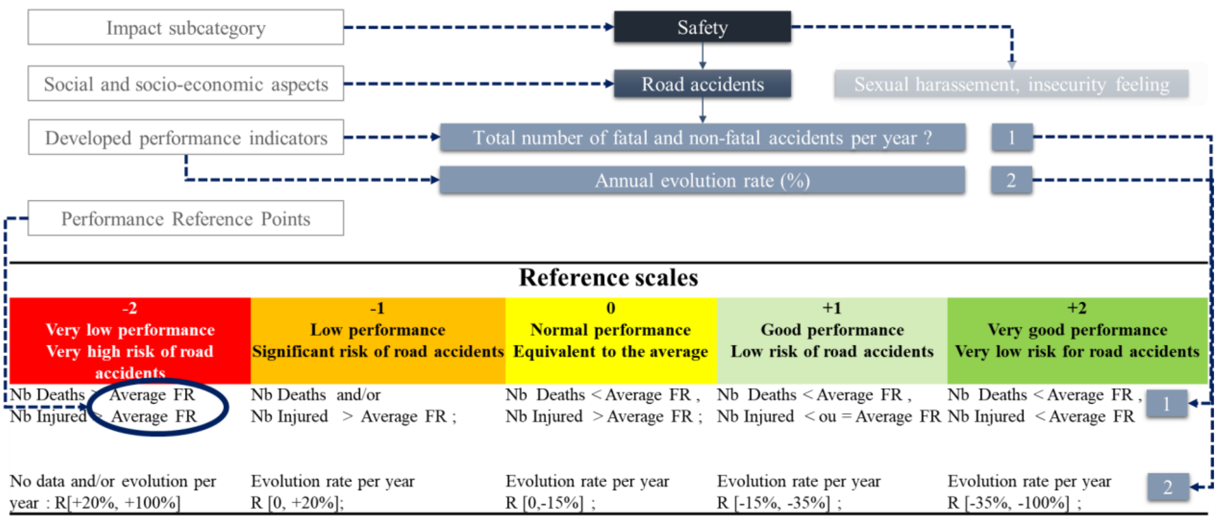


Figure 40 Simplified representation of the main elements of the assessment including, impact subcategory, measured aspect, performance indicators and PRPs as well as the reference scales, e.g., safety of users.

Table 11 summarizes the core set of impact subcategories and their related performance indicators and the identified data sources to enable the assessment of potential social and socio-economic impacts.

Table 11 The suggested performance indicators for each of the defined users' impact subcategories

	Aspects	Performance indicators	Data	Sources
Safety and Security	Road accident rates	Accident rates (fatalities and injuries) in the region/by technology and by transport mode	qnt	(ONISR, 2019)
		Evolution of accident rates (fatalities or injuries) per year (effectiveness of road safety measures)	qnt	(Bondaz et al., 2014; ONISR, 2019)
	Infrastructure security	Total number of accidents related to transportation equipment or infrastructure degradation (lack of lighting, lack of dedicated bike lanes, etc.)	qnt	(ONISR, 2019)
		Existence of a system to improve the safety of the infrastructure (bicycle paths, technical controls, etc.)	s-qnt	
	Feeling of personal insecurity	The rate of sexual assault casualties par year.	qnt	(Noble, 2015; INSEE-ONDRP-SSMSI, 2019)
		Evolution of casualty rate per year (effectiveness of policy response)	qnt	
		Existence of a system for the control and prevention of aggressions and the improvement of the security of transport users.	s-qnt	
		Existence of a platform for handling cases of harassment and aggression and studies on women's accessibility to public and shared transport	s-qnt.	
Health and Comfort	Noise	Compliance with AVAS EU 2019 + EU Directive 2002/49/EC associated with the assessment and management of noise—the Environmental Noise Directive (END)	s-qnt	(Fortino et al., 2016; EC 2019; EEA, 2021)
	Congestion and delays	Duration of commute to and from work or an educational establishment, using any types of modes.		SUMI indicators (European Commission, 2020c)
		Delays in road traffic and in public transport during peak hours compared to off-peak travel (private road traffic) and optimal public transport travel time (public transport).		
	Contribution to the improvement of user comfort	Existence of a mechanism to take into account the adequacy of the facilities (delimited area for shared mobility services, bus station shade, etc.), indoor air quality, thermal comfort, etc.	s-qnt	PSIA handbook (Goedkoop et al., 2020b)
Users' data privacy	Service/technology: management of users' personal data	Number of complaints associated with abuse of transportation users' personal data	qnt	PSIA handbook (Goedkoop et al., 2020b)
		Compliance with the general regulations on personal data protection RGPD- EU & CNIL	s-qnt	(RGPD | CNIL, 2018)
		Number of passenger data breaches per service	qnt	PSIA handbook (Goedkoop et al., 2020b)
Communication system	Feedback Mechanism: After Sales Services	Existence of a system for considering user feedback to improve the quality of the service/technology	s-qnt	(Silva et al., 2018)
		Percentage of complaints handled (+ presence of a protocol to track complaints)	qnt	Meth. Sheets (Benoît Norris et al., 2013)

	Environmental and social responsibility and transparency	Publication of an annual report, accessible by all users, on environmental and social impact studies. Display of impacts by passenger (up to date)/mode of transport	s-qnt	Meth. Sheets (Benoît Norris et al., 2013) & PSIA handbook
		Existence of certificates for environmental and social performance (ISO14001, ISO14040/44, ISO26000, ISO50001 standards, social responsibility labels, etc.)	s-qnt	Meth. Sheets (Benoît Norris et al., 2013)
	Information related to the movement of people—quality of the service	Availability of functional and efficient tools for direct and real-time communication with users: communication platform (application) Information related to the movement of people	s-qnt	(CIVITAS, 2010)
		Percentage of users with access to a central communication platform Frequency of updates and responsiveness to unexpected incidents.	qnt	
	Information related to technologies	Availability of information (eco-driving guide, training in new electric vehicle technologies)	s-qnt	
		Presence of an effective system for repair instructions accessible to users and independent repairers and availability of spare parts (also for maintenance and service)	s-qnt	
	End of life responsibility	Support for end-of-life management of technology	s-qnt	Meth. Sheets (Benoît Norris et al., 2013)
		Establishment of a system for the reuse of technologies (batteries) in other possible applications in second life	s-qnt	
		Presence of label, certificate on the respect of the management of the end of life	s-qnt	
Accessibility and Affordability	Affordability	Technology price/purchasing power comparison	qnt	SUMI indicators (European Commission, 2020c)
		Share of population with appropriate access to mobility services (public transport)	qnt	
		Existence of an incentive system for the use of low environmental footprint transport solutions (economic)	s-qnt	
		Percentage of people who do not have access to transportation due to economic cost	qnt	
	Accessibility	Accessibility of public transport for mobility-impaired groups with visual and audible impairments and those with physical restrictions, such as pregnant women, users of wheelchairs and mobility devices, the elderly, parents and caregivers using buggies, and people with temporary injuries.		SUMI indicators (European Commission, 2020c)
Accessibility and interoperability of	Mobility services	Geographical coverage of points served by transportation mode: Number of stations or points served/km².	qnt	(Gompf et al., 2020)
		Urban planning and urban travel plans adapted to public transport modes	s-qnt	
		Development of the road network and organization of the traffic lanes of the various modes of transport: km of road network/mode of transport	qnt	
		The perceived satisfaction of public spaces. SUMI indicators	qlt	(European Commission, 2020c)

4.3. Social Life Cycle Impact assessment (S-LCIA) of electric mobility scenarios:

The S-LCIA phase has been carried out at two levels. The first level involves a generic assessment of vehicles by covering both electric and conventional transportation technologies. The second level of the S-LCIA phase is conducted through a specific assessment and focuses on users' impact subcategories by analyzing three mobility services, namely personal use, public transport and shared transport.

The generic assessment was performed using OpenLCA software (1.9) and version 2 of PSILCA database. A cut-off criterion of 1 E-5 was applied for the definition of the product systems, according to the features of the used version of the PSILCA database. The assessment method implemented in PSILCA database is the "Social Impacts Weighting method". Social risks related to all involved processes in the life cycle of the product system are aggregated by price (inputs), working time (activity variable) and various impact factors (characterization factors), which enables to express social assessment results in [medium risk hours].

The considered life cycle stages and their corresponding process activities selected from PSILCA database for both electric and conventional transportation technologies are presented in Table 12. Such table presents the existing process activities that cover vehicles production, batteries and powertrains production, raw material manufacturing, electricity, and fuel production and those related to recycling. For some process activities, multiple locations were identified and used to allow the comparison of social and socio-economic topics and the identification of social hotspots depending on the geographical context. Energy processes linked to vehicles operation in France were also analyzed for both electricity and fuel production for the French context.

Table 12 Process activities considered from PSILCA database for the different vehicle technologies analyzed

Object	Identified process Activity in PSILCA (sectors)	Countries
Battery production	Electric Accumulator & Battery	Thailand (TH)
	Batteries	Japan (JP)
	Primary battery	USA (US)
Vehicles and semi-trailer production, and related main components	Manufacture of motor vehicles, trailers, and semi-trailers	France (FR)
	Manufacture of electrical machinery	France (FR)
	Trade, maintenance and repair services of motor vehicles and motorcycles; retail sale of automotive fuel	France (FR)
	Recycling	France (FR)
Electricity Production and related activities	Electrical energy, gas, steam, and hot water	France (FR)
	Mining of uranium and thorium ores	France (FR)
Fuel production	Coke, refined petroleum products and nuclear fuel	France (FR)
	Crude petroleum and natural gas	France (FR)

- **<u>Specific analysis of mobility services:</u>**

Within the specific analysis of mobility services, a scoring system is required to translate the raw data into social performance levels (very low, low, medium, high, very high). The rating system adopted in this work was initially proposed by the PSIA Handbook (2016, 2018, 2020) and now is entailed in the updated S-LCA guidelines (UNEP, 2020). Five performance levels of social and socio-economic performance are proposed accounting both for positive (+2) and negative (-2) social performance. Social performance assessment measures thus, the effectiveness of practices, actions and measures as well as the social management system efficiency of organizations (in this study, mobility services' providers and car manufacturers).

This scoring system was adapted to the considered mobility scenarios by using sector-specific regulations, normative references and national statistical studies in France and in the European context in case national/regional data was missing. In addition, several sustainability and social responsibility assessment references, as well as the main references for Social Life Cycle Assessment (Benoît Norris et al., 2013; Goedkoop et al., 2020a; UNEP, 2020) were used to define the reference scales.

The defined core set of performance indicators in section 4.2, *Table 11* was assigned to the reference scales for each of the impact subcategories for users' stakeholder group.

To perform the evaluation, the data collected for the defined performance indicators is compared to national and international references, in order to estimate the performance of each scenario according to the transportation mode/technology. The results of the assessment of each of the mobility services are provided in section 4.4.5.

4.4.Social Life Cycle Interpretation of results

In this phase, results of the prioritization of impact subcategories and those selected for S-LCIA evaluation phase are analyzed. The selected impact subcategories and the inventory indicators are used from PSILCA database for the evaluation. In this study, users-related impact subcategories for mobility scenarios are defined and prioritized following the proposed participatory approach. In addition, social risks associated with electric and conventional vehicles supply chains are analyzed for four stakeholder categories workers, local communities, value chain actors and society through a generic assessment. A total number of nine impact subcategories and 11 social inventory indicators are discussed.

The S-LCIA phase is conducted for the prioritized social and socio-economic impact subcategories selected from the prioritization stage. **Erreur ! Source du renvoi introuvable.** lists the selected impact subcategories and the inventory indicators used from PSILCA database for their evaluation.

4.4.1. S-LCIA results for workers

The results for workers' impact subcategories are presented in Figure 41. The figure illustrates impact subcategories that were perceived as the most relevant following the designed participatory approach, corresponding to “child labor”, “health and safety of workers”, and “forced labor”. Four inventory indicators were selected to measure social risks for child labor, total [CL medium risk h], fatal accidents [FA medium risk h], non-fatal accidents [NFA medium risk h], and goods produced by forced labor [GFL medium risk h].

Child labor: the calculated indicator for total child labor [CL medium risk h] is higher for EV technologies production than for the conventional (ICEV) transportation technologies. The contribution analysis shows that for EV technologies, the supply chain of motor vehicles manufactured in France accounts for 60.10% of the total CL medium risk h, and a share of 35% is linked to batteries production supply chain in Japan while electricity production in France represents 2% of the obtained results. For ICEV production, manufacturing of the vehicles took 97.14% of the total amount of CL medium risk h related mainly to extraction and manufacturing process activities outside Europe. The analysis of battery production supply chain in Japan reveals that the main contributors for child labor are non-ferrous metals extraction activities in South Africa (16.34%) and regenerated lead and zinc production in Japan (11.56%).

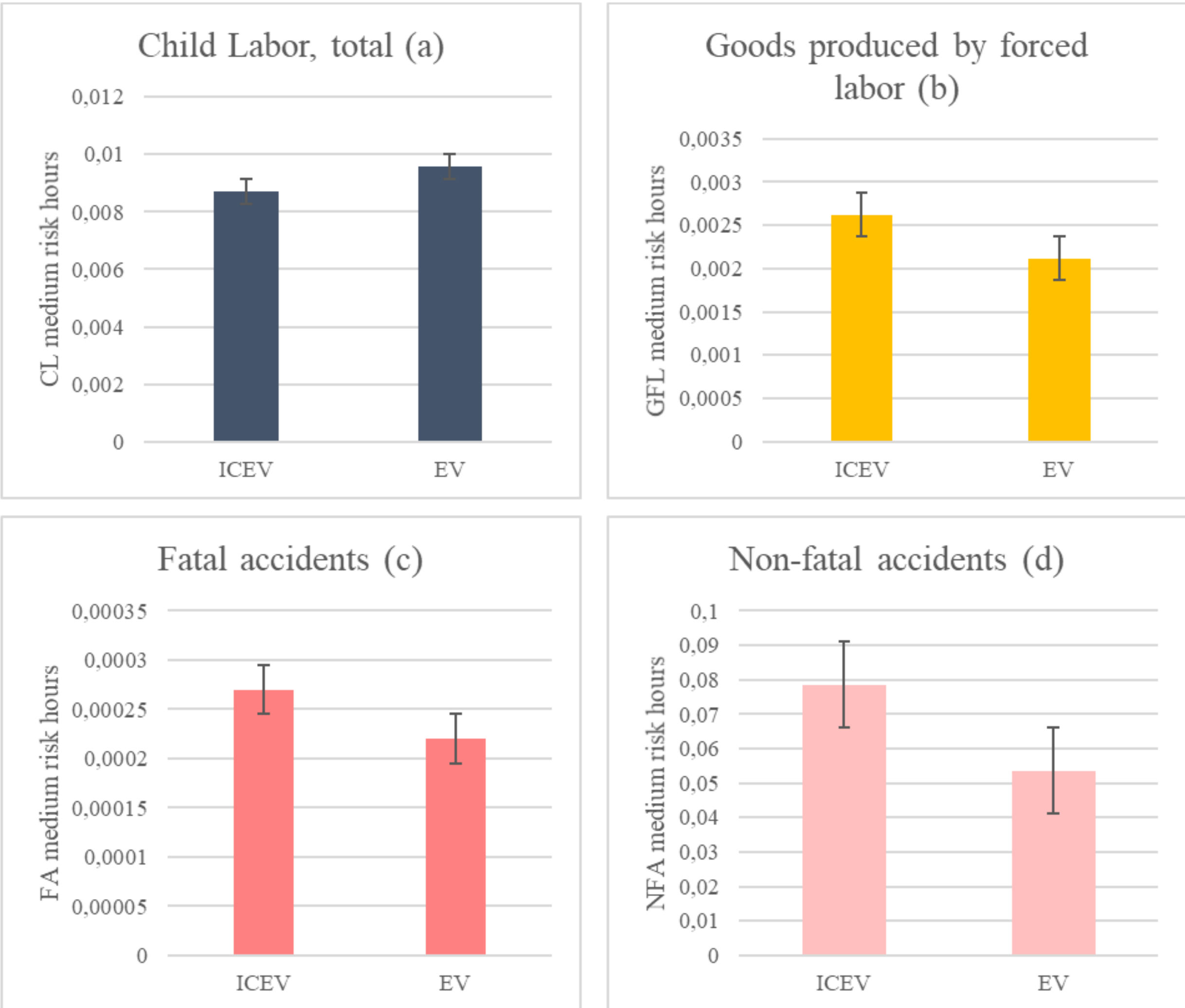


Figure 41 Results of the evaluation of social inventory indicators through PSILCA database for workers for both electric (EV) and conventional (ICEV) transportation technologies

The analysis of the geographical coverage of both EV and ICECV processes allows the identification of countries that have the highest scores for social risks. We have consequently observed that, for EV technologies, child labor risks arise mainly from process activities in Russia 42.64% of total CL medium risk h due to mining and quarrying activities for energy production and non-ferrous metals manufacturing and China with 26.90% of total CL medium risk h related mostly to electric machinery and equipment, plastics and metal products and communications equipment manufacturing. For ICEV technologies, China has the highest share of contributor process activities with 44.32% of total CL medium risk h associated mainly to extraction of raw materials (metal products, plastic products, steel and iron, electronic elements and devices, and raw chemical materials), followed by manufacturing supply chain in France (17.45% of total CL medium risk h), Russia presented a share of 11.48%, linked to metal products and mining and quarrying activities for energy. Process activities in Russia are mainly associated to the supply chain of batteries' production in Japan, which may explain the limited contribution share for ICEV compared to EV technologies and the difference observed in Figure 41 (a) for this indicator between the two technologies. Recycling activities in France did not present any social risk related to child labor for both processes.

Forced labor: Figure 41 (b) illustrates the results for goods produced by forced labor [GFL medium risk h]. ICEV technologies present higher social risk (0.00262 GFL medium risk h) compared to EV technologies (0.00212 GFL medium risk h). The main process activities that are contributing to forced labor in the case of EV technologies are motor vehicles manufacturing supply chain in France (75% share of tot GFL medium risk h), followed by batteries production (12% of total GFL medium risk h) and finally the electricity production (3.68%). In the case of ICEV technologies, the amount of goods produced by forced labor is mainly linked to the France vehicles' manufacturing supply chain (90.50%). Energy-related services (raw petroleum products extraction, refining and manufacturing) in France could be a significant factor for such result as the main process contributing associated to ICEV manufacturing is other business services in France.

Health & safety of workers: Two inventory indicators are calculated to analyze health and safety of workers and are illustrated in Figure 41 (c) and (d) corresponding to fatal accidents [FA medium risk h] and non-fatal accidents [NFA medium risk h]. For both indicators ICEV technologies presented a higher social risk compared to EV technologies. Concerning the latter, motor-vehicle production in France presented 74.67% of total FA medium risk h, followed by batteries production in Japan by 13.01% FA mid risk hours. For ICEV, 90.64% of FA medium risk h is related to motor vehicles production in France. Despite the significant advances in safety regulations at work, France still presents a higher fatal accidents rate than the European average with 2.74 per 100,000 persons employed in France against 1.77 in Europe (Eurostat, 2020a). The countries that presented the highest social risks for fatal accidents related to EV technologies are France (vehicles manufacturing process), followed by China (metal products and raw materials extraction), Japan (batteries production) and finally Spain (vehicles parts manufacturing supply chain). The analysis of contributing processes to non-fatal accidents reveals that vehicle production activities, metal products manufacturing and recycling in Spain was responsible for 40.35% of total NFA medium risk h, while it presented 11% in France mostly linked to the construction sector and finally Turkey that presented around 4% of total FA medium risk h; where manufacturing activities for textiles, basic metal products and motor vehicles are the main contributors. France and Spain presented the higher incidence rates per 100,000 persons employed in 2018 for non-fatal accidents in Europe (Eurostat, 2020b). Mining, manufacturing, and construction sectors are the major source of both fatal and non-fatal accidents in Europe, which also tend to be male-dominated sectors, explaining the relatively higher number of work-related accidents among men compared to women (Eurostat, 2020c).

4.4.2. S-LCIA results for local communities

Results of the S-LCIA evaluation phase for local communities' impact subcategories are presented in Figure 42. It corresponds to those subcategories perceived as the most relevant for the evaluation of electric and conventional transportation technologies. The calculated indicators from PSILCA database are (Maister et al., 2020): Drinking Water coverage [DW mid risk h] and DALYs due to indoor and outdoor air and water pollution [DALY mid risk h] for safe and healthy living conditions, unemployment rate [U medium risk h] for local employment and finally Net Migration [NM medium risk h] for migration and delocalization impact subcategories. Figure 42 (a), (b), (c) and (d) shows the results for the selected social and socio-economic impact subcategories of both electric and conventional transportation technologies

Healthy and safe living conditions: Results for this indicator are shown in Figure 42 (a) and (b), obtained for the two calculated indicators within this impact subcategory. EV technologies present higher social risks for the drinking water coverage [DW medium risk h] and, on the other hand, ICEV technologies present higher social risks for DALYs due to indoor and outdoor air and water pollution. To investigate these results, we took a closer look into the contributor processes for each indicator. Batteries production was found responsible for 65.18% of total DW medium risk hours in the case of EV technologies due to mineral extraction activities (namely, non-ferrous metals in Russia, lead and zinc in Japan, and basic metals extraction in Mexico). Motor vehicles manufacturing in France present 28.51% of total DW medium risk hours, followed by electricity supply chain in France with 3% associated with mining activities for energy and nuclear fuel production. In the case of ICEV technologies, social risks are mostly related to motor vehicles manufacturing with 98.68% of total DW medium risk hours associated to mineral extraction and refined petroleum products. These results can be explained by the significant dependency of mining activities to water consumption which could decrease the accessibility of local communities to water resources and affect their quality (Northey et al., 2019). The second indicator that was analyzed within this impact subcategory is the pollution level of the country [P medium risk h] based on the pollution index by Numbeo (2019) due to water pollution, air pollution, noise levels, green parks in the city, etc. The contribution analysis demonstrates that for EV technologies, motor vehicles supply chain in France is responsible for 83.10% of tot P medium risk h associated with various extraction and production activities that take place in China while 11.41% of tot P medium risk h is generated by batteries production due mostly to non-ferrous metals activities in Russia. For ICEV technologies, France's supply chain for motor vehicles is responsible for 96.08% of pollution-related social risks [P medium risk h] that are linked to the significant number of extraction and manufacturing processes in China. In fact, the geographical analysis of the various processes showed that for the two analyzed transportation technologies, the major source of social risks is induced by activities located in China (52,469% of total P medium risk hours for EV technologies and 61.39% of total P medium risk hours for ICEV technologies).

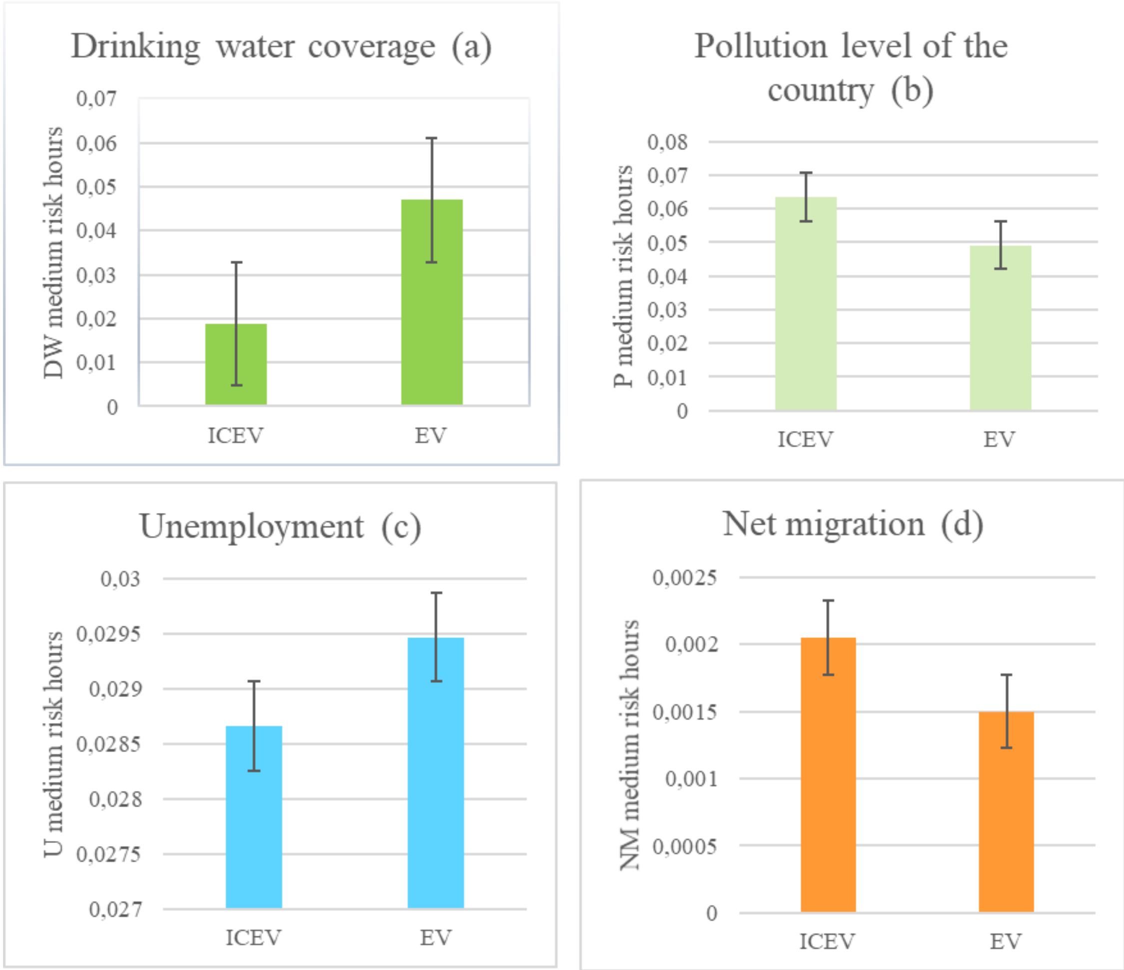


Figure 42 Results of the evaluation of inventory indicators for local communities through PSILCA database for both electric (EV) and conventional (ICEV) transportation

Local employment: Figure 42 (c) shows the obtained results for unemployment indicator [U medium risk h]. Electric transportation technologies show more significant social risks in terms of the unemployment rate due to batteries production that gives place to more extraction and manufacturing processes for non-ferrous metals and other mining activities in South Africa. The major contributor process activity for both electric and conventional technologies is related to motor vehicles production in France (50.39% of total U medium risk h) and Spain (31.47% of total U medium risk h) in the case of EV technologies, which can be explained by the delocalization of mineral extraction processes and batteries manufacturing in China and South Africa.

Migration and delocalization: Results of the net migration indicators [NM medium risk h] calculated for both EV and ICEV technologies, illustrated in Figure 42 (d), confirm the last assumption made for unemployment rates results. In fact, following the contribution analysis, motor-vehicle production in Spain appears to be the major source of social risks related to this impact subcategory accounting for 45.40% of total NM medium risk h in the case of EV technologies and 46.83% of total NM medium risk h in the case of ICEV technologies.

4.4.3. S-LCIA results for value chain actors

The analysis of S-LCIA results for impact subcategories related to value chain actors' is conducted for the "promotion of social responsibility" and "fair competition" that were selected based on the participatory approach and are presented in Figure 43.

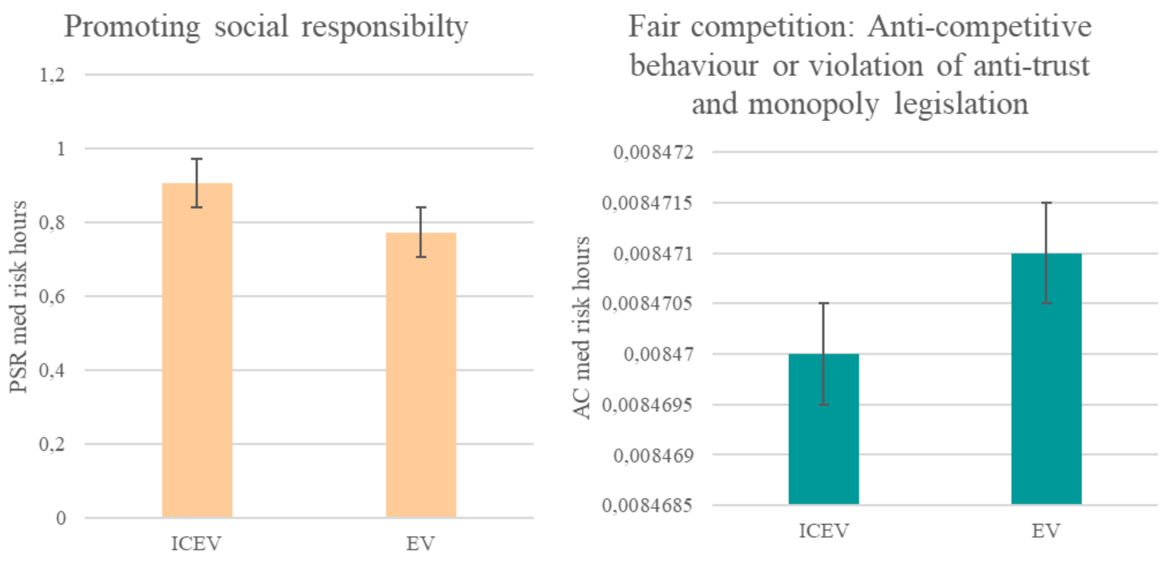


Figure 43 Results of the evaluation of inventory indicators for value chain actors through PSILCA database for both electric (EV) and conventional (ICEV) transportation

Promotion of social responsibility: The proposed indicator by PSILCA database to evaluate the promotion of social responsibility, examines the number of companies involved in corporate social responsibility policy along the supply chain (Maister et al., 2020). Results illustrated in Figure 43 (a) show that for both EV and ICEV technologies, the main contributing processes to the promotion of social responsibility (positive effects) are associated to manufacturing activities located in Europe (France and Spain) which in part can be explained by the European regulatory context and the rise of ecological awareness related to environmental and social performances of organizations.

Fair competition: The measured indicator for fair competition, anti-competitive behavior of organizations, demonstrates similar results for both EV and ICEV technologies (0.00848 AC medium risk h) as illustrated in Figure 43 (b). The contribution analysis allowed identifying the main contributing process activities for these results. For electric vehicles, motor vehicles manufacturing in France is responsible for 76.54% of total AC medium risk h associated mainly with refined petroleum products, followed by electricity production and hot water supply in France that presents 17.72% of total AC medium risk h and finally batteries production in Japan with 3% of total AC medium risk h. The high identified social risks for AC medium risk that is associated to the use of refined petroleum products come only from motor vehicles production (without batteries production). On the other hand, motor vehicles production for ICEV technologies is the main contributor to social risks related to anti-competitive behavior (97.06%), mostly related to mining and quarrying activities for energy in Russia 17.38%, Algeria 2.61% and other services incidental to oil and gas extraction in France. All the identified processes activities for both EV and ICEV related to fair competition impact subcategory highlight the high likelihood of anti-competitive behavior associated to the energy sector. Achieving social sustainability in future mobility scenarios, should focus on improving the social performance of the energy sector on which electric mobility strongly relies.

4.4.4. S-LCIA results for society

Contribution of the sector to economic development: The measured indicator for society's impact subcategory is the contribution of the sector to economic development [CED medium risk h]. This indicator accounts for positive impacts by measuring opportunity levels presented by the evaluated process activity. Results of this impact subcategory are shown in Figure 44. For both EV and ICEV technologies, motor vehicles manufacturing presented the higher share of CED medium risk h, mostly related to research and development activities.

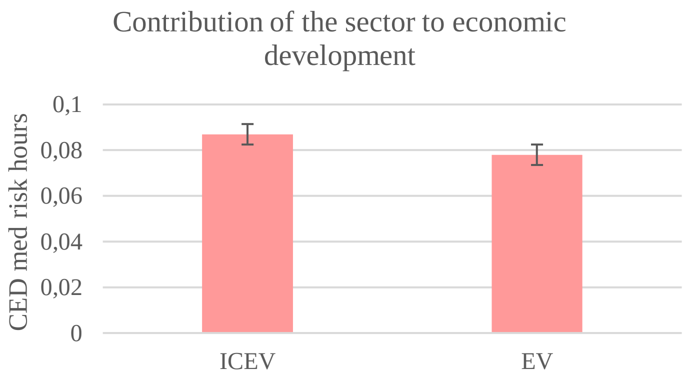


Figure 44 Contribution to the sector economic development through the analysis of inventory indicator provided by PSILCA database

As a general outcome, the S-LCIA evaluation phase is very challenging as very few studies consider a complete product system in S-LCA (Ciroth & Franze, 2011); they rather focus on one specific process activities (Pastor et al., 2018; Werker et al., 2019). Modeling transportation technologies requires considering multiple input processes for which data is often scarce. We extrapolated available data for similar processes in PSILCA database to model the two considered scenarios. It is therefore important to note that further work should account for large uncertainties when analyzing the results. Future enhancement of databases transparency is also recommended to better identify individual contributions in the S-LCIA phase.

4.4.5. S-LCIA results for users' stakeholder group: Analyzing mobility services with a user-centric approach

Results from the specific analysis are illustrated in Figure 45. These are obtained following the assessment of nine different impact subcategories for users as defined in within the participatory approach. The figure illustrates the results for 10 different indicators as a distinction has been made between safety of users from road accidents and the insecurity feeling or the sexual-based casualties. In fact, the analysis of the indicators has demonstrated variable, even contradictory social performance between these two indicators depending on the service that were evaluated.

The analysis of the obtained results can be very challenging as the three mobility services demonstrate variable positive and negative performance. The interpretation step imposes here consideration of trade-offs that occur between the three use scenarios.

The following paragraphs are discussing the results for the impact subcategories that were perceived as the most relevant according to users, namely safety, health and comfort

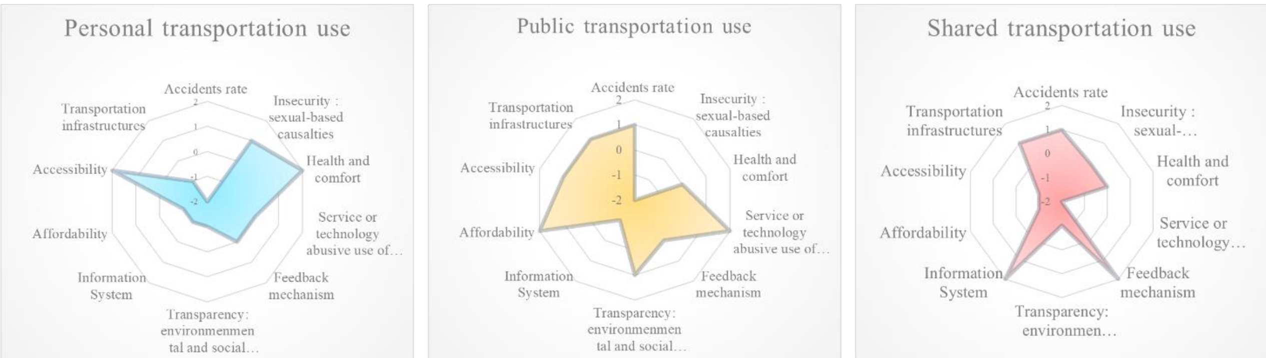


Figure 45 S-LCIA Results from the specific assessment of mobility services with a user-centric approach

Users' safety in terms of road accidents is computed based on the defined performance indicators in Table 11 namely, the accidents rate per year and the evolution of accidents rate which measures the efficiency of road accidents prevention measures. This aspect has shown a very low performance in the case of personal transportation use (-2) as the accidents rate in the region considered for the study is higher than the French average and the evolution of accidents rate which is the second-measured indicator is +40% between 2018 and 2019 (ONISR, 2019). On the other hand, users' safety in terms of aggression and harassment acts presents a better performance (+1) in the case of personal transportation use as the most majority of casualties are related to theft and non-violent acts (INSEE-ONDRP-SSMSI, 2019). The indicator measured here victimization rate amounts to 0.80% in the case of personal transport use against more than 10% for public transportation while for shared transportation the victimization rate varies between 5 and 10%.

The accessibility and affordability of the mobility service was also perceived as the most important according to users. This impact subcategory was divided to two different aspects namely the physical accessibility and the affordability of the mobility service. The performance indicators used to perform the social impact assessment arises from the European Commission SUMI core set or urban sustainability indicators. The results show a positive performance for both indicators in the case of public transportation use, i.e. (+2) for the affordability and (+1) for the accessibility. The accessibility performance was estimated based on the available measures for increasing the inclusiveness of mobility services to all people.

Transportation infrastructures efficiency and availability was also perceived among the most relevant impact subcategories to analyze mobility services. In fact, the performance indicators that were used to perform the analysis calculate the amount of mobility points of service and their geographical coverage. The analysis was performed by collected specific data from the regional mobility service provider. This indicator showed a relatively positive performance for shared transportation while for personal and public transportation use a lower performance was demonstrated. In fact, this impact subcategory was analyzed by using the total number of transport points in the specific region under consideration. For public transportation, the collected data was mapped to enable the calculation of this indicator. The ratio was estimated at 1225 in total for the location. However, to increase representativeness the geographical scope was narrowed down to urban and suburban areas. In this case, the No of served transport points amounted to 734 which is equivalent to a positive performance (+1) according to defined reference scales in (Gompf et al., 2020).

As illustrated in Figure 45, personal transportation use showed a positive performance in terms of accessibility, health and comfort and the safety of users—sexual-based casualties—it shows a very low performance for road-accident rate, transportation infrastructures due to public space occupancy and affordability. By contrast, public transportation use demonstrated a positive performance in terms of affordability, users' personal data protection and transparency on the environmental and social responsibility. Shared transportation shows a positive performance for the feedback mechanism, the quality and efficiency of the communication system, safety in terms of road accidents and transport infrastructures.

5. Conclusions of the chapter

Throughout this research, a comprehensive methodological framework for S-LCA was developed and a step-by-step description for its (operational) application is provided. This S-LCA framework was adapted by considering the four S-LCA phases recommended by ISO 14,040 as a starting point, while adding two main innovative features to overcome current bottlenecks: (1) a participatory approach to account for different stakeholders' perspective for the selection of impact subcategories, (2) a user-centric social impact assessment to better characterized the effects on this specific stakeholder.

The participatory approach entails two main stages: (1) the identification stage enables the definition of sectorial-based impact subcategories for each stakeholder group throughout the life cycle of the product,

(2) a general consultation process designed to enable the prioritization of the identified impact subcategories and to consider the most relevant ones from the perspective of all concerned stakeholders. The selected social and socio-economic impact subcategories were then used to perform the S-LCIA phase and thus, contribute to a comprehensive analysis in the interpretation phase.

The defined framework explained for each of the iterative phases of S-LCA how to integrate the proposed features and how to tailor them to fit other product systems and sectors. In addition, the S-LCIA phase in the current work was carried out through a generic impact assessment using PSILCA database and completed by a specific assessment of mobility scenarios that include users-dependent impact subcategories. The user-centric assessment approach is therefore detailed from the definition of new impact subcategories, the data collection, to the assessment and interpretation of the obtained results. Yet, in the S-LCIA phase, it was not possible to link the assessment of mobility services to the analyzed vehicle technologies to be expressed in the same functional unit. This goes back to the missing correlation with the used activity variable. These issues should be investigated in future studies and users' stakeholder category should not be left out of the assessment. The application to different case studies with new activity variables besides worker hours may allow covering potential social and socio-economic impact subcategories valid for all stakeholder groups.

The developed step-by-step S-LCA framework was implemented to analyze the three mobility scenarios considered in the current thesis namely personal, public and shared transportation use with a special focus on electric and conventional vehicle technologies.

The proposed list of social and socio-economic impact subcategories resulting from its implementation is a contribution towards harmonized social and socio-economic indicators to the mobility sector. Moreover, the implementation of the participatory approach demonstrated the interest of stakeholders' involvement within S-LCA framework. Indeed, social significance of social and socio-economic impact subcategories has varied significantly according to each of the consulted stakeholders (e.g., users, industrial actors, public actors, worker unions, etc.). These discrepancies have revealed different concerns and interests for the considered social topics and confirm their importance to account for within the evaluation phase avoiding thus a partial representation of significant impacts. The comprehensive analysis comparing electric and conventional technologies has been performed based on S-LCIA phase and results from the participatory approach. This phase underlined further the interest of introducing important information on stakeholders' perceptions into the interpretation of results.

The main limitations of the proposed participatory approach laid in its duration and sample size. In fact, the surveys and data collection were time-consuming and should be carefully designed. The sample size being dimensioned to 70 different consulted stakeholders, might raise questions as no similar study has been conducted before. It is therefore recommended to broaden the sample size as much as possible. Specificities may be revealed when consulting the different stakeholders and the design of the surveys might require to be tailored to each consulted stakeholder and product system.

Although the present work did not cover the new proposed stakeholder categories and impact subcategories by UNEP guidelines, the proposed step-by-step S-LCA framework is fortunately general enough to integrate these categories. Future research can focus on; (i) adding new impact subcategories and stakeholder categories but also (ii) to identify other specificities for such other product systems and sectors, and (iii) to confirm the generality of the approach.

6. References

ADEME. (2019). La pollution de l'air en 10 questions— comment respirer un air de meilleure qualité. *ADEME*. https://www.ademe.fr/particuliers-eco-citoyens/pollution-lair

ADEME. (2020). *Impact économique et potentiel de développement des usages du vélo en France en 2020*. ADEME. https://librairie.ademe.fr/mobilite-et-transport/332-impact-economique-et-potentiel-de-developpement-des-usages-du-velo-en-france-en-2020.html

AFNOR. (2002). *Norme Européene EN 13816:2002— Service de transport de voyageurs* (X 50-805; p. 36). AFNOR. https://ecolesdemennecy.files.wordpress.com/2014/04/norme-nf-en-13816-qualitc3a9-service-transport-public-de-voyageurs.pdf

Alix, C. (2017). Devant la justice, l'Urssaf perd face à Uber. *Libération*. https://www.liberation.fr/futurs/2017/03/17/devant-la-justice-l-urssaf-perd-face-a-uber_1556255/

Amnesty International. (2020, May 6). They can't escape the dust. *Amnesty International*. https://www.amnesty.org/en/latest/news/2020/05/drc-alarming-research-harm-from-cobalt-mine-abuses/

Amnesty International. (2021). *Amnesty International Report 2020/21: The state of the world's human rights*. Amnesty International Ltd. https://www.amnesty.org/en/wp-content/uploads/2021/06/POL1032022021ENGLISH.pdf

ATC. (2017). *Lignes directrices pour définir et mesurer la congestion urbaine*. Association des transports du Canada. https://www.tac-atc.ca/sites/default/files/site/doc/Bookstore/prm-dmuc-f.pdf

Azapagic, A. (2004). Developing a framework for sustainable development indicators for the mining and minerals industry. *Journal of Cleaner Production*, *12*(6), 639—662. https://doi.org/10.1016/S0959-6526(03)00075-1

Aznar-Sánchez, J. A., Velasco-Muñoz, J. F., Belmonte-Ureña, L. J., & Manzano-Agugliaro, F. (2019). Innovation and technology for sustainable mining activity: A worldwide research assessment. *Journal of Cleaner Production*, *221*, 38–54. Scopus. https://doi.org/10.1016/j.jclepro.2019.02.243

Benoît Norris, C., Franze, J., Valdivia, S., Traverso, M., Vickery, G., & Siddharth, P. (2013). *The methodological sheets for subcategories in social life cycle assessment (SLCA)*. https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf

Bjørgen, A., Fossheim, K., & Macharis, C. (2021). How to build stakeholder participation in collaborative urban freight planning. *Cities*, *112*, 103,149. https://doi.org/10.1016/j.cities.2021.103149

Blom, M., & Solmar, C. (2009). *How to socially assess biofuels: A case study of the UNEP/SETAC Code of Practice for social—economical LCA.* http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-46146

Bobba, S., Podias, A., Di Persio, F., Messagie, M., Cusenza, M. A., Eynardu, U., Fabrice, M., & Pfrang, A. (2018). *Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB)* (p. 140) [JRC Technical Reports].

https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112543/saslab_final_report_2018_2018-08-28.pdf

Bondaz, M., Panhaleux, J., Helbronner, C., Paquette, O., Miramon, G., Sion, L., Aubert, D., & Bodino, P. (2014). *Evaluation de la politique de sécurité routière : Rapport de diagnostic (Tome1)*. https://www.vie-publique.fr/sites/default/files/rapport/pdf/154000563.pdf

Brand, M. J., Schuster, S. F., Bach, T., Fleder, E., Stelz, M., Gläser, S., Müller, J., Sextl, G., & Jossen, A. (2015). Effects of vibrations and shocks on lithium-ion cells. *Journal of Power Sources*, *288*, 62–69. https://doi.org/10.1016/j.jpowsour.2015.04.107

CGDD. (2021). *Chiffres clés du transport—Edition 2021* (p. 92). Commissariat Général au Développement Durable, Ministère de la transition écologique. https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-transport-2021/livre.php

CGDD, D. (2020). *Bilan social annuel du transport routier de voyageurs — Édition 2020* (p. 100). http://temis.documentation.developpement-durable.gouv.fr/docs/Temis/0080/Temis-0080643/21584_2020.pdf

Chalkia, E., Mueller, B., & L'Hostis, A. (2017). The role of societal resistance in transportation innovation. *8th International Congress on Transportation Research: Transportation by 2030: Trends and Perspectives*, 12P. https://doi.org/10.5281/zenodo.1216917

Ciroth, A., Di Noi, C., & Srocka, M. (2019). *Revisiting the activity variable in Social LCA beyond worker hours*. LCA XIX, Tucson. https://www.greendelta.com/wp-content/uploads/2019/11/2019_LCA_XIX_Revisiting-the-activity-variable-in-SLCA.pdf

Ciroth, A., & Franze, J. (2011). *LCA of an ecolabeled notebook: Consideration of social and environmental impacts along the entire life cycle*. GreenDelta. https://www.greendelta.com/wp-content/uploads/2017/03/LCA_laptop_final.pdf

CIVITAS. (2010). *Amélioration de la qualité des services de transport en commun* (p. 12p) [Policy advice notes]. http://civitas.eu/sites/default/files/civitas_ii_policy_advice_notes_11_public_transport_quality_fr.pdf

CNIL. (2016). *Pack de conformité : Véhicules connectés et données personnelles*. https://www.cnil.fr/sites/default/files/atoms/files/pack_vehicules_connectes_web.pdf

Délibération de la formation restreinte n° SAN-2018-011 du 19 décembre 2018 prononçant une sanction pécuniaire à l'encontre de la société X, Pub. L. No. SAN-2018-011 (2018). https://www.legifrance.gouv.fr/cnil/id/CNILTEXT000037830841/#:~:text=La%20formation%20restreinte%20rappelle%20qu,ne%20puissent%20pas%20%C3%AAtre%20divulgu%C3%A9s.

Coderre-Proulx, M., Campbell, B., & Mandé, I. (2016). *International Migrant Workers in the Mining Sector* [Report]. International Labour Office. Sectoral Policies Dept.; International Labour Office. Conditions of Work and Equality Dept. http://www.ilo.org/global/topics/labour-migration/publications/WCMS_538488/lang--en/index.htm

Del Duce, A., Gauch, M., & Althaus, H.-J. (2016). Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3. *The International Journal of Life Cycle Assessment*, *21*(9), 1314—1326. https://doi.org/10.1007/s11367-014-0792-4

Dobrzyński, M., Dziekoński, K., & Jurczuk, A. (2015). Stakeholders mapping: A case of international logistics project. *Polish Journal of Management Studies*, *11*(2), 17–26.

ECF. (2018). *Low-carbon cars in Europe: Asocial and socio-economic assessment* (p. 102) [Final report]. European Climate Foundation & Cambridge econometrics. https://europeanclimate.org/wp-content/uploads/2019/12/20-02-2019-low-carbon-cars-in-europe-a-socioeconomic-assessment-technical-report.pdf

EEA. (2021). *Exposure of Europe's population to environmental noise—European Environment Agency* [Indicator Assessment]. https://www.eea.europa.eu/data-and-maps/indicators/exposure-to-and-annoyance-by-2/assessment-4

Eisfeldt, F., Rodriguez, C., & Ciroth, A. (2017). *SOCA—A database add-on for Life Cycle Sustainability Assessment*. CILCA, by Greendelta, Medellin.

Eskerod, P., & Huemann, M. (2013). Sustainable development and project stakeholder management: What standards say. *International Journal of Managing Projects in Business*, *6*(1), 36–50. https://doi.org/10.1108/17538371311291017

Esztergár-Kiss, D., & Tettamanti, T. (2019). Stakeholder engagement in mobility planning. In *Autonomous vehicles and future mobility* (pp. 113–123). Elsevier. https://doi.org/10.1016/B978-0-12-817696-2.00009-3

EU. (2020). *Protection des données et respect de la vie privée en ligne*. L'Europe est à vous — Citoyens. https://europa.eu/youreurope/citizens/consumers/internet-telecoms/data-protection-online-privacy/index_fr.htm

Véhicules hors d'usage : Directive 2000/53/CE, Pub. L. No. Directive 2000/53/CE du Parlement européen et du Conseil du 18 septembre 2000 relative aux véhicules hors d'usage-Déclarations de la Commission (2000). https://eur-lex.europa.eu/legal-content/FR/TXT/?uri=LEGISSUM:l21225

Electric and hybrid cars: New rules on noise emitting to protect vulnerable road users, (2019). https://ec.europa.eu/growth/content/electric-and-hybrid-cars-new-rules-noise-emitting-protect-vulnerable-road-users_en

European Commission. (2020). *Technical support related to sustainable urban mobility indicators (SUMI)* (Harmonisation Guideline Final [Web] Version MOVE/B4/2017-358; p. 25). https://ec.europa.eu/transport/sites/default/files/sumi_wp1_harmonisation_guidelines.pdf

European Commission. Joint Research Centre. (2018). *Platform workers in Europe: Evidence from the COLLEEM survey.* Publications Office. https://data.europa.eu/doi/10.2760/742789

European Commission. Joint Research Centre. (2019). *Women in European transport with a focus on research and innovation :an overview of women's issues in transport based on the Transport Research and Innovation Monitoring and Information System (TRIMIS).* Publications Office. https://data.europa.eu/doi/10.2760/56299

European Commission. Joint Research Centre. Institute for Prospective Technological Studies. (2016). *The passions and the interests: Unpacking the "sharing economy".* Publications Office. https://data.europa.eu/doi/10.2791/561134

Eurostat. (2020a). *Fatal accidents at work, 2017 and 2018 (incidence rates per 100,000 persons employed) AAW2020.png—Statistics Explained*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File: Fatal_accidents_at_work,_2017_and_2018_(incidence_rates_per_100_000_persons_employed)_AAW2020.png

Eurostat. (2020b). *Non-fatal accidents at work, 2017 and 2018 (incidence rates per 100,000 persons employed) AAW2020.png*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Non-fatal_accidents_at_work,_2017_and_2018_(incidence_rates_per_100_000_persons_employed)_AAW2020.png

Eurostat. (2020c, November 16). *Non-fatal accidents at work by size of enterprise and economic activity, EU-27, 2018 (% of non-fatal accidents for each activity) AAW2020.png*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Non-fatal_accidents_at_work_by_size_of_enterprise_and_economic_activity,_EU-27,_2018_(%25_of_non-fatal_accidents_for_each_activity)_AAW2020.png

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The New International Standards for Life Cycle Assessment: ISO 14,040 and ISO 14,044. *The International Journal of Life Cycle Assessment*, *11*(2), 80—85. https://doi.org/10.1065/lca2006.02.002

Folcher, V., & Lompré, N. (2012). Accessibilité pour et dans l'usage : Concevoir des situations d'activité adaptées à tous et à chacun. *Le travail humain*, *Vol. 75*(1), 89–120. https://www.cairn.info/revue-le-travail-humain-2012-1-page-89.htm

Fontes, J., Gaasbeek, A., Goedkoop, M., Contreras, S., & Evitts, S. (2016). *Handbook for Product Social Impact Assessment 3.0*. PréSustainability. http://dx.doi.org/10.13140/RG.2.2.23821.74720

Foolmaun, R. K., & Ramjeeawon, T. (2013). Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius. *The International Journal of Life Cycle Assessment*, *18*(1), 155–171. https://doi.org/10.1007/s11367-012-0447-2

Fortino, A., Eckstein, L., Viehöfer, J., & Pampel, J. (2016). Acoustic Vehicle Alerting Systems (AVAS)—Regulations, Realization and Sound Design Challenges. *SAE International Journal of Passenger Cars—Mechanical Systems*, *9*(3), 995–1003. https://doi.org/10.4271/2016-01-1784

Gallez, C., & Motte-Baumvol, B. (2017). Inclusive Mobility or Inclusive Accessibility? A European Perspective. *Cuadernos Europeos de Deusto*, *56*, 79. https://doi.org/10.18543/ced-56-2017pp79-104

Garrido Fernández, A. (2018). *Towards transport futures using mobile data analytics: Stakeholder identification in the city of Stockholm* [KTH, School of Architecture and the Built Environment (ABE), Sustainable development, Environmental science and Engineering.]. urn: nbn: se:kth:diva-240604

Goedkoop, M., De Beer, I., Harmens, R., Saling, P., Morris, D., Florea, A., Hettinger, A. L., Indrane, D., Visser, D., Morao, A., Musoke-Flores, E., Alvarado, C., Rawat, I., Schenker, U., Head, M., Collotta, M., Andro, T., Viot, J.-F., & Whatelet, A. (2020a). *Product Social Impact Assessment Handbook 2020*. https://product-social-impact-assessment.com/wp-content/uploads/2020/12/20-01-Handbook-2020_10.pdf

Goedkoop, M., De Beer, I., Harmens, R., Saling, P., Morris, D., Florea, A., Hettinger, A. L., Indrane, D., Visser, D., Morao, A., Musoke-Flores, E., Alvarado, C., Rawat, I., Schenker, U., Head, M., Collotta, M., Andro, T., Viot, J.-F., & Whatelet, A. (2020b). *Product Social Impact*

Assessment—Social Topics Report—2020. https://product-social-impact-assessment.com/wp-content/uploads/2020/11/Social-Topics-Report-2020_06.pdf

Gompf, K., Traverso, M., & Hetterich, J. (2020). Towards social life cycle assessment of mobility services: Systematic literature review and the way forward. *The International Journal of Life Cycle Assessment*, *25*(10), 1883–1909. https://doi.org/10.1007/s11367-020-01788-8

Graham, I. (2010). *Working Conditions of Contract Workers in the Oil and Gas Industries* (Working Paper Working paper 276). International Labour Office. http://www.ilo.org/sector/Resources/publications/WCMS_161194/lang--en/index.htm

GRI. (2016). *GRI-2016-Consolidated set of GRI sustainability Reporting Standards*. Global Reporting Initiative. https://www.globalreporting.org/

Harrington, T. S., Singh Srai, J., Kumar, M., & Wohlrab, J. (2016). Identifying design criteria for urban system "last-mile'solutions—a multi-stakeholder perspective. *Production Planning & Control*, *27*(6), 456–476.

Hilson, G., & Maconachie, R. (2020). Artisanal and small-scale mining and the Sustainable Development Goals: Opportunities and new directions for sub-Saharan Africa. *Geoforum*, *111*, 125–141. https://doi.org/10.1016/j.geoforum.2019.09.006

Holger, S., Petra, Z., Josephine, M., Andrea, S., Sandra, V., & Jürgen-Friedrich, H. (2017). The social footprint of permanent magnet production based on rare earth elements—a social life cycle assessment scenario. *Energy Procedia*, *142*, 984–990. https://doi.org/10.1016/j.egypro.2017.12.157

Holzwarth, S. (2015). *Analysis of the transport relevance of each of the 17 SDGs* (p. 20). UN-Habitat, UNEP, SLoCaT. https://sustainabledevelopment.un.org/content/documents/8656Analysis%20of%20transport%20relevance%20of%20SDGs.pdf

Hoque, N., Mazhar, I., & Biswas, W. (2020). Application of Life Cycle Assessment for Sustainability Evaluation of Transportation Fuels. In S. Hashmi & I. A. Choudhury (Eds.), *Encyclopedia of Renewable and Sustainable Materials* (pp. 359–369). Elsevier. https://doi.org/10.1016/B978-0-12-803581-8.10792-1

Hosseinijou, S. A., Mansour, S., & Shirazi, M. A. (2014). Social life cycle assessment for material selection: A case study of building materials. *The International Journal of Life Cycle Assessment*, *19*(3), 620–645. https://doi.org/10.1007/s11367-013-0658-1

ILAB. (2020). *2020 List of Goods Produced by Child Labor or Forced Labor* (p. 104). The Bureau of International Labor Affairs United States Department of Labor. https://www.dol.gov/agencies/ilab/resources/reports/child-labor

ILO. (2002). *The evolution of employment, working time and training in the mining industry. Report TMMI/2002*. http://www.ilo.org/global/publications/ilo-bookstore/order-online/books/WCMS_PUBL_9221132234_EN/lang--en/index.htm

Imre Keseru, Thierry Coosemans, Eliza Gagatsi, & Cathy Macharis. (2018). *User-centric vision for mobility in 2030: Participatory evaluation of scenarios by the multi-actor multi-criteria analysis (MAMCA)*. https://zenodo.org/record/1483459#.XI-3vbiNyUk

İmre, Ş., & Çelebi, D. (2017). Measuring Comfort in Public Transport: A case study for İstanbul. *Transportation Research Procedia*, *25*, 2441–2449. https://doi.org/10.1016/j.trpro.2017.05.261

Ingber, S. (2018, April 10). France Can Bring Criminal Charges Against Uber, Judges Rule. *NPR*. https://www.npr.org/sections/thetwo-way/2018/04/10/601317786/france-can-bring-criminal-charges-against-uber-judges-rule

INSEE. (2017). *Tableaux de l'économique française*. Institut national de la statistique et des études économiques. www.insee.fr

INSEE-ONDRP-SSMSI. (2019). *Victimation 2018 et perceptions de la sécurité : Résultats de l'enquête Cadre de vie et Sécurité 2019*. Institut National des Hautes Etudes de la Sécurité et de la Justice : Observatoire National de la Délinquance et des Réponses Pénales. https://www.ihemi.fr/sites/default/files/publications/files/2019-12/RA_ONDRP_2019.pdf

International Energy Agency. (2019). *Global EV Outlook 2019: Scaling-up the transition to electric mobility*. OECD. https://doi.org/10.1787/35fb60bd-en

International Labour Office. (2001). *Safety and health in the non-ferrous metals industries* (p. 185) [Code of practice]. International Labour Office. http://www.ilo.org/global/topics/safety-and-health-at-work/normative-instruments/code-of-practice/WCMS_107713/lang--en/index.htm

International Labour Office. (2005). *Safety and health in the iron and steel industry—Sectoral Activities Programme* (Code of Practice MEISI/2005/8; p. 117). http://www.ilo.org/global/topics/safety-and-health-at-work/normative-instruments/code-of-practice/WCMS_112443/lang--en/index.htm

International Labour Office. (2010). *Benefits of improved road access* (p. 31) [Report]. International Labour Organization (ILO). http://www.ilo.org/jakarta/whatwedo/publications/WCMS_150112/lang--en/index.htm

International Labour Office. (2015a). *Impact Assessment Study of Improved Rural Road Maintenance System under PMGSY* (p. 124). Ministry of Rural Development. https://www.ilo.org/wcmsp5/groups/public/---ed_emp/---emp_policy/---invest/documents/publication/wcms_434255.pdf

International Labour Office. (2015b). *Priority safety and health issues in the road transport sector—Report for discussion at the Tripartite Sectoral Meeting on Safety and Health in the Road Transport Sector* (Meeting Report TSMRTS/2015; p. 76). https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---sector/documents/publication/wcms_400598.pdf

International Labour Office. (2015c). *Occupational safety and health in the oil and gas production and oil refining sector* [Resource list]. http://www.ilo.org/global/topics/safety-and-health-at-work/industries-sectors/WCMS_219028/lang--en/index.htm

International Labour Office. (2016). *Sectoral Studies on Decent Work in Global Supply Chains: Comparative Analysis of Opportunities and Challenges for Social and Economic Upgrading* (p. 182) [Publication]. International Labour Organization (ILO). http://www.ilo.org/sector/Resources/publications/WCMS_485367/lang--en/index.htm

International Labour Office. (2018). *Back to the Future: Challenges and opportunities for the future of work addressed in ILO sectoral meetings since 2010* [Working paper]. http://www.ilo.org/sector/Resources/publications/WCMS_628793/lang--en/index.htm

International Labour Office. (2019a). *Occupational safety and health in the mining industry in Ukraine* (p. 54) [Publication]. International Labour Organization (ILO). http://www.ilo.org/budapest/what-we-do/publications/WCMS_670764/lang--en/index.htm

International Labour Office. (2019b). *Convening actors to reduce child labour and improve working conditions in artisanal and small-scale gold mining (CARING GOLD MINING PROJECT): Fact sheet* (p. 4) [Fact sheet]. International Labour Organization (ILO). http://www.ilo.org/manila/publications/WCMS_720740/lang--en/index.htm

International Labour Office. (2020). *Guidelines on the promotion of decent work and road safety in the transport sector* (p. 84). International Labour Organization (ILO). https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---sector/documents/normativeinstrument/wcms_742633.pdf

International Labour Office. (2021). *Challenges and opportunities for productive employment and decent work in the natural stone mining industry supply chain in Rajasthan* (p. 94) [Report]. ILO Country Office for India and Sectoral Policies Department. http://www.ilo.org/sector/Resources/publications/WCMS_781885/lang--en/index.htm

Interstat, M. de. (2021). *Les vols et violences dans les réseaux de transports en commun en 2019 – Interstats Analyse n°31*. Service statistique ministériel de la sécurité intérieure. http://www.interieur.gouv.fr/Interstats/Actualites/Les-vols-et-violences-dans-les-reseaux-de-transports-en-commun-en-2019-Interstats-Analyse-n-31

ISO 2631-1. (2010). *ISO 2631-1:1997/Amd 1:2010 Vibrations et chocs mécaniques—Évaluation de l'exposition des individus à des vibrations globales du corps—Partie 1 : Spécifications générales—Amendement 1*. ISO. https://www.iso.org/cms/render/live/fr/sites/isoorg/contents/data/standard/04/56/45604.html

ISO26000. (2010). *ISO 26000:2010 (en), Guidance on social responsibility*. https://www.iso.org/obp/ui/#iso:std:iso:26000:ed-1:v1: en

ITF. (2018). *Women's Safety and Security: A Public Transport Priority* (p. 45). International Transport Forum, OECD Publishing. https://www.itf-oecd.org/sites/default/files/docs/womens-safety-security_0.pdf

Johannessen, B. (2009). *Building rural roads*. International Labour Office. http://www.ilo.org/global/publications/ilo-bookstore/order-online/books/WCMS_111496/lang--en/index.htm

Jones, S., Tefe, M., & Appiah-Opoku, S. (2015). Incorporating stakeholder input into transport project selection—A step towards urban prosperity in developing countries? *Habitat International*, *45*, 20–28.

Kamenopoulos, S. N., Agioutantis, Z., & Komnitsas, K. (2016). Framework for Sustainable Mining of Rare Earth Elements. In *Rare Earths Industry* (pp. 111–120). Elsevier. https://doi.org/10.1016/B978-0-12-802328-0.00007-3

Karlewski, H., Lehmann, A., Ruhland, K., & Finkbeiner, M. (2019). A Practical Approach for Social Life Cycle Assessment in the Automotive Industry. *Resources*, *8*(3), 146. https://doi.org/10.3390/resources8030146

Kelly, P., Kahlmeier, S., Götschi, T., Orsini, N., Richards, J., Roberts, N., Scarborough, P., & Foster, C. (2014). Systematic review and meta-analysis of reduction in all-cause mortality from walking and cycling and shape of dose response relationship. *International Journal of Behavioral Nutrition and Physical Activity*, *11*(1), 132. https://doi.org/10.1186/s12966-014-0132-x

Keoleian, G. A., Miller, S., De Kleine, R. D., & Mosley, J. (2012). *Life Cycle Material Data Update for GREET Model* (No. CSS12-12; p. 214). Center for Sustainable Systems—University of Michigan. http://css.snre.umich.edu/

König, A., Nicoletti, L., Schröder, D., Wolff, S., Waclaw, A., & Lienkamp, M. (2021). An Overview of Parameter and Cost for Battery Electric Vehicles. *World Electric Vehicle Journal*, *12*(1), 21. https://doi.org/10.3390/wevj12010021

Kostiainen, J., & Tuominen, A. (2019). Mobility as a Service—Stakeholders" Challenges and Potential Implications. In B. Müller & G. Meyer (Eds.), *Towards User-Centric Transport in Europe: Challenges, Solutions and Collaborations* (pp. 239–254). Springer International Publishing. https://doi.org/10.1007/978-3-319-99756-8_16

Kougias, I., Nikitas, A., Thiel, C., & Szabó, S. (2020). Clean energy and transport pathways for islands: A stakeholder analysis using Q method. *Transportation Research Part D: Transport and Environment*, *78*, 102,180.

Kühnen, M., & Hahn, R. (2017). Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience: Indicators in Social Life Cycle Assessment. *Journal of Industrial Ecology*, *21*(6), 1547–1565. https://doi.org/10.1111/jiec.12663

Le Pira, M., Ignaccolo, M., Inturri, G., Pluchino, A., & Rapisarda, A. (2016). Modelling stakeholder participation in transport planning. *Case Studies on Transport Policy*, *4*(3), 230–238.

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A Global Multi-Region Input—Output Database at High Country and Sector Resolution. *Economic Systems Research*, *25*(1), 20–49. https://doi.org/10.1080/09535314.2013.769938

Leurent, F., & Windisch, E. (2015). Benefits and costs of electric vehicles for the public finances: An integrated valuation model based on input—output analysis, with application to France. *Research in Transportation Economics*, *50*, 51–62.

Levy, J. I., Buonocore, J. J., & von Stackelberg, K. (2010). Evaluation of the public health impacts of traffic congestion: A health risk assessment. *Environmental Health*, *9*, 65. https://doi.org/10.1186/1476-069X-9-65

L'Hostis, A., MULLER, B., meyer, G., BRUCKNER, A., FOLDESI, E., Dablanc, L., Blanquart, C., TUOMINEN, A., KOSTIAINEN, J., POU, C., URBAN, M., KESERU, I., COOSEMANS, T., DE LA CRUZ, M. T., VAL, S., Golfetti, A., Napoletano, L., SKOOGBERG, J., HOLLEY-MOORE, G., … LANGHEIM, J. (2016). *MOBILITY4EU—D2.1—Societal needs and requirements for future transportation and mobility as well as opportunities and challenges of current solutions* (p. 85p.) [Research Report]. IFSTTAR — Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux. https://hal.archives-ouvertes.fr/hal-01486783

Limon, T., Estines, S., Gavaud, O., & Pochez, R. (2018). *Management de la mobilité : Synthèse bibliographique, cadre et définitions, outils et études de cas* (p. 117). Bureau des études économiques énérales : service de l'Administration Générale de la stratégie. https://www.ecologique-solidaire.gouv.fr/sites/default/files/161109_Maitrise%20de%20la%20demande_Rapport%20COP%2022.pdf

Lindenau, M., & Böhler-Baedeker, S. (2014). Citizen and stakeholder involvement: A precondition for sustainable urban mobility. *Transportation Research Procedia*, *4*, 347–360.

Litmanen, T., Jartti, T., & Rantala, E. (2016). Refining the preconditions of a social licence to operate (SLO): Reflections on citizens' attitudes towards mining in two Finnish regions. *The Extractive Industries and Society*, *3*(3), 782–792. https://doi.org/10.1016/j.exis.2016.04.003

Loayza, N., & Rigolini, J. (2016). The Local Impact of Mining on Poverty and Inequality: Evidence from the Commodity Boom in Peru. *World Development*, *84*, 219—234. https://doi.org/10.1016/j.worlddev.2016.03.005

Lopez-Arboleda, E., Sarmiento, A. T., & Cardenas, L. M. (2019). Systematic review of integrated sustainable transportation models for electric passenger vehicle diffusion. *Sustainability*, *11*(9), 2513.

Ludovico, N., Dessi, F., & Bonaiuto, M. (2020). Stakeholders Mapping for Sustainable Biofuels: An Innovative Procedure Based on Computational Text Analysis and Social Network Analysis. *Sustainability*, *12*(24), 10,317.

Macombe, C., Leskinen, P., Feschet, P., & Antikainen, R. (2013). Social life cycle assessment of biodiesel production at three levels: A literature review and development needs. *Journal of Cleaner Production*, *52*, 205–216. https://doi.org/10.1016/j.jclepro.2013.03.026

Maister, K., Di Noi, C., Ciroth, A., & Srocka, M. (2020). *Product Social Impact Life Cycle Assessment (PSILCA) Database v.3 Documentation* (Databse Documentation version 1.0; p. 124). GreenDelta. https://www.openlca.org/wp-content/uploads/2020/06/PSILCA_V3_manual.pdf

Mancini, L., Eynard, U., Eisfeldt, F., Ciroth, A., Blengini, G., & Pennington, D. (2019). *Social assessment of raw materials supply chains. A life-cycle-based analysis*. https://doi.org/10.2760/470881

Mancini, L., & Sala, S. (2018). Social impact assessment in the mining sector: Review and comparison of indicators frameworks. *Resources Policy*, *57*, 98–111. https://doi.org/10.1016/j.resourpol.2018.02.002

Mattila, T. J. (2018). Use of Input—Output Analysis in LCA. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment* (pp. 349–372). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3_14

McQuilken, J., & Perks, R. (2021). *2020 State of the Artisanal and Small Scale Mining Sector*. International Labour Organization (ILO). https://delvedatabase.org/resources/2020-state-of-the-artisanal-and-small-scale-mining-sector

Loi-Mobilités-Présentation du projet de loi d'orientation des mobilités, (2018) (testimony of MTES). https://www.ecologique-solidaire.gouv.fr/sites/default/files/18191_DP_LOM_16p_DEF_Web.pdf

Newman, W. (2015). *Health and safety concerns about the increasing use of mobility scooters on New Zealand roads* (RCA Forum Research and Guidelines Steering Group Report, No. 2). https://rcaforum.org.nz/sites/public_files/images/Mobility%20Scooters-Health%20and%20Safety%20Concerns%20.pdf

Noble, J. (2015). L'insécurité personnelle dans les transports en commun. *Deviance et Societe, Vol. 39*(3), 343–364. https://www.cairn.info/revue-deviance-et-societe-2015-3-page-343.htm

Noel, L., De Rubens, G. Z., & Sovacool, B. K. (2018). Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark. *Energy*, *153*, 628–637.

Northey, S. A., Mudd, G. M., Werner, T. T., Haque, N., & Yellishetty, M. (2019). Sustainable water management and improved corporate reporting in mining. *Water Resources and Industry*, *21*, 100,104. https://doi.org/10.1016/j.wri.2018.100104

Numbeo. (2019). *Pollution Index by Country 2019*. https://www.numbeo.com/pollution/rankings_by_country.jsp?title=2019

OECD. (2016). *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas: Third Edition*. OECD. https://doi.org/10.1787/9789264252479-en

OECD. (2019a). *Interconnected supply chains: A comprehensive look at due diligence challenges and opportunities sourcing cobalt and copper from the Democratic Republic of the Congo*. OECD. https://mneguidelines.oecd.org/Interconnected-supply-chains-a-comprehensive-look-at-due-diligence-challenges-and-opportunities-sourcing-cobalt-and-copper-from-the-DRC.pdf

OECD. (2019b). *OECD Reference Note on Environmental and Social Considerations in Quality Infrastructure* (p. 23). OECD. https://www.oecd.org/g20/summits/osaka/OECD-Reference-Note-on-Environmental-and-Social-Considerations.pdf

OECD. (2021). *Trends in Stakeholder Reporting: Mineral Supply Chains* (p. 39). OECD. https://mneguidelines.oecd.org/trends-in-stakeholder-reporting-mineral-supply-chains.pdf

OIE. (2017). *Les enjeux de l'intégration des véhicules électriques dans le système électrique* [Fiche pédagogique]. OIE est le portail économique et statistique de l'Union Française de l'Électricité. https://observatoire-electricite.fr/IMG/pdf/oie_-_fiche_pedago_mobilite_sept_2017.pdf

Omahne, V., Knez, M., & Obrecht, M. (2021). Social Aspects of Electric Vehicles Research—Trends and Relations to Sustainable Development Goals. *World Electric Vehicle Journal*, *12*(1), 15.

Onat, N. C., Kucukvar, M., Tatari, O., & Egilmez, G. (2016). Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: A case for electric vehicles. *The International Journal of Life Cycle Assessment*, *21*(7), 1009–1034. https://doi.org/10.1007/s11367-016-1070-4

ONISR. (2019). *La sécurité routière en France : Bilan de l'accidentalité de l'année 2018*. Observatoire national interministériel de sécurité routière. http://www.onisr.securite-routiere.gouv.fr/sites/default/files/2019-09/Bilan%20de%20l%20accidentalit%C3%A9%20routi%C3%A8re%20de%20l%20ann%C3%A9e%202018.pdf

Orozco, C. G. (2018). The Global Mining Cluster and Decoding Sustainable Mining. *Journal of Historical Archaeology & Anthropological Sciences*, *3*(1). https://doi.org/10.15406/jhaas.2018.03.00074

Osorio-Tejada, J. L., Llera-Sastresa, E., Scarpellini, S., & Hashim, A. H. (2020a). An integrated social life cycle assessment of freight transport systems. *The International Journal of Life Cycle Assessment*, *25*(6), 1088—1105. https://doi.org/10.1007/s11367-019-01692-w

Osorio-Tejada, J. L., Llera-Sastresa, E., Scarpellini, S., & Hashim, A. H. (2020b). An integrated social life cycle assessment of freight transport systems. *The International Journal of Life Cycle Assessment*, *25*(6), 1088–1105. https://doi.org/10.1007/s11367-019-01692-w

Ostojski, L. (2018). *Données collectées par le véhicule, un nouvel Eldorado ?* https://www.argusdelassurance.com/dossier-ja/donnees-collectees-par-le-vehicule-un-nouvel-eldorado.129970

Pardi, T. (2017). *L'avenir du travail dans le secteur automobile : Les enjeux de la déglobalisation — Synthèse* (p. 16). https://www.ilo.org/wcmsp5/groups/public/---dgreports/---inst/documents/publication/wcms_551604.pdf

Pardi, T. (2021). Prospects and contradictions of the electrification of the European automotive industry: The role of European Union policy. *International Journal of Automotive Technology and Management*. https://hal.archives-ouvertes.fr/hal-03102947

Pastor, M. M., Schatz, T., Traverso, M., Wagner, V., & Hinrichsen, O. (2018). Social aspects of water consumption: Risk of access to unimproved drinking water and to unimproved sanitation facilities—an example from the automobile industry. *The International Journal of Life Cycle Assessment*, *23*(4), 940–956. https://doi.org/10.1007/s11367-017-1342-7

Patil, L. N., & Khairnar, H. P. (2021). *Investigation of Human Safety Based on Pedestrian Perceptions Associated to Silent Nature of Electric Vehicle*. *8*. https://doi.org/10.5109/4480704

Peron, M. (2010). *La communication dans les transports publics interurbains de voyageurs* [Ecole Nationale des Ponts et Chaussées]. https://pastel.archives-ouvertes.fr/tel-00523273/document

Petti, L., Serreli, M., & Di Cesare, S. (2016). Systematic literature review in social life cycle assessment. *The International Journal of Life Cycle Assessment*, *23*(3), 422–431. https://doi.org/10.1007/s11367-016-1135-4

Peugeot. (2020). *Configurateur Peugeot 208 | Votre citadine sur-mesure*. https://www.peugeot.fr/nos-vehicules/e-208/configurez.html/finitions

Renault. (2020). *RENAULT ZOE E-TECH ELECTRIQUE*. https://www.renault.fr/vehicules-electriques/zoe.html

Roesch, A., Sala, S., & Jungbluth, N. (2020). Normalization and weighting: The open challenge in LCA. *The International Journal of Life Cycle Assessment*, *25*(9), 1859—1865. https://doi.org/10.1007/s11367-020-01790-0

RTE. (2015). *Valorisation socio-économique des réseaux électriques intelligents-Méthodologie et premiers résultats* (p. 232) [Rapport d'étude]. Réseau de transport d'électricité-ademe. https://www.rte-france.com/sites/default/files/rei_bd_1.pdf

RTE. (2019). *Enjeux du développement de l'électromobilité pour le système électrique* (p. 82) [Principaux résultats]. https://www.rte-france.com/sites/default/files/electromobilite_synthese_9.pdf

Russo-Spena, T., Tregua, M., & De Chiara, A. (2018). Trends and Drivers in CSR Disclosure: A Focus on Reporting Practices in the Automotive Industry. *Journal of Business Ethics, 151* (2), 563–578. https://doi.org/10.1007/s10551-016-3235-2

Rutter, H., Cavill, N., Racioppi, F., Dinsdale, H., Oja, P., & Kahlmeier, S. (2013). Economic impact of reduced mortality due to increased cycling. *American Journal of Preventive Medicine*, *44*(1), 89—92. https://doi.org/10.1016/j.amepre.2012.09.053

Schlör, H., Venghaus, S., Zapp, P., Marx, J., Schreiber, A., & Hake, J.-Fr. (2018). The energy-mineral-society nexus—A social LCA model. *Applied Energy*, *228*, 999–1008. https://doi.org/10.1016/j.apenergy.2018.06.048

Shen, X., Feng, S., Li, Z., & Hu, B. (2016). Analysis of bus passenger comfort perception based on passenger load factor and in-vehicle time. *SpringerPlus*, *5*, 62. https://doi.org/10.1186/s40064-016-1694-7

Silva, M., Vieira, E., Signoretti, G., Silva, I., Silva, D., & Ferrari, P. (2018). A Customer Feedback Platform for Vehicle Manufacturing Compliant with Industry 4.0 Vision. *Sensors (Basel, Switzerland)*, *18*(10). https://doi.org/10.3390/s18103298

Smaragdakis, A., Kamenopoulos, S., & Tsoutsos, T. (2020). How risky is the introduction of fuel cell electric vehicles in a Mediterranean town? *International Journal of Hydrogen Energy*, *45*(35), 18075–18088.

Soula, C. (2021, April 24). Le boom de la voiture électrique en France met 65 000 emplois en danger. *L'Obs*. https://www.nouvelobs.com/economie/20210424.OBS43217/le-boom-de-la-voiture-electrique-en-france-met-65-000-emplois-en-danger.html

Spickermann, A., Grienitz, V., & Heiko, A. (2014). Heading towards a multimodal city of the future?: Multi-stakeholder scenarios for urban mobility. *Technological Forecasting and Social Change*, *89*, 201–221.

Sureau, S., Mazijn, B., Garrido, S. R., & Achten, W. M. J. (2018). Social life-cycle assessment frameworks: A review of criteria and indicators proposed to assess social and socioeconomic impacts. *The International Journal of Life Cycle Assessment*, *23*(4), 904–920. https://doi.org/10.1007/s11367-017-1336-5

Tietge, U., Mock, P., Lutsey, N., & Campestrini, A. (2016). *Comparison of leading electric vehicle policy and deployment in Europe* (p. 88) [White paper]. International Council for Clean Transportation. https://theicct.org/sites/default/files/publications/ICCT_EVpolicies-Europe-201605.pdf

Tseng, H.-K., Wu, J. S., & Liu, X. (2013). Affordability of electric vehicles for a sustainable transport system: An economic and environmental analysis. *Energy Policy*, *61*, 441–447. https://doi.org/10.1016/j.enpol.2013.06.026

Turnbull, P. (2013). *Promoting the employment of women in the transport sector obstacles and policy options* (Working Paper No. 298; p. 57). International Labour Organization (ILO). /docman/rosasec/efe474/16711.pdf

Le règlement général sur la protection des données—RGPD | CNIL, no. Règlement (UE) 2016/679 du Parlement européen et du Conseil du 27 avril 2016, relatif à la protection des personnes physiques à l'égard du traitement des données à caractère personnel et à la libre circulation de ces données, et abrogeant la directive 95/46/CE (règlement général sur la protection des données). (2018). https://www.cnil.fr/fr/reglement-europeen-protection-donnees#

UNEP. (2018). *Shout it Out: Communicating Products' Social Impacts—A white paper of the one planet network consumer information programme*.

http://www.oneplanetnetwork.org/sites/default/files/white_paper_-_communicating_products_social_impacts_ci-scp_2018.pdf

UNEP. (2020). *Guidelines for Social Life Cycle Assessment of Products and Organizations* (C. Benoît Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A. Lehmann, M. Finkbeiner, & G. Arcesse, Eds.). United Nations Environment Programme (UNEP). https://www.lifecycleinitiative.org/wp-content/uploads/2020/12/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-sml.pdf

Walle, M. (2001). *Safety & health in small-scale surface mines, a handbook*. International Labour Office. https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---sector/documents/publication/wcms_162738.pdf

Werker, J., Wulf, C., Zapp, P., Schreiber, A., & Marx, J. (2019). Social LCA for rare earth NdFeB permanent magnets. *Sustainable Production and Consumption*, *19*, 257–269. https://doi.org/10.1016/j.spc.2019.07.006

World Bank. (2006). *Social Analysis in Transport Projects: Guidelines for Incorporating Social Dimensions into Bank-Supported Projects* (p. 54). Wold Bank—Social Development Department. https://www.ssatp.org/sites/ssatp/files/publications/HTML/Gender-RG/Source%20%20documents/Tool%20Kits%20&%20Guides/Social%20Analysis/SA_Transport_wb.pdf

World Bank. (2010). *Social development and infrastructure—Making Transport Work for Women and Men Tools for Task Teams* (No. 68,750). Wold Bank—Social Development Department. https://openknowledge.worldbank.org/bitstream/handle/10986/12555/687500ESW0P1100ng0Transport0WorkFor.pdf?sequence=1&isAllowed=y

World Bank. (2015). *The Next Step for Transport in the SDGs: Devising the Right Indicators Shaping Transport's SDG Impact* [Text/HTML]. World Bank. https://www.worldbank.org/en/topic/transport/brief/the-next-step-for-transport-in-the-sdgs-devising-the-right-indicators-shaping-transports-sdg-impact

World Bank. (2020). *Violence Against Women and Girls in Public Transport: Policy Recommendations for Mexico City*. World Bank,. https://openknowledge.worldbank.org/bitstream/handle/10986/35015/Violence-Against-Women-and-Girls-in-Public-Transport-Policy-Recommendations-for-Mexico-City.pdf?sequence=1&isAllowed=y

Zamagni, A., Pesonen, H.-L., & Swarr, T. (2013). From LCA to Life Cycle Sustainability Assessment: Concept, practice and future directions. *The International Journal of Life Cycle Assessment*, *18*(9), 1637—1641. https://doi.org/10.1007/s11367-013-0648-3

Zambrano-Gutiérrez, J. C., Nicholson-Crotty, S., Carley, S., & Siddiki, S. (2018). The Role of Public Policy in Technology Diffusion: The Case of Plug-in Electric Vehicles. *Environmental Science & Technology*, *52*(19), 10914–10922. https://doi.org/10.1021/acs.est.8b01149

Zambre, A. (2015). *Stakeholder's perspectives on integrating sustainability in project management* [Dublin Business School]. https://esource.dbs.ie/handle/10788/2838

Zanchi, L., Delogu, M., Zamagni, A., & Pierini, M. (2018). Analysis of the main elements affecting social LCA applications: Challenges for the automotive sector. *The International Journal of Life Cycle Assessment*, *23*(3), 519—535. https://doi.org/10.1007/s11367-016-1176-8

Zanchi, L., Zamagni, A., Maltese, S., Riccomagno, R., & Delogu, M. (2020). Social Assessment in the Design Phase of Automotive Component Using the Product Social Impact Assessment Method. In M. Traverso, L. Petti, & A. Zamagni (Eds.), *Perspectives on Social LCA: Contributions from the 6th International Conference* (pp. 105–117). Springer International Publishing. https://doi.org/10.1007/978-3-030-01508-4_10

Zhang, A., Moffat, K., Lacey, J., Wang, J., González, R., Uribe, K., Cui, L., & Dai, Y. (2015). Understanding the social licence to operate of mining at the national scale: A comparative study of Australia, China and Chile. *Journal of Cleaner Production*, *108*, 1063–1072. https://doi.org/10.1016/j.jclepro.2015.07.097

Zimmer, K., Fröhling, M., Breun, P., & Schultmann, F. (2017). Assessing social risks of global supply chains: A quantitative analytical approach and its application to supplier selection in the German automotive industry. *Journal of Cleaner Production*, *149*, 96–109. https://doi.org/10.1016/j.jclepro.2017.02.041

Appendix 4

Survey 1 (was addressed to users)

List of questions: 7 questions

1st part: Social and socio-economic issues related to users (passengers) in mobility

1- I am mainly user of:

a. Personal transportation
b. Public transportation
c. Shared transportation
d. Combination of personal and collective
e. Combination of shared and Public
f. Combination of shared and personal

2- Public transportation: What are the social and socio-economic issues that you consider critical concerning this transportation mode?

3- Personal transportation: What are the social and socio-economic issues that you consider critical concerning this transportation mode?

4- Shared transportation: What are the social and socio-economic issues that you consider critical concerning this transportation mode?

5- In the context of an electric mobility transition, what would be the social and socio-economic issues that you are most concerned about?

a. Transparency
b. Health
c. Consumer privacy
d. Performance of the communication System
e. Safety (accidents, insecurity feeling, aggression, and harassment)
f. End of life responsibility
g. Availability and interoperability of infrastructures
h. Accessibility and affordability
i. Feedback mechanism

6- Do you have any comments or other suggestions for social and economic issues that have not been identified?

2nd part: Social and socio-economic issues related to workers (question 7) and local communities (question 8) for which users are concerned.

According to you, what is the order of importance of the information provided by manufacturers on the social and socio-economic issues associated with workers in the production phase (outside Europe)?

a. Health and safety of workers

    b. Child labor
    c. Forced labor
    d. Gender equity
    e. Working hours
    f. Freedom of association and collective bargaining
    g. Fair salary
    h. Equal opportunities/discrimination
    i. Social benefits/social security

7- **According to you, what is the order of importance of the information provided by the manufacturers on the social and socio-economic issues associated with the local communities in the production phase (outside Europe)?**
    a. Local employment
    b. Delocalization and migration
    c. Safe and healthy living conditions
    d. Access to immaterial resources
    e. Access to material resources
    f. Community engagement

Survey 2 (was addressed to worker unions)
List of questions: 7 questions

1- **Which category of workers do you represent?**
    a. Auto workers' unions—manufacturing, recycling, repair
    b. Urban Transport Unions
    c. VTC Drivers' Unions

2- **How would you rate the following social and socio-economic issues for your category of workers?**
Matrix performance levels (very low, low, positive, very positive, I don't know)/Social and socio-economic issues

3- **In which order of priority do you attribute the social and socio-economic issues (positive or negative) associated with your category of workers?**
    a. Health and safety of workers
    b. Child labor
    c. Forced labor
    d. Gender equity

e. Working hours
f. Freedom of association and collective bargaining
g. Fair salary
h. Equal opportunities/discrimination
i. Social benefits/social security

4- As part of the shift to electric mobility, is/will your category of worker be directly affected?

a. Yes
b. No

5- If yes in question (4):

6- In your opinion, which type of mobility (electric or conventional) presents the highest risk to your category of workers with regard to each of the following issues?

a. Health and safety of workers
b. Child labor
c. Forced labor
d. Gender equity
e. Working hours
f. Freedom of association and collective bargaining
g. Fair salary
h. Equal opportunities/discrimination
i. Social benefits/social security

7- Do you have any comments or other suggestions for social and economic issues that have not been identified?

Survey 3: Industrial, academic, and public actors — 11 questions and 5 parts corresponding to the five stakeholder categories

1- Which category of actors do you represent?

a. Industrial actors
b. Public actors
c. Academic actors

1st part: social and socio-economic issues related to users in mobility

2- **According to you, what are the most significant social and socio-economic issues associated with users to consider for the development of sustainable mobility?** *Please move the thumbnails according to the order of preference/importance you assign to each of the following issues*

3- Users: how do you compare the importance of these issues depending on the type of mobility (electric or conventional)?

a. Transparency
b. Health
c. Consumer privacy
d. Performance of the communication System
e. Safety (accidents, insecurity feeling, aggression, and harassment)
f. End of life responsibility
g. Availability and interoperability of infrastructures
h. Accessibility and affordability
i. Feedback mechanism

2nd part: social and socio-economic issues related to workers

4- **According to you, what are the most significant social and socio-economic issues associated with workers in the extraction, production and transport phases?** *Please move the thumbnails according to the order of preference/importance you assign to each of the following issues*

5- **According to you, what are the most significant social and socio-economic issues associated with workers in the use phase—drivers, infrastructure workers, service managers, etc.? (France)?** *Please move the thumbnails according to the order of preference/importance you assign to each of the following issues*

6- Workers: how do you compare the importance of these issues depending on the type of mobility (electric or conventional)?

a. Health and safety of workers
b. Child labor
c. Forced labor
d. Gender equity
e. Working hours
f. Freedom of association and collective bargaining
g. Fair salary
h. Equal opportunities/discrimination
i. Social benefits/social security

3rd part: social and socio-economic issues related to local communities

7- **What is the order of importance you attribute to the social and socio-economic issues associated with local communities (extraction-manufacturing phase and end of life)?** *Please move the thumbnails according to the order of preference/importance you assign to each of the following issues*

8- What do you think are the most significant social and socio-economic issues for local communities to consider when developing urban mobility plans (France)? *Please move the thumbnails according to the order of preference/importance you assign to each of the following issues*

9- Local communities: how do you compare the importance of these issues depending on the type of mobility (electric or conventional)?

a. Local employment
b. Delocalization and migration
c. Safe and healthy living conditions
d. Access to immaterial resources
e. Access to material resources
f. Community engagement

4th part: social and socio-economic issues related to value chain actors

10- What is the order of priority you assign to the social and socio-economic issues associated with the value chain actors? *Please move the thumbnails according to the order of preference/importance you assign to each of the following issues*

11- Value chain actors: how do you compare the importance of these issues according to the type of mobility (electric or conventional)?

   a. Promotion of social responsibility
   b. Fair competition
   c. Supplier relationships
   d. Respect of intellectual property rights

5th part: social and socio-economic issues for society

12- **What are the most significant social and socio-economic issues for the development of sustainable electric mobility services?** *Please move the thumbnails according to the order of preference/importance you assign to each of the following issues*

13- **Society: how do you compare the importance of these issues according to the type of mobility (electric or conventional)?**
   a. Corruption
   b. Contribution to socio-economic development
   c. Prevention and mitigation of armed conflicts
   d. Technology development

Chapter V: Life Cycle Costing: a systematic approach for an economic evaluation of electric mobility scenarios

Summary (V)

The aim of this chapter is to assess the economic dimension through life cycle costing (LCC) of three electric mobility scenarios by analyzing both transportation technologies and mobility services.

The chapter starts by introducing in **section 2** the main elements commonly introduced by LCC studies. In **section 3**, a literature review is conducted, covering a large scope of mobility scenarios: transportation systems, infrastructures, and the main transportation components. The main limitations related to the methodological development of LCC are highlighted, together with the main challenges linked to its implementation within a sustainability framework. **Section 4** sets up the key stages for conducting a conventional LCC for mobility scenarios in compliance with ISO standards for LCA. Four phases are identified enabling the definition of a core set of elements to be covered within the economic assessment of mobility scenarios. **Section 5** entails the application of conventional LCC to the considered mobility scenarios which complies with the proposed systematic approach. A focus is made on the users' perspective, in accordance with the objective of this thesis, to analyze the cost effectiveness of the three scenarios. Hence, the Life Cycle Costs Assessment (phase 3) is conducted both for (i) the analysis of vehicle technologies and (ii) the analysis of mobility services.

The obtained result from this chapter is to be used in chapter 6 conjointly with those obtained from the analysis of the environmental and social impacts within LCSA framework proposed in this thesis.

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1. Introduction

Life Cycle Costing (LCC) is commonly recognized as a methodology that enables comparative cost assessments for products or services throughout their life cycle. It can be used for analyzing both investment costs and future operational costs by predicting potential infrastructure costs related to a massive development of electric mobility for example (Schroeder & Traber, 2012). LCC can help decision makers to identify key pathways to lower the manufacturing and deployment costs through a better understanding of cost drivers (Gallagher & Nelson, 2014). Figure 46 illustrates the key elements that are introduced in LCC studies and are explained in the paragraphs below.

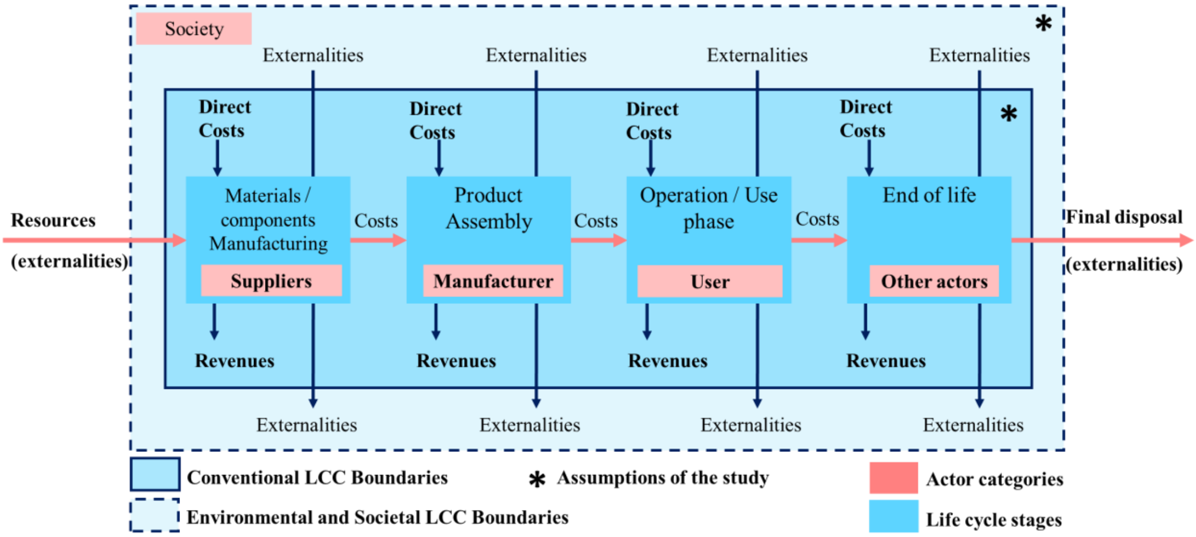

Figure 46 Mapping LCC boundaries, the main parameters, cost categories, and the interested parties (adapted from Hunkeler 2008 and Neugebauer 2016)

- **Costs vs. externalities:**

LCC can address both direct costs and externalities, namely environmental and societal costs. Direct costs, as represented in figure 46, can occur from the manufacturing stage, i.e., materials extraction, components manufacturing and vehicle assembly, or costs from the use phase related to the operation phase, i.e., vehicle traction energy, road and infrastructure and costs incurred by the final disposal of the transportation system.

Externalities represent the social and environmental costs for damages that are likely to occur throughout the life cycle of transportation systems. For instance, the use of fossil energy sources for the operation of the vehicle can be translated into substantial public health issues linked to noise, air quality damages, climate change. The treatment of these effects can be very expensive for the public authorities.

- **LCC boundaries:**

Depending on the objective of the study, the investigated cost categories can include only direct costs or both direct costs and externalities. Thus, three LCC boundaries are distinguished in the literature, namely, Conventional LCC, Environmental LCC and Societal LCC (Hunkeler et al., 2008; Neugebauer et al., 2016). Conventional LCC analyzes direct costs while environmental and societal LCC address respectively environmental and social externalities.

- **Categories of actors**

The economic assessment of transportation systems can be performed in different ways, depending on the investigated life cycle stages. In fact, the generated costs and externalities are supported by different actors of the society. As illustrated in figure 46., suppliers and manufacturers face continuously increasing society's expectations that require constantly improving technological performances and quality of the products they provide to market, thus, involving higher investments costs. LCC can be used to support the design of products and services by selecting most cost-effective technologies, materials, and components, but also to anticipate the return on investment by calculating the total cost of production and the revenues. Policymakers and local authorities can use LCC to choose more economically viable mobility scenarios within the current fleet electrification and predict the future costs that are associated to the development of charging infrastructures.

The third category of actors that can be distinguished are the users of vehicle technologies and mobility services. This category supports the costs incurring from the ownership of the vehicle, from the purchase to the final disposal. LCC can be used in this case to analyze the costs of ownership and, thus, inform the users in their purchase decision and guide them to convert their mobility choices into more sustainable ones (Moon & Lee, 2019).

A broad range of techniques are used to address the economic performance of mobility scenarios through LCC. However, these are targeting different scopes, cost categories and actors' perspectives. To analyze this issue in depth and to identify the most suitable LCC technique to be used in the current thesis a literature review was conducted. This latter is presented in section 3 for the automotive sector with a focus on electric vehicles and mobility services.

2. Life Cycle Costing for mobility scenarios: State of the art

2.1. A literature review of LCC studies addressing mobility-related costs

In this thesis, an analysis of the existing LCC studies is performed. The literature review comprises 26 scientific publications addressing the assessment of costs in the automotive industry, presented in Table 13. The analysis of the identified studies is conducted based on their goal and scope, the used LCC techniques, together with the considered actor perspective, cost categories and their related indicators.

The review summarized in Table 1 highlights three main life cycle stages for which the analysis was performed:

i) Manufacturing-related costs, which are generally assessed from the organization perspective (i.e., manufacturers, designers of products and services).

ii) Operating costs that address users-related costs incurred from the ownership of the vehicle or costs for decision-makers perspective in the case of public transportation.

iii) End of life costs that address the costs related to the final disposal of the vehicles or automotive components.

Among the 26 studies, only five addressed the manufacturing stage (Gallagher & Nelson, 2014; G.R. van Aalst, 2016; Shi et al., 2019), two targeted the end of life (Madlener & Kirmas, 2017), while most studies only focused on the operation of vehicles. The manufacturing costs include capital costs, material and energy costs, transport costs and labor costs. The limited number of LCC studies dealing with this costs category can be explained by the fact that such studies usually require manufacturers data which sometimes can include sensitive information, i.e., labor costs. In fact, labor costs are generally computed based on a percentage of the price rather than direct collected data. The used value, generally ranging from 10 to 15% for passenger vehicles (Ayodele & Mustapa, 2020), is hence, very uncertain as it depends on the location of the production activity and the organization itself.

The operating costs are most of the time calculated through Total Cost of Ownership (TCO) which considers every cost associated to the use of the vehicle from a user's perspective. Several studies have used this technique to inform users' purchase decisions by including all the direct and indirect costs from the ownership of the vehicles (K. Lebeau, Lebeau, Macharis, & Mierlo, 2013; Dumortier et al., 2015; Moon & Lee, 2019). This entails calculation of costs from the vehicles' purchase, maintenance, fuel and/or electricity use, insurance, taxation, etc. All studies that investigated public transportation costs focused on acquisition and operation costs to support investments decision-making and analyzed the cost effectiveness of electric buses compared to conventional ones.

Costs that are associated with the end of life of the vehicles were poorly addressed in LCC studies and rather were addressed separately. Madlener & Kirmas (2017) analyzed the economic profitability and viability of electric vehicles' batteries in the case of a second application to energy storage.

In accordance with Hunkeler et al. (2008) model, several studies implemented a conventional LCC by calculating the direct costs while others aimed at addressing the environmental and societal costs. De Clerck et al. (2018) used the TCO as a basis for calculating the costs supported by the society, namely total external costs from the environmental and social damages, i.e., climate change, air pollution, noise, accidents, congestion. Such technique can be overlapping with the environmental and social LCC which address the same cost categories. Other studies integrated the willingness to pay to LCA to enable the calculation of external costs (Istamto et al., 2014; Kochhan & Hörner, 2015; Shi et al., 2019). For example, Istamto et al. (2014) analyzed the willingness to pay to avoid health risks from road traffic from air pollution and noise.

In an attempt to extend the scope of LCC from a direct costs' calculation to the analysis of economic indicators, several studies added other economic indicators together with the conventional LCC ones, i.e., value added, net present value, profitability, viability, benefits, etc. These additional indicators are in accordance with the LCC model proposed by Moreau & Weidema (2015) which integrated the value added to LCC. Manzo & Salling (2016) integrated a cost-benefit analysis to the environmental LCA of transport infrastructures and vehicles. Such analysis was performed by converting the environmental impacts into monetary flows to enable their accounting in transportation project costs. However, the covered cost categories were not addressed with a life cycle perspective. Thoft-Christensen (2012) used the life cycle cost-benefit analysis to calculate the direct operation costs and benefits related to different vehicle technologies. Delogu et al., (2018) analyzed the economic viability of lightweight automotive components by comparing production costs with cost savings during the use phase.

Within Life Cycle Sustainability Assessment (LCSA) – based on LCSA literature review in chapter 2 – most reviewed studies accounted for the direct cost categories. On the other hand, these studies did not address LCC from a methodological point of view to ensure its coherence with the overall LCSA framework. In fact, the integration of LCC to LCSA involves the development of characterization models of the economic sustainability indicators which can stand for the impact assessment phase (Neugebauer et al., 2016). An example of such characterization models was developed by Neugebauer et al. (2016), who selected profitability as an economic impact category enabling an impact pathway assessment of the economic sustainability of products and services. Profitability and viability indicators were also analyzed by Madlener & Kirmas (2017) study but not integrated to a life cycle assessment approach. LCSA can make use in the future of such economic models to expand the assessment scope to non-monetary economic aspects.

Tarne et al. (2019) integrated the added value for consumers through the introduction of product sustainability budget to ensure the cost effectiveness within LCSA and improve the decision-making process. Moreover, in another study targeting automotive components, Tarne, Lehmann, & Finkbeiner (2019) calculated manufacturing costs to enable the comparison of different scenarios from the designer’s perspective.

In a study by Neugebauer et al. (2016) introduced an economic life cycle assessment to go beyond a simple compilation of cost categories and analyze the economic impact of products and services according to a cause-effect chain as it is the case in LCA. Stark et al. (2017) performed such economic life cycle assessment within LCSA by considering the value added for the manufacturer through the calculation of three cost categories, i.e., materials costs, operating costs (by means of labor costs) and the income from sold products.

Onat et al., (2019) performed a conventional LCC by considering users-related costs incurred over the operation of the vehicles. Such study used economic parameters such as interest rates, inflation rate, and vehicle depreciation to perform the analysis, yet no economic impact assessment was performed.

Table 13 literature review of LCC studies with a focus on the technique used and the indicators calculated in the automotive sector by covering different scopes, i.e., vehicles and infrastructure and different perspectives, i.e., users, society and designers supported costs, NA: not available in the study.

Ref	**Location**	**Technique**	**LCC boundaries**		**Goal**	**Scope**	**Actors' Perspective & Life cycle Stage**	**Cost categories and indicators**
			C- LCC	E-LCC S-LCC				
1. (Thoft-Christensen, 2012)	Denmark	Life Cycle Cost-benefit analysis	X		Analysis of costs and benefits	Transportation infrastructures	Users **Operation**	**Costs** **Benefits**
2. (Manzo & Salling, 2016)	Denmark	Cost-benefit analysis		X	Integrating LCA into cost-benefit analysis through monetarization of environmental impacts	Transport projects: infrastructures and vehicles	Decision-makers **Operation**	Net Present Value (NPV) Benefit Cost Ratio Internal Rate of return
3. (Hallmark & Sperry, 2012)	USA	Conventional LCC – Operating costs	X		Comparative costs assessment of two buses technologies	Hybrid buses & conventional buses	Decision-makers **Operation**	**Fuel cost** (including Fuel Economy) **Electrical cost** **Replacement costs** **Maintenance costs**
4. (K. Lebeau, Lebeau, Macharis, & Mierlo, 2013)	Brussels	LCC – Total Costs of Ownership	X		Comparative costs assessment of various vehicles segments from the consumer's perspective	Passenger vehicles: small city cars (14 segments), medium cars (19 segments) and premium cars (12 segments)	Users / consumer-oriented costs **Operation**	Periodic costs Present Value of the one-time and the recurring costs **Costs per km**
5. (Lajunen, 2014)	Finland	Cost-benefit analysis by integrating LCC	X		Costs comparison through LCC	Five different segments for hybrid and electric city buses in fleet operation – Conventional bus	Decision makers – **Operation**	Capital costs (purchase) Operating costs, Costs for energy storage system replacements.
6. (Gallagher & Nelson, 2014)	USA	LCC-Manufacturing costs	X		Cost drivers for EV batteries and costs	Lithium-ion (Li-ion) batteries	Designers **Production**	Material costs Capital costs

						comparison for different batteries chemistries			Additional investment costs and expenses (launch costs and working capital)
7.	**(Freire & Marques, 2012)**	NA	LCC - Equivalent annual cost (CAE) –	X		Cost analysis through LCC and	Vehicle technologies, compact and subcompact passenger cars	Decision-makers **Production and Operation**	**Acquisition cost** of vehicles and residual value (interest rate 5 & 10 years) **Operation costs** (Price of energy for a specific year)
8.	**(Wong et al., 2010)**	Singapore	Societal LCC and Consumer LCC		X	Analysis of upfront, operation and external costs of cars	Electric and conventional vehicles	Societal and consumer-oriented costs **Operation**	**Upfront costs** (Open market Value, Excise duty, Goods and services tax, Certification of entitlement fee, Registration fee, green vehicle rebate scheme) **Operation costs** (electronic road pricing system) **External costs** (environmental externalities)
9.	**(Sen et al., 2017)**	USA	Conventional LCC – Hybrid IO-LCA	X		Comparative costs assessment of conventional and alternative vehicles	Heavy-duty trucks 7 different powertrains (CNG, biodiesel, diesel, hybrid mild, hybrid full, BEV-270kWh – 400kWh)	Decision-makers **Manufacturing** and **Operation**	**Manufacturing costs** **Infrastructures costs** **Operation costs** (fuel, battery replacement, tailpipe, etc.) Air pollution externalities (exhaust emissions)
10.	**(Hao et al., 2017)**	China	Cost-effectiveness	X		Comparison of Cost-effectiveness analysis through LCC	Hybrid electric vehicles and battery electric vehicles	Decision-makers **Operation**	**Vehicle and battery costs** **Maintenance costs** **Energy costs**
11.	**(Moon & Lee, 2019)**	Korea	Total cost of ownership (TCO)	X		Develop a consumer-based optimal electric vehicle investment model using TCO	Electric and conventional vehicles	Consumers **Operation**	**Ownership costs** (purchase costs, resale price, fuel costs, insurance, costs, maintenance and repair cost, taxes, subsidy)

12. (Mitropoulos et al., 2017)	USA	Total Cost of Ownership (TCO)		X	Cost (direct and indirect) analysis of the vehicle life cycle on consumer and society	Three different vehicle types and tradeoffs	Decision makers (sustainable transportation planning) **Operation**	**Direct costs** (manufacturer suggested retail price, shipping cost -based on average sales tax rate 6%-) **Indirect / External costs** (health damage through air pollution, loss of productivity through loss of time of users)
13. (Palmer et al., 2018)	UK, US, Japan	Total Cost of Ownership	X		Comparative costs assessment temporal (1996-2017) and geographical analysis	Powertrains, Electric, hybrid, petrol, and diesel	Users / Decision-makers **Operation**	Initial vehicle costs and subsidies Fuel costs Maintenance and insurance costs Vehicle tax
14. (Dumortier et al., 2015)	NA	Total Cost of Ownership	X		The role of TCO in supporting users towards more informed purchase decision	Gasoline, conventional hybrid, plug-in hybrid, battery electric vehicles	Users **Operation**	Fuel economy – savings 5 years-based calculation – **Operation cost** (purchase, maintenance, fuel, insurance, registration costs – tax rate 6%)
15. (G.R. van Aalst, 2016)	NA	Total Cost of Ownership	X		Development of LCC model for the automotive sector	Conventional and electric vehicles	Users and designers	**TCO-Acquisition** (materials, labor, assembly, costs) **TCO-Ownership** (purchase, maintenance, fuel consumption, insurance)
16. (Kochhan & Hörner, 2015)	Singapore	Costs and Willingness to pay		X	Parameter based model to analyze the differences between the costs of electric cars and users' willingness to pay	Electric vehicles	Users **Operation**	Influence of parameters on the Willingness to Pay

17. (Gert Berckmans et al., 2017)	NA	Manufacturing costs and learning curves	X	Costs analysis and projections for electric vehicle batteries	Electric vehicles for different batteries technologies	Designers **Manufacturing**	**Manufacturing costs** (material cost, energy cost, labor cost, overhead and total cost of goods sold) **Profit margin** (manufacturer profit margin, retailer profit margin, sales price)
18. (Schroeder & Traber, 2012)	Germany	Operation costs and return on investment	X	Economic evaluation through estimation of contribution margins and investment cost	Charging infrastructures (fast chargers for EV)	Decision makers (investment) Operation	**Capital expenditure** (CAPEX) **Operational expenditure**s (OPEX) **Return on investment** (annual net profit/levelized investment cost)
19. (Macharis et al., 2013)	Belgium	Total Cost of Ownership	X	Comparative cost assessment through TCO model – competitiveness of different technologies	Logistics: 8 EV and7 ICEV	Decision-makers Operation	**Ownership costs (**present value of one-time and the recurring costs) **Costs per km** (PV on total VLT)
20. (Raustad, 2017)	USA	LCC-Operation costs and economic factors analysis	X	Development of an LCC model for automotive vehicles to account for the operation costs and to evaluate photovoltaics as a power option	Passenger vehicle: electric vehicles (ICEV, BEV, HEV, PHEV) and power option with photovoltaics	Users	**Ownership costs** (purchase, maintenance, fuel consumption, insurance, etc.) **Economic factors** (inflation rate, discount, fuel escalation, battery degradation)
21. (Madlener & Kirmas, 2017)	Germany	Economic viability & profitability	X	Analysis of profitability and viability through a techno-economic simulation model	Second use batteries from electric vehicles With three different scenarios (increase electricity price, upward and downward deviation)	Decision-making (homeowners, manufacturers & policymakers) **End of life**	**Input parameters** (PV systems costs, electricity storage cost, electricity prices) **Economic model** (Cash flow calculation, Revenue calculation, Net present value)

22.	**(De Clerck et al., 2018)**	Belgium	Total cost for society - Societal LCC		X	Analysis of total external costs (TCE) supported by the society through a persona-based analysis	Three passenger car segments (EV and ICEV) with 6 different drivers' profiles	Society **Operation**	**TCO** (present value, costs per km, initial purchase costs, depreciation tax, registration, charging fuel, infrastructures, insurance, road tax) **TCE** (climate change costs, air pollution costs, noise, accidents, congestion)
23.	**(Potkany et al., 2018)**	Europe	LCC – Acquisition and operating costs	X		Comparative costs assessment to support decision-making	Electric and conventional buses	Decision makers (investments) Acquisition & **Operation**	**Acquisition cost** (discount rate, net Book Value) **Operating costs** (fuel/electricity costs, maintenance, tires, discount, RBF time factor to net present value)
24.	**(IFP Energies Nouvelles, 2018)**	France	TCO	X		Comparative costs assessment through TCO	Electric and conventional vehicles: passenger vehicles, public transportation, heavy-duty trucks	Investment Decision-maker support **Operation**	**Acquisition costs** **Operation costs** **TCO:** Calculation of costs per km
25.	**(Cimerdean et al., 2019)**	Austria	LCC – conventional & environmental costs	X	X	Comparative costs assessment based on different driving cycles (energy profiles)	Driving cycles (M.U., JC-08, WTVC, HYZEM, ARTEMIS)	Users **Operation**	**Operating costs** (energy costs) **External costs** (CO_2, NO_x, HC, PM emissions)
26.	**(Shi et al., 2019)**	China	LCC-conventional, environmental, and possible costs	X	X	Combined assessment of conventional and environmental costs through LCA method and social willingness to pay	Mechanical product: heavy-duty truck	Designers' Mechanical product **manufacturing**	**Conventional costs** (materials costs, labor, capital, transport, energy) **Environmental costs** (social willingness to pay) **Possible costs (**future damage costs)

2.2. The main findings from the literature and challenges to overcome considering mobility scenarios

The conducted literature review reveals several limitations and challenges that can be drawn as the following:

a. LCC studies for mobility scenarios do not systematically overlay with the ISO standards, unless they are conducted simultaneously to an environmental LCA (Schwab Castella et al., 2009; Shi et al., 2019). Hence, in this case the cost assessment is conducted as a supplementary step but not individually addressed from a methodological point of view.
b. There is a strong need for the standardization of LCC to bring together the different used approaches, especially within LCSA framework.
c. The economic impact assessment is still lacking in most LCC studies, which mainly focus on direct costs evaluation due to the lack of coherence with the LCIA recommended steps (i.e., classification, characterization and weighting).
d. Although externalities of transportation systems have been targeted in several studies, impact conversion into monetary values is still subject to a high level of uncertainty and ethical concerns. The methodological development of environmental and social LCC can thus rely on impact pathway analysis as developed by Rabl, Spadaro, et Holland (2014) which enable a more accurate estimation of impacts and damage costs of transport pollution.
e. When the economic assessment is undertaken as part of a sustainability framework in which environmental and social LCA are also conducted, environmental and societal LCC cannot be conducted to avoid a double counting of impacts. In this case, conventional LCC should be selected.
f. Within the analysis of mobility scenarios, studies often target the technologies' level, yet no study has addressed either mobility services through LCC or through LCSA.
g. The life cycle perspective is not fully covered, as most studies focus on the operation of the vehicles through the TCO technique and fail to consider the end-of-life phase
h. mitigation costs associated with modal shift from personal mobility to carpooling or public transportation are not fully addressed, and calculation methods are still in an exploratory stage (Criqui, 2021).

This chapter seeks to tackle some of the above-listed challenges by setting the following two targets

- ✓ **In response to the identified challenges (a), (b) and (c), the current chapter sets up the key steps for the economic assessment of mobility scenarios by adapting ISO standards for environmental LCA to conventional LCC. In view of the objective of this study to serve the proposed LCSA framework, external cost categories are not considered. Hence, challenges (d) and (e) are not addressed, since not applicable given the selected approach.**
- ✓ **To address the challenges (f), (g) and (h), this chapter focuses on the analysis of the cost effectiveness of mobility scenarios from the users' perspective. In fact, an economic assessment**

approach is proposed by conducting both a direct cost calculation of vehicle technologies and also a cost calculation of the mobility services.

3. Towards a coherent LCC approach for mobility scenarios: key steps to be conducted

The current thesis uses prior published studies and scientific publications as a basis to propose the key steps that should be followed to perform a comprehensive Conventional LCC. The following proposed steps are structured according to the four phases for LCA recommended by ISO standards (ISO 14040-44, 2006) and can be adapted to other scenarios. Section 5 presents a practical implementation that complies with the proposed steps for mobility scenarios analyzed within this thesis.

3.1. Phase 1: Goal and scope of the study

1- Goal of the assessment: economic assessment studies can target different goals. For instance, it can be related to the investigation of users' purchase decision over the ownership period, an investment decision for public transportation alternatives comparison, investigation of future infrastructures costs, as well as return on investment and cost projections for automotive materials supply chain (Gert Berckmans et al., 2017) and batteries production, as well as the environmental and social externalities of the product. The goal should also state if the economic assessment is conducted within a larger sustainability evaluation framework, i.e., LCSA.

The scope of the study covers

- **The system boundaries:** following the goal of the study, the assessment should focus on a specific life cycle stage or cover a« cradle to gate » or "cradle to grave" perspective.
- **Actor perspective:** This step defines which perspective (i.e., users, manufacturers, local authorities) is considered for the assessment following the goal of the study defined in step 1.
- **Products or services to be analyzed:** The different technologies analyzed within the study are to be defined, as well as their main characteristics.
- **Techniques of the economic assessment and indicators to be analyzed:** Here, the most adequate technique shall be chosen to perform the economic assessment in a way that can serve the objective of the study. The cost calculation can thus be performed through a Total Cost of Ownership, a Cost-Benefit Analysis, or focus on a direct costs' comparison for a specific stage. The indicators to be used are also to be defined and explained with respect to the objective of the study.
- **LCC boundaries and cost categories:** The study can assess direct cost categories, following a conventional LCC approach, or external cost categories through environmental and/or societal LCC. In case of monetizing the environmental and social impacts, the study should ensure that double counting of impacts is avoided.

- **Assumptions of the study and geographical coverage:** discount rate, vehicle lifetime and/or vehicles ownership period and other specific assumptions in case of regionalization of the calculation model must be carefully selected and transparently presented. This can be performed by integrating local input parameters for the geographical scope of the study, i.e., infrastructures costs, electricity costs, parking, and taxation.
- **Input parameters:** The calculation of cost categories requires the definition of a set of input parameters, i.e., energy consumption, fuel price, electricity price, taxation for fuel use, etc. The identified parameters can be grouped in two categories, namely fixed parameters and variable parameters, which are subject to a change over time.

3.2. Phase 2: Life Cycle Cost Inventory

Following the definition of the main elements previously presented, the second phase of LCC entails data collection in order to perform the evaluation phase. Data collection includes all cost indicators and input parameters defined within the goal and scope and with respect to the system boundaries. As suggested by Windisch, (2014), specific data is essential to ensure the representativeness of the conducted assessment and to account for the utmost uncertainties that may be linked to the analyzed scenarios. To do so, data should account for the specificities of the product market, i.e., current prices in the market for energy, materials, products, etc. and policies in the geographical area of the study. In fact, using the most recent cost information is key to guarantee an up-to-date study reflecting the market trends.

3.3. Phase 3: Life Cycle Cost Assessment

In view of the goal of study, this third phase can be conducted by either following conventional steps entailed in the ISO standards (ISO14040-44, 2006), i.e., classification and characterization, or through a direct cost calculation. For example, Shi et al. (2019) study covers costs classification and costs analysis due to the use of an environmental LCC. In this case, the assessment phase is performed through environmental-impact analysis in the first place and complemented with an additional step for converting the impacts results to monetary value. This can also be the case when using economic sustainability indicators through an impact pathway model, as proposed by Neugebauer et al. (2016). However, when direct costs are analyzed, only a classification step is performed to facilitate the interpretation of results as entailed in this study. No characterization models are therefore needed, as the input and output flows are expressed in same monetary units.

3.4. Phase 4: Life Cycle Costs Interpretation

The purpose of this phase is to explain and analyze the obtained results for the indicators used in the assessment throughout the life cycle stages of the evaluated scenarios. A contribution analysis can, thus, be conducted to identify the most significant sources for costs, i.e., process activities, energy sources, materials, etc. The interpretation of results is expected to determine the cost effectiveness of analyzed products and services and thus support the decision-making process based on the actor perspective considered within the study.

4. Economic assessment of electric mobility scenarios with user's perspective

4.1. Goal and scope of the study for electric mobility scenarios

The goal of the present study is to compare the cost effectiveness of three mobility scenarios namely, personal mobility, public and shared mobility services, with a special focus on electric vehicle alternatives. The analysis is thus performed based on a common functional unit, which is here defined as the transportation of users at a specific duration (in common with the different scenarios) within a geographical are. The analysis is conducted based on a user perspective to enable the definition of most cost-effective mobility solutions during the use phase.

The economic assessment aims to be included within a comprehensive sustainability analysis conducted according to the proposed LCSA framework in this thesis. Hence, the selected scope is limited to a Conventional LCC and does not cover the environmental and social externalities as these are accounted for in the environmental LCA and S-LCA, respectively. In view of the goal of the study, costs evaluation is conducted at two levels. First, personal mobility use case is analyzed by calculating the TCO of different vehicle technologies. In a second level, the costs per kilometer are determined for three mobility services, namely personal, public and shared transportation. To perform the assessment of personal mobility, seven different powertrains are analyzed corresponding to conventional vehicles (ICEV) powered with petrol (ICEV-p) and diesel (ICEV-d) as well as electric vehicles (EV) representing various electrification levels and powertrains, full hybrid (HEV-d and HEV-p) together with Plug-in Hybrid EV (PHEV-d and PHEV-p). The vehicle models derive from those analyzed within the environmental and social dimensions and the driving cycle is defined following the WLTC cycle for urban area.

To perform the costs assessment, a Total Cost of Ownership is conducted as the most suitable technique to analyze the costs supported by the users and to investigate the cost effectiveness of mobility alternatives. An additional step is proposed in complementarity with the TCO model to determine the costs supported by users when using public transportation and carpooling services. The calculation methods and the used indicators are explained in sections 5.3.1 and 5.3.2.

Description of the geographical area of the study:

The scope of this research focuses on the south region of France, at the "Communauté d'Agglomération Sophia Antipolis" (CASA). All input parameters are based on the existing values from 2019. The analyzed travel distance corresponds to a commuting travel from Antibes to Sophia Antipolis, equivalent to 8 km. The available mobility solutions are thus analyzed with respect to the characteristics of the geographical area.

The ownership period considered in this study is 5 years. In fact, the average value of car ownership duration varies generally between 3 and 7 years in France (Franfinance & CSA, 2018). Within TCO calculation, a distinction is to be made between the vehicle lifetime, which can amount to 12 years, and the ownership duration. This issue has been highlighted by Windisch (2014), where most reviewed LCA studies analyzed the TCO based on the vehicle lifetime rather than the ownership period, which can substantially affect the results representativeness. The study entails 4 cost categories, namely acquisition costs, operating costs (energy), maintenance costs and other operating costs (insurance, taxation). These are explained further in the coming sections.

A discount rate of 4.5% is applied, based on CGDD (2017) available data for this region. The average annual traveled distance considered in this study corresponds to 17 000 km in accordance with data used for the analysis of other sustainability dimensions. To enable the comparison of personal mobility scenario with other mobility services, i.e., shared and public transportation services, the same commuting distance is considered, and user-supported costs are determined for this basis. First, the costs are computed for the total distance traveled per year and then are expressed per km to allow the comparison. The used input parameters for the cost's calculation are further explained in section 5.3.2.

4.2. Life Cycle Cost Inventory for electric mobility scenarios

Data was collected for the defined cost categories, namely, acquisition costs, energy-related operation costs, maintenance costs and other operation costs (non-energy related). The required input parameters were also defined to allow the calculation of each cost category below explained.

Within all studies that have been reviewed in section 3, there is a significant divergence in the used approaches to compute the TCO calculation. Even though the goal and scope of the analyses are similar, the cost categories are different. For example, Windisch (2014) distinguished between initial fixed costs (i.e. investment) and continuous use costs. Such model allows increasing the representativeness of the assumptions and input parameters through the introduction of regional specific parameters to TCO calculation model. Lebeau et al. (2013) developed a TCO model that was further adopted by (K. Lebeau et al 2013; Macharis et al., 2013; P. Lebeau, 2016; De Clerck et al., 2018) by focusing on three cost categories, namely acquisition costs, traction energy costs and non-energy costs.

The used TCO model derives from the Clean Fleet project co-funded by the European Commission in 2015. Such tool has been adapted to cover the cost categories and input parameters as illustrated in Figure 47. An aggregation of all costs incurred from the vehicle ownership is performed enabling to compute the TCO as the following:

TCO = Acquisition costs + Operating costs (energy) + Maintenance costs + Other operating costs

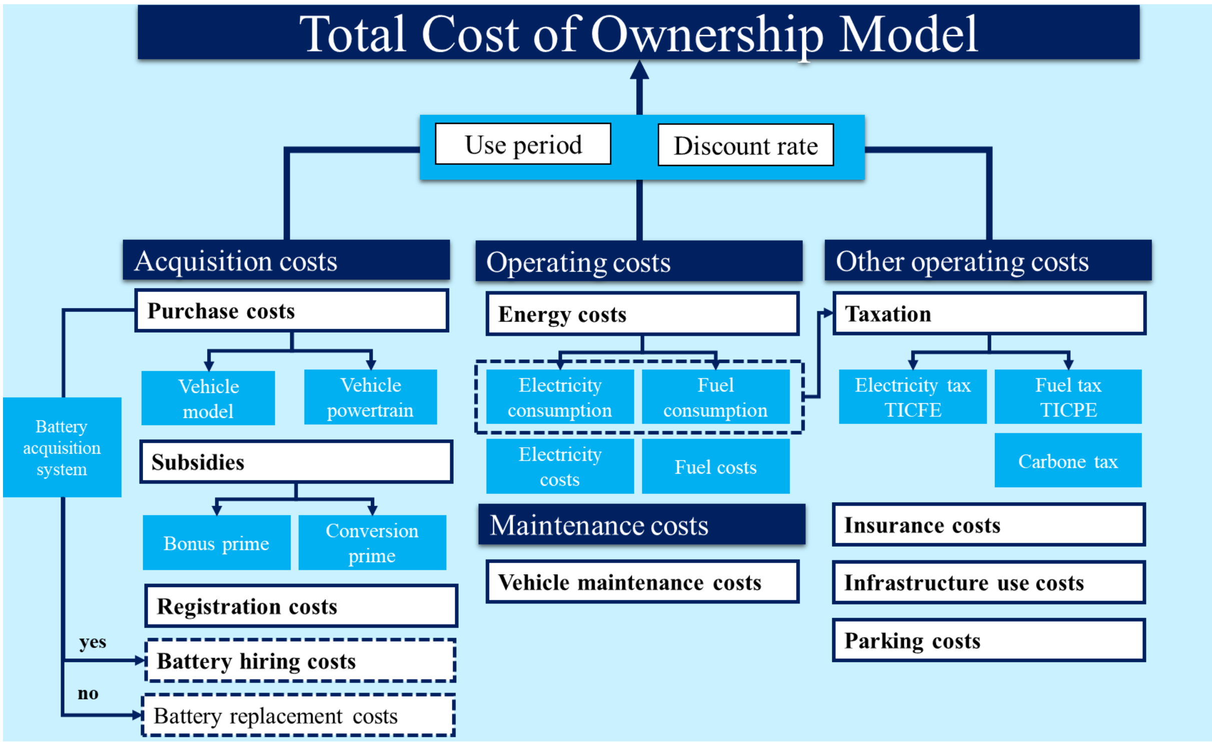

Figure 47 Total Cost of Ownership model adopted within this thesis for personal mobility use scenarios analysis

a. **Acquisition costs:** This cost category comprises all the potential costs for the purchase of the vehicle, its registration tax and/or the specific subsidies depending on the region or country. Both have been set up in the context of the energy transition law and the fleet electrification promoted by the government. Such policy measures can substantially affect the acquisition costs thus, they need to be accounted for within the TCO model.

- **Registration tax:** In France, to enhance the promotion of electric mobility alternatives, the registration costs are 100% exempted in all metropolitan regions except for Bretagne and Centre-Val-de-Loire (50% discount) (MEFR, 2020).On the other hand, registration tax for conventional vehicles was modified in 2020 and since then, it is only applied to vehicles with a CO_2 threshold exceeding 133gCO_2/km (Légifrance 2020).
- **Battery hiring costs:** as illustrated in Figure 47 Total Cost of Ownership model adopted within this thesis for personal mobility use scenarios analysis users can choose whether to include the battery in the vehicle purchase contract or not. In the first case, it is up to them to cover the costs of replacing it at the end of its life. Otherwise, they can choose a battery leasing contract that involves rental costs throughout the ownership period. In this regard, the battery hiring cost depends on the purchase contract. In this study, battery costs are included within initial costs as the battery acquisition makes part of the vehicle purchases contract. Hence, the leasing scenario is not considered. In fact, although the battery ownership was a key factor for

promoting electric vehicles, it appears that since January 2021 Renault ZOE model, which is the most used in France for BEV, includes no battery leasing in the contracts (Lemaur, 2021).

- **Subsidies**: The integration of subsidies calls for gathering specific data on the policy measures underway. In France, two main measures are proposed for the promotion of electric mobility, namely the ecological bonus or penalty (Bonus/Malus) and the conversion bonus. The ecological bonus is paid by the State for the purchase of an electric vehicle (i.e., car, van, 2 or 3 motorized wheels and bicycles) to promote low-carbon mobility alternatives. The conversion bonus (or scrappage bonus) is an aid paid by the State when an old and polluting vehicle is substituted by another one, either new or used, that has lower emissions of pollutants. Since July 2021, the French government has updated the financial incentives provided for low-emission vehicles through the modification of the prerequisites related to the conversion prime and the "Bonus/Malus" incentive, but also reduced the subsidies levels for both BEV and HEV technologies (Légifrance, 2021). Current values in France are presented in table 14. The ecological penalty is calculated according to the rate of CO_2 emissions per kilometer (km) of the vehicle based on a WLTC urban driving cycle. A penalty is applied in the case of vehicle exhaust emissions exceed the threshold of 133gCO_2/km which is not the case for both ICEV-p (petrol powered ICEV) and diesel powered ICEV (ICEV-d)

Table 14 Subsidies in France including Bonus/Malus and conversion primes for BEV, HEV, PHEV and ICEV vehicle technologies

	BEV	HEV-p	PHEV	ICEV-p	ICEV-d
Bonus (€)	6000	1000	1000	0	0
Malus (€)	0	0	0	0	0
Conversion prime (€)	2500	2500	2500	0	0
Total (€)	8500	3500	3500	0	0

b. Operating costs or use costs: This cost category covers the costs related to fuel consumption, either through fossil fuel use (i.e., diesel, petrol) or electricity use. Energy costs are performed based on an urban WLTC driving cycle in the same way as environmental impacts, according to the driving profile and the consumed energy. The input parameters used for energy costs calculation are the energy consumption of the vehicle (kWh/km or L/km) and the fuel (chemical or electricity) price (€/kWh or €/L) as illustrated in Figure 2.

Clean Fleet tool uses a discount rate for the price of the fuels and electricity and are applied with respect to the vehicle ownership period. The input values (fuel price and energy consumption values are presented in *Table 16*)

c. Maintenance costs: Maintenance costs data have been collected from the information provided by CGDD (2017) for each vehicle technology (c€/km). These costs do not cover the replacement of the battery as this latter has been considered/included within the acquisition costs. *Table 15* presents the cost categories corresponding to maintenance costs but also insurance and taxation that are presented in subsequent paragraphs.

d. Other operating costs: This third cost category includes all other use costs that are likely to occur during the ownership period. These costs can be related to the insurance and infrastructure use costs (Table 15). Taxation, also included within this cost category, is applied in France for both electricity use (TICFE: *"Taxe intérieure de consommation finale d'électricité")* and petrol-based products' use (TICPE: "*Taxe intérieure de consommation sur les produits énergétiques*"). Taxation-related costs are calculated based on a given ownership period, by considering the possible tax levels over that period. Both vehicle ownership period (km) and tax level (€ / L or € / Wh) are used together with the fuel consumption to determine the annual tax value. The Clean Fleet model also integrates the evolution of fuel prices over the defined period of ownership to improve the representativeness of the assessment. The calculated values are available in table 16.

Table 15 Cost categories corresponding to maintenance, insurance and taxation (according to CGDD (2017)

	Maintenance costs		**Other Operating costs**	
	Maintenance c€ /km	Maintenance € /yr	Insurance € / yr	Taxation € /yr
BEV	4,7	804,1	400	65,8
ICEV-d	5,2	892,5	500	120,7
ICEV-p	5,2	892,5	500	149,9
HEV-p	6,3	1071	600	123,9
PHEV-p	6,3	1071	600	13,5

Table 16 Taxation calculation for fuel use, electricity, and petrol-based products (year 2021 and 17 000 km of annual driven distance)

4.3. Life Cycle Costs Assessment for electric mobility scenarios

Fuel Type	**Consumption**		**CO_2 emissions WLTC**		**TICPE**		**TICFE**		**Carbon costs**		**Tax per year**
ICEV-d	4	L/100km	106	gCO_2/km	59,4	c€ /L	0		44,6	€/tCO2	120,76 €
ICEV-p	5,3	L/100km	119	gCO_2/km	66,29	c€ /L	0		44,6	€/tCO2	149,95 €
BEV	0,17	kWh/km	0	gCO_2/km	0	-	22,5	€ / MWh	0	-	65,79 €
HEV-p	4,4	L/100km	98	gCO_2/km	66,29	c€ /L	0		44,6	€/tCO2	123,89 €
PHEV-p	1,2	L/100km	28	gCO_2/km	66,29	c€ /L	0		44,6	€/tCO2	13,52 €

Life Cycle Costs assessment is performed for the three mobility scenarios considered within this thesis. This consists of analyzing five different vehicle powertrains for both electric and conventional vehicles, as well as the mobility services that are considered: personal use, collective use, and shared transportation use. Such assessment is conducted in accordance with the goal of this research to investigate the sustainability of the three mobility scenarios according to a user perspective. Hence, a user-centric approach is herein introduced through two steps of costs evaluation phase: section 5.3.1.

entails the analysis and costs calculation for vehicle technologies through TCO and section 5.3.2. aims at assessing the costs for the three mobility scenarios.

4.3.1. Passenger mobility analysis: a Total Cost of Ownership (TCO) model per vehicle technology

This first section aims at analyzing the costs involved during the vehicle operation through a Total Cost of Ownership Model. The cost calculation through TCO is presented in *Table 17 Input parameters for TCO model calculation within the economic assessment of vehicle technologies, Battery Electric Vehicles (BEV), conventional vehicle powered with petrol (ICEV-p) and diesel (ICEV-d)* for five different technologies corresponding to electric and conventional vehicles. The lease price and battery lease price in gray are not accounted in the model as the vehicle acquisition system includes direct cost purchase for both the vehicle and battery. The TCO is determined per each vehicle technology as well as the cost per km as presented in Table 17.

Table 17 Input parameters for TCO model calculation within the economic assessment of vehicle technologies, Battery Electric Vehicles (BEV), conventional vehicle powered with petrol (ICEV-p) and diesel (ICEV-d)

GENERAL CONDITIONS										
Contract length/period of vehicle ownersh	5	years								
Annual use of a car	12500	years								
Discount rate	4,5	%								
ACQUISITION COSTS										
	Values	Units	Values	Units	Values	Units	Values	Units	Values	Units
Name of bidder/vehicle model	BEV		ICEV-p		ICEV-d		HEV-p		PHEV-p	
Purchase price	32300	€/unit	23000	€/unit	20600	€/unit	23750	€/unit	37600	€/unit
(or) Lease price		€/unit/year		€/unit/year		€/unit/year		€/unit/year		€/unit/year
Costs of Acquisition	32300	€	23000	€	20600	€	23750	€	37600	€
OPERATING COSTS (Energy-related and storage system)										
Type of Fuel	Electricity		Petrol		Diesel		Petrol		Petrol/Electricity	
Fuel consumption per vehicle	17,2	kWh/100k	5,3	l/100km	4	l/100km	4,4	l/100km	1,2	l/100km
Fuel price	0,1558	€/kWh	1,57	€/l	1,41	€/l	1,57	€/l	1,57	€/l
Replacement battery price	169	€/unit		€/unit		€/unit		€/unit		€/unit
Expected lifetime of battery	10	Years		Years		Years		Years		Years
(or) Battery lease price		€/unit/year		€/unit/year		€/unit/year		€/unit/year		€/unit/year
Operating Costs per vehicle	1927,5117	€	5985,172	€	4056,7684	€	4968,822	€	1355,1333	€
MAINTENANCE COSTS										
Estimated annual maintenance costs	804,1	€/unit/year	892,5	€/unit/year	892,5	€/unit/year	1071	€/unit/year	1071	€/unit/year
(or) Annual service agreement		€/unit/year		€/unit/year		€/unit/year		€/unit/year		€/unit/year
Maintenance costs	3529,9803	€	3918,0542	€	3918,0542	€	4701,6651	€	4701,6651	€
OTHER OPERATING COSTS (Taxes, insurance and subsidies)										
Vehicle tax	65,79	€/unit/year	149,96	€/unit/year	120,76	€/unit/year	128,83	€/unit/year	13,85	€/unit/year
Insurance costs	400	€/unit/year	500	€/unit/year	500	€/unit/year	600	€/unit/year	600	€/unit/year
(One off initial subsidy)	8500	€		€		€	3500	€	3500	€
Taxes, insurance and subsidies	-6455,1927	€	2853,3093	€	2725,122	€	-300,45325	€	-805,21278	€

4.3.2. Costs assessment of electric mobility services from a user perspective

Considering the goal of the study which consists of performing costs assessment of both vehicle technologies and mobility services, this section presents a user-centric approach for computing the costs calculation within a mobility service use.

As stated in section 2, the literature review revealed that the comparison of mobility services is still poorly addressed within LCC studies, and few elements were found in the literature. In fact, the assessment is very complex, given the significant number of costs drivers within each specific mobility service investigated. It is also important to note that a significant number of uncertainties may influence/affect the results, due to the variable nature of mobility services. However, to allow a full representation of these costs, the study also analyzes congestion costs, travel lost costs.

To enable a transparent and coherent comparison, a simplified approach is here carried out. The approach focuses on the direct costs supported by users from a mobility service. To do so, it is required to address a specific trip that can be accommodated by the three mobility services. In the present case study, the commuting travel considered is 8 km from Antibes to Sophia-Antipolis.

Personal mobility costs are determined following the TCO model sketched in figure 47. The TCO and cost per km are used to perform the comparison with the other mobility services following equation [2]:

[2]: $$\text{Cost per kilometer for personal mobility } [\frac{€}{\text{km}}] = \frac{\text{TCO } [€]}{\text{Total annual commuting travel distance [km]}}$$

The costs supported by a user in the case of public transportation are computed based on the fees incurred from the purchase of an annual transportation pass. In CASA, the annual price that covers the investigated commuting travel distance amounts to 90 € per year. This value is then divided by the total traveled distance per year to obtain the cost per km, following equation [3]:

[3]: $$\text{Cost per kilometer for public transportation } \left[\frac{€}{\text{km}}\right] = \frac{\text{Total Cost supported by the user per year } [€]}{\text{Total annual commuting travel distance [km]}}$$

Shared mobility-related costs are determined based on generic data for passengers. In fact, carpooling relies on the share of costs between the driver and the passengers. It is important to note that, it is forbidden for the driver to make a profit. The price estimation must therefore be fair and is calculated here based on "Laroueverte" carpooling application which published the cost calculation method for the drivers and passengers and can thus, be expressed as the following equation [4]. It should be noted that the traveled distance can include highway tolls that need to be accounted for within the calculation.

[4]: $$\text{Cost per kilometer for carpooling service } \left[\frac{€}{\text{km}}\right] = \frac{\text{Fuel price } \left[\frac{€}{\text{km}}\right] * \text{Travel distance[km]}}{\text{Total number of passengers per travel}}$$

4.4. Life Cycle Costs Interpretation for electric mobility scenarios

Figure 48 illustrates the results for personal mobility cost calculated according to a user's perspective and assuming a 5-year ownership period. Both the TCO for each vehicle powertrain and the cost per kilometer are determined, as illustrated in figure 48 (a) and (b).

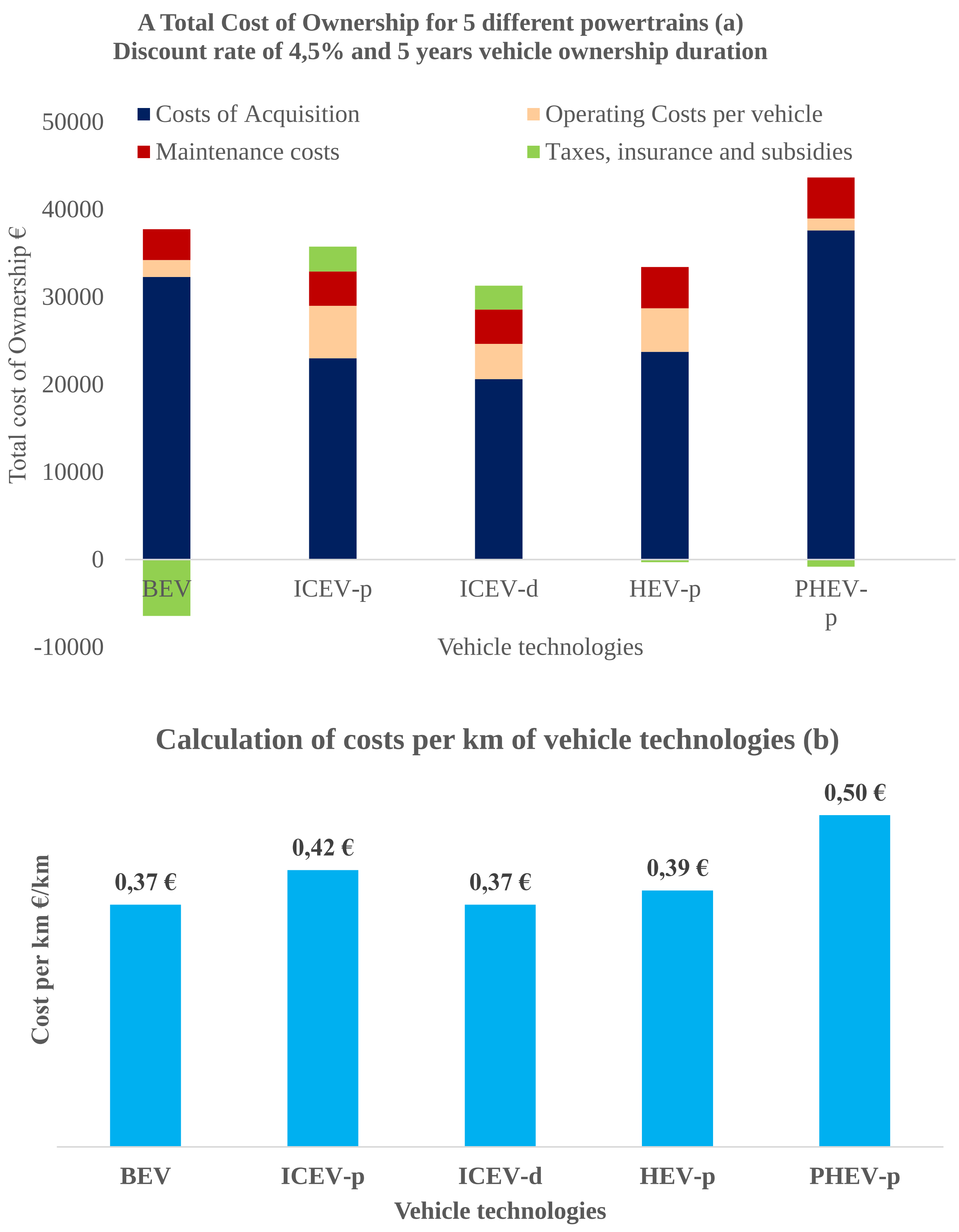

Figure 48 Total Cost of Ownership and costs per km for the evaluated vehicle technologies (personal mobility)

BEV technologies and diesel-powered ICEV-d present the lowest TCO among the different evaluated powertrains. In fact, the BEV although the return in investment is usually expected after 12 years, results demonstrate that within 5 years of ownership the cost is equal to that in case of using diesel-powered ICEV-d technologies. For BEV, the number of subsidies that are attributed in case of its acquisition is a significant factor to reduce performed TCO. For, ICEV-d the fuel consumption (compared to a petrol-powered vehicle ICEV-p) is a determining factor with the acquisition costs.

The highest TCO is obtained for the use of PHEV-p vehicles, mainly associated with the high acquisition costs and the reduced subsidies compared to those of the BEV technologies. Despite a substantial initial investment, particularly due to a purchase subsidy limited to current 1000€, the TCO of the plug-in hybrid vehicle remains close to that of other hybrid vehicles, even with the WLTC procedure which increases the probability of occurrence of cycles involving the combustion engine.

This result can be explained by the assumption of a 5-year ownership period. In contrast, a study from ADEME & IFPEN (2018) demonstrated the economic profitability of BEV technologies after a 12,000-km-ownership duration, which is not accurate, considering the actual real-world values. The obtained results from the current case study are in accordance with Windisch (2014) statement on the influence of the discount rate and ownership period on the computed costs.

Finally, and in view of the expected evolutions in the urban environment, especially regarding, on the one hand, tolls or penalties taxation on polluting vehicles and, on the other hand, parking facilities and other promotion measures for electric vehicles, it seems that the future of the compact urban vehicle is promising for the electric vehicle. Nevertheless, given the current trend to increase the size of the battery to extend the electric vehicle's autonomy, the latter could face strong competition with other hybrid vehicles. In the future, it may strongly compete with HEV solutions (especially PHEV from an environmental impact point of view as demonstrated in Chapter III of this thesis) which offer a much higher range without recharging than the BEV.

Comparison of the three electric mobility scenarios through LCC

Based on the defined calculation methods for costs analysis of mobility services, the obtained results for costs per km according to a user's perspective are illustrated in figure 49 for the three mobility services.

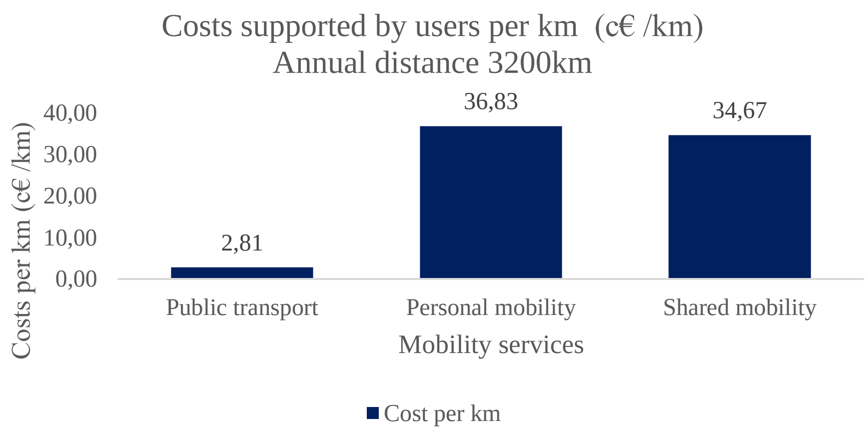

Figure 49 Mobility services analysis; costs calculation per km for the three mobility services in CASA region in 2020; (8 km per commuting travel and 200 days of work)

Public transportation service is by far the most cost-effective mobility service while personal mobility presents the highest costs for users, closely followed by shared mobility.

The results from the comparison of mobility services can be quite controversial, as the cost supported by the user is not the real cost for the development of the transportation solution. In fact, although the users-supported costs in the case of public transportation are very low, the expenditures for public transportation development amounted to 11 billion euros (CGDD, 2021) which cannot be overlooked. It is to note that, the comparison of mobility services can also be conducted with respect to a local authority's perspective in order to support investments decisions and promote the most sustainable alternatives within a specific geographic area. For example, in a study from the French government (France Stratégie), calculation methods were developed to analyze mitigation costs from a modal shift scenario (Criqui, 2021).

However as stated before, accounting for all costs from the same perspective is very complex – if not impossible – and subject to large uncertainties. For these reasons, defining the actor perspective in the goal and scope, as proposed in this study, should enhance the clarity of the intended use of LCC study, e.g., either compare operation costs, material costs, infrastructure costs, etc.

The user-centric approach introduced in this work allowed to focus on the use-related cost, which is coherent with the goal of this thesis to account for the users' perspective.

Shared transportation service is still considered as a niche market and public authorities are initiating debates at both the French and the European level, in order to promote further this mobility service through financial incentives for passengers. In fact, although it is considered a pillar for developing sustainable mobility alternatives, it is still poorly addressed which has also been proved in the literature review conducted in the present chapter.

5. Conclusions

Regarding the settled targets, this chapter explored the existing LCC studies for mobility scenarios and identified the main issues related to the methodology and its practical implementation. A literature review was therefore conducted to investigate the main techniques used to perform LCC, the targeted actors and life cycle stages as well as the cost categories.

This work highlighted the variability of the economic assessment techniques and used them as a lever to progress in the understanding of the economic sustainability dimension. In this regard, the key stages proposed to carry out an economic assessment through LCC are a contribution towards a harmonized framework which is currently missing. To enhance the comparability of LCC studies, the proposed stages comply with ISO recommendations for LCA. This structure may facilitate the apprehension of the common features between LCA approaches.

With respect to the LCSA framework proposed in this thesis and the consideration of users' perspective, this chapter targeted the analysis of both vehicle technologies within a personal mobility use through a TCO model and mobility services through the comparison of the cost effectiveness of the three mobility scenarios. Public transportation showed a better economic performance based on the costs per km calculated for each of the three mobility scenarios considered in this thesis. In contrast, individual mobility showed the highest costs for users followed by shared transportation.

However, the present work did not explore economic indicators other than cost categories because of the complexity of developing the characterization models. In fact, future research can focus on their development to properly assess the short- and long-term economic impacts of mobility scenarios.

Moreover, as previously explained in the chapter, other actors' perspectives can/may be considered to analyze mobility scenarios. For instance, when considering public authorities' perspective, LCC can be very relevant to support the investment decisions and the definition of mobility strategies. This may, thus, contribute to better inform the decision makers on potential costs incurred from a massive development of electric mobility and analyze the costs projection of the automotive market to predict future direct and indirect costs for the society.

The costs assessment performed in this chapter has been conceived in such a way that can serve the sustainability analysis through the comprehensive LCSA framework proposed in this thesis. Hence, the obtained results are used in the coming chapter VI, together with the environmental (chapter III) and social (chapter IV) evaluation results. Within the developed LCSA framework and are analyzed through an MCDA approach.

6. References

Ayodele, B. V., & Mustapa, S. I. (2020). Life Cycle Cost Assessment of Electric Vehicles : A Review and Bibliometric Analysis. *Sustainability*, *12*(6), 2387. https://doi.org/10.3390/su12062387

CGDD. (2017). *Analyse des coûts bénéfices des véhicules électriques : Les voitures* (p. 98). CGDD-Service de l'économie, de l'évaluation de l'intégration du développement durable. https://www.ecologie.gouv.fr/sites/default/files/Th%C3%A9ma%20-%20Analyse%20co%C3%BBts%20b%C3%A9n%C3%A9fices%20des%20v%C3%A9hicules%20%C3%A9lectriques.pdf

CGDD. (2021). *Chiffres clés du transport—Edition 2021* (p. 92). Commissariat Général au Développement Durable, Ministère de la transition écologique. https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-transport-2021/livre.php

Cimerdean, D., Burnete, N., & Iclodean, C. (2019). Assessment of Life Cycle Cost for a Plug-in Hybrid Electric Vehicle. In N. Burnete & B. O. Varga (Éds.), *Proceedings of the 4th International Congress of Automotive and Transport Engineering (AMMA 2018)* (p. 273-290). Springer International Publishing. https://doi.org/10.1007/978-3-319-94409-8_32

Criqui, P. (2021). *Les coûts d'abattement, partie 2 : Transports*. France Stratégie. https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-2021-rapport-les_couts_dabattement-_partie_2_transports-juin.pdf

De Clerck, Q., van Lier, T., Messagie, M., Macharis, C., Van Mierlo, J., & Vanhaverbeke, L. (2018). Total Cost for Society : A persona-based analysis of electric and conventional vehicles. *Transportation Research Part D: Transport and Environment*, *64*, 90-110. https://doi.org/10.1016/j.trd.2018.02.017

Delogu, M., Maltese, S., Del Pero, F., Zanchi, L., Pierini, M., & Bonoli, A. (2018). Challenges for modelling and integrating environmental performances in concept design : The case of an automotive component lightweighting. *International Journal of Sustainable Engineering*, *11*(2), 135-148. https://doi.org/10.1080/19397038.2017.1420110

Dumortier, J., Siddiki, S., Carley, S., Cisney, J., Krause, R. M., Lane, B. W., Rupp, J. A., & Graham, J. D. (2015). Effects of providing total cost of ownership information on consumers' intent to purchase a hybrid or plug-in electric vehicle. *Transportation Research Part A: Policy and Practice*, *72*, 71-86. https://doi.org/10.1016/j.tra.2014.12.005

Franfinance & CSA. (2018). *Les français et leur auto* (p. 15). FRANFINANCE & Consumer Science Aanlytics. https://www.franfinance.fr/wp-content/uploads/2018/10/etude-francais-auto-csa-franfinance.pdf

Freire, F., & Marques, P. (2012). Electric vehicles in Portugal : An integrated energy, greenhouse gas and cost life-cycle analysis. *2012 IEEE International Symposium on Sustainable Systems and Technology (ISSST)*. https://doi.org/10.1109/ISSST.2012.6227988

Gallagher, K. G., & Nelson, P. A. (2014). 6—Manufacturing Costs of Batteries for Electric Vehicles. In G. Pistoia (Éd.), *Lithium-Ion Batteries* (p. 97-126). Elsevier. https://doi.org/10.1016/B978-0-444-59513-3.00006-6

Gert Berckmans, Maarten Messagie, Jelle Smekens, Noshin Omar, Lieselot Vanhaverbeke, & Joeri Van Mierlo. (2017). Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030. *Energies*, *10*(9), 1314. https://doi.org/10.3390/en10091314

G.R. van Aalst, R. (2016). *Structuring a Whole Life Cost model for the automative-sector.pdf* [Thèse de Master]. University of Twente.

Hallmark, S., & Sperry, R. (2012). Comparison of In-Use Operating Costs of Hybrid-Electric and Conventional School Buses. *Journal of Transportation Technologies*, *02*(02), 158-164. https://doi.org/10.4236/jtts.2012.22017

Hao, H., Cheng, X., Liu, Z., & Zhao, F. (2017). Electric vehicles for greenhouse gas reduction in China : A cost-effectiveness analysis. *Transportation Research Part D: Transport and Environment*, *56*, 68-84. https://doi.org/10.1016/j.trd.2017.07.025

Hunkeler, D., Lichtenvort, K., & Rebitzer, G. (2008). *Environmental Life Cycle Costing*. CRC Press.

IFP Energies Nouvelles. (2018). *Bilan transversal de l'impact de l'électrification par segment* (p. 21). PROJET E4T. ADEME. www.ademe.fr/mediatheque

ENR - Timbres et taxes assimilées—Droits de délivrance de documents et perceptions diverses—Documents relatifs à la conduite des véhicules à moteur—Taxes additionnelles à la taxe sur les certificats d'immatriculation des véhicules (ou cartes grises), (2020). https://bofip.impots.gouv.fr/bofip/2707-PGP.html/identifiant=BOI-ENR-TIM-20-60-30-20201104

ISO 14040. (2006). *Management environnemental—Analyse du cycle de vie—Principes et cadre* (p. : 23). Internationanl Standardization Organization. https://www.iso.org/cms/render/live/fr/sites/isoorg/contents/data/standard/03/74/37456.html

ISO14044. (2006). *ISO 14044:2006—Management environnemental—Analyse du cycle de vie—Exigences et lignes directrices*. https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:fr

Istamto, T., Houthuijs, D., & Lebret, E. (2014). Willingness to pay to avoid health risks from road-traffic-related air pollution and noise across five countries. *Science of The Total Environment*, *497-498*, 420-429. https://doi.org/10.1016/j.scitotenv.2014.07.110

Kochhan, R., & Hörner, M. (2015). Costs and Willingness-to-Pay for Electric Vehicles. In I. Denbratt, A. Subic, & J. Wellnitz (Éds.), *Sustainable Automotive Technologies 2014* (p. 13-21). Springer International Publishing.

Lajunen, A. (2014). Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies*, *38*, 1-15. https://doi.org/10.1016/j.trc.2013.10.008

Lebeau, K., Lebeau, P., Macharis, C., & Mierlo, J. V. (2013). *How expensive are electric vehicles ? A total cost of ownership analysis.* 12.

Lebeau, K., Lebeau, P., Macharis, C., & Van Mierlo, J. (2013). *How expensive are electric vehicles? A total cost of ownership analysis*. 1-12. https://doi.org/10.1109/EVS.2013.6914972

Lebeau, P. (2016). *Towards the electrification of city logistics?* [Université libre de Bruxelles]. http://rgdoi.net/10.13140/RG.2.1.3527.9768

Décret n° 2021-977 du 23 juillet 2021 relatif aux aides à l'acquisition ou à la location de véhicules peu polluants, TRER2117874D 2021-977 (2021). https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043852172

Lemaur, F. (2021, janvier 18). *Renault ZOE : Arrêt de la location de la batterie !* L'Automobile Magazine. https://www.automobile-magazine.fr/voitures-electriques/article/28726-la-location-de-la-batterie-arretee-sur-la-renault-zoe

Macharis, C., Lebeau, P., Mierlo, J. V., & Lebeau, K. (2013). *Electric versus conventional vehicles for logistics : A total cost of ownership*. *6*, 10.

Madlener, R., & Kirmas, A. (2017). Economic Viability of Second Use Electric Vehicle Batteries for Energy Storage in Residential Applications. *Energy Procedia*, *105*, 3806-3815. https://doi.org/10.1016/j.egypro.2017.03.890

Manzo, S., & Salling, K. B. (2016). Integrating Life-cycle Assessment into Transport Cost-benefit Analysis. *Transportation Research Procedia*, *14*, 273-282. https://doi.org/10.1016/j.trpro.2016.05.064

MEFR. (2020). *L'impôt sur le revenu par collectivité territoriale—Data.gouv.fr*. https://www.data.gouv.fr/fr/datasets/l-impot-sur-le-revenu-par-collectivite-territoriale/

Mitropoulos, L. K., Prevedouros, P. D., & Kopelias, P. (2017). Total cost of ownership and externalities of conventional, hybrid and electric vehicle. *Transportation Research Procedia*, *24*, 267-274. https://doi.org/10.1016/j.trpro.2017.05.117

Moon, S., & Lee, D.-J. (2019). An optimal electric vehicle investment model for consumers using total cost of ownership : A real option approach. *Applied Energy*, *253*, 113494. https://doi.org/10.1016/j.apenergy.2019.113494

Moreau, V., & Weidema, B. P. (2015). The computational structure of environmental life cycle costing. *The International Journal of Life Cycle Assessment*, *20*(10), 1359-1363. https://doi.org/10.1007/s11367-015-0952-1

Neugebauer, S., Forin, S., & Finkbeiner, M. (2016). From Life Cycle Costing to Economic Life Cycle Assessment—Introducing an Economic Impact Pathway. *Sustainability*, *8*(5), 428. https://doi.org/10.3390/su8050428

Onat, N. C., Kucukvar, M., Aboushaqrah, N. N. M., & Jabbar, R. (2019). How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar. *Applied Energy*, *250*, 461-477. https://doi.org/10.1016/j.apenergy.2019.05.076

Palmer, K., Tate, J. E., Wadud, Z., & Nellthorp, J. (2018). Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. *Applied Energy*, *209*, 108-119. https://doi.org/10.1016/j.apenergy.2017.10.089

Potkany, M., Hanzl, J., & Hlatká, M. (2018). Comparison of the Life cycle Cost Structure of Electric and Diesel Buses. *Naše More*, *65*(4), 270-275. https://doi.org/10.17818/NM/2018/4SI.20

Rabl, A., Spadaro, J., & Holland, M. (2014). *How Much is Clear Air Worth? Calculating the Benefits of Pollution Control*. https://doi.org/10.1017/CBO9781107337831

Raustad, R. (2017). *Electric Vehicle Life Cycle Cost Assessment* (Research Study Report FSEC-CR-1984-14; p. 27). Eletric Vehicle Transportation Center. https://rosap.ntl.bts.gov

Schroeder, A., & Traber, T. (2012). The economics of fast charging infrastructure for electric vehicles. *Energy Policy*, *43*, 136-144. https://doi.org/10.1016/j.enpol.2011.12.041

Schwab Castella, P., Blanc, I., Gomez Ferrer, M., Ecabert, B., Wakeman, M., Manson, J.-A., Emery, D., Han, S.-H., Hong, J., & Jolliet, O. (2009). Integrating life cycle costs and environmental impacts of composite rail car-bodies for a Korean train. *The International Journal of Life Cycle Assessment*, *14*(5), 429-442. https://doi.org/10.1007/s11367-009-0096-2

Sen, B., Ercan, T., & Tatari, O. (2017). Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. *Journal of Cleaner Production*, *141*, 110-121. https://doi.org/10.1016/j.jclepro.2016.09.046

Shi, J., Wang, Y., Fan, S., Ma, Q., & Jin, H. (2019). An integrated environment and cost assessment method based on LCA and LCC for mechanical product manufacturing. *The International Journal of Life Cycle Assessment*, *24*(1), 64-77. https://doi.org/10.1007/s11367-018-1497-x

Stark, R., Buchert, T., Neugebauer, S., Bonvoisin, J., & Finkbeiner, M. (2017). Benefits and obstacles of sustainable product development methods : A case study in the field of urban mobility. *Design Science*, *3*. https://doi.org/10.1017/dsj.2017.20

Tarne, P., Lehmann, A., & Finkbeiner, M. (2019). Introducing weights to life cycle sustainability assessment—How do decision-makers weight sustainability dimensions? *The International Journal of Life Cycle Assessment*, *24*(3), 530-542. https://doi.org/10.1007/s11367-018-1468-2

Tarne, P., Lehmann, A., Kantner, M., & Finkbeiner, M. (2019). Introducing a product sustainability budget at an automotive company—One option to increase the use of LCSA results in decision-making processes. *The International Journal of Life Cycle Assessment*, *24*(8), 1461-1479. https://doi.org/10.1007/s11367-018-1576-z

Thoft-Christensen, P. (2012). Infrastructures and life-cycle cost-benefit analysis. *Structure and Infrastructure Engineering*, *8*(5), 507-516. https://doi.org/10.1080/15732479.2010.539070

Windisch, E. (2014). *Driving electric ? A financial analysis of electric vehicle policies in France* [Statistical finance, Ecole des Ponts ParisTech - Université Paris-Est]. https://tel.archives-ouvertes.fr/tel-00957749

Wong, Y. S., Lu, W.-F., & Wang, Z. (2010). Life Cycle Cost Analysis of Different Vehicle Technologies in Singapore. *World Electric Vehicle Journal*, *4*(4), 912-920. https://doi.org/10.3390/wevj4040912

Chapter VI: Implementation of Conjoint Analysis to LCSA results interpretation: A support for the decision-making process towards sustainable mobility accounting for users' perspective

Summary (VI)

This chapter seeks to provide insight on the applicability of the proposed framework coupling MCDA techniques to LCSA results interpretation. To meet this goal, a case study is designed to test how LCSA results can be used by public and private actors within the development of sustainable mobility alternatives, while accounting for users' needs and expectations. Hence, the conjoint analysis, which was selected in the thesis as an appropriate MCDA approach to integrate users' preferences into the decision-making, is herein implemented. The findings are compared to the results of a large-scale survey conducted by local authorities. The comparison aims at pinpointing to what extent the method can be used to guide decision makers.

The chapter starts by defining the objective of the case study. In addition, **section 1** reminds the main stages of the proposed framework, introducing the conjoint analysis to support LCSA results interpretation. In this regard, sustainability weighting factors are determined through a preference analysis by applying the choice-based conjoint approach. **Section 2** defines the decision scenario considered in the case study by presenting: (i) the geographical and urban characteristics (ii) the main sustainability issues related to the area of the study and (iii) the decision makers and key mobility actors, namely users. **Section 3** comprises the definition of sustainability decision criteria by involving mobility users. A focus group was designed for this purpose leading to two outcomes; (i) the generation of sustainability criteria and (ii) the ranking of the decision criteria to select the most relevant ones. These criteria are used subsequently for the implementation of the conjoint analysis, as detailed in **section 4**. The application of the conjoint analysis requires defining two elements: (i) the attributes, corresponding to the selected sustainability decision criteria, and (ii) their relative specifications, which consist of the sustainability performance. These two enable the definition of the different combinations that reflect all the possible alternatives users would be faced to. These combinations are subsequently used within the preference analysis. Finally, **section 5** discusses the resulting sustainability weighting factors for each dimension. Results interpretation is supported by a validation step to check the consistency of the findings to support the decision makers in the definition of the most sustainable mobility alternatives. To do so, data is collected from a large-scale survey among 3,642 transportation users are compared to the findings of the conjoint analysis. Hence, a thorough analysis is conducted to investigate how such a methodology combining LCSA and MCDA could play in such decision-making process. The generalization of the proposed LCSA framework is finally discussed to enable the application of such a methodological proposal to other scenarios while accounting for other actors' perspectives.

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1. The objective of the case study

The present chapter aims, through a real-world case study, to demonstrate the applicability of the proposed framework and pinpoint to what extent it can guide mobility decisions. The objective of the second research question, presented in Chapter 1 of this thesis, is to support decision makers, both public and private actors, in the development of more sustainable mobility alternatives, by using LCSA results and accounting for users' needs and expectations.

The sustainability analysis was conducted in chapters 3, 4 and 5 for the environmental, social and economic dimensions, respectively. These chapters have delivered multidimensional results reflecting significant trade-offs where the three considered mobility scenarios (i.e., personal, public and shared) computed different performances. As demonstrated in chapter 2, the designed LCSA framework calls for the use of multicriteria analysis to handle the compromises induced from the three impact assessment approaches, namely environmental LCA, S-LCA, and LCC. To this end, an MCDA technique was introduced to support the interpretation of LCSA results and inform the decision makers within the design process. Figure 50 illustrates the overall framework that has been proposed in chapter 2 covering LCSA and the introduced MCDA approach, namely the conjoint analysis.

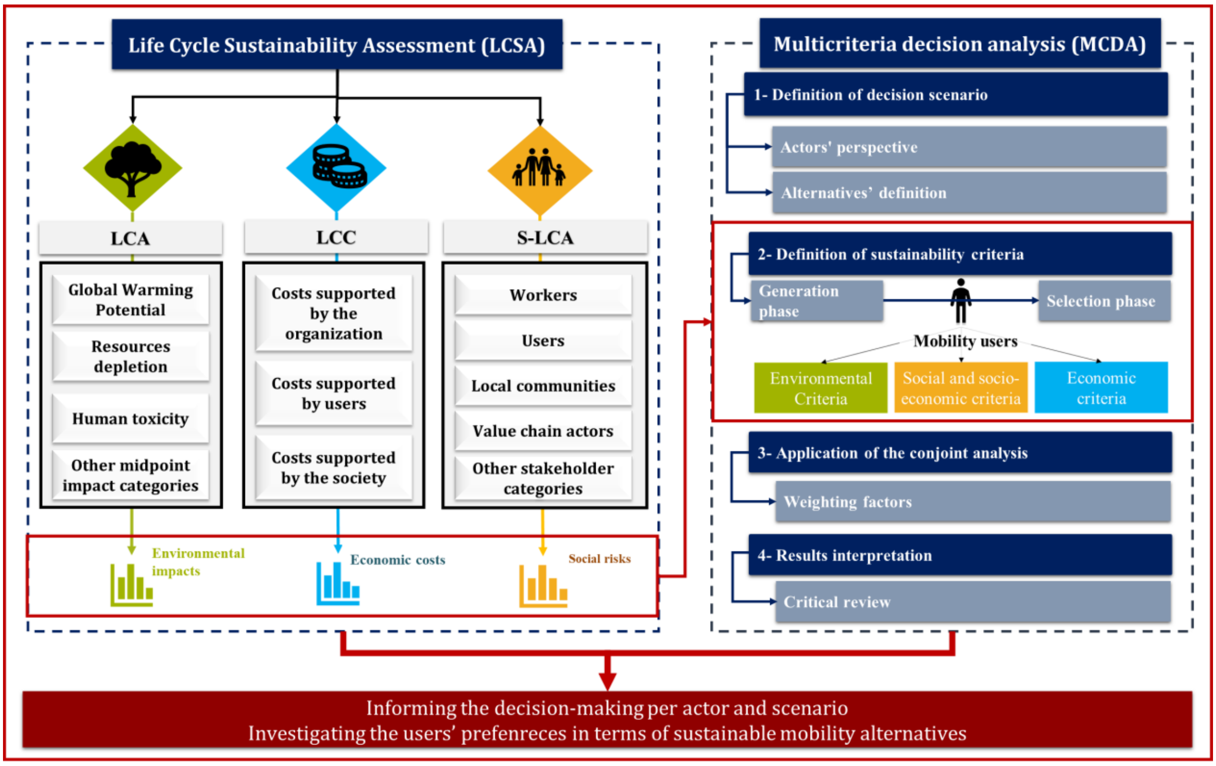

Figure 50 Implementation of the designed framework to a real-world case study *from LCSA to the decision-making: introduction of the Conjoint Analysis to support private and public decision makers within the design of sustainable mobility alternatives and accounting for users' preferences.*

The conjoint analysis has been selected among other MCDA techniques for its ability to integrate users' preferences and is therefore experimented in this chapter. In fact, mobility users have been given particular attention in the present thesis, to integrate their perspective within the design phase of mobility alternatives (i.e., transportation technologies, mobility services, etc.). For this purpose, they are directly involved in this framework to select the most relevant sustainability decision criteria and to perform the preference analysis.

To enable the application of the conjoint analysis to investigate thoroughly the different sustainability aspects, the scope of the case study was narrowed down to a specific commuting travel in Sophia Antipolis. Three main steps are included in the proposed framework as illustrated in Figure 50. They are defined and detailed in the following sections: (i) definition of mobility decision scenario (ii) definition of sustainability decision criteria by the users, and (iii) the application of the conjoint analysis. LCSA results are herein used to define the sustainability performance scales for the different sustainability criteria. The applied conjoint analysis allows the integration of users' preferences to define the weighting factors for each sustainability decision criterion. The determined weighting factors are subsequently validated through a large-scale survey. A critical review is therefore conducted to check the relevance of MCDA techniques to support the interpretation of LCSA results and questions its ability to guide the decision-making processes.

2. Definition of the case study: Decision-making scenario

2.1. Characterization of the study area

This first section defines the case study that serves as a validation ground for the proposed LCSA framework in chapter 2. The characterization of the study area allows to narrow down the focus on a specific geographical location and to investigate the present mobility alternatives, the geographical and urban characteristics together with the main actors taking place in the decision-making scheme.

a) <u>Geographical zone:</u>

The geographical area targeted by this study is the "Alpes-Maritimes region" in the south of France. More precisely, "La communauté d'Agglomération Sophia Antipolis" (CASA), which covers a total area of 482 km² and gathers 24 municipalities, was selected. Three zones are distinguished in CASA based on their urban density: "Sophia et littoral" where 80% of the population is located and the urban density amounts to 2900 inhabitants per km², "Moyen pays" with a lower urban density amounting to 480 inhabitants/km², and finally "Le Haut Pays" which is considered as a rural area of about 12 inhabitants/km² of urban density. "Sophia et littoral" is selected for the study in view of its interesting geographical and urban characteristics. In fact, this work aims to investigate the different mobility scenarios within an urban geographical context which makes this zone the most suitable. Both Antibes and Sophia Antipolis are located in "Sophia and littoral" zone. While Antibes gathers the highest share of population (24,395 inhabitants per km^2 in 2019), Sophia Antipolis is the first European technology park, where 2,500 companies are located. In view of the economic activities (5.6 billion euros in 2019) in Sophia Antipolis and the high urban density of Antibes, this makes the journey from Antibes to Sophia Antipolis the most solicited commuting travel compared to leisure journeys.

b) <u>Mobility patterns:</u>

The urban nature of the area and its evolution have anchored a reliance on the use of private cars. Hence, congestion is one of the most problematic issues in the region causing thus frequent and long traffic jams. In the Alpes-Maritimes region, a working person loses an average of 25 days per year due to congestion. Moreover, about 82,000 people are exposed to exceeding air quality threshold values for air pollutants (ADEME-CASA, 2018).

Which is today a major challenge for CASA. In fact, as illustrated in figure 51, private cars are the most common means of commuting to work in the area, with 71% of total modal share, while the use of shared public transport amounts to 6%, 1% for cycling and 22% of walking. It is worth to note that walking is common in city centers of CASA for an average distance of 700 m (ADEME-CASA, 2018), whereas the commuting travel Antibes-Sophia Antipolis involves a distance of about 8 km. For this reason, walking has been excluded from the scope of this case study.

These rates are consistent with France is average where, 80% of trips are made by individual car, with 50% of travel not exceeding 5 kilometers (ADEME, 2019). The use of individual transport is mainly associated with commuting, shopping and leisure. In view of the above sketched reasons, an average commuting travel between Antibes and Sophia Antipolis is considered in the case study.

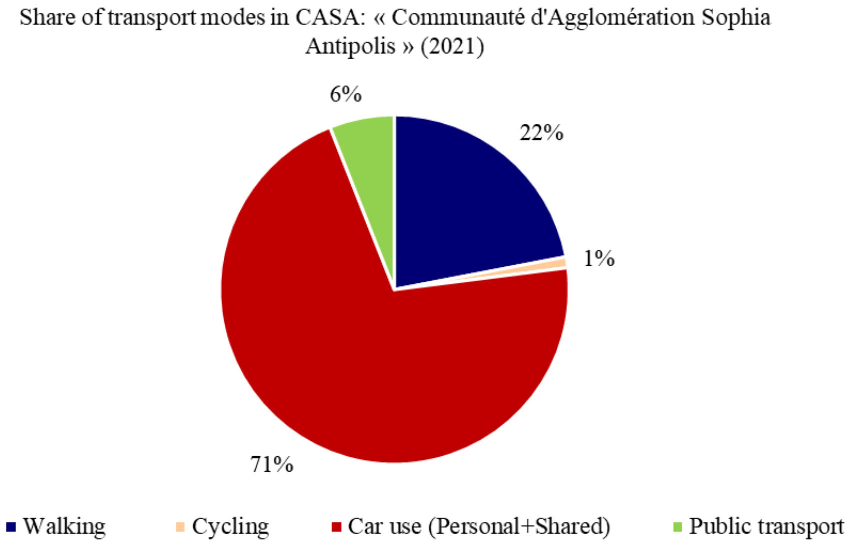

Figure 51 Share of transport modes from CASA 2021

2.2. Definition of the actors

Public policies are evolving in favor of an energy transition that affects the transportation sector among others (Bigo, 2020). Transportation users are in turn increasingly aware of the sustainability issues at stake and are turning to solutions that are more respectful towards the environment but also towards social and economic dimensions. Consequently, local authorities and industrial actors are compelled to invest more in the deployment of new sustainable mobility alternatives and technologies while respecting the needs of users.

To understand the high dependency of users on personal mobility within the investigated region, it is of utmost importance to understand the key drivers and barriers for adopting other transportation modes. Several studies have investigated the societal drivers for future transportation alternatives (L'Hostis et al., 2016; Chalkia et al., 2017; Imre Keseru et al., 2018; Kostiainen & Tuominen, 2019), among which users-related issues have been considered as key factors. For instance, within the MOBILITY EU project of the European Commission (L'Hostis et al., 2016), three key drivers have been identified for users namely, habits, accessibility, technophobia and data protection.

In France, the national personal travel survey conducted by the government in 2019 reveals that a working person spends an average of 7 hours and 12 minutes per week traveling, all modes of transport combined. The success of private cars in increasing people's freedom and autonomy is, however, less appreciated when it comes to the negative issues affecting the quality of life in cities (e.g., increasing local pollution and urban congestion). Hence, 65% of French people are willing to use public transport more, 40% consider the alternative of carpooling and 60% would be willing to reduce the use of their vehicle (ADEME 2019). Three mobility alternatives are investigated in accordance with the three mobility scenarios analyzed in this thesis.

Alternative 1: personal transportation use – midsize electric vehicle

Alternative 2: public transportation use – natural gas-powered vehicle

Alternative 3: shared transportation use – midsize electric vehicle

3. Definition of sustainability decision criteria: involving users through a focus group

Different types of consultation processes can be used to select the most appropriate and representative decision criteria. For example, Lebeau et al. (2012) have used previous studies to define the relevant attributes to consider through the preference analysis, while Tarne et al. (2019) have identified the most representative indicators for each dimension and selected those who were better known by companies, to ease the understanding of sustainability issues during the preference analysis.

The present case study targets transportation users within the considered geographical area, in order to identify sustainability decision criteria according to their perspectives. To do so, the proposed framework in this thesis recommends the involvement of users from this stage, to enable the definition of the criteria that are significant and those who can influence their mobility daily choices. Hence, sustainability attributes considered within the conjoint analysis should reflect the needs and expectations of users and thus contribute to better inform decision makers (i.e., public authorities and private mobility actors) in the design of more sustainable mobility alternatives.

A focus group was chosen as a consultation approach because of its effectiveness in a short duration. In fact, the focus group method aims to gather a group of individuals to discuss on a set of proposed themes. The interactions between participants provide relevant qualitative information in a limited time duration. Such technique may be very useful to directly interview a group of people. It makes use of the interactions that are likely to occur between them to stimulate the debate and observe the process of collective sense making (Wilkinson, 1998). However, this social character can also be criticized due to the risk of enforced consensus and, thus, it may not fully account for individuals' authentic points of view (Grudens-Schuck et al., 2004).

In this study, the focus group has been chosen as an alternative to individual interviews, to collect qualitative information form the user's perspective. Moreover, conducting a focus group offers the opportunity to explore an alternative to online surveys, which were already used in chapter 4 for the definition of relevant social impact subcategories. The focus group was guided by an animator and monitored to ensure that the participants could freely express themselves. To improve the consistency of the focus group, a semi-structured consultation was organized for data collection. Hence, the designed focus group includes three main steps as presented in figure and aims to define the sustainability decision criteria to be integrated in the MCDA framework. The proposed procedure is explained in section 3.1, covering from the design to the execution of the focus group as well as the results analysis.

3.1. Design of the focus group: Materials and methods

The steps followed to enable the consultation of transportation users within the focus group are described below:

3.1.1. Sampling:

Transportation users are selected according to the objectives of the study and targeted within the considered geographical area. Several sources of recruitment can enrich the sample, depending on the issue to be studied and the objectives. To ensure the representativeness of the sample, three criteria should be met when selecting the users:

- Diversity: makes it possible to capture the reality and to explore the widest possible spectrum of opinions in order to bring out all the views on the subject.
- Neutrality: it is preferred that participants know neither each other nor the topic of the meeting in detail, to prevent them from doing research on it beforehand. The reason is that the aim of a focus group is to explore the spontaneous reactions and personal experiences of the participants.
- Validity: the sample conditions the validity of the findings and should be characterized during the results analysis

Ideally, the number of participants is six to eight people, all volunteers. A minimum number of 4 people is essential to ensure a dynamic group. A maximum of 12 people is recommended to ensure that everyone has the chance to express themselves and to be able to moderate the group (Grudens-Schuck et al., 2004). It is also suggested to over-recruit participants by 30% to ensure that there is a suitable number of participants for the focus group, in case some people fail to attend (Plummer-D'Amato, 2008).

3.1.2. Preparation of the semi-structured interview: 2 hours

It is important to define the scenario and the complete planning of the focus group in advance, to ensure the fulfillment of the precise goals of the session. The planning can be reproduced and adapted if multiple sessions are planned to enhance the quality of the outcome. With respect to the objective of the case study, the focus group design should entail the definition of adequate data collection methods. In the present study, the focus group was supported by both qualitative and semi-qualitative approaches. To enable the definition of sustainability decision criteria, two stages are settled based on Vernette (1987) method:

- ***Generation phase:*** seeking to obtain an extensive list of potentially determining attributes. This step is conducted through a direct citation method to generate the maximum number of decision criteria for each sustainability dimension.

  Two main rounds of 10 minutes each were proposed: the first round was dedicated to the environmental dimension, the second to social and economic dimension. Open-ended questions were therefore used in this step: "What are the key environmental criteria guiding your choices for your daily commute?" and "What are the key social and economic criteria guiding your choices for your daily commute?". To enable the exercise, an online tool was chosen to facilitate the interactions with users. This step also included a discussion between all the participants, animated by the moderator, to understand the mindsets and obtain the information needed for the results' analysis. Other methods can be used instead of the focus group such as in-depth interviews, group interviews, observation methods, verbal protocols, etc.

  - ***Selection phase:*** this second step aims to draw a restricted list in which only the really determining attributes are retained. To do so, a prioritization of the previously generated criteria is proposed. Users are asked to individually rank through an online platform the criteria by each dimension (i.e., environmental, social and economic). Hence, the ranking enables the selection of the attributes that are perceived as the most influencing and guiding for their daily mobility choices. Here again, several methods can be used: dual questionnaire and self-evaluation, joint measurements, information tables, Delphi method, regression coefficients, relevance index. The same online tool used in the generation step is recommended, to allow the prioritization. A duration of 30 minutes is dedicated to performing this step. To help select the decision-making criteria, four qualities should be fulfilled by the attributes (Guillot-Soulez & Soulez, 2011):

  ✓ attributes should be decisive, namely important and discriminating, which easily can be distinguished between each other.

- ✓ attributes should be independent, that is, non-redundant, no confusion can be entailed,
- ✓ attributes should completely describe the attributes,
- ✓ attributes should have the possibility to be manipulated, i.e., calculated, processed in next steps.

3.2. Design and implementation of the focus group to account for the users' perspectives

The focus group was held on February 10, 2021, through an online workshop entitled "What are the sustainability factors that influence your daily travel choices Antibes - Sophia Antipolis?". A total number of 13 transportation users took part of the workshop. Participants were mainly affiliated to MINES ParisTech. The focus group was supported by the French Environmental Agency (ADEME), who was present in the workshop. It was carried out following three stages as illustrated in Figure 52 and detailed in the paragraphs below:

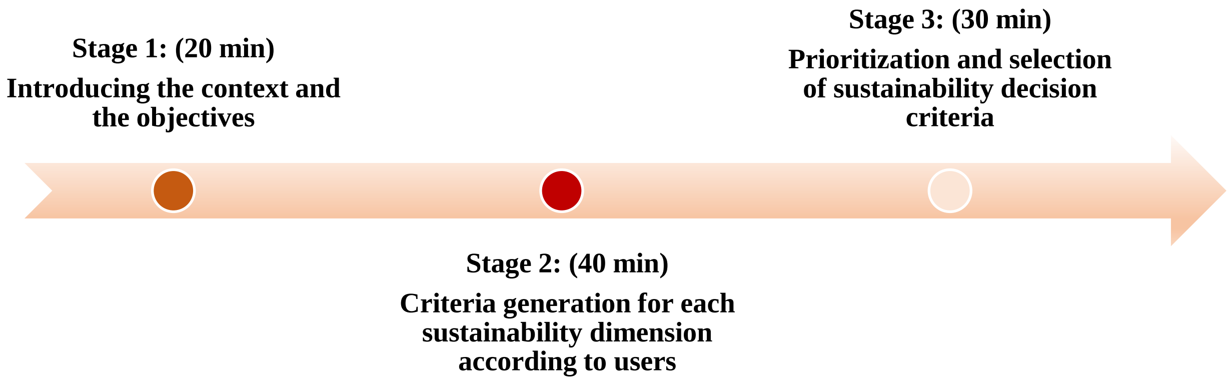

Figure 52 Main stages conducted within the focus group for the definition of sustainability decision criteria

3.2.1. Stage 1: Introducing the context & objectives (20 minutes)

This stage comprised an introduction to the study, including the moderator and the participants. A presentation of the main objectives of the focus group is presented, as well as the state of knowledge on mobility sustainability aspects and the main issues related to the geographical area of the study in Sophia Antipolis. The "rules of the game" were clearly stated, assuring the participants of the anonymity of the data, and emphasizing the importance of individual participation, as the goal is to gather a range of divergent ideas. At the end of this first stage, users were asked if all the needed information were clear to proceed to the generation step and the prioritization step later.

3.2.2. Stage 2: Criteria generation following users' perspective (40 minutes)

In accordance with the designed semi-structured group interview, users were asked to generate the maximum number of attributes by each dimension by using mentimenter tool (https://www.mentimeter.com/). Figure 53 illustrates a snapshot of all the generated criteria, which are grouped in three categories, corresponding to the three sustainability dimensions. Within the environmental dimension, a total number of 22 criteria were generated and mainly concerned the following categories:

(i) climate change (CO_2 emissions, GHG emissions, Carbone footprint),

(ii) air quality, for which several environmental indicators were identified (i.e., air quality, NO_x emissions, Particular Matter, pollution levels, air quality index, etc.) and,

(iii) noise emissions and other environmental criteria were identified, such as the land use for roads and infrastructure, the effects on the landscape and the olfactive pollution, which are associated to impacts from the use of mobility alternatives.

Users also identified some environmental criteria that can guide their purchase decision – in case of personal vehicles use – such as the vehicle powertrain, the energy consumption of the vehicle and its quietness.

In the second round, dedicated to social sustainability dimension, a higher number of 42 social and socio-economic criteria were generated by transportation users. This reflects the increasing awareness and concerns of users about the social and socio-economic impacts associated with the different mobility alternatives, including both technologies and mobility services. The generated criteria were grouped into four main categories:

(i) health and safety, mostly related to insecurity feeling, road accidents and health issues from covid-19 sanitary situation,

(ii) availability and accessibility of mobility offer: the users highlighted the importance of the travel duration, the adaptability of mobility offers more particularly within a public transportation scenario, the ability to meet specific users' needs, inclusiveness for all groups of people and the geographical coverage of mobility services,

(iii) provided facilities, which include the simplicity of the service acquisition, on-board comfort, responsiveness to incidents (linked to the efficiency of the communication system), and the possibility to do other activities during the trip.

(iv) local engagement, which was emphasized by the users to analyze the contribution to the local economy and overlaying principles of decision makers with a fair and social economy model. The generated criteria also reflected the awareness of the users about the need for transparency on the environmental and social performance of the mobility alternatives provided in the market. Other generated criteria highlighted the importance of community engagement, local actions to limit the gentrification, fight against the use of private cars and promote more sustainable mobility alternatives through incentives and subventions for cycling, walking and shared mobility.

Finally, for the economic dimension, the five criteria identified by users concerned mostly the costs related to the mobility technologies (acquisition and operation costs) and the affordability of the mobility services as well as the monthly budget supported in each of the mobility scenarios.

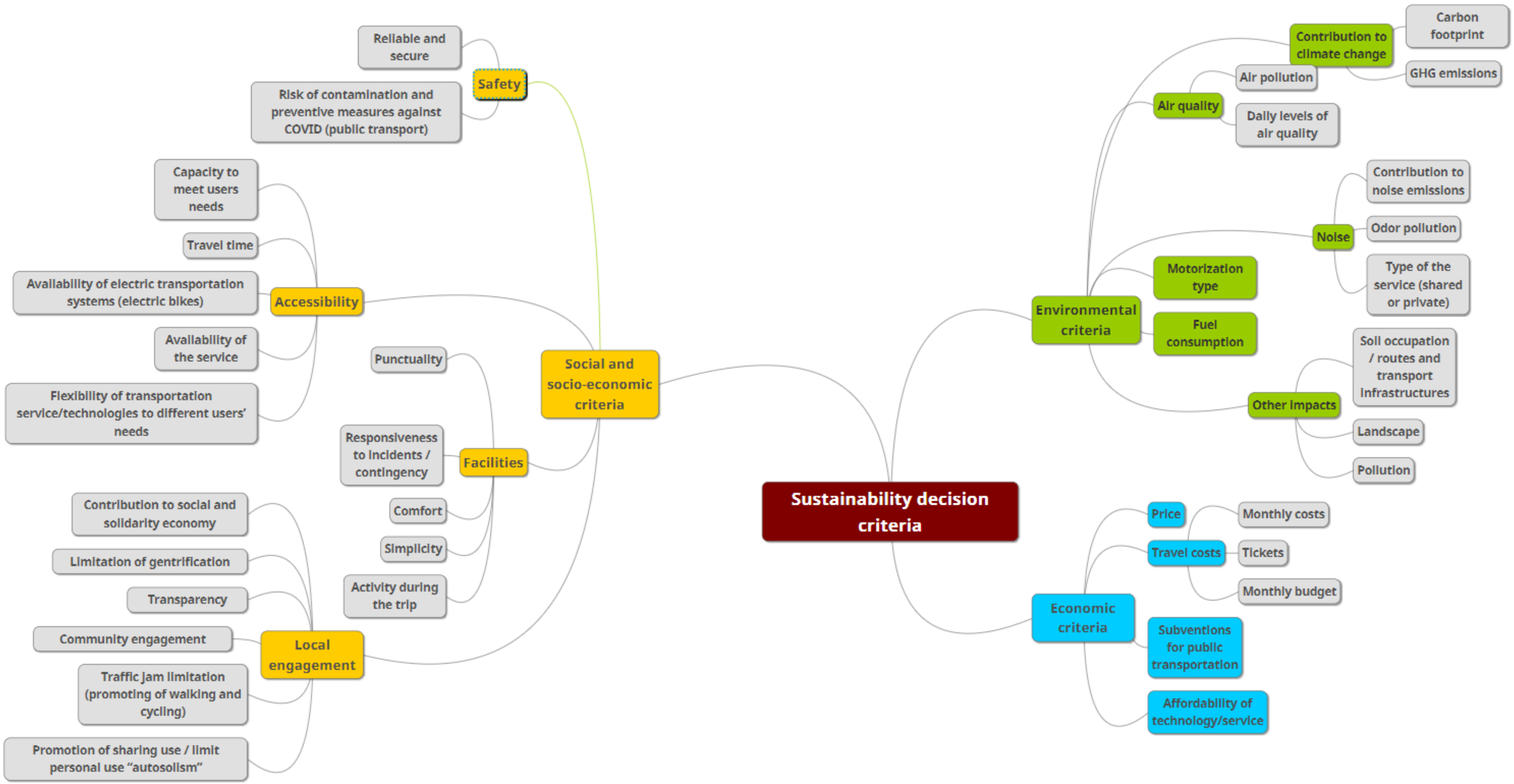

Figure 53 Mapping of the 69 generated mobility decision criteria by each sustainability dimension following the stage 2 of the focus group conducted with transportation users in Sophia Antipolis

3.2.3. Stage 3: Prioritization and selection of the most significant decision criteria (30 minutes)

After the generation stage of the environmental, social and economic criteria, users were asked during a second round of the focus group to prioritize the most important criteria for their daily mobility choices. This stage of the focus group was conducted in three steps corresponding to each of the sustainability dimensions. The users were therefore asked, through the same online tool, to rank the list of generated criteria from the previous step.

Climate change and air quality indicators took the first positions within the environmental dimension followed by noise levels, and other categories such as the land use and the landscape. On the other hand, accessibility and availability of mobility alternatives took the first position in the ranking of social aspects, followed by health and safety and comfort. Finally, for the economic dimension, the monthly budget cost was chosen as the most representative indicator to facilitate the implementation of the conjoint analysis later on. In fact, the cost criteria were all describing different indicators for users' supported costs. During the focus group, the participants expressed that the ranking was challenging and reflecting their own personal experiences related to the travel characteristics. This issue may reveal a limitation, given the limited number of the sample, and will be subsequently discussed in the coming sections.

In order to enable the application of the conjoint analysis, the attributes should be selected among those who were deemed as the most important in this prioritization step. The definition of the number of criteria (i.e. attributes) to be considered is a key step, as it not only affects the applicability of the conjoint analysis, but also the representativeness of the results (Wittink et al., 1990). When a sustainability decision-making scenario is investigated, implicitly three dimensions are to be covered. Thus, a minimum number of three attributes is to be considered. This was the case in Tarne et al. (2019) study where three attributes were defined to each dimension. However, reducing the number of attributes can be limited to address all LCSA impact categories that were analyzed. Moreover, such selection can be problematic due to value choice introduction which calls for

- discriminating the attributes that do not meet the quality levels as explained in the selection phase, or
- calculating a unique performance score of the different considered attributes.

In this research, the attributes that were most prioritized by users were chosen. Such procedure addresses the above-mentioned issues by introducing user's value choices to the selection process. However, it was necessary to limit the number of the considered attributes to five in order to enable the implementation of the conjoint analysis. In fact, a high number of attributes lead to a very substantial number of combinations to be proceeded, which makes it difficult to collect data on the actors' preferences (highly time-consuming and difficult survey process for the consulted actors). Moreover, the five criteria fixed in this case study should increase the relevancy of the outcomes compared to other studies that only consider one criterion per each sustainability dimension. Hence, following the prioritization step, two different attributes for the environmental (climate change and air quality) and social (accessibility and travel duration) dimensions and one criterion for the economic dimension (i.e., monthly costs supported by users).

4. Application of the conjoint analysis to LCSA results

4.1. Definition of sustainability performance scales based on LCSA results normalization

Once the main elements that are required for any MCDA technique, regardless of the applied method, were defined, the first step to specifically apply the conjoint analysis consists of preparing the attributes for the preference analysis and their relative specifications. To this end, the sustainability decision criteria selected by users are herein used together with results from LCSA of the analyzed mobility scenarios. In fact, the impact categories from environmental LCA, S-LCA and LCC are linked to selected attributes referring to the same effect, to allow the subsequent definition of the different combinations. Table 18 Selected sustainability decision criteria by users (participants of the focus group) and their corresponding impact categories lists the criteria selected by users and their corresponding impact categories from LCA approaches. Thus, in the coming section, the focus is made on the five selected criteria, to analyze the different mobility scenarios from a sustainability perspective.

Table 18 Selected sustainability decision criteria by users (participants of the focus group) and their corresponding impact categories

Sustainability dimension	Sustainability decision criteria selected by users in the focus group	Equivalent impact categories / subcategories / cost categories
Environmental	Climate change	Global Warming Potential (CO_2 eq/km)
	Air quality	NO_x and Particular Matter
Social	Accessibility and availability	Geographical coverage of the service and corresponding infrastructures (unit)
	Travel duration	Travel duration (unit)
Economic	Costs	TCO and service costs calculation (€/km)

To enable the application of the conjoint analysis method, normalization of LCSA results was conducted. Indeed, the application of the conjoint analysis requires two main elements:

(i) attributes, which correspond to sustainability criteria, in our case, and
(ii) their relative specifications, for which 3 levels of performance scale were defined, ranging from favorable performance to unfavorable performance. Various regulations, normalizations were used as a basis in this step (ADEME 2018). Table 19 presents the attributes (i.e., sustainability

decision criteria) and their specifications (i.e., sustainability performance scales). To determine each of the performance levels, the largest variability should be accounted for between the low performance and high-performance levels. For the environmental dimension, the average value of the selected impact categories is computed for France for both the contribution to climate change (kgCO_2 eq/p.km) and the air quality emissions.

Table 19 Definition of the combinations and the performance scales for the preference analysis

		Performance scales	
Selected criteria	Unfavorable performance	Average performance	Favorable performance
Travel duration	More than 1 hour	Between 30 minutes and 1 hour	Less than 30 minutes
Adaptability and accessibility	Geographical coverage stations/km² very low and frequency very low	Geographical coverage, Number of stations/km² average in Fr, Frequency average (+20 min)	Geographical coverage, Number of stations/km² higher than average in Fr high frequency <10 min
Emissions CO_2: labeled values	CO_2 emissions exceeding regulatory thresholds	CO_2 emissions equivalent to regulatory thresholds	CO_2 emissions lower than the threshold.
Air quality (NO_X, PM): labeled values (Data from ADEME, Euro standards)	NOx and PM levels above EURO6 limits	NO_x and PM levels equal to EURO6 limits	NO_x and PM levels above EURO6 limits
TCO: monthly costs	More than 50 euros per month	Between 20 and 50 euros / month	Less than 20 euros /month

4.2. Preference Analysis: Choice-Based Conjoint (CBC)

Mobility users' preferences are analyzed in this step for the three sustainability dimensions and within the decision scenarios that have been considered in the study. Based on the defined attributes and specifications in the prioritization step, the preference analysis can be conducted following two different techniques: preferences ranking or choice-based models.

The choice-based conjoint (CBC) approach uses discrete choice models to collect users' preferences. The respondents are expected to select the combination of specifications that fits the most of their needs and expectations among a set of other combinations. The interest in using such an approach compared to full-profile preference ranking is the ability of CBC to reduce the number of combinations by simulating the most realistic options and scenarios. In fact, the number of combinations that are generated is proportionally dependent on the number of criteria and their relative performance scales.

For instance, in the present case study, five attributes and three specification levels are defined, which makes the number of combinations rise to 125 ($=5^3$) in case of using a full-profile preference ranking model. Instead, CBC allows the total number of combinations to be reduced by eliminating the combinations that do not comply with realistic scenarios, i.e., all attributes present low performance scales. The preference analysis was conducted using the online tool ProQuestion, which allows the conjoint analysis to be performed according to CBC approach. Following the consultation of the users, the relative importance of the attributes which correspond to the weighting factors of each sustainability decision criteria. The relative importance ($Rimp_i$) is calculated as :

$$\boldsymbol{Rimp_i = \frac{R_i}{\sum_{i=1}^{m} R_i}}$$

With: $$\boldsymbol{R_i = \max(u_{ij}) - \min(u_{ik})}$$

- **u_{ij}:** part-worth contribution (i.e., the utility of level per each attribute corresponding to the decision criteria)
- **k_i:** number of levels (i.e., performance scales) for attribute
- **m:** number of attributes

It is worth to note that the conjoint analysis method uses a linear regression, where the target variable depends on the used approach. In the present case study, the employed CBC models attribute binary variables which derive from the choice (yes or no) for each combination. Hence, the coming sections present the results of the weighting factors calculated for each sustainability dimension. These weighting factors are subsequently investigated through a comparison of the results to a large-scale survey.

5. Results Interpretation

5.1. Development of weighting factors and application of LCSA results

The individual weight of each sustainability decision criterion is illustrated in Figure 54. The environmental criteria (i.e., contribution to climate change and air quality) together with the costs criteria turn out to be the most important according to users followed by the social criteria (i.e., travel time and accessibility of mobility alternatives), which appear to have the less influence on users' choices in terms of mobility.

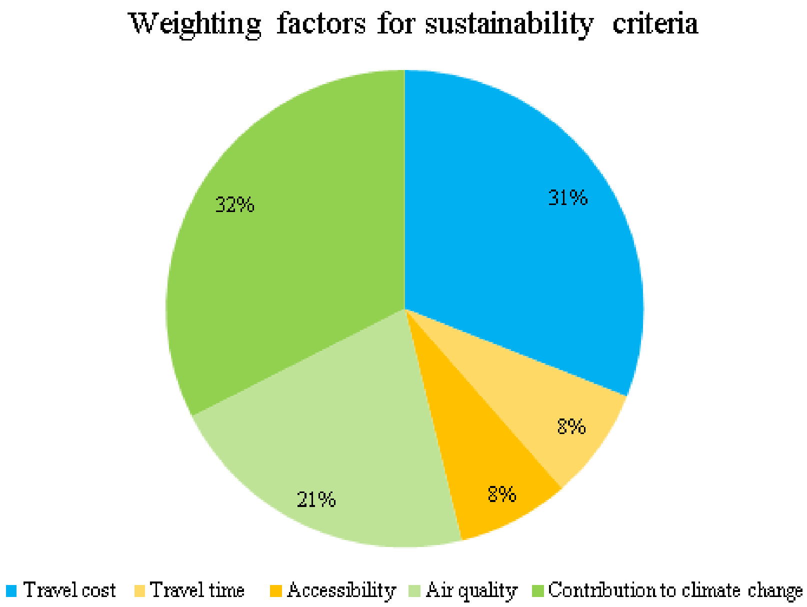

Figure 54 Calculated weighting factors for the five considered attributes (i.e., sustainability decision criteria)

The deriving weights for the environmental dimension are highlighted as the most relevant by users, with the sum of both considered criteria (i.e., climate change and air quality) attaining a total weight of 53%. When considering each environmental criteria individually, the relative importance of climate change was weighted at 32% while that of air quality was weighted at 21%. The economic dimension took the second place, with 31% of relative importance attributed to the monthly budget as a driver for users' mobility choices. Finally, the results show that the respondent users gave the same exact importance for each of the social criteria (i.e., travel duration and accessibility), which have been weighted at 8% of relative importance, each.

The overall results from weighting reveal users' awareness to the environmental dimension which was perceived as more important than the other sustainability dimensions. However, when considering each sustainability dimension individually, no clear clustering is demonstrated, which can confirm the difficulty respondents expressed when making the ranking. Such observations have also been highlighted by Tarne et al. (2019), who showed relatively close results of weighting factors from the preference analysis for each of the criteria. Moreover, performing such technique separately for each sustainability dimension might require consequent knowledge from the respondents of the sustainability issues linked to the investigated systems. This may also raise questions on the representativeness of the sample. In this case study, the preference analysis was performed within a very limited number of users.

5.2. Validation of the results for the weighting factors

While performing the case study, a large-scale survey was conducted in Sophia Antipolis by the local authorities with the objective of reorganizing the transportation network. This survey was conducted during the year 2021 across 3642 transportation users and aimed at: (i) characterizing the users' profiles in the geographical area (i.e., mobility patterns, type of travels, share of mobility services use, etc.) (ii) understanding and investigating users' mobility choice drivers from a sustainability perspective. Other questions concerned the impact of the current pandemic situation on users' mobility patterns and the characterization of their specific needs to facilitate the development of low-impact mobility alternatives (i.e., electric bikes, modal shift, intermodality).

In this regard, local authorities in CASA were contacted within this thesis. The interaction was motivated by the need for a significant sample size that could be used in support to the current case study. Such large-scale survey can also be used to challenge the assumptions set within its design. Hence, the collected data from this large-scale survey was analyzed with a focus on two elements:

(i) Characterization of the sample to check if the consulted mobility users in the large-scale survey are representative for the travel type analyzed in the case study of this thesis namely, commuting travel from Antibes to Sophia Antipolis

(ii) Coherence between the users' preferences in terms of sustainability dimensions that are influencing their choices the most, and the weighting factors generated from the conjoint analysis.

This adds a new feature to the interpretation of results, which seeks to challenge the legitimacy of the weighting factors. Hence, the present research work opens the discussion on the validation of the ability of the MCDA approaches to provide relevance guiding to decision-making process.

5.2.1. Characterizing the representativeness of the sample

The gathered data was first analyzed to characterize the sample of users that have responded to the survey. Figure 55 illustrates the different travel types that are performed by the users. This latter shows that 55% of the travels concern commuting to work and school, corresponding to the journey from Antibes to Sophia Antipolis. Such results are in accordance with the assumptions settled within the design of the case study. The other part of the trips concerns 26.1% for shopping, leisure and food provisions, 10.2% for health and 8.7% for other travel types.

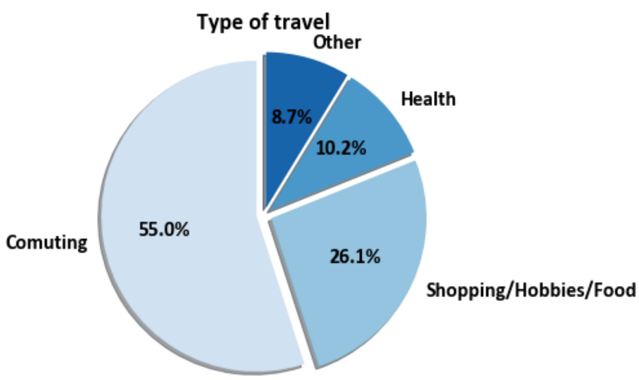

Figure 55 travel types for users in CASA (sample=3642) Data from the CASA local authorities- conducted survey in 2021 for restructuration of the ENVIBUS network (public transport provider)

5.2.2. Users' perceptions on the relative importance of the three sustainability dimensions

The survey conducted by CASA local authorities also concerned the identification of users' main mobility drivers from a sustainability perspective. Such result is herein compared with the findings of the conjoint analysis in order to check the consistency of the determined weighting factors. As illustrated in figure 56, **the conducted survey was performed by considering the sustainability dimension levels rather than sustainability criteria levels**. In fact, to ease the data collection process, the large-scale survey has categorized the criteria by the sustainability dimension rather than considering the comparison at the level of each criterion.

The overall ranking shows that social drivers are the most contributing to users' mobility choices. In fact, the social drivers comprise safety issues, comfort, accessibility and facilities or availability of the mobility offers. In the second position, 30% of users ranked the environmental criteria as the most important, 19.9% of users stated that having no other mobility alternative imposes the use of public transportation and finally 9.8% of respondents accorded the first position for the economic drivers.

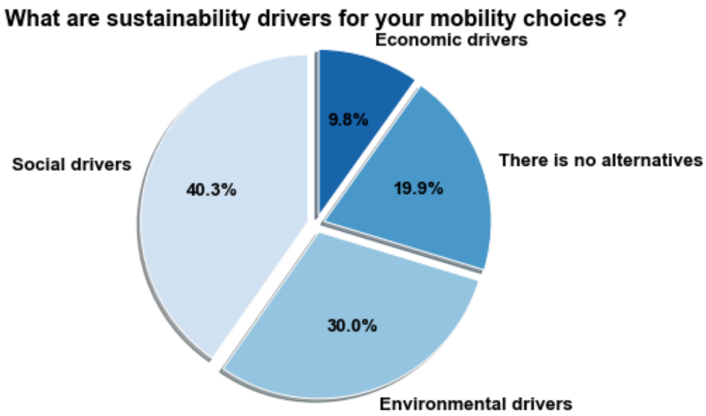

Figure 56 : Main sustainability drivers for users' mobility choices – Data from ENVIBUS 2021 (public transport service provider)

The large-scale survey highlights divergent results for mobility users' choice drivers with respect to the findings obtained through the conjoint analysis. In fact, the ranking order of the three sustainability dimensions differs: environmental dimension > economic dimension > social dimension (results of the case study), in contrast, social dimension > environmental dimension > economic dimension (results from the large-scale survey). To understand the sources explaining of such difference and the possible influencing factors, the following analysis is now proposed:

- **The sample size** is the first factor that can be highlighted. In fact, the number of consulted users within the conjoint analysis being limited can raise questions on the representativeness of the sample, thus the outcomes.
- **The level of detail** associated with the attributes. In fact, the large-scale survey was conducted at the level of sustainability dimensions rather than at the level of sustainability decision criteria. The

number of attributes to be considered directly affects the feasibility of the survey. On the other hand, a limited number of decision criteria, despite required to make conjoint analysis feasible, may lead to a partial representation of LCSA results and cannot be sufficient to fully inform decision makers. The question that arises from the two above-mentioned limiting factors is the following:

What is the optimal balance between the sample size and the level of detail?

- How to select **attributes,** namely sustainability decision criteria in the case study, need to be considered. Indeed, the direct citation method used during the focus group resulted in a lack of life cycle perspective for the social dimension and did not reflect other stakeholder impact subcategories. Such approach can also be questioned due to the resulted distortion between the decision criteria and the impact categories analyzed through the proposed LCSA framework.

Is it more relevant to give stakeholders the ability to generate the criteria that describe best their needs and expectations, as implemented in this study, or to impose a list of impact subcategories that require high knowledge from the consulted actors?

The above-listed statements reveal limitations and challenges to overcome in future research studies. These observations challenge the role that LCSA can play in guiding the decision-making. The question that is raised at this stage is the following:

Are the determined weighting factors appropriate and reliable to support decision-making process in assessing relative sustainability for different mobility scenario?

Although the role LCSA can play in informing the decision-making process is undeniable, it is legitimate to question the limits of the methodology, scientifically speaking, to guide decisions that belong to political decision makers. In fact, although LCSA provides scientifically based information of the magnitude of impacts and highlights the possible improvements that can be made on the technology, materials and process levels, several drawbacks can be identified linked to the introduction of weighting factors. These can result in a simplistic representation of the actual impacts and consequently mislead decision makers' choices. In addition to this, cautious choices should be made when selecting the type of MCDA approach, the survey design, the selection of the attributes, as they have been identified as sources of uncertainties and variability in the results.

6. Conclusions

The present chapter aimed at exploring how LCSA can be used to guide public and private decision makers within the design of sustainable mobility alternatives while accounting for the users' perspective. The proposed LCSA comprehensive framework in chapter 2 introduced MCDA approaches to support the interpretation phase of LCSA in response to the research questions of this thesis. Throughout a specific case study related to daily commuting travels, an MCDA approach was selected to support

LCSA results' interpretation, namely, the conjoint analysis. Such technique was selected among others due to its ability to understand users' needs and help integrate them in the early stages of sustainable mobility design. Conjoint analysis allows, thus, the induced trade-offs from the sustainability analysis to be tackled by introducing MCDA approaches.

By means of a real-world case study, the conjoint analysis has been tested on a specific commuting travel from Antibes to Sophia Antipolis, in the south of France. The chapter started by defining the mobility decision scenario (urban area), the existing mobility alternatives (public transportation, personal and shared mobility) and the key actors that are involved in the mobility scheme. The users who are considered as a key actor for developing future mobility alternatives in the future, were involved in the designed case study. To this end, a focus group was designed with the aim of generating and selecting the most relevant sustainability decision criteria from their perspective. Impact categories evaluated through the proposed LCSA framework in chapters 3, 4 and 5 were subsequently linked to the five sustainability decision criteria selected by users (i.e., travel duration, accessibility, climate change, air quality, monthly costs). In addition, the sustainability performance scales, which are required for the application of the conjoint analysis (i.e., specification of the attributes), were defined based on LCSA results for each of the sustainability decision criteria. This made it possible to conduct the preference analysis with a choice-based model, across mobility users to determine the sustainability weighting factors. The obtained weighting factors have highlighted the awareness of the consulted users to the environmental, social and economic aspects. The environmental dimension was the first ranked and was weighted at 53%, the economic dimension at 31% and the social dimension at 16%.

The obtained values for the weighting factors were compared with results of users' preferences from a large-scale survey conducted by CASA across 3642 users in Sophia Antipolis. Through this survey, users were asked about their mobility choice drivers with respect to the three sustainability dimensions. The collected data on this survey was therefore analyzed in the present chapter with the aim of testing the applicability of the conjoint analysis and the coherence between the two findings. The results showed a divergence in the user's preferences as the ranking order of the sustainability dimensions did not comply with the finding from the conjoint analysis.

A set of the potential limiting factors that could influence the results on the weighting was thus defined including the sample size and its representativeness, the number of the considered attributes (i.e., sustainability decision criteria), the approaches for the selection of attributes, and the used MCDA approach. To conclude, the following paragraphs state the main limitations and recommendations for future research studies.

Benefits from adopting this new approach and Recommendation:

- ✓ The conjoint analysis has proven to be an appropriate approach for understanding users' preferences and avoiding the use of a pairwise comparison to prevent practitioners from facing two main drawbacks: (1) pairwise contribution relies on a direct ranking of the criteria, (2) it requires a high knowledge from the actors to the proposed impact categories – as decision criteria –.

- ✓ The use of the choice-based conjoint analysis allows to reduce the number of the combinations and ease the implementation of the preference analysis through the elimination of ones that do not comply with realistic scenarios.
- ✓ The involvement of users within the LCSA demonstrated a real interest for improving the local relevancy of the findings. Involvement of users for the selection of sustainability decision criteria can be an interesting alternative for a conventional selection by the LCSA practitioners and enable the decision makers to account for their needs and expectations in the upstream of the design phase. -->Thus, the interest of coupling both approaches.
- ✓ Large-scale surveys can be used by decision makers to adapt the design of the mobility alternatives to users' needs and expectations. Surveys can also be recommended, whenever possible, to validate the results from the weighting approaches.
- ✓ Although it is not possible to provide a general conclusion on "the most suitable" MCDA technique, the conjoint analysis appeared to be appropriate to understand users' preferences and enable presenting very concrete and clear decision profiles to users based on the criteria they have generated (e.g., distance, travel duration, etc.). Future research studies may focus on exploring other MCDA approaches.
- ✓ MCDA techniques that involve multiple involved actors may be used to investigate the variability of the results compared to MCDA approaches that reflects a single perspective and those who do not call for the stakeholders' involvement, e.g., decision utility methods.
- ✓ Future research studies can also explore other MCDA techniques and investigate to what extent the statistical approaches (i.e., decision utility methods) can be better than participatory approaches (pairwise comparisons and preference ranking methods).

Main limitations

- The implemented MCDA technique (i.e., the conjoint analysis) may lead to a significant number of uncertainties that derive from the assumptions and methodological choices settled within the design of the present case study.
- The sample size is limited to guarantee the feasibility of the study, which questions the representativeness of the obtained weighting factors,
- The chosen data collection methods (qualitative rather than quantitative), namely through the focus group can significantly influence the outcomes of the study.
- The direct citation method can restrain the integration of the life cycle perspective and other stakeholder categories. In fact, the involved stakeholders are likely to consider solely the criteria that directly affect them.

- When using a direct citation method, a distortion between the decision criteria and LCSA impact categories has been found. On the one hand, the conjoint analysis allows processing indicators that are familiar to users, but, on the other hand, they are not the same ones as those directly derived from LCSA. A step should, thus, be added to link both. Otherwise, other approaches shall be used imposing a set of impact categories to the involved stakeholders.
- Only a limited number of sustainability criteria can be integrated when applying the conjoint analysis in order to limit the number of induced combinations. Thus, this approach systematically calls for a limited selection of sustainability decision criteria.

7. References

ADEME-CASA. (2018). *Séminaire mobilité : Changeons nos comportements—Révision plan de déplacements urbains*. Ademe et Communauté d'agglomération Sophia Antipolis. https://docplayer.fr/149057311-Seminaire-mobilite-changeons-nos-comportements.html

Bigo, A. (2020). *Les transports face au défi de la transition énergétique* [PhD Thesis, Ecole Doctorale de l'Institut Polytechnique de Paris (ED IP Paris)]. http://www.chair-energy-prosperity.org/wp-content/uploads/2019/01/These-Aurelien-Bigo.pdf

Chalkia, E., Mueller, B., & L'Hostis, A. (2017). The role of societal resistance in transportation innovation. *8th International Congress on Transportation Research: Transportation by 2030: Trends and perspectives*, 12P. https://doi.org/10.5281/zenodo.1216917

Grudens-Schuck, N., Allen, B. L., & Larson, K. (2004). *Methodology Brief : Focus Group Fundamentals*. *5*, 7. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1011&context=extension_communities_pubs

Guillot-Soulez, C., & Soulez, S. (2011). L'analyse conjointe : Présentation de la méthode et potentiel d'application pour la recherche en GRH. *Revue de gestion des ressources humaines*, *80*(2), 33. https://doi.org/10.3917/grhu.080.0033

Imre Keseru, Thierry Coosemans, Eliza Gagatsi, & Cathy Macharis. (2018). *User-centric vision for mobility in 2030 : Participatory evaluation of scenarios by the multi-actor multi-criteria analysis (MAMCA)*. https://zenodo.org/record/1483459#.XI-3vbiNyUk

Kostiainen, J., & Tuominen, A. (2019). Mobility as a Service—Stakeholders' Challenges and Potential Implications. In B. Müller & G. Meyer (Éds.), *Towards User-Centric Transport in Europe : Challenges, Solutions and Collaborations* (p. 239-254). Springer International Publishing. https://doi.org/10.1007/978-3-319-99756-8_16

Lebeau, K., Van Mierlo, J., Lebeau, P., Mairesse, O., & Macharis, C. (2012). The market potential for plug-in hybrid and battery electric vehicles in Flanders : A choice-based conjoint analysis. *Transportation Research Part D: Transport and Environment*, *17*(8), 592-597. https://doi.org/10.1016/j.trd.2012.07.004

L'Hostis, A., MULLER, B., meyer, G., BRUCKNER, A., FOLDESI, E., Dablanc, L., Blanquart, C., TUOMINEN, A., KOSTIAINEN, J., POU, C., URBAN, M., KESERU, I., COOSEMANS, T., DE LA CRUZ, M. T., VAL, S., Golfetti, A., Napoletano, L., SKOOGBERG, J., HOLLEY-MOORE, G., … LANGHEIM, J. (2016). *MOBILITY4EU - D2.1—Societal needs and requirements for future transportation and mobility as well as opportunities and challenges of current solutions* (p. 85p.) [Research Report]. IFSTTAR - Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux. https://hal.archives-ouvertes.fr/hal-01486783

Plummer-D'Amato, P. (2008). Focus group methodology Part 1 : Considerations for design. *International Journal of Therapy and Rehabilitation*, *15*(2), 69-73. https://doi.org/10.12968/ijtr.2008.15.2.28189

Tarne, P., Lehmann, A., Kantner, M., & Finkbeiner, M. (2019). Introducing a product sustainability budget at an automotive company—One option to increase the use of LCSA results in decision-making processes. *The International Journal of Life Cycle Assessment*, *24*(8), 1461-1479. https://doi.org/10.1007/s11367-018-1576-z

Vernette, E. (1987). Identifier les attributs determinants : Une comparaison de six methodes. *Recherche et Applications En Marketing*, *2*(4), 1-21. https://doi.org/10.1177/076737018700200401

Wilkinson, S. (1998). Focus group methodology : A review. *International Journal of Social Research Methodology*, *1*(3), 181-203. https://doi.org/10.1080/13645579.1998.10846874

Wittink, D. R., Krishnamurthi, L., & Reibstein, D. J. (1990). The Effect of Differences in the Number of Attribute Levels on Conjoint Results. *Marketing Letters*, *1*(2), 113-123. https://www.jstor.org/stable/40216150

Chapter VII: General Conclusions and Perspectives

Mobility is undergoing a total metamorphosis. Public policies are continuously moving towards more restrictive regulations to ensure the transition from the current fossil fuel-based transportation systems, causing significant adverse effects for the environment and the society, to alternative scenarios with lower impacts. Indeed, the **substantial use of petroleum-based products in the transport sector,** on one hand, and the increasing use of **individual mobility,** on the other hand, highly contribute to climate change, air quality degradation, resources depletion and noise emissions. In addition to these environmental impacts, transportation can have a substantial social and socio-economic impact on different stakeholder categories (i.e., users, workers, value chain actors, etc.).

The methodological framework developed in this PhD thesis supports the sustainability assessment of the ongoing energy transition, which requires radical transformations in production and consumption patterns. In the transport sector, the shift towards electric mobility, in particular, raises questions regarding its sustainability. While the environmental impacts of electric mobility have been widely addressed in the literature, **the associated social and socio-economic impacts are yet not fully addressed.** The weak knowledge of the social sustainability dimension is directly linked to the lack of availability and low level of maturity of the methods and tools for the identification, monitoring and management of the social and socio-economic impacts.

Among the most widely recognized evaluation methods for all three sustainability dimensions lies the Life Cycle Assessment (LCA). **LCA allows the analysis of the impacts that are generated all along the life cycle of products and services, from the extraction of raw materials to final disposal of products**. LCA approaches have significantly gained in maturity over the last years and are increasingly adopted to investigate the three sustainability dimensions through environmental LCA, Social-LCA and Life Cycle Cost (LCC). However, Life Cycle Sustainability Assessment (LCSA), which aims at bringing together the three LCA approaches into one integrated methodology, still faces major challenges.

The main findings of this thesis:

The present research sought to develop a **comprehensive framework for sustainability assessment based on LCSA**. This research contributes to enhance sustainability evaluation methods and provides insights on the assessment of the three dimensions. Moreover, the present thesis has explored how LCSA results can support the decision-making by integrating users' perspectives and, thus, help public and private actors better adapt their mobility offers to users' needs and expectations when developing sustainable mobility alternatives. To achieve this goal, two research questions were investigated:

<u>First Research question (RQ1):</u>

How can environmental, societal, and economic impacts be integrated into a comprehensive methodological framework to address sustainability with a life cycle perspective?

The first research question that has been explored sought to conceptualize a methodological framework for LCSA by integrating the three sustainability pillars. To achieve this goal, several challenges were highlighted. LCSA has been poorly addressed from a methodological point of view as most publications tends to focus on case studies. In response, chapter 2 is a key support for research in the field and provides insight on the different pathways to be explored for further developing a comprehensive LCSA methodology. Hence, **guidelines are presented by including the key features for each phase of the LCSA, in accordance with the ISO standards.** The main methodological issues to be addressed are highlighted.

The first issue was to ensure a clear **definition of the goal and scope** of the study to reach the coherence between all three sustainability dimensions, including the functional unit, system boundaries, and impact categories. Such elements were further explored through the definition of mobility scenarios studied in this thesis. Each scenario was characterized by four elements, namely the transportation technology, the mobility service, the transportation infrastructures, and the energy powering of the vehicle. Moreover, **introducing the users' perspective in the whole process has been a major milestone in the thesis as it adds a new feature to LCSA goal and scope definition.**

This novelty consists of the identification of the actors that are involved in the mobility scheme; main involved actors in the decision-making and those affected by these decisions. Such definition provides guidance for the development of LCSA framework and its implementation to a precise goal, namely supporting the decision-making process towards a sustainable mobility by integrating users' perspective in the present work. In fact, the literature review revealed a **major gap to overcome in order to better understand users' needs and expectations and to integrate them within LCSA for better informing decisions.** This need was also identified among the impact evaluation phase, especially in S-LCA, in which users' impact subcategories were poorly addressed in previous work. In response, **a new scheme was proposed by integrating their perception into the overall proposed framework.**

The second issue was linked to **LCSA impacts' evaluation phase.** Two methodological pathways for impact assessment were identified and explored. Pathway 1 aimed at developing a combined impact assessment for LCSA by developing specific characterization models for each sustainability dimension. Although it can be beneficial for ensuring the coherence of the framework, this pathway poses major obstacles due to the need to gain more knowledge of the social and economic dimensions. In fact, current development of S-LCA and LCC does not allow covering a similar level of detail as the environmental LCA. Moreover, the accuracy of such quantitative models was questioned in view of the limitations that can occur to address all the significant impacts and stakeholder categories. In this regard, a second pathway was explored and adopted in this thesis to design the comprehensive LCSA framework using an individual application of the impact assessment approaches. **Such pathway enables the consideration of the heterogeneous nature of each sustainability dimension by choosing compatible assessment approaches for the environmental, social, and economic impacts**.

The implementation of LCIA approaches was performed for three electric mobility scenarios for passengers' transportation in urban areas:

- **Scenario 1: personal mobility,** consists of the individual use of private passenger cars including five different electric and conventional powertrains.
- **Scenario 2: shared transportation**, consists of buses transportation including four conventional and electric powertrains.
- **Scenario 3: shared mobility,** which consists of a carpooling use including five different electric and conventional powertrains.

The evaluation was conducted for the French context by considering the national electricity mix. Moreover, the implementation of the LCIA approaches to these scenarios enabled specific methodological issues within each of them to be addressed. To enable the implementation of the overall framework following the second identified LCSA assessment pathway, chapters 3, 4 and 5 have targeted the three sustainability dimensions separately.

The environmental evaluation was performed in chapter 3 for the three defined mobility scenarios. A literature review was conducted according to the main environmental impact categories (i.e., climate change, air quality, noise levels, resources depletion) and life cycle stages of transportation systems (i.e., manufacturing stage, use phase and end of life). This analysis enabled the definition of key input parameters to be integrated within the environmental LCA studies, such as the driving cycles, fuel pathways and electricity mixes.

This chapter **proposed a systematic approach for the implementation of parametrized LCA models** allowing to consider the defined key input parameters within the assessment. Such approach entails the main steps to integrate LCA parametrized models, which enhance the representativeness of the existing datasets by including the multiple specificities and technological advances that may occur over time. Hence, it was used to integrate different LCA models from the literature and to adjust the identified key input parameters to the defined mobility scenarios in this thesis. The interpretation of results for the environmental impact categories did not show a clear clustering in the environmental performance as the different powertrains conducted to a large variability of the environmental impact results.

⇨ Electric vehicles exhibited a low contribution to climate change, to a large extent linked to the use of electricity from the French mix, relatively dominated by nuclear energy, as the energy source in the use phase.

⇨ In contrast, higher environmental impacts were recorded by electric vehicles compared to their conventional counterparts for resource depletion (i.e., use of water and metal resources) and ecosystem quality (i.e., ionizing radiation, freshwater ecotoxicity and marine eutrophication). These impacts mainly derived from the electric batteries' production which led to higher impacts in the case of full BEV than in the case of PHEV.

⇨ Public transportation (scenario 2) showed a better environmental performance compared to personal and shared mobility; hybrid electric technologies can be a lever for reducing the environmental footprints of transportation and improving local air quality in dense urban areas.

Chapter 4 presents the social and socio-economic evaluation of the considered mobility scenarios. The present thesis especially contributed to S-LCA methodological development focusing on the enhancement of evaluation of social and socio-economic impacts. To this end, chapter 4 started by identifying the main methodological issues and current limitations within S-LCA studies for mobility and introduced the bottlenecks to be addressed.

- The definition of impact subcategories to be analyzed in S-LCIA is blurred and calls indirectly for a selection step. Most S-LCA studies solely use the literature review to do such selection, which often lacks transparency. In contrast, participatory approaches have been rarely introduced, which can further legitimate such process.
- The evaluation of social and socio-economic impacts hardly dealt with users' stakeholder group due to the lack of data and the complexity that may arise when conducting a specific impact analysis.

In response, the present thesis proposed a comprehensive S-LCA framework in accordance with ISO standards to address the above-mentioned issues. The proposed step-by-step S-LCA framework integrates two innovative features:

⇨ **A participatory approach for the selection of the relevant impact subcategories within S-LCA (Bouillass et al. 2021)**[8]

The participatory approach introduced in this chapter entails two stages: (1) the identification stage, enabling the definition of sectorial-based impact subcategories for each stakeholder group throughout the life cycle of the product, and (2) a general consultation process designed to enable the prioritization of the identified impact subcategories and to consider the most relevant ones from the perspective of all concerned stakeholders. The selected social and socio-economic impact subcategories were then used to perform the S-LCIA phase and thus, contribute to a

[8] G. Bouillass, I. Blanc et P. Perez-Lopez (2021) Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios, International Journal of Life Cycle Assessment (In press)

comprehensive analysis in the interpretation phase. This work is published in the International Journal of Life Cycle Assessment.

⇨ **A specific analysis of user-related impact subcategories.**

The second introduced feature sought to support the evaluation phase, usually conducted through a generic evaluation, by adding a user-centric specific impact assessment of mobility services (i.e., personal, public and shared mobility use). The user-centric impact assessment approach was therefore explained, covering from the definition of new impact subcategories and data collection to the assessment and the interpretation of results.

In addition to these two methodological features, chapter 4 proposed different toolboxes to support S-LCA practitioners to generalize the proposed framework to other product systems. These provide some key requirements for designing the consultation process and conducting the specific analysis.

The work carried out in this chapter demonstrated the interest of participatory approaches to boost stakeholders' involvement within S-LCA framework. This is essential for further legitimating the selection of impact subcategories and improving the representativeness of the finding. Nevertheless, the chapter pointed out the main limitations that might be raised when applying this framework:

- The long duration and large sample size required of the surveys that need to be carefully designed,
- The data availability
- The missing link between the proposed specific assessment and the used activity variable (working hours) in the evaluation phase.
- The difficulty to cover the evaluation phase of S-LCA with a similar level of detail to that of the environmental dimension, due to missing data and the complexity of modeling the different powertrains.

Future research should further focus on the development of appropriate activity variables and account for users-related impact categories. The proposed framework can be used, adapted and/or adjusted to analyze other products and sectors by adding new impact subcategories and stakeholder groups, namely the ones proposed in the most recent version of UNEP S-LCA guidelines.

Within the economic evaluation of electric mobility scenarios, chapter 5 started by introducing the main elements of LCC together with an extensive literature review of LCC studies that targeted a wide scope of transportation (i.e., technologies, services, infrastructures, etc.). The main limitations linked to the development of LCC were highlighted, especially when conducted in the frame of a sustainability analysis. In fact, this chapter served to identify two main categories of issues linked to

- **The methodological development of LCC. T**here is still an important methodological gap for a standardized LCC method that brings together the different techniques for economic assessment (Cost-benefit analysis, externalities, TCO, etc.). In addition, economic impact assessment approaches are still lacking, which is even more critical when conducting a combined impact assessment within LCSA (pathway 1).

- **The application of LCC to mobility scenarios:** most studies in the literature targeted a technological level, yet no prior study has used LCC for mobility services analysis. Moreover, the life cycle perspective is not fully covered as most studies fail to consider the manufacturing and end of life cycle stages.

In view of the identified challenges, chapter 5 provided two main outcomes:

- ⇨ **Establishment of key LCC phases in accordance with ISO standards (ISO 14040).** Key features to be covered within each phase of LCC are introduced. The provided insight should help LCC practitioners to better characterize their specific needs and enable the selection of the appropriate LCC approach that better fits the needs of their studies.
- ⇨ **Introduction of a user-centric approach to enable the cost assessment of the three defined mobility scenarios.** Such approach entails the assessment of transportation technologies through a TCO model, and mobility services were analyzed by computing the cost effectiveness of the three considered mobility services.

The delivered results from the three chapters corresponding to the environmental, social and economic evaluation of mobility scenarios were used in the interpretation phase. However, a straightforward interpretation of LCSA results appeared to be insufficient to support decision makers within the development of sustainable mobility alternatives. This is due to the multidimensional nature of sustainability, namely resulting in potential environmental impacts from LCA, social risks and performance from S-LCA and cost indicators from LCC. This nature induces a multicriteria problem in which the analyzed mobility scenarios delivered heterogeneous performances among the different sustainability dimensions, but also within each dimension. Such issues where, thus, addressed in the present PhD thesis by introducing MCDA approaches which may help tackling the emerging trade-offs from LCSA results. This methodological contribution is directly linked with the second research question that was identified in the introduction of this PhD thesis.

Second Research Question (RQ2):

How can LCSA results support the decision-making process within electric mobility context considering actors' perspectives, including users?

This PhD work looks, through this second research question, **to support private and public actors of mobility within the design of sustainable mobility alternatives integrating users' needs and expectations.** To this end, MCDA techniques were introduced to manage the trade-offs induced from LCSA results. Three main groups of MCDA approaches were therefore identified and explored to select the most appropriate approach to serve the goal of this study.

(1) The proposed framework was presented in chapter 2, to couple the chosen MCDA approach to LCSA results. **Users are involved in the proposed framework to select the most relevant sustainability decision criteria that guide their mobility choices and subsequently to perform the preference analysis.** The proposed stages entailed the definition of the decision-making scenarios including the mobility alternatives, the key actors and the travel characteristics to be investigated,
(2) The selection of sustainability decision-making criteria according to the considered actor's perspective, and
(3) The application of the selected MCDA approach for the study.

The conjoint analysis was selected among different MCDA techniques to be explored in view of its ability to integrate users' preferences and, thus, help public and private actors better adapt their mobility offers to their needs and expectations when developing sustainable mobility alternatives. **Such technique avoids the use of a pairwise comparison** that generally requires high knowledge of the considered sustainability decision criteria from the involved actors, which is usually not the case in this field of application. The **preference analysis focuses on the performance of the different criteria rather than their direct ranking,** which makes it possible to define a set of alternatives profiles that are closer to real-world decision scenarios. Such technique **may enhance the accuracy and representativeness of the investigated decision scenarios.**
However, to reduce the number of combinations and enable the practical application of the conjoint analysis, **only a limited number of decision criteria are allowed**. This can raise questions especially within sustainability analysis, which calls for a significant number of impact categories to be analyzed. To explore these issues, chapter 6 presented a real-world case study where the overall proposed framework was implemented.

The case study was carried out for **a specific daily commuting travel from Antibes to Sophia Antipolis** and focused on the application of the proposed framework coupling MCDA to LCSA results interpretation. The objective of this case study was to demonstrate the applicability of the proposed framework to enhance the interpretation phase of LCSA. Key elements of decision scenarios including mobility actors, mobility alternatives and travel characteristics were defined. It is important to remind that within this thesis, **users are considered as key actors for mobility but not as decision makers.** Mobility alternatives from the specific case study were analyzed.
A divergence was revealed between standard LCSA impact categories and sustainability criteria generated by the consulted users which are not familiar with LCA. This was identified as an issue related to LCSA results exploitation. Thus, the previous environmental LCA, S-LCA and LCC did not include some of the decision criteria identified by users, whereas the life cycle perspective was not systematically integrated within these criteria, especially for the social dimension (travel duration,

accessibility, health and safety). In fact, all generated issues were linked to users' impact subcategories and did not translate the social and socio-economic impacts for other stakeholder groups. The use of the direct citation method in the conducted focus group can therefore raise questions in view of the impact it can have in leading the whole results of the defined framework. It is important to note that the selection of decision criteria often introduces a value choice, which may lead to certain limitations. Close-ended questions can raise question giving that the practitioner affects to some extent the choice of the involved actors by imposing a set of criteria to be selected. In addition, using such approach can be limited due to the required knowledge of LCSA and the different impact subcategories. Future research can focus on exploring other alternatives for the selection of the decision criteria, but also consider other MCDA techniques that do not call for this selection. For instance, decision-making utility methods that are based on empirical observations, may be relevant to analyze decision scenarios. These approaches allow a maximum number of decision criteria to be considered, but do not enable the involvement of stakeholders which was the reason they have not been selected. The preference analysis was conducted through a Choice-Based Conjoint (CBC) which allowed the number of the combinations to be reduced and thus enabled a higher number of decision criteria to be considered, compared to a full-profile preference analysis. Five different decision criteria were considered, namely:

- → Accessibility (social dimension)
- → Travel duration (social dimension),
- → Contribution to climate change (environmental dimension)
- → Local air quality (environmental dimension)
- → Monthly costs (economic dimension)

The application of the CBC approach allowed determining the weighting factors for each of the criteria. According to the results, the environmental dimension was perceived as more important than the other dimensions and was weighted at 53% in total, with 32% attributed to climate change and 21% to air quality. The economic dimension took the second place and was weighted at 31%. Finally, the social dimension took the third position and was weighted at 16% with 8% equally attributed to accessibility and travel duration. The interpretation of the results has brought to light the awareness of mobility users to the environmental, social and economic aspects related to their daily choices. Such results highlight the importance of considering users' perspective within the design of sustainable mobility alternatives. The conjoint analysis was for this and very relevant and enabled introducing users' preferences in an effective way.

Several prior studies have introduced weighting approaches to LCSA. These studies used different MCDA techniques to better manage the trade-offs induced from LCSA results and to communicate sustainability assessment results in a clearer manner. However, the consistency of these approaches has not been thoroughly analyzed in previous studies. In fact, a wide range of MCDA approaches can be used, as previously explained, which often calls for value choices that are not sufficiently justified and transparent. In this regard, the present work added a deeper insight in the interpretation of results to check the accuracy of the weighting factors with a large-scale survey conducted in the same geographical area of the study across 3 642 transportation users. The results of data analysis for the large-scale study revealed a significant divergence in the results with respect to the focus group results. Thus, in the large-scale study, social dimension obtained the highest score among the different drivers for users' choices. The consulted users ranked the environmental dimension as second position and finally the economic dimension took the last position of the scoring.

Such results reveal a major limitation and question the whole weighting approach and its reliability to support the decision-making process. In fact, the integration of such approaches can lead to a simplistic interpretation of sustainability results and a misuse of the results in the decision-making. This can be explained by the following reasons:

- ⇨ **The number of selected decision criteria selected needs to be limited, so as to facilitate the implementation of the chosen MCDA approach**. Hence, it prevents considering all the analyzed impact categories within LCSA to support the decision-making.
- ⇨ **Weighting approaches call for the introduction of value choices that systematically induce a partial representation from the concerned stakeholder of the significant impact categories**. In fact, the focus group revealed that users identified merely decision criteria that directly affect them but do not consider the impacts on other stakeholder categories and other life cycle stages.
- ⇨ **Representativeness of the used sample can significantly influence the final obtained results.** The conducted focus group and the preference analysis although targeting users from the same geographical area, demonstrated significant differences in the results.
- ⇨ **Outcomes from the MCDA are highly dependent on the MCDA technique type**. Hence, the consistency of the obtained results should be carefully analyzed. Future research can focus on experimentation of different MCDA techniques and comparison of the results to identify the variability of the ranking. In the present study, the ranking was analyzed regarding the representativeness of the sample.

Other MCDA approaches should be defined to ensure that decision-making based on LCSA is consciously made and accounts for the different sustainability dimensions and for the impact categories within each dimension. It is also important to ensure that the life cycle perspective is respected, and the defined decision criteria cover the impacts for the different stakeholder categories. Compensation between the different positive and negative impacts, which can lead to a misinterpretation of results, should be carefully handled. Hence, it is for future research studies to investigate how to avoid such compensation of impacts within a sustainability dimension or among the three dimensions when considered jointly.

Generalization of the proposed framework to other mobility scenarios and other actors

The current thesis work sought to contribute to research and application of LCSA by proposing a consistent methodological framework for mobility scenarios. Such framework paid especial attention to stakeholders' involvement and, more specifically, users' expectations and needs in terms mobility to support the decision-making towards a sustainable mobility. The proposed framework can be adjusted to cover other products and systems and include other stakeholders' perspectives. The following suggestions are proposed as an outcome of this PhD thesis to ease adopting the framework and its application to other product systems:

- ⇨ **The study should pay especial attention to the goal and scope of the study, to clearly define the system boundaries and prevent important key stakeholders from being excluded**. In S-LCA, users' or consumers' stakeholder groups should not be let out of the scope and efforts should be deployed to further account for their relative social and socio-economic impacts. The involvement of users within the design phase can significantly improve the accuracy of decision-making by investigating potential future societal resistance from the development of the alternatives under consideration.
- ⇨ **The involvement of stakeholders within the definition of the impact categories appeared to be very relevant for narrowing down the scope to indicators that were perceived for them as important.** If possible, the study should include a participatory approach that enables a large panel of stakeholders' perceptions to be covered for the definition of the relevant impact subcategories. Participatory approaches can be an interesting alternative instead of classical weighting of impact assessment results, which introduces the value choices impact subcategories before the assessment.
- ⇨ Future studies can use the proposed stages to explore **other MCDA techniques and account for other stakeholders' perspectives and decision scenarios.** These studies should carefully select the most appropriate MCDA technique in such a way that serves their specific goal and scope. In the present thesis, the conjoint analysis was convenient to account for the users' perspective. Nevertheless, it should be noted that this approach can also be adapted for other stakeholders. The proposed recommendations in chapter 5 can be used to explore other data collection procedures through the design of different consultation processes to involve the different stakeholders.

The work carried out in this PhD has the ambition to foster the development of LCSA, which undeniably can provide thorough insight on the three sustainability dimensions with a life cycle perspective. Such comprehensive vision is more than ever necessary to inform the ongoing transition towards sustainable production and consumption patterns.

Finally, in order to bypass wild storms, the ship does not only need strong stirring, but also skillful captain that know how to follow the available maps.

Glossary

Term	Definition
Activity variable	"An activity variable is a measure of process activity or scale which can be related to process output. Activity variables, scaled by the output of each relevant process, are used to reflect the share of a given activity associated with each unit process. A relevant activity variable is worker-hours. Process-specific coefficients of worker-hours per unit of process output are used to estimate the share of total life cycle worker-hours associated with each unit process."[9]
Area of protection	"A state that is desired to be sustained or protected which is of recognizable value to society, in the specific context of sustainability assessment. In the field of S-LCA, one area of protection has been defined and is referred to as human well-being (health and happiness) or simply social well-being." **Erreur ! Signet non défini.**
Attributes	In MCDA, the attributes correspond to the decision-making criteria that are considered within the study.
Characterization factor	Factor, derived from a characterization model, that is applied to convert an assigned Life Cycle Inventory Analysis result to the common unit of the category and/or subcategory indicator.[10]
Choice-based conjoint (CBC)	Technique that enables the preference analysis within the conjoint analysis by proposing a set of possible profiles that reflect different specifications of the attributes (e.g. decision-making criteria)
Conjoint Analysis (CA)	A type of MCDA that uses an outranking preferences model. The considered stakeholders are thus involved to rank different combinations / profiles according to their preference and meeting their needs and expectations.
Cost category	A class of cost indicators, which helps categorizing the different indicators within a Life Cycle Cost Inventory phase. These indicators can correspond to a specific sustainability dimension (environmental cost categories, social cost categories) or to a specific stakeholder (e.g. users-related costs, manufacturers and designers-related costs), or to a specific life cycle stage (manufacturing costs, operation costs, energy production costs, end of life costs).
Decision-maker	Public actors developing transportation-specific policies and action plans and/orprivate actors such as designers of transportation technologies and services providers, etc.
Decision-making scenario	A specific scenario that involves different mobility actors, mobility alternatives with specific geographical and urban characteristics.

[9] Definition from **UNEP. (2020)**. *Guidelines for Social Life Cycle Assessment of Products and Organizations* (C. Benoît Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A. Lehmann, M. Finkbeiner, & G. Arcesse, Eds.). United Nations Environment Programme (UNEP). https://www.lifecycleinitiative.org/wp-content/uploads/2020/12/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-sml.pdf

[10] ISO 14040. (2006). *Environmental management—Life cycle assessment—Principles and framework*. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html

Focus group	"A focus group is a type of group interview organized to acquire a portrait of combined local perspective on a specific set of issues. What distinguishes the focus group technique from the wider range of group interviews is the explicit use of the group interaction to produce data and insights that would be less accessible without the interaction found in a group."[9]
Functional unit	"Quantified performance of a product system for use as a reference unit in a life cycle assessment study, and also valid for an S-LCA"[9]
Impact category	"A social impact category is a class that covers certain social issues of interest to stakeholders and decision makers. In practice, impact categories are logical groupings of S-LCA (subcategory) results."[9]
Impact Pathway Social Life Cycle Assessment	"Impact pathway S-LCIA assesses potential or actual social impacts by using causal or correlation/regression-based directional relationships between the product system/organizations' activities and the resulting potential social impacts – a process called "characterization". Here, the analysis focuses on identifying and tracking the consequences of activities possibly to longer-term implications along an impact pathway."[9]
Impact subcategory	"It is a constituent of an impact category that is assigned to a stakeholder group, for example "Health and Safety" for the stakeholder group "Workers". Multiple subcategories, possibly across various stakeholder groups, may be part of an overarching impact category" **Erreur ! Signet non défini.**
Inventory indicator	"An indicator is a measurement or value which gives you an idea of what something is like"[9]
Life Cycle Assessment (LCA)	"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"[10]
Life Cycle Cost Inventory (LCCI)	In this research, LCCI consists of data collection including all cost indicators and input parameters defined within the goal and scope and with respect to the system boundaries.
Life Cycle impact assessment (LCIA)	"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product."[10]
Life Cycle Interpretation	"Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations"[10]
Life cycle inventory analysis	"Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle."[10]
Life Cycle Sustainability Assessment (LCSA)	Methodological framework that introduces the life cycle perspective to the three-sustainability dimension by bringing together the environmental LCA, S-LCA and LCC. It allows the evaluation of the environmental impact categories, stakeholder impact subcategories and costs categories of the product system under consideration.
Life Cycle Thinking	"Going beyond the traditional focus on production site and manufacturing processes so to include the environmental, social, and economic impact of a product over its entire life cycle. [*UNEP-DTIE-Life Cycle Management, a Business Guide to Sustainability*]"[9]
Materiality Assessment	"Materiality assessment is a process to select topics that are more important because of their impact on stakeholders and/or on the business. The Global Reporting Initiative consider material issues to be the ones that reflect the organization's significant social impacts; or that substantively influence the assessments and decisions of stakeholders. This is also recommended by ISO 26000"[9]

Methodological framework	Coherent set of methods
Mobility	Is the ability of people and goods to be moved by means of transportation
Mobility actors	Key stakeholders that are directly involved in the decision-making process. It can be **decision-maker**s, e.g. public authorities and transportation policy-makers, or private actors such as transportation manufacturers, services providers, etc. or a**n interested party** who is significantly and directly affected by the mobility decision scheme such as users, local communities, etc.
Mobility scenario	Defined through four elements in this research: mobility services, transportation technologies, transportation infrastructure and energy consumption
Mobility services use	Service whose purpose is to provide mobility solutions to people. Three main categories are distinguished in this research: personal mobility, public / collective mobility and shared mobility.
Modal shift	Designates the modification of the market shares between the various modes of transportation. It is most commonly used to promote alternative modes of transport to substitute the individual use of private vehicles.
Multicriteria decision analysis (MCDA)	A methodology that aims through various available techniques to support the decision-making process by explicitly managing the multiple conflict criteria and that could present antagonist results, e.g. cost versus comfort versus emissions, could be considered when purchasing a car.
Organization	"Company, corporation, firm, enterprise, authority, or institution, or part or combination thereof, whether incorporated or not, public or private, that has its own functions and administration. [ISO 14001 (2004)]"[9]
Parametrized LCA model	Model assessing the environmental impacts in LCA according to set parameters identified with a high influence on results.
Participatory approach	"Approach in which actors participate and contribute to the study or scientific process"[9]
Performance indicators	"Quantitative and qualitative markers of performance for each of the social topics, e.g. number of working hours during weekends, minimum wage paid, etc."[11]
Performance Reference Points (PRPs)	"Thresholds, targets, or objectives that set different levels of social performance or social risk. PRPs allow to estimate the magnitude and significance of the potential social impacts associated with organizations in the product system. The PRPs are context-dependent and are often based on international standards, local legislation, or industry best practices – Comparing inventory indicator data with PRPs allows to qualify performance on a scale"[9]
Potential social and socio-economic impacts	"Social topic for which an adverse impact is probable; the probability could also be quantified (e.g. child labor is a social risk, with high probability, since cotton production takes place in Country X where probability for child labor is generally high)"[9]
Reference Scale Social Life Cycle Impact Assessment	"Reference scale S-LCIA assesses the social performance in the product system. More specifically, it assesses the social performance of activities of organizations in the product system (e.g., the practices implemented to manage social impacts) based on specific reference points of expected activity (called performance reference points - PRPs)."**Erreur ! Signet non défini.**

[11] Fontes, J., Gaasbeek, A., Goedkoop, M., Contreras, S., & Evitts, S. (2016). *Handbook for Product Social Impact Assessment 3.0*. PréSustainability. http://dx.doi.org/10.13140/RG.2.2.23821.74720

Reference scales	"Reference scales are ordinal scales, typically comprised of 1 to 5 levels, each of which corresponds to a performance reference point (PRP)."[9]
Social hotspot	"A social hotspot is a location and/or activity in the life cycle where a social issue (as impact) and/or social risk are likely to occur. It is usually linked to life cycle stages or processes. It needs to contribute significantly to the impact (overall, by impact category or subcategory). In other words, social hotspots are unit processes located in a region where a problem, a risk, or an opportunity may occur in relation to a social issue that is considered to be threatening social well-being or that may contribute to its further development." Erreur ! Signet non défini.
Social impact	"Social impacts are consequences of positive or negative pressures on social endpoints of area of protection (i.e. well-being of stakeholders)."[9]
Social inventory indicators	"Social indicators are evidence, subjective or objective, qualitative, quantitative, or semi-quantitative being collected in order to facilitate concise, comprehensive and balanced judgements about the condition of specific social aspects with respect to a set of values and goals."[9]
Social performance	"Refers to the principles, practices, and outcomes of businesses' relationships with people, organizations, institutions, communities, and societies in terms of the deliberate actions of businesses toward these stakeholders as well as the unintended externalities of business activity measured against a known standard (Wood, 2016). Commonly, social performance is measured at the inventory indicator level."[9]
Social risk	"Social topic for which an adverse impact is probable; the probability could also be quantified (e.g. child labor is a social risk, with high probability, since cotton production takes place in Country X where probability for child labor is generally high)"[9]
Sectorial social risk analysis	A screening of social risks related to the investigated product system, including the geographical location, sector, activities, stakeholders that are involved.
Social significance	"Social significance is a judgment on the degree to which a situation or impacts are important. It is highly dependent on context, based on criteria, normative, contingent on values, and entails considering trade-offs."[9]
Socio-economic	"Which involves a combination of social and economic factors or conditions."[9]
Stakeholder	"Individual or group that has an interest in any activities or decisions of an organization. [ISO 26000, 2008]."[9]
Stakeholder category	"Cluster of stakeholders that are expected to have similar interests due to their similar relationship to the investigated product system."[9]
Sustainability decision-criteria	Represent the LCSA impact categories that are processed in the interpretation phase through an MCDA approach. They can be directly derived from LCSA or selected by the involved stakeholders.
Transportation	The means by which people and freight are moved from point A to point B.
Unit process	"Smallest element considered in the life cycle inventory analysis for which input, and output data are quantified"[10]
Users	Refers to "consumers", "customers", or "passengers". This category corresponds to primary users by whom the investigated product is intended to be used or consumed. It does not include the secondary users, namely workers in the use phase such as bus drivers.
Weighting	"Converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices; data prior to weighting should remain available."[9]

Acronyms & Signification

AVAS	Acoustic Vehicle Alerting System
BEV	Battery Electric Vehicle
CA	Conjoint Analysis
CASA	Communauté d'Agglomération Sophia Antipolis
CBC	Choice-Based Conjoint
CE	Circular Economy
CSR	Corporate Social Responsibility
CSS	Country Specific Sector
EC	European Commission
E-LCC	Environmental Life Cycle Costing
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
IP S-LCIA	Impact Pathway Social Life Cycle Impact Assessment
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
ISO	International Standardization Organization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
MCDA	Multicriteria Decision Analysis
MRIO	Multi Regional Input Output
NEDC	New European Driving Cycle
OECD	Organization for Economic Co-Operation and Development
PHEV	Plugin Hybrid Electric Vehicle
PM	Particulate Matter
PRP	Performance Reference Points
PSIA	Product Social Impact Assessment
PSILCA	Product Social Impact Life Cycle Assessment
RS S-LCIA	Reference Scale Social Life Cycle Impact Assessment
SDG	Sustainable Development Goals
SETAC	Society of Environmental Toxicology and Chemistry
SHDB	Social Hotspot Database
S-LCA	Social Life Cycle Assessment
S-LCC	Social Life Cycle Costing
S-LCI	Social Life Cycle Inventory
S-LCIA	Social Life Cycle Impact Assessment
TCO	Total Costs of Ownership
UNEP	United Nations Environmental Program
WHO	World Health Organization
WLTC	Worldwide Harmonized Light Vehicles Test Conditions

RÉSUMÉ

Le transport est l'un des principaux moteurs du développement socio-économique, mais il est aussi une source majeure de pollution qui menace l'environnement et la société dans son ensemble. Substituer les systèmes actuels de transport basés sur les énergies fossiles vers des modèles de mobilité plus durables est une orientation qui mérite d'être explorée, notamment la mobilité électrique qui explose actuellement sur le marché. A cet égard, il est incontournable de caractériser les impacts environnementaux, sociaux et économiques qui lui sont associés. Ces informations sont indispensables pour permettre aux acteurs publics et privés de prendre des décisions éclairées afin de gérer au mieux cette période de transition.

Cette thèse de doctorat vise à concevoir un cadre global d'évaluation de la durabilité de scénarios de mobilité, en adoptant une perspective de cycle de vie. L'analyse de la durabilité du cycle de vie (ADCV) est au cœur de la contribution méthodologique de ces travaux. Celle-ci étant encore à un stade précoce de développement, implique la résolution de défis méthodologiques majeurs. À cet égard, des lignes directrices pour la conduite de LCSA sont proposées avec un cadre complet pour évaluer les scénarios de mobilité électrique sous l'angle à la fois des technologies et des services de transport. L'implication des parties prenantes est explorée à travers une vision intégrée de l'ADCV à la prise de décision. En particulier, les usagers des transports sont au centre de l'attention de ces travaux pour permettre la prise en compte de leurs besoins et attentes dans le contexte d'une prise de décision par les décideurs (pouvoirs publics et industriels) en faveur d'une mobilité durable. Ainsi, afin d'apporter des connaissances pertinentes sur la durabilité aux décideurs, l'analyse multicritères de décisions est introduite pour gérer les conflits potentiels issus des résultats de l'analyse de durabilité tout en tenant compte des perceptions des utilisateurs. Cette approche devrait faciliter la connexion avec les autorités publiques et les acteurs industriels, impliqués dans le processus de prise de décision, en leur fournissant simultanément des informations scientifiques sur les trois dimensions de la durabilité et les perceptions des utilisateurs.

MOTS CLÉS

Mobilité électrique, Analyse de durabilité, Analyse de Cycle de Vie environnementale, Analyse Sociale de Cycle de Vie, Analyse de Coûts de Cycle de vie, Approche participative, Analyse multicritère de prise de décision

ABSTRACT

Transportation is one of the main drivers of socio-economic development, but it is also a major source of pollution that threatens the environment and society. Substituting current fossil fuel-based transportation systems for more sustainable mobility models is a worthy direction to explore, especially electric mobility which is currently exploding on the market. In this respect, it is essential to characterize the environmental, social and economic impacts associated with it. This information is essential to allow public and private actors to make informed decisions to best manage this transition period.

This PhD thesis aims to design a comprehensive framework for assessing the sustainability of mobility scenarios, adopting a life cycle perspective. Life cycle sustainability analysis (LCSA) is at the core of the methodological contribution of this work. It is still at an early stage of development and involves the resolution of major methodological challenges. In this respect, guidelines for conducting LCSA are proposed with a comprehensive framework for evaluating electric mobility scenarios with respect to both technologies and transport services. Stakeholder involvement is explored through an integrated view from LCSA to decision making. In particular, transport users are at the center of attention of this work to allow their needs and expectations to be accounted for in the context of decision making by decision makers (public authorities and industry) in favor of sustainable mobility. Thus, to provide relevant knowledge on sustainability to decision makers, multi-criteria decision analysis is introduced to manage potential conflicts arising from the results of the sustainability analysis while accounting users' perspective. This approach should facilitate the connection with public authorities and industrial actors, involved in the decision-making process, by providing them simultaneously with scientific information on the three dimensions of sustainability and users' perspective.

KEYWORDS

Electric mobility, Life Cycle Sustainability Assessment, Environmental Life Cycle Assessment, Social Life Cycle Assessment, Life Cycle Costing, Participatory approaches, Multicriteria Decision Making