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Optimal decarbonization of residential heating till 2050 : technology choices and sectorial implications of carbon neutrality trajectories for France

Zixuan Wang

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THÈSE DE DOCTORAT
DE L'UNIVERSITÉ PSL

Préparée à Mines Paris - PSL

**Optimal decarbonization of residential heating till 2050:
technology choices and sectorial implications of carbon
neutrality trajectories for France**

**Décarbonation optimale de la chaleur résidentielle à l'horizon
2050: choix technologiques et implications sectorielles de
trajectoires de neutralité carbone pour la France**

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Le 08/07/2024

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Abbreviations

ADEME: Agence de l'environnement et de la maîtrise de l'énergie (in French)

Agreste: La statistique, l'évaluation et la prospective agricole du ministère de l'Agriculture et de la Souveraineté alimentaire (in French)

AME: Avec Mesures Existantes (in French)

AMS: Avec Mesures Supplémentaires (in French)

BECCS: Bioenergy with Carbon Capture and Storage

bioNGV: Natural Gas Vehicles fueled by biogas

CAGR: Compound Annual Growth Rate.

CCS: Carbon Capture and Storage

CEREN: Centre d'études et de recherches économiques sur l'énergie (in French)

CGDD: Commissariat général au développement durable (in French)

CSTB: Centre Scientifique Technique Du Bâtiment (in French)

DACCS: Direct Air Carbon Capture and Storage

DGEC: Direction générale de l'énergie et du climat (in French)

DHW: Domestic hot water

DROM: Départements et Régions d'Outre-Mer (in French)

EPR2: Evolutionary Power Reactor 2

ETSAP: The Energy Technology Systems Analysis Program

Gpkm: billions of passenger-kilometers

Gt: gigaton

IGCC: integrated gasification combined cycle

IGN: Institut national de l'information géographique et forestière (in French)

IH: Individual house

INSEE: Institut national de la statistique et des études économiques (in French)

IPCC: Intergovernmental Panel on Climate Change

IRIS: îlots regroupés pour l'information statistique (in French)

JRC: Joint Research Center of the European Commission.

LPG: Liquefied Petroleum Gas

LTECV: Loi relative à la transition énergétique pour la croissance verte (in French)

LUV: Light Utility Vehicle

Mt: megaton

ONRE: Observatoire national de la rénovation énergétique (in French)

PACTE: Programme d'Action pour la qualité de la Construction et la Transition Energétique (in French)

Phébus: Enquête Performance de l'Habitat, Équipements, Besoins et Usages de l'énergie (in French)

PPE: Programmations pluriannuelles de l'énergie (in French)

PSP: Pumped storage power plants.

RES: Renewable energy sources

RRE: Renewable and Recovered Energies

RTE: Réseau de transport d'électricité (in French)

SDES: Service des données et études statistiques (in French)

SNBC: Stratégie nationale bas carbone (in French)

SNCU: Syndicat National du Chauffage Urbain et de la Climatisation Urbaine (in French).

SPEGNN: Syndicat Professionnel des Entreprises Gazières Non Nationalisées (in French)

STEP: Storing Energy through Pumped hydro

TREMI: Enquête sur les travaux de rénovation énergétique dans les maisons individuelles (in French)

V2G: Vehicle-to-Grid

Table of contents

Remerciements.....	2
Abbreviations	4
Table of contents.....	6
General introduction	11
Chapter One: The challenge of decarbonizing residential buildings in France	14
Introduction.....	14
Résumé	17
1.1 Role of residential buildings in national environment ambitions	20
1.1.1 Energy and emissions balance: the importance of mitigating emissions from residential buildings to achieve carbon neutrality.....	20
1.1.2 Efforts achieved until now and the challenges of reaching carbon neutrality.....	25
1.2 Overview of published scenarios up to 2050: energy transition visions of different stakeholders	28
1.2.1 AME 2021 and AMS 2018	29
1.2.2 ADEME scenarios.....	34
1.2.3 NégaWatt 2022.....	38
1.2.4 Gas and electricity perspectives	39
1.3 Current state of residential building stock: large presence of buildings with low energy efficiency	43
1.3.1 Climate features and geographical location as important factors to consider.....	43
1.3.2 High presence of buildings with low thermal performance.....	46
1.3.3 Overview of heating equipment stock: high presence of heating oil and natural gas.....	48
1.3.4 Challenge of the future energy transition: illustration from DPE statistics	49
1.4 An overview of eligible technology solutions for the future residential energy transition	51
1.4.1 Thermal insulation as a key solution for existing residential buildings.....	52
1.4.1.1 Techniques for insulation retrofits	52
1.4.1.2 Fabric retrofits as an important solution for existing housings and policy ambitions ..	52
1.4.1.3 Current pace of renovation: unbalanced level between individual houses and apartments	54
1.4.1.4 Potential difficulties for insulation retrofits in buildings.....	55
1.4.2 An overview of efficient heating solutions for buildings.....	58
1.4.2.1 Condensing boiler.....	59

1.4.2.2 Electric heat pumps	61
1.4.2.3 Solar thermal systems	63
1.4.2.4 Residential fuel cells for heating	66
1.4.2.5 Efficient district heating (DH) networks	68
Conclusion	71
Chapter Two Exploring an energy solution for a future decarbonized residential system: a TIMES approach.....	72
Introduction.....	72
Résumé	75
2.1 A prospective modeling approach: TIMES.....	79
2.1.1 Key features of TIMES.....	79
2.2.1.1 Energy system in the view of TIMES.....	79
2.2.1.2 Optimization paradigm of TIMES	81
2.2.1.3 Temporal definition	82
2.2.2 TIMES-FR, a detailed representation of the French energy system.....	83
2.2.2.1 General description of model structure	83
2.2.2.2 Time slices and time periods	85
2.2.3 Representing the building energy system: TIMES compared with other solutions	86
2.2 Our contributions on the modeling side	88
2.2.1 Improvement of supply side.....	89
2.2.1.1 Renewable gas supply	89
2.2.1.1.1 Overview of technologies to produce renewable gases	89
2.2.1.1.2 Representation of the renewable gas sector in TIMES-FR	100
2.2.1.2 District heating supply	103
2.2.1.2.1 Context: disparity of development potential for district heat linked with demand density	103
2.2.1.2.2 Improved modeling structure for residential district heating distribution.....	106
2.2.2 Improvement in supply side: the case of biomass	108
2.2.2.1 Context: current biomass supply in France presents high complexity.....	108
2.2.2.2 Disaggregated structure for the biomass supply sector.....	111
2.2.2.3 Stock of solid biomass energy supply and two scenarios of future availability	113
2.2.3 Improving the demand side.....	116

2.2.3.1 Updating the building energy system.....	116
2.2.3.1.1 Building energy system in TIMES-FR and modeling of thermal insulation.....	117
2.2.3.1.2 Review of technical-economic parameters for building energy systems	119
2.2.3.1.3 Calibrating useful demand profiles for buildings and availability factors for building processes	121
2.2.3.2 Improved modeling structure for electric heat pumps	124
2.2.3.2.1 Context: energy efficiency of electric heat pumps is highly variable.....	124
2.2.3.2.2 Detailed modeling of electric heat pumps for space heating	124
2.2.4 Improvement on the demand side: calibrating demand scenarios	127
2.2.4.1 Review of published scenarios of demand.....	128
2.2.4.1.2 Overview of macroeconomic framework of reviewed scenarios.....	128
2.2.4.1.2 Visions of sectorial energy demand in the future	130
2.2.4.2 Retained hypotheses for future demand by our exercise.....	138
2.2.4.2.1 Hypotheses of building and agricultural demand trajectories.....	139
2.2.4.2.2 Retained demand trajectories.....	141
Conclusion	144
Annex Technical-economic parameters of residential technologies and detailed hypotheses.....	145
Chapter Three Transition to a future carbon-free heating system – an in-depth analysis.....	148
Introduction.....	148
Résumé.....	150
3.1 Key dimensions for low-carbon building construction and hypotheses for scenario definition.....	153
3.1.1 Effectiveness of thermal insulation	154
3.1.2 Extreme cold events	158
3.1.3 Neutrality and mitigation pace between 2030 and 2050.....	162
3.1.4 Opportunity cost of gas	163
3.2 Scenario design.....	165
3.3 Results and discussion	167
3.3.1 The contrafactual scenario	167
3.3.1.1 Pathway of the global energy system	167
3.3.1.2 Mitigation burden share.....	169
3.3.1.3 Solution for space heating.....	172
3.3.2 Impact of extreme cold demand situation and the role of HHP	175
3.3.2.1 Choice for space heating with the presence of extreme cold.....	175

3.3.2.2 Effect of hybrid heat pumps on the electricity system	177
3.3.2.3 Economic analysis.....	179
3.3.3 The role of insulation in the future building sector.....	180
3.3.4 Proposed solutions for various mitigation paces between 2030 and 2050	183
3.3.4.1 Scenarios with anticipated mitigation efforts between 2030 and 2045	183
3.3.4.2 Scenarios of late achievement of mitigation target between 2030 and 2050	188
3.3.4.3 Economic analysis.....	190
3.3.5 Opportunity cost of gas	192
3.3.5.1 Alternative solutions to gas for different energy sectors.....	193
3.3.5.2 Cases with hydrothermal gasification	196
3.3.5.3 Economic analysis.....	198
Conclusion	200
Chapter Four French energy transition under carbon neutrality – analysis of core dimensions.....	202
Introduction.....	202
Résumé	204
4.1 Key study dimensions: our hypotheses.....	206
4.1.1 Key hypotheses for insulation effectiveness, biomass supply potential, and demand scenario	206
4.1.2 Deployment pace of low-carbon electricity technologies.....	209
4.1.3 Carbon sinks and emissions from international transport.....	212
4.1.4 Decarbonization target for international transport	215
4.1.5 Discount rate	216
4.2 Result analysis	218
4.2.1 Overview of the roles of various energy sources in the transition to carbon neutrality	218
4.2.2 Share of mitigation burden over end-use sectors.....	221
4.2.3 Uncertainties for the future role of gas.....	225
4.2.3.1 Sensitivity analysis of future gas consumption: demand driven by carbon sinks and biomass potential	225
4.2.3.2 Gas supply in 2050: future transition led by renewable gases	228
4.2.4 Role of key dimension: analysis of specific scenarios	230
4.2.4.1 Different mitigation burden perspectives for the energy system, effects of carbon sinks, and carbon mitigation of international transport	230

4.2.4.2 Future demand from energy services as a key element shaping the energy transition	236
4.2.4.3 Role of discount rate	238
Conclusions	242
General conclusion	244
Key findings	244
Main limits of study and perspectives	247
List of figures	249
List of tables	253
Bibliography	255

General introduction

Global warming due to carbon emissions linked with human activity has become one of the major concerns of human society. Faced with this environmental challenge, an increasing number of countries, including France, have made commitments to reduce their carbon emissions. The national objective of France is to reach carbon neutrality by 2050. Achieving the emission target is a great challenge for the energy system, especially for residential buildings where a high share of energy consumption is based on carbon-intensive energies.

In this context, this Ph.D. thesis proposes to explore solutions to decarbonize residential buildings to achieve carbon neutrality by 2050. We focus on the long-term technology choices of residential buildings, by investigating in detail the role of various available or emerging efficient technologies for heating. To answer this research question from a residential energy perspective, we use a systemic approach to study the interaction of different energy sectors in the future energy transition, in particular the distribution of the mitigation burden and competition between usage of energy sources. In our research, we will account for multiple elements that may have a significant impact on investment choices for the energy system, including the availability of multiple energy resources such as biomass, district heating, renewable electricity, the development potential of the renewable gas industry, and the effectiveness of building renovation.

We will use a prospective modeling approach for our study. The modeling exercise is based on a bottom-up, linear optimization energy model, TIMES-FR, developed at the Center for Applied Mathematics at Mines Paris, PSL University. TIMES-FR represents the entire energy system of France, including multiple energy production and end-use sectors. It describes in detail technologies for the energy system and can consider technical, economic and environmental constraints. In order to better reply to the research question, multiple improvements will be elaborated concerning the energy supply and demand sides of the building energy sector of TIMES-FR.

The Ph.D. project is based on a collaboration between Gaz Réseau Distribution France (GRDF), the main operator of the gas distribution network in France, and the Center for Applied Mathematics (CMA) of Mines Paris, PSL University. The research topic is in line with the interests of the Strategy Department of GRDF in understanding the energy prospective of residential buildings and the future role of gas.

The manuscript of this Ph.D. thesis is organized into four chapters. Chapter One presents the main elements of context that enable us to understand the ramifications of our research question. We will be able to understand the challenge that the carbon neutrality target has established for the energy system and the important role of residential buildings in decarbonization efforts. An overview of

recently published energy prospective scenarios will help the reader apprehend how efforts can be oriented in the future energy transition. Besides, we carry out a detailed review of the technical and economic features of the range of eligible technologies that may contribute to the future transition of the residential energy system. This provides essential elements for our modeling exercise.

In Chapter Two, we present our research goal and modeling approach. We introduce several essential features of TIMES as a bottom-up model generator, so that the reader can understand how TIMES can produce an optimal solution for the future energy system. We will focus on introducing the four major improvements in the model carried out by us: renewable gas and district heating supply, provision of biomass, update of the building energy system, and improvements in presenting the electric heat pump sector.

Chapters Three and Four present the study results obtained. Chapter Three provides a complete analysis of the future transition of space heating towards carbon neutrality. Different scenarios are elaborated from key elements including the presence of extreme cold situations, the efficiency of thermal insulation, the pace of carbon mitigation, and the limits of gas usage. By studying in detail these scenarios, we will be able to understand several key questions including the role of the building sector in global mitigation efforts, the future role of various heating options, in particular electric heat pumps and gas boilers, the impacts of mitigation targets in intermediary time steps, and the opportunity cost of gas.

Chapter Four applies a broader view of the transition of the global energy system. Seven key dimensions of the energy transition are identified, including electricity capacity, carbon sinks, mitigation of international transport, thermal insulation, biomass potential, demand from energy services and discount rates. By analyzing scenarios based on different hypotheses of these key dimensions, we will be able to investigate a broad range of possibilities for the future energy transition towards carbon neutrality. We will thus better understand the role of different energy sources in the future, and the uncertainties involved. This completes and extends our analysis.

Throughout the work, we have communicated the results of multiple studies based on the topic of this Ph.D. thesis at international conferences. At the IAEE (International Association for Energy Economics) online conference in 2021, we presented our proposal to account for socio-technical nodes in future sustainable heat strategies for French residential buildings. At the 30th EUBCE (European Biomass Conference and Exhibition) conference, we presented a study of the role of Forest Biomass in French Energy Transition. At the 7th AIEE Energy Symposium on Energy Security and ICAE 2023 (International Conference on Applied Energy), we presented our considerations for the long-term role of hybrid heat pumps in the design of resilient heating system. Lastly, at the SDEWES 2022 conference (Sustainable

Development of Energy, Water and Environment Systems), we presented our analysis of the future energy transition under different scenarios of low-carbon electricity deployment potential and carbon sinks.

The analysis, views and opinions expressed are those of the author and do not necessarily reflect the position and views of GRDF.

Chapter One: The challenge of decarbonizing residential buildings in France

Introduction

The main focus of our study is to analyze the future technical choices of residential buildings from a systemic point of view, by considering the challenges of mitigation, emerging technologies, and the complexity of the gas and electricity systems. In this chapter, we present and review the main elements of context that enable us to understand the ramifications of our research question. This chapter is divided into three sections.

The first section highlights the environmental challenges for France, their implications for the energy system, and the role of residential buildings in national efforts of decarbonation. We present the political ambitions to reach carbon neutrality outlined by environmental laws and energy policies, and the objectives for residential buildings. This enables us to understand that carbon neutrality is a key element of national strategy and that its consideration is absolutely vital for the future energy system. Apart from policy context, we present several statistics about carbon emissions and energy consumption in France, including energy and emissions balances for both the global and residential systems. We show that the energy balance features a significant share of fossil fuels, resulting in high carbon emissions. Besides, the residential sector consumes a high volume of carbon-based energies and represents a considerable share of national carbon emissions. These statistics underline the fact that, in order to reach carbon neutrality, a huge challenge consists in decarbonizing the energy system, currently characterized by very high usage of fossil fuels, and that major efforts of decarbonization are required from residential buildings. We present the fact that maintaining the current rhythm of carbon mitigation is far from adequate to reach the neutrality goal of SNBC¹ in 2050. This further illustrates that the challenge of carbon neutrality calls for massive efforts.

Section one focuses on the question of the decarbonization challenge facing the energy system. The next question addresses how effort can be oriented in the future in order to approach the goal of carbon neutrality and the potential solution for residential buildings. Section two provides some insights by reviewing published energy prospective scenarios that represent the visions of various stakeholders in France for the future energy transition. The review covers various standpoints including those of the French government (DGEC²), a thinktank (négaWatt), a public company (ADEME³), and

¹ SNBC: Stratégie nationale bas carbone (*in French*)

² DGEC: Direction générale de l'énergie et du climat (*in French*)

³ ADEME: Agence de l'environnement et de la maîtrise de l'énergie (*in French*)

electricity and gas network operators (GRDF, RTE⁴, Enedis⁵, GRTGaz⁶, etc.). We present two scenarios of the French Ministry of Ecological Transition, the AME⁷ scenario which is a trend scenario, and the AMS⁸ scenario, which is the reference energy transition scenario for France to reach carbon neutrality. In presenting the AMS scenario, we are able to better understand the official vision of France and the rationale behind the national low carbon strategy (SNBC), which is the guideline of energy policies. A comparison of AMS and AME underlines the additional efforts required to reach carbon neutrality. A description of multiple scenarios elaborated by négaWatt and ADEME illustrates various possibilities beyond the official vision. In addition, the perspective of gas and electricity provides important insights for possible solutions for future gas and electricity production in a carbon-free context. All these visions are important elements to be studied and considered in the analysis of energy prospective for France. The review outlines multiple eligible solutions that may answer the question, including the integration of renewable gases, electrification by nuclear and renewable power plants, bio-energies, the development of the CCS⁹ industry, energy renovation for buildings, as well as efforts of energy sufficiency. This overview provides us with an initial idea of the range of possible technology drivers that may contribute to decarbonizing the energy system. In addition, it helps us understand that multiple possible pathways exist to reach carbon neutrality.

The third section of Chapter One is dedicated to an overview of the characteristics of current housing stock in France. In this section, we illustrate that the current stock has a large variety of buildings with different features closely linked to heat consumption, including climate zone, thermal quality, and heating source, and these features may be decisive to the technical solution. These statistics help us to understand that the question of technical choice for residential buildings presents a high level of complexity. Besides, we show in detail that the current housing stock has an important share of buildings with low energy efficiency linked to poor thermal quality or low performance of energy equipment. This further highlights the challenge of energy transition for residential buildings.

Given the ambitions and challenges induced by the goal to reach carbon neutrality for residential buildings, section four proposes an overview of the eligible technologies that may contribute to the future transition of the residential energy system. In section four, we give a detailed description of their technical-economic features and development potential. We review a wide range of technologies of energy production for residential buildings, including thermal insulation, condensing boilers, electric

⁴ RTE: Réseau de transport d'électricité (*in French*)

⁵ Enedis: formerly known as ERDF (Électricité Réseau Distribution France) (*in French*), the main electricity distribution network operator in France.

⁶ GRTgaz: the largest operator of the natural gas transport network in France.

⁷ AME: Avec Mesures Existantes (*in French*)

⁸ AMS: Avec Mesures Supplémentaires (*in French*)

⁹ CCS: Carbon Capture and Storage

heat pumps, solar thermal systems, district heating and fuel cells. The purpose of the review is firstly to provide a thorough understanding of the technology side of the residential energy transition, and secondly to set out key information to represent these technologies in the energy model. One focus of the review is energy renovation using thermal insulation. We put forward that insulation is an efficient solution to reduce the heating demand of buildings, and that current housing stock has considerable potential for energy saving through renovation. In addition, energy policies propose ambitious energy renovation goals. This illustrates that energy renovation may make an important contribution to mitigating residential carbon emissions and play a key role in the national strategy for the residential energy transition. We also highlight that the perspective of energy renovation is uncertain due to the presence of several impediments.

Résumé

L'objectif principal de notre étude est d'analyser les futurs choix technologiques des bâtiments résidentiels d'un point de vue systémique, en prenant en compte les défis de la réduction des émissions de CO₂, les technologies émergentes, et la complexité des systèmes de gaz et d'électricité. Dans ce chapitre, nous présentons et examinons les principaux éléments de contexte qui nous permettent de comprendre les ramifications de notre question de recherche. Ce chapitre est divisé en trois sections.

La première section met en lumière les défis environnementaux pour la France, leurs implications pour le système énergétique, et le rôle des bâtiments résidentiels dans l'effort national de décarbonation. Nous présentons les ambitions politiques pour atteindre la neutralité carbone telles qu'elles sont définies par les lois environnementales et les politiques énergétiques, ainsi que les objectifs pour les bâtiments résidentiels. Cela nous permet de comprendre que la neutralité carbone est un élément clé de la stratégie nationale et que sa prise en compte est absolument vitale pour le futur système énergétique. Outre le contexte politique, nous présentons plusieurs statistiques sur les émissions de carbone et la consommation d'énergie en France, y compris les bilans énergétiques et d'émissions pour les systèmes globaux et résidentiels. Nous montrons que le bilan énergétique comprend une part significative de combustibles fossiles, entraînant des émissions de carbone élevées. De plus, le secteur résidentiel consomme une grande quantité d'énergies carbonées et représente une part considérable des émissions nationales de carbone. Ces statistiques soulignent le fait que, pour atteindre la neutralité carbone, un grand défi consiste à décarboner le système énergétique, actuellement caractérisé par une utilisation très élevée de combustibles fossiles, et que des efforts majeurs de décarbonation sont nécessaires dans les bâtiments résidentiels. Ensuite, nous présentons le fait que le maintien du rythme actuel de réduction du carbone est loin d'être suffisant pour atteindre l'objectif de neutralité de la SNBC en 2050. Cela illustre encore une fois que le défi de la neutralité carbone exige des efforts massifs.

La première section se concentre sur la question du défi de la décarbonation auquel est confronté le système énergétique. La question suivante est de savoir comment les efforts peuvent être orientés à l'avenir pour approcher l'objectif de neutralité carbone et quelles solutions peuvent potentiellement être envisagées pour les bâtiments résidentiels. La deuxième section cherche à éclairer cette question en passant en revue des scénarios prospectifs énergétiques publiés, qui représentent les visions de divers acteurs en France pour la future transition énergétique. Cette revue couvre différents points de vue, y compris ceux du gouvernement français (DGEC), d'une association (négaWatt), d'une entreprise publique (ADEME), et des opérateurs de réseaux d'électricité et de gaz (GRDF, RTE, ENEDIS, GRTGaz, etc.). Nous présentons deux scénarios du ministère français de la Transition écologique : le scénario AME, qui est un scénario tendanciel, et le scénario AMS, qui est le scénario de référence pour la

transition énergétique de la France vers la neutralité carbone. En présentant le scénario AMS, nous pouvons mieux comprendre la vision officielle de la France et la logique derrière la stratégie nationale bas carbone (SNBC), qui constitue la ligne directrice des politiques énergétiques. Une comparaison entre les scénarios AMS et AME souligne les efforts supplémentaires nécessaires pour atteindre la neutralité carbone. Une description de plusieurs scénarios élaborés par négaWatt et ADEME illustre diverses possibilités au-delà de la vision officielle. De plus, la perspective du gaz et de l'électricité fournit des informations importantes sur les solutions possibles pour le futur mix de production de gaz et d'électricité dans un contexte sans carbone. Toutes ces visions sont des éléments importants à étudier et à prendre en compte dans l'analyse prospective des systèmes énergétiques pour la France. La revue met en évidence plusieurs solutions envisageables pour répondre à la question, notamment l'intégration des gaz renouvelables, l'électrification par les centrales nucléaires et les énergies renouvelables, les bioénergies, le développement de l'industrie du CCS (captage et stockage du carbone), la rénovation énergétique des bâtiments, ainsi que les efforts d'efficacité énergétique. Cette vue d'ensemble nous donne une première idée de la gamme des leviers technologiques possibles qui pourraient contribuer à la décarbonation du système énergétique. En outre, elle nous aide à comprendre qu'il existe plusieurs voies possibles pour atteindre la neutralité carbone.

La troisième section du premier chapitre donne un aperçu des caractéristiques du parc du logement existant en France. Dans cette section, nous montrons que le parc actuel comprend une grande variété de bâtiments avec des caractéristiques différentes, étroitement liées à la consommation de chaleur, telles que la zone climatique, la qualité thermique et la source de chauffage. Ces caractéristiques peuvent être déterminantes pour la solution technique. Ces statistiques nous aident à comprendre que la question du choix technique pour les bâtiments résidentiels présente un haut niveau de complexité. De plus, nous montrons en détail que le parc immobilier actuel comprend une part importante de bâtiments à faible efficacité énergétique, en raison d'une mauvaise qualité thermique ou d'une faible performance des équipements énergétiques. Cela met encore plus en lumière le défi de la transition énergétique pour les bâtiments résidentiels.

Compte tenu des ambitions et des défis induits par l'objectif d'atteindre la neutralité carbone pour les bâtiments résidentiels, la quatrième section propose un aperçu des technologies éligibles qui pourraient contribuer à la future transition du système énergétique résidentiel. Dans cette section, nous donnons une description détaillée de leurs caractéristiques technico-économiques et de leur potentiel de développement. Nous passons en revue un large éventail de technologies pour la production de l'énergie pour les bâtiments résidentiels, y compris l'isolation thermique, les chaudières à condensation, les pompes à chaleur électriques, les systèmes solaires thermiques, le chauffage urbain et les piles à combustible. Le but de cette revue est d'abord de fournir une compréhension

approfondie de l'aspect technologique de la transition énergétique résidentielle, et ensuite de présenter les informations clés pour représenter ces technologies dans le modèle énergétique. Un des axes de cette revue est la rénovation énergétique par l'isolation thermique. Nous avançons que l'isolation est une solution efficace pour réduire la demande de chauffage des bâtiments, et que le parc immobilier actuel présente un potentiel considérable d'économie d'énergie grâce à la rénovation. En outre, les politiques énergétiques proposent des objectifs ambitieux de rénovation énergétique. Cela montre que la rénovation énergétique pourrait apporter une contribution importante à la réduction des émissions de carbone et jouer un rôle clé dans la stratégie nationale de transition énergétique des bâtiments résidentiels. Nous soulignons également que la perspective de la rénovation énergétique est incertaine en raison de la présence de plusieurs obstacles.

1.1 Role of residential buildings in national environment ambitions

Global warming due to carbon emissions linked with human activity is today one of the major concerns of human society. Faced with this environmental challenge, an increasing number of countries, including France, have committed to reduce their carbon emissions. After the Paris Agreement in 2015, the French government promulgated the Energy Transition for Green Growth Act (LTECV¹⁰) to make carbon mitigation a national objective. The LTECV introduces the National Low-Carbon Strategy as a national road map to achieve the national climate policy for the short and medium terms, and a Pluriannual Energy Plan (PPE¹¹) as an energy policy monitoring goal for the very short term. The SNBC underlines the objectives of carbon mitigation for important time steps in the future and defines a carbon budget which is the maximum sectorial limit on carbon emissions on a national level over five-year periods. The first SNBC was introduced in 2015, following an update in 2020. In the last SNBC revision of 2020, the global objective is to reach 40% carbon mitigation by 2030 compared with 1990, and carbon neutrality for the entire French territory by 2050. Underlined by energy law, the ambition of carbon neutrality thus crucially considers the future energy system.

1.1.1 Energy and emissions balance: the importance of mitigating emissions from residential buildings to achieve carbon neutrality

Considering the current situation of the energy balance, the ambitious carbon neutrality goal represents a great challenge for energy system. In 2021, France consumed in total 1617 TWh of final energy. The final energy balance is highly dependent on carbon-based energies including oil products and natural gas (SDES, 2022a) (Figure 1). Oil products are the most important energy resource for the French energy system, accounting for 37% of total final energy consumption. Consumption of oil products is mainly driven by fuel demand from the transport sector: In 2021, consumption of all types of fuel products, including diesel, gasoline and jet fuel amounted to 450 TWh, which is more than 90% of transport demand. The rest of transport demand comprised gas, electricity and biofuel. The total consumption of gas was around 336 TWh, accounting for around 20% of total energy consumption. Currently, gas consumption is mostly fossil-based natural gas, and only a very small quantity of gas consumption is based on green gas (0.4% of total injection into the gas grid (GRDF et al., 2022)).

¹⁰ LTECV: Loi relative à la transition énergétique pour la croissance verte (*in French*)

¹¹ PPE: Programmes pluriannuels de l'énergie (*in French*)

Electricity is the second energy source after oil products, with a 27% share of the final energy balance. Besides, RES and waste¹² represents 12% of national final energy consumption (190 TWh).

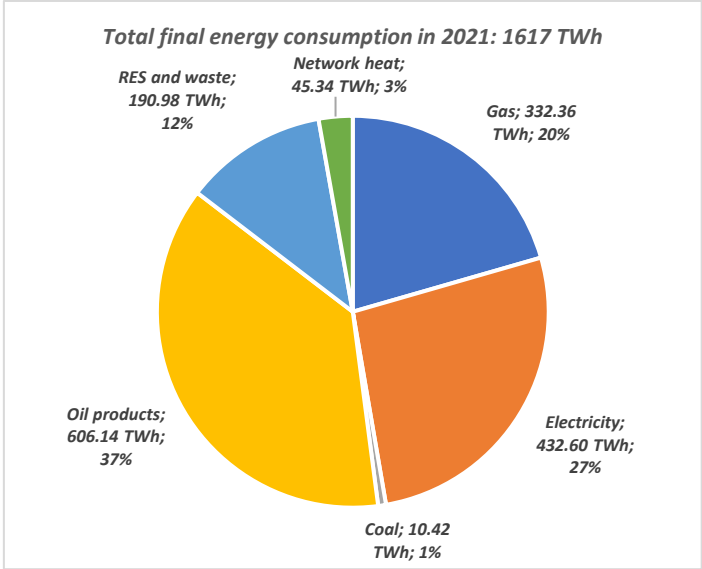


Figure 1 Energy balance of France in normal climate conditions (SDES, 2022a)

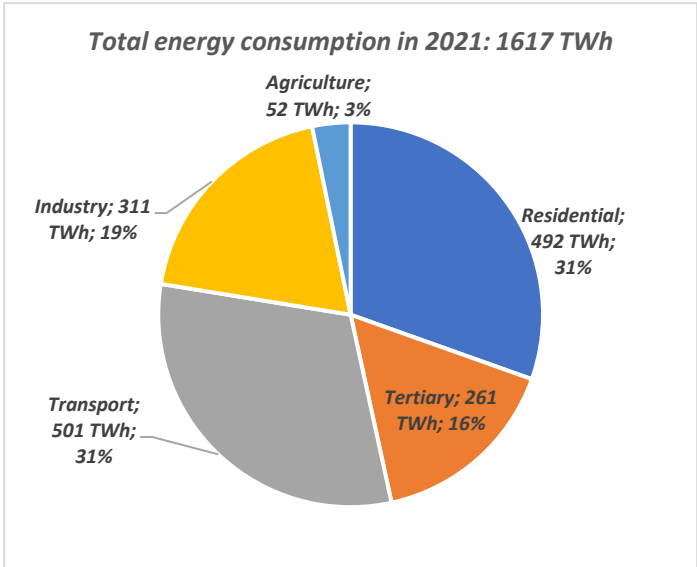


Figure 2 Final energy consumption by 5 sectors in normal climate conditions (SDES, 2022a)

¹² Solid biomass, biofuel, solar thermal energy, ambient heat from heat pumps, recovered heat, etc.

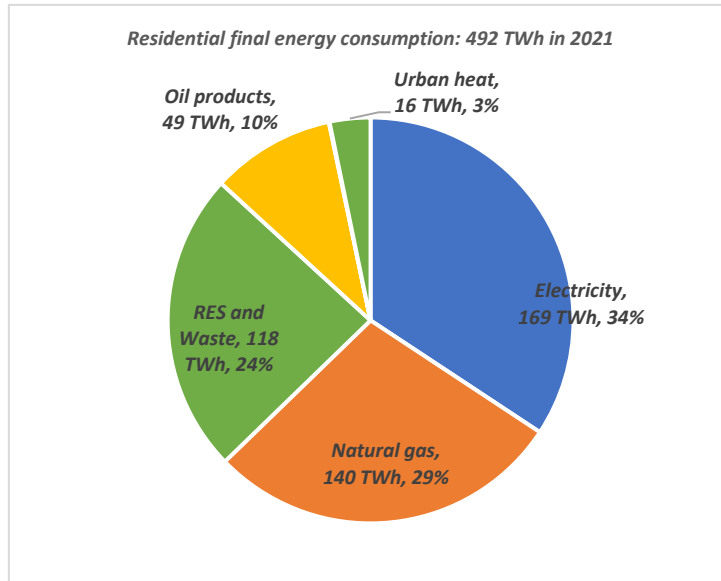


Figure 3 Final energy balance of residential sector in normal climate conditions (SDES, 2022a)

Residential buildings account for a significant share of national final energy demand. In addition, they represent a high volume of fossil energy consumption. In 2021, residential building was the second largest energy consumer after the transport sector. The final energy demand of residential usages reached 492 TWh, accounting for 31% of national energy consumption (SDES, 2022b) (Figure 2). Final energy demand in the residential sector is driven by four usages: space heating, domestic hot water production (DHW), cooking, and specific usage of electricity. Space heating accounts for the largest share of final energy consumption in the residential sector. As suggested by CEREN¹³ statistics, in 2020, heating usages accounted for 65% of total consumption, with specific electricity usage accounting for 18%, domestic hot water around 11%, and cooking 6% (CEREN, 2022) (Figure 4).

In 2020, final energy demand for space heating (for all principal residencies in Metropolitan France) was estimated at around 273 TWh. The balance of space heating presents important share of fossil energies, in particular natural gas and heating oil. Gas is the most important heating energy source for French households, accounting for more than 39% of total energy consumption. Carbon-intensive heating oil represents around 12% of heating energy sources. The share of electricity amounts to 13%, which is only one-third of the gas consumption for heating. In addition, solid biomass plays a significant role, fueling 29% of heating consumption (Figure 5).

¹³ CEREN: Centre d'études et de recherches économiques sur l'énergie (in French)

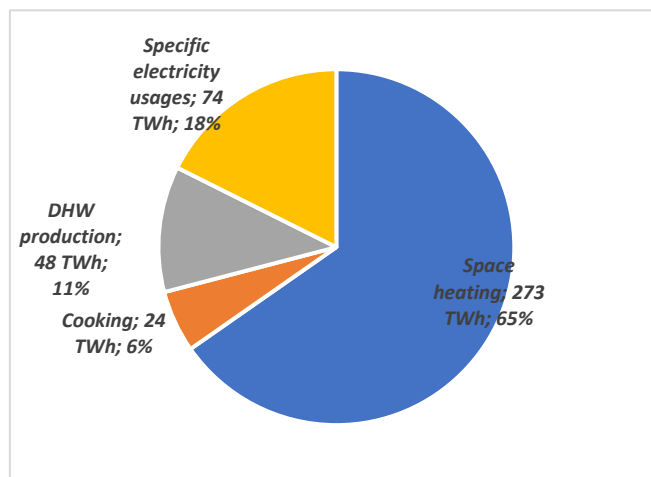


Figure 4 Final energy consumption by 4 residential energy usages in 2020, (Principal residences of Metropolitan France, normal climate¹⁴) (CEREN, 2022)

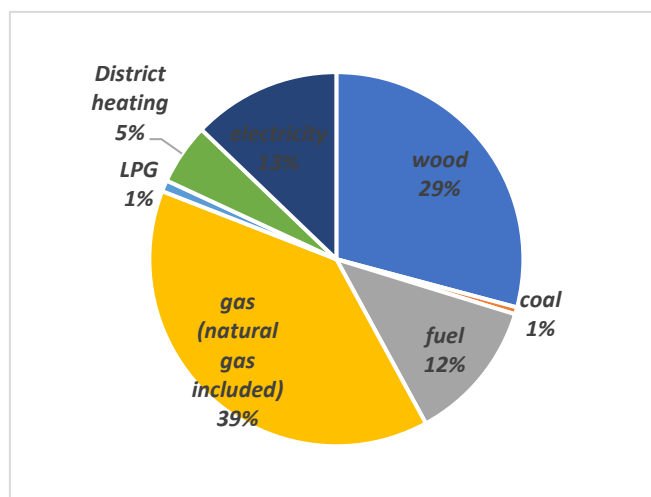


Figure 5 Final energy balance of space heating of residential buildings in 2020 (principal residences, normal climate) (CEREN, 2022)

As carbon-intensive fossil energies make up a significant share of final energy consumption, the French energy system emits a high volume of greenhouse gases (GHG). A significant amount of carbon emissions is emitted by residential buildings. According to the Eurostat air emissions inventory, in 2021, carbon emissions related to fuel combustion were estimated at 287 MtCO₂e¹⁵, which is equal to over 70% of total emissions on the French territory (Eurostat, 2023). Direct fuel combustion by households explains 15% of total emissions from fuel combustion (42.6 MtCO₂e). If we consider the carbon emissions of electricity and district heating consumed by residential buildings (emissions from fuel combustion by energy industries amounts to 39.4 MtCO₂e, 14% of total emissions), the total emissions resulting from residential energy consumption could be higher. Space heating is the predominant

¹⁴ Average weather conditions over 1991-2020 (CEREN, 2022)

¹⁵ MtCO₂e: Million Metric Tons of CO₂ equivalent

usage in terms of carbon emissions, representing around 80% of total emissions, followed by DHW production (12%) and cooking (7%).

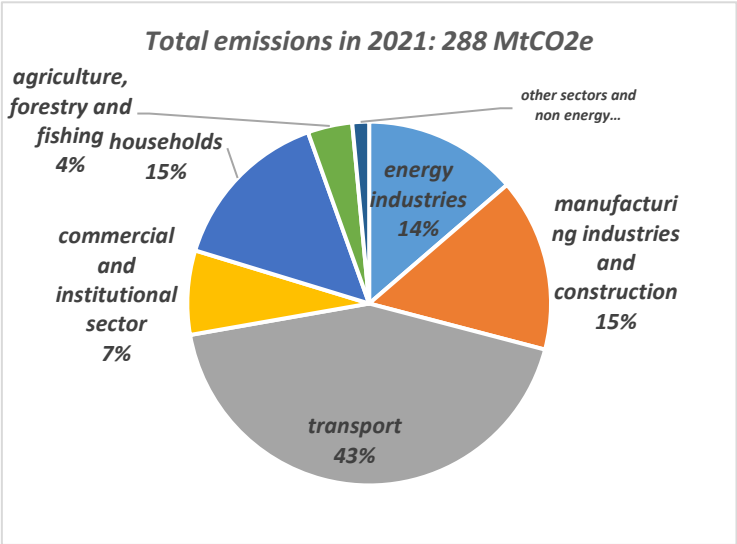


Figure 6 Balance of GHG emission linked with fuel combustion, international transport not included (Eurostat, 2023)

The energy and emission balances presented above suggest that, in order to reach carbon neutrality, residential building is a major sector in which efforts must be made.

1.1.2 Efforts achieved until now and the challenges of reaching carbon neutrality

From the recent evolution of the residential GHG inventory and energy balance, we can observe that the decarbonization efforts made since the beginning of the 2000s have led to a visible effect on carbon mitigation. The figure below presents the evolution of GHG emissions by residential fuel combustion and the index of climatic rigor for the period 1990-2021. From the figure, we observe that emissions from residential buildings have followed a decreasing trend in recent years. With a similar climatic rigor index, residential GHG emissions in 2021 are around 37% lower than in 2004 (Eurostat, 2023), from 69 MtCO_{2e} to 43 MtCO_{2e}. Compared with 1990, residential air emissions have dropped by 28%.

The recent reduction in carbon emissions can be explained by the increasing use of renewable energies. It is estimated that the emissions factor of energy consumption (expressed in gCO₂/kWh of final energy consumption) dropped by 22% in the residential-tertiary sector from 1990-2014 (SDES, 2020b). As suggested by the recent evolution of the residential final energy balance, the use of very carbon-intensive energies, including coal, LPG¹⁶ and heating oil have been gradually decreasing and the share of renewables such as biomass, and ambient heat have increased. A considerable share of heating oil consumption is replaced by natural gas, with a relatively smaller emission factor, and electricity. Heating oil accounted for nearly 40% of space heating demand in 1982, with an annual consumption of 152 TWh, while it only represented 12% of total demand (49 TWh) in 2021. The consumption of natural gas rose from 87 TWh in 1982 to 140 TWh in 2021, and the share of natural gas in the final energy balance increased from 19% to 28%. Electricity demand rose from 68 TWh in 1982 (22% total consumption) to 169 TWh in 2021 (34% of total consumption).

¹⁶ LPG: Liquefied Petroleum Gas

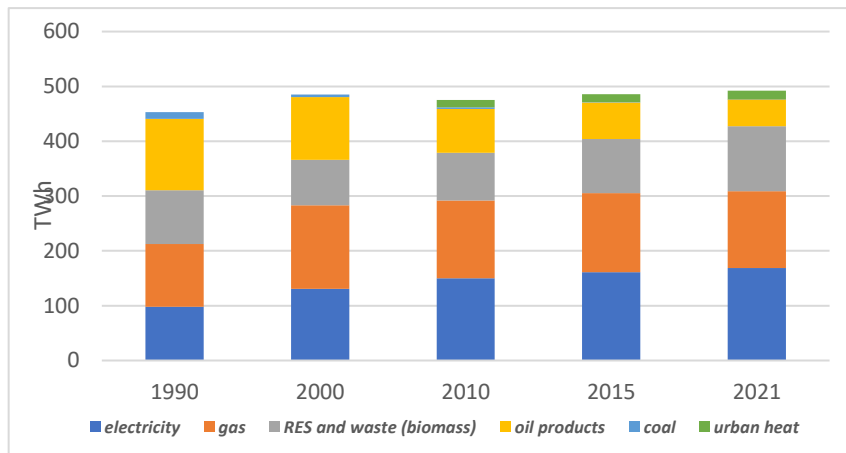


Figure 7 Final energy balance of residential sector from 1990 to 2021 in normal climate conditions (metropolitan France + DROM) (SDES, 2022a)

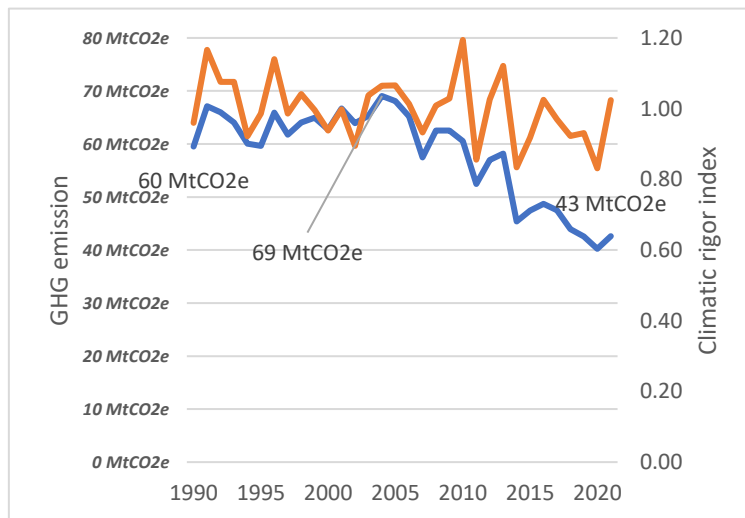


Figure 8 Trajectory of GHG emissions from direct fuel combustion by residential buildings and climatic rigor index from 1990 to 2021 (Eurostat, 2023; SDES, 2023)

Although recent decarbonization efforts have led to important reductions in carbon emissions, the residential energy system still faces difficult challenges in order to achieve carbon neutrality. The figure below compares two projections of residential emissions trajectories. The orange line is the projected trajectory of carbon emissions till 2050 based on a mitigation rhythm between 2015 and 2021. The blue line shows the proposed trajectory for carbon neutrality as set out in the SNBC. We can see that, if the future emissions trajectory follows the tendency of 2015-2021, the estimated emissions will be around 36 MtCO_{2e} by 2030 and 25 MtCO_{2e} by 2050, far exceeding the SNBC objectives. This suggests that, to reach carbon neutrality by 2050, the pace of mitigation needs to accelerate, which requires more decarbonization efforts compared with the current level.

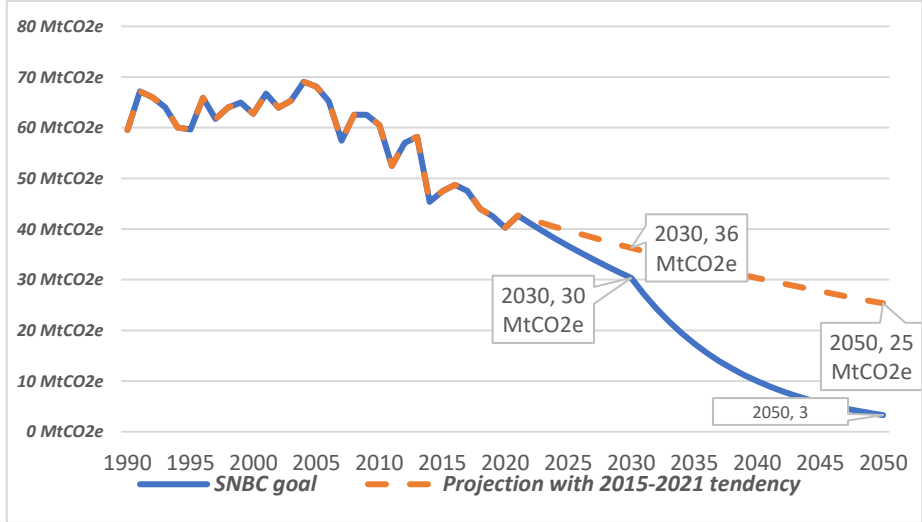


Figure 9 History and projection of GHG emissions from the building sector from 1990 to 2050 in MtCO_{2e} (Ministère de la Transition écologique et de la Cohésion des territoires, 2020a)

1.2 Overview of published scenarios up to 2050: energy transition visions of different stakeholders

By describing various environmental and energy policies, the statistics of energy and emissions balances and their recent evolution, we are able to better understand the challenge faced by the energy system to reach carbon neutrality. The next question is how efforts can be oriented in the future and the appropriate solution for residential buildings. To tackle this question, energy perspective scenarios produced by stakeholders in France can provide us with some insights. The scenarios published by the Ministry of Ecological Transition represent the official vision of the future energy transition in France. Apart from the French government, the question of the future energy balance in a carbon neutrality context has drawn attention from various other stakeholders, including public and private companies, think tanks, associations, energy network operators, etc. Their scenarios are also important and illustrate possibilities other than the official vision. In this section, we propose to review a range of recently published scenarios, including AMS and AME by DGEC, scenario S1-S4 by ADEME, négaWatt 2022 and Perspectives Gaz by gas network operators, and Energy Pathways 2050 by RTE.

1.2.1 AME 2021 and AMS 2018

The AME and AMS scenarios published by DGEC represent the official vision of France for the future energy transition. They meet with the obligation of French government to publish a transition trajectory following its commitment in reducing GHG emissions (Ministère de la Transition Ecologique et de la Cohésion des Territoires, 2023). These two scenarios describe in detail the trajectory of the final energy balance and carbon emissions on national and sectorial levels up to 2050. The results of the energy balance and carbon emissions are obtained from hypothesis construction and modeling steps. The AME scenario is a trend scenario that describes a future where current existing measures are maintained. Under the AME, the neutrality objective is not taken into account. The AMS scenario outlines a possible trajectory for reaching carbon neutrality in 2050. A comparison of the AME and AMS trajectories gives an indication of what additional efforts are needed to reach emissions-cutting objectives (carbon neutrality) (Millot, 2019). Since 2014, several updates have been elaborated. The latest versions are AME 2021 and AMS 2018. AME 2021 assesses the impact of all policies and measures implemented until the end of 2019 on energy consumption and greenhouse gases up to 2050. AMS 2018 is the reference scenario for SNBC and PPE 2019, providing a guideline for national energy policy. It is thus a very important element to understand.

Complementary information 1 Construction of AME and AMS scenario

The process to construct scenario of AME and AMS includes steps of hypotheses construction (“scénarisation”), sectorial technical-economic modeling, aggregation and macro-economic modeling. Firstly, a multitude of hypotheses of economics, politic and technologic context linked with future energy transition are identified. These hypotheses include for example macro-economic framework (demography, economic growth, energy prices, etc.), performance and cost of energy equipment, as well as choice of public policies. They then serve as input of technical-economic modeling by sector, giving sectorial trajectory of energy balance and carbon emission. For AME 2021, the main modeling tools are developed by DGEC (GEStime), CGDD¹⁷ (tertiary model, Modev), CSTB¹⁸ (Menfis) (DGEC, 2020b). The national energy balance is then aggregated by sectorial results. GEStime is an internal modeling tool of DGEC. It represents energy consumption and carbon emission linked with a range of physical processes of agricultural, forest, residential, tertiary, transport, industry and renewable gas sector.

¹⁷ CGDD: Commissariat général au développement durable (*in French*)

¹⁸ CSTB: Centre Scientifique Technique Du Bâtiment (*in French*)

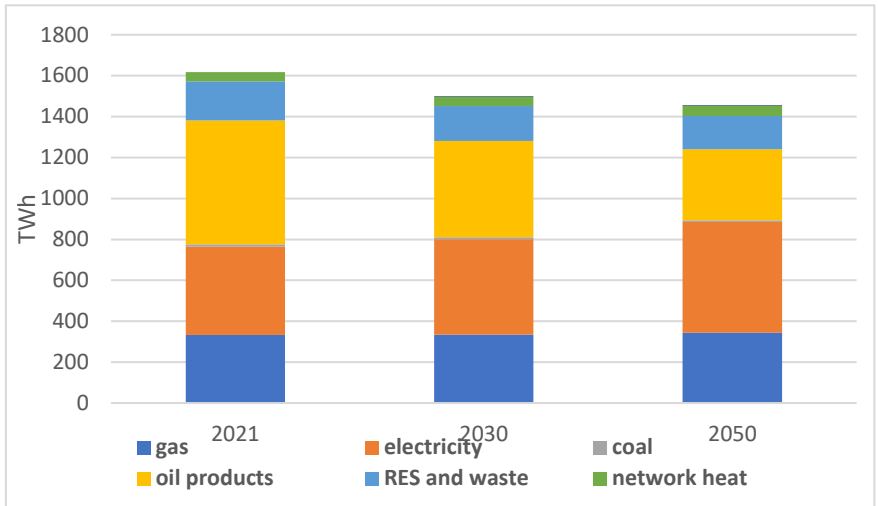


Figure 10 Trajectory of final energy balance, AME 2021, range: Metropolitan France and DROM (DGEC, 2021a)

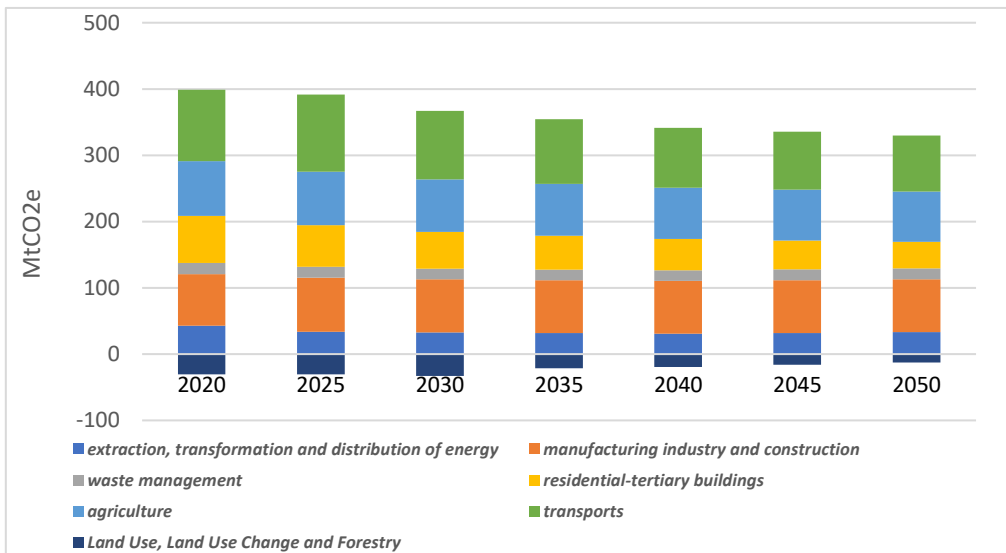


Figure 11 Trajectory of GHG emissions by AME 2021 (DGEC, 2021a)

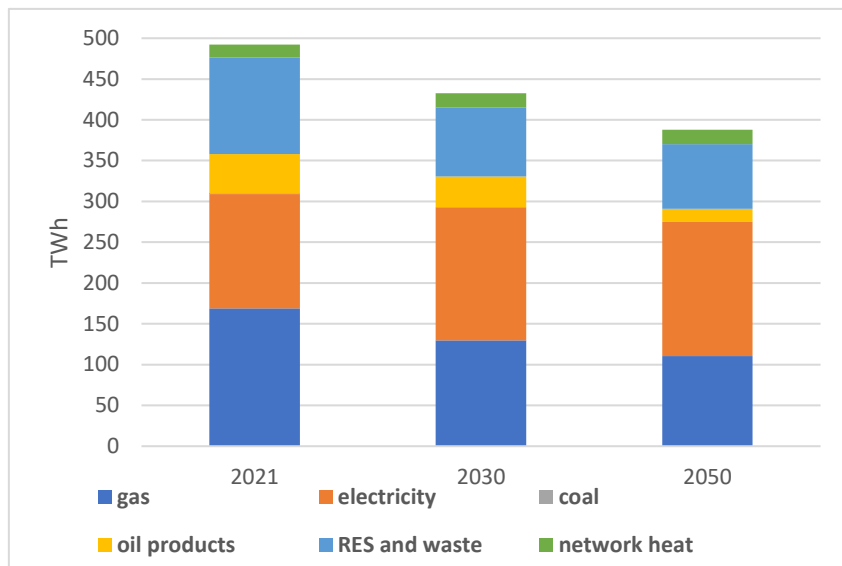


Figure 12 Trajectory of residential energy balance by AME 2021, range: Metropolitan France and DROM (DGEC, 2021a)

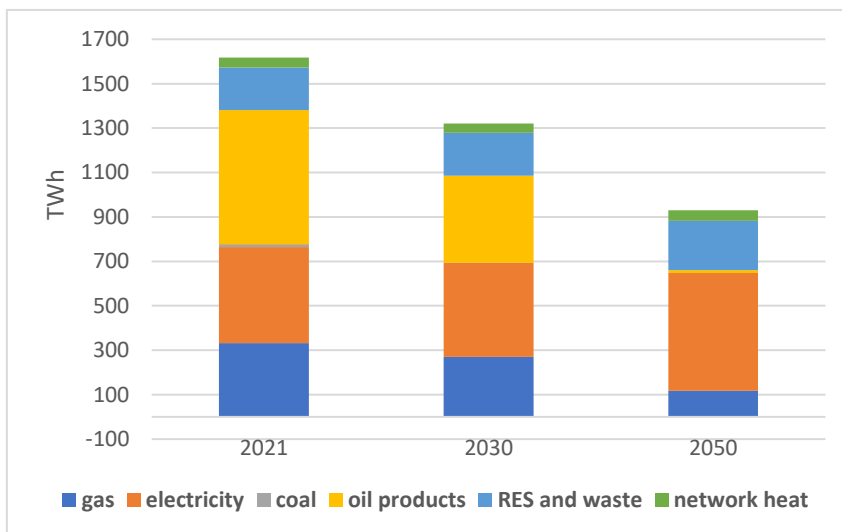


Figure 13 Trajectory of final energy balance, AMS 2018, range: Metropolitan France and DROM (DGEC, 2021a)

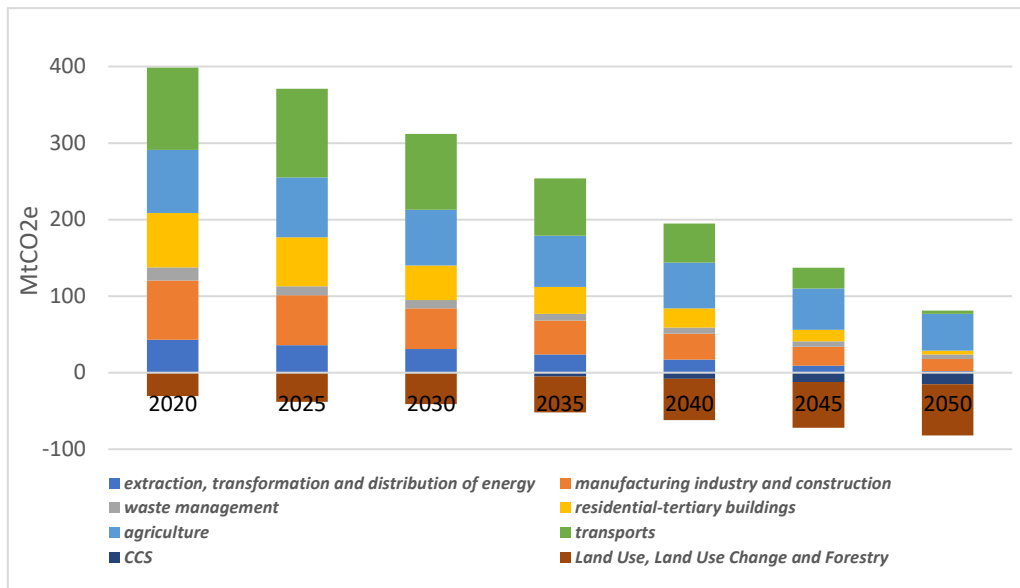


Figure 14 Trajectory of carbon emissions balance, AMS 2018, range: Metropolitan France and DROM (DGEC, 2020b)

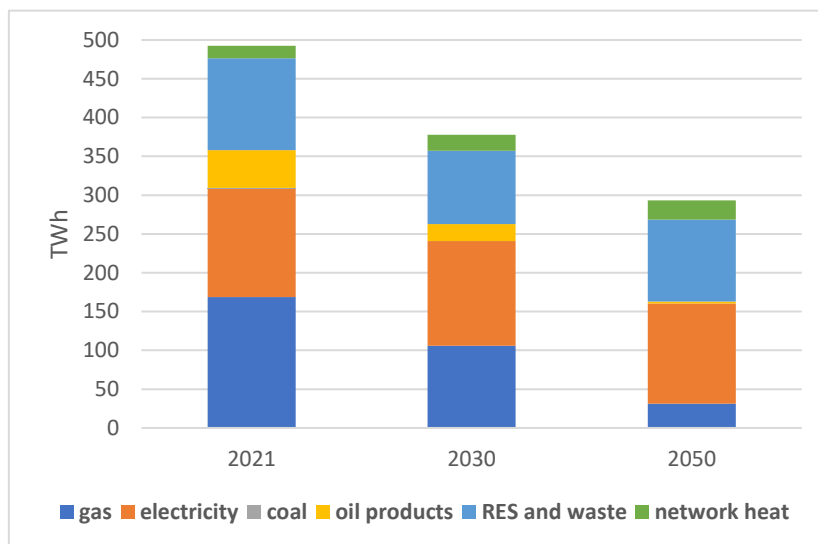


Figure 15 Trajectory of residential final energy balance by AMS 2018, range: Metropolitan France and DROM (DGEC, 2020b)

The figures above illustrate the proposed trajectories of final energy consumption for the entire energy system and for residential buildings by the AME 2021 and AMS 2018 (SNBC-PPE) scenarios. Under AME 2021, by 2050, the final energy demand of France remains at the relatively high level of around 1500 TWh per year, around 10% less than current demand. Electricity accounts for around 40% of the final energy balance. More than 96% of electricity is produced from decarbonized energy sources including nuclear, hydraulic, solar and wind power. Compared with today (91% of non-fossil sources are present in the current electricity balance), the electricity supply system is more decarbonized. The presence of fossil energy sources including oil products and natural gas remains high. Oil products still account for

around 24% of final energy consumption. The share of gas remains constant, and by 2050, gas demand is estimated to be 344 TWh, slightly higher than in 2021. Under the trend scenario, the residential balance presents a higher share of electricity (42%) and a lower share of gas (28%) in 2050 compared to current levels. In addition, the total residential energy demand decreases by 21% in 2050 compared to the current level. However, a future energy balance with a high share of fossil energy presented by AME 2021 will not be capable of significantly abating carbon emissions.

The AMS 2018 scenario based on the context of carbon neutrality presents a final energy balance with a much lower consumption level and dominated by renewable energy sources and decarbonized electricity. National final energy demand is around 900 TWh by 2050, 40% lower than the current level. The share of electricity is estimated to be around 57%. Electricity production is almost decarbonized: the total emissions of energy production are estimated to be around 2 Mt CO₂e, only 4% of the 2020 level. However, the details of the future electricity balance are not studied by the AMS scenario. Gas consumption is around 120 TWh, which is about 12.5% of total final energy demand, much lower than the current level (330 TWh). It is also estimated that biogas will account for most of gas consumption. Carbon-intensive oil products will nearly disappear by 2050, representing only around 1% of energy demand. We note that the AMS scenario presumes a significant contribution of carbon sinks to achieve the neutrality goal. In 2050, the capacity of natural carbon sinks and CCS will reach 67 Mt CO₂e and 15 Mt CO₂e.

For residential buildings, under the AMS scenario, the final energy balance is completely decarbonized: by 2050, electricity presents 44% of residential energy demand, followed by RES and waste (36%), gas (10.7%), and district heating (8.3%). Final energy demand of residential buildings drops to under 300 TWh by 2050, around 40% lower than the current level. This significant saving of final energy will rely on several factors: firstly, integration of efficient equipment, secondly, improvement of the energy performance of buildings, thirdly, energy-saving behaviors (Ministère de la Transition écologique et de la Cohésion des territoires, 2020a).

1.2.2 ADEME scenarios

Four ADEME scenarios have been produced, namely the “génération frugale (S1), coopération territoriales (S2), technologies vertes (S3), pari réparateur (S4)” study, as well trajectories of the final energy balance and carbon emissions. These four scenarios were elaborated using a similar method to AME and AMS, and all are based on carbon neutrality by 2050 (ADEME, 2021b). ADEME’s S1-S4 scenarios present the influences of rather contrasted lifestyles, economic models, technology evolution, and policy frameworks on the energy-climate transition in the future. Besides, compared to AME and AMS, the ADEME scenarios allow for assessing a wider range of hypotheses. All scenarios regard energy sufficiency and increased productivity (energy efficiency) as two major drivers to achieve carbon neutrality. The level of energy efficiency increases from S1-S4, while the level of demand energy sufficiency follows a decreasing order.

S1 depicts an ideal situation where the consumption level of society decreases to a very low level as a result of voluntary behavior by citizens and coercive measures (obligation, interdiction, quotas, etc.). Energy sufficiency is the major driver of the transition while technology progress is limited. Similar to S1, S2 foresees an energy-sufficient society that largely contributes to GHG mitigation, while the level of consumption is less constrained than in S1. S3 and S4 are scenarios that put more weight on technological development than energy sufficiency to respond to future environmental changes. Under S3, despite slight changes, the future consumption level remains very similar to currently. The demand for consumer goods and services is satisfied by more efficient technologies widely deployed and accessible to French citizens. S4 interprets another extreme case where the future society is highly consumerist, and the goal of carbon neutrality is nearly 100% achieved by technology progress. The lifestyle of citizens at the beginning of the 21st century remains the same till 2050, leading to a high level of consumption and potentially strong environmental impacts. Society relies on its capacity to manage and even repair the ecology system with more material and financial resources.

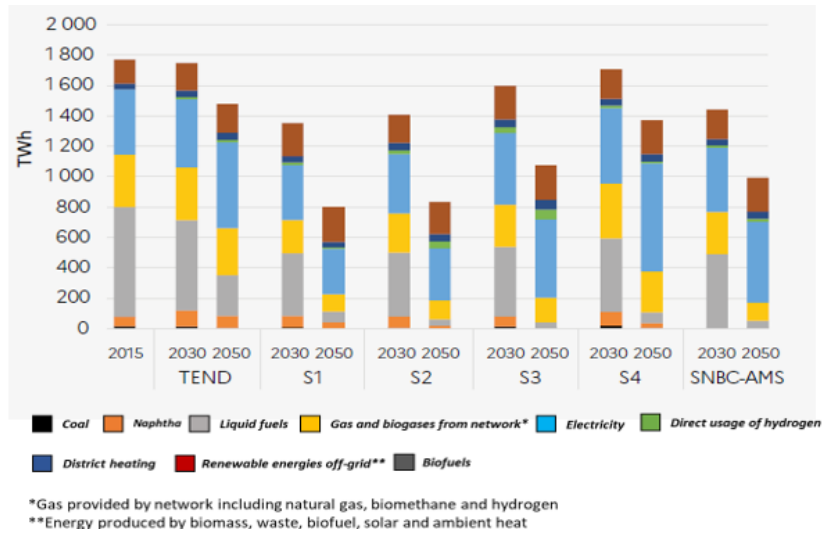


Figure 16 Trajectory of national final energy consumption (including non-energy usage), ADEME S1-S4 (ADEME, 2021b)

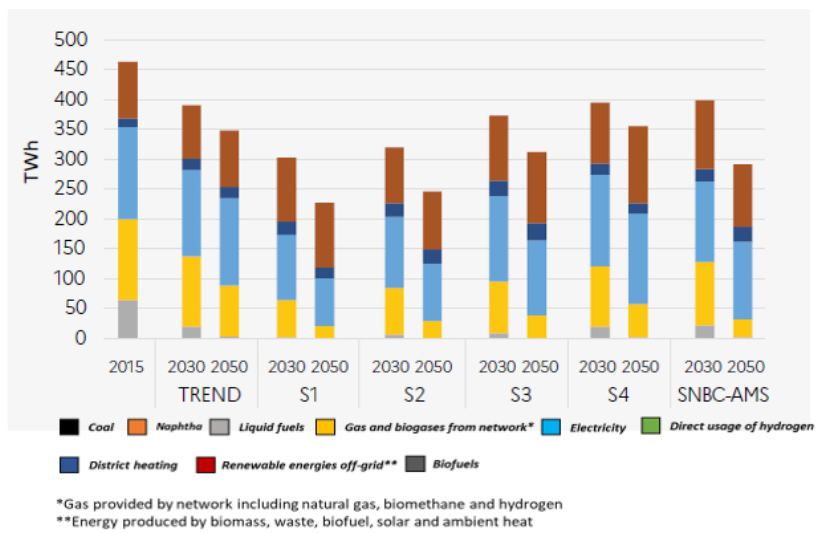


Figure 17 Trajectory of residential final energy consumption by ADEME scenarios (ADEME, 2021b)

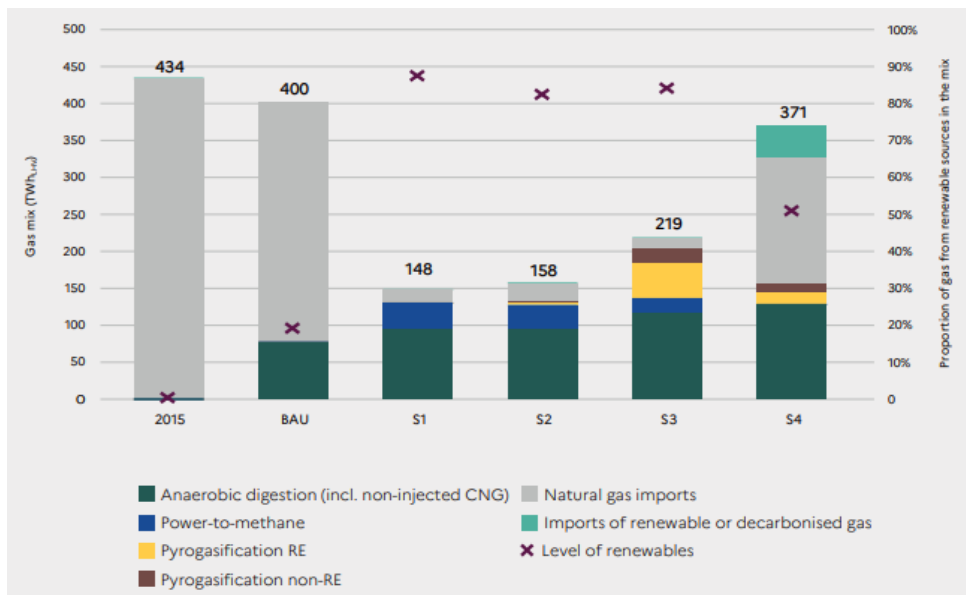


Figure 18 Gas balance (production) by ADEME scenarios (ADEME, 2021b)

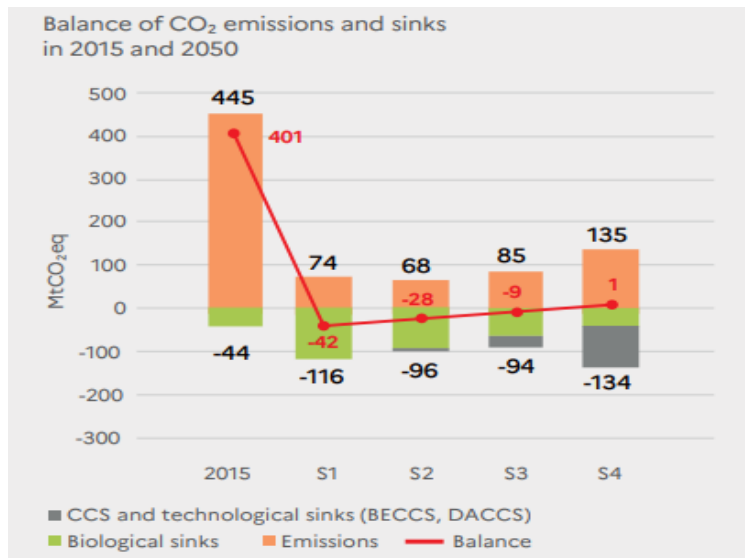


Figure 19 Balance of carbon emissions and sinks by ADEME scenarios (ADEME, 2021b)

Figure 16-19 describe the trajectories of the national and residential energy balances in S1-S4, as well as the trajectories of the gas balance, the emission factor of electricity generation, and carbon sinks. In all the scenarios, achieving carbon neutrality requires a significant decrease in final energy consumption. All of the neutrality scenarios have a lower consumption level than the trend scenario (1735 TWh in 2030 and 1466 TWh in 2050). Final energy demand in 2050 ranges from 790 TWh in S1 (scenario with the strongest hypotheses of energy sufficiency) to 1338 TWh in S4, representing from 23% to 55% of consumption abatement compared to 2015. Compared with the AMS scenario, final

energy consumption in 2050 is lower under S1 and S2 (16% and 20% less) and higher under S3 and S4 (8% and 37% more). Under S3 and S4, with a relatively higher final energy consumption, the development of carbon capture technologies is required: S4 presents around 100 Mt CO₂e of negative emission issues from artificial carbon sinks including CCS, BECCS¹⁹ and DACCS²⁰.

In all scenarios, the final energy balance is subject to considerable changes in the future. The general tendency is to replace carbon-based energy sources with renewables. Depending on the scenario, electricity covers 38-52% (increasing from S1-S4) of final energy demand by 2050, compared with 24% in 2015. In all scenarios, the emission factor of electricity production significantly decreases in 2030 and 2050. Under S3 and S4 with higher demand, the electricity system is relatively less decarbonized than the S1 and S2 in 2050. This is because a small number of gas power plants remain, in order to guarantee the flexibility of the electricity system. Similar to AMS and AME, the details of the future electricity system are not provided in the ADEME scenarios. Gas consumption is estimated to surpass 148 TWh in all cases, and the share of gas in the final energy balance remains stable (at least 21% of total energy demand across these scenarios). The gas sector makes significant contribution to decarbonization. The production of decarbonized gas ranges from 130 TWh to 185 TWh in 2050, and the share of renewable gas in the gas balance is at least 55%. In all scenarios, a high volume of injected biomethane is produced from methanisation (90-126 TWh).

For residential buildings, all of the ADEME scenarios foresee an important decrease in final energy consumption. The level of residential final energy demand in 2050 ranges from 225 to 347 TWh (including ambient heat and principal residences). Without considering the consumption of ambient heat, the abatement rate ranges from 58% under S1 to 46% under S4 compared to 2015 (principal residences). The future balance is dominated by electricity and ambient heat. In 2050, the share of electricity is between 34.6%-42.4%, slightly higher than in 2015 (32%). Ambient heat has a greater presence, accounting for 19.1-31.7% of final consumption, far exceeding the level of 2015 (1%). The high consumption of electricity and extraction of ambient heat is associated with massive integration of electric heat pumps.

¹⁹ BECCS: Bioenergy with Carbon Capture and Storage

²⁰ DACCS: Direct Air Carbon Capture and Storage

1.2.3 NégaWatt 2022

The scenario published by négaWatt in 2022 shows different pathways for the energy transition. négaWatt is an independent association focusing on the energy perspective of France. It has been publishing scenarios of transitions since 2003. Following négaWatt 2022, the national final energy balance of 2050 is composed of 44% electricity, 25% gas, 12% solid biomass (négaWatt, 2022). Compared with the AMS scenario, the share of electricity in 2050 is lower under négaWatt 2022, while the share of gas is higher. The production of electricity and gas is completely decarbonized. For the electricity system, wind parks and solar PV rapidly develop in the future. By 2050, wind power is the first source for electricity generation, representing more than 60% of total electricity generation (more than 300 TWh). Solar PV accounts for around 30% of electricity production. NégaWatt 2022 has a very pessimistic vision for nuclear power: there are no new constructions of nuclear power plants, and all existing nuclear power plants stop operating by around 2045. Due to the large-scale presence of intermittent renewable energies, flexible solutions such as power-to-gas, electricity storage and gas cogeneration are developed in order to guarantee the equilibrium of the electricity system.

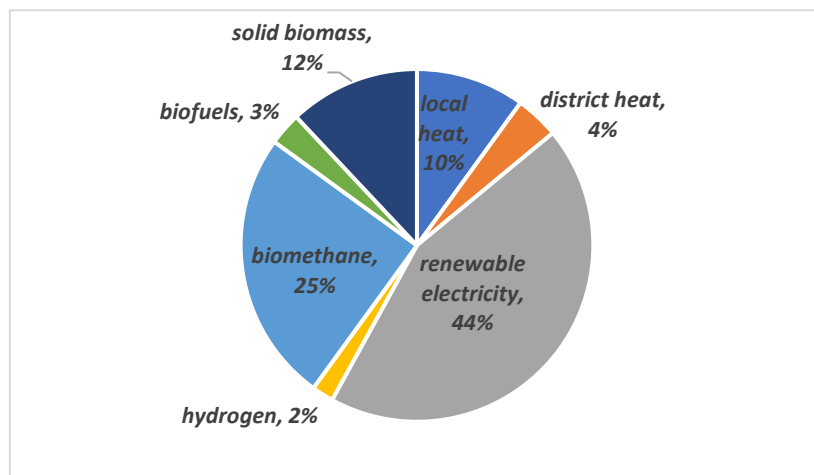


Figure 20 Final energy consumption of 2050 by scenario NégaWatt 2022 (négaWatt, 2022)²¹

²¹ Local heat: geothermal energy, ambient heat, etc.

1.2.4 Gas and electricity perspectives

Apart from public stakeholders and associations, gas and electricity network operators share their visions of the future energy sector. These visions are published in Gas Perspective by GRDF, GRTgaz, Teréga²² and SPEGNN²³ (GRDF et al., 2022), Energy pathways 2050 and Prevision Balance by RTE (RTE, 2022). Both reports meet with network operators' obligation to elaborate perspectives of the gas/electricity consumption and production structure established in the energy law.

Gas Perspective is a yearly exercise for gas network operators in France. It studies the trajectory of sectorial gas demand and the production of renewable gas for the future. In Gas Perspective 2020, three scenarios are elaborated for carbon neutrality: "NATIONAL gaz bas", "NATIONAL gaz haut" and "TERRITOIRE", (GRDF et al., 2020). However, these scenarios only provide projections of the gas system up to 2030. The latest update of the "TERRITOIRE" scenario in 2022 (GRDF et al., 2022) extends the trajectory to 2050. Note that the "TERRITOIRE" scenario considers faster carbon mitigation in 2030 than the SNBC objective ("Fit for 55") (European Parliament, 2024). The consumption of gas in 2050 is significantly lower than the current level under the "TERRITOIRE" scenario. The total gas demand in 2050 is 312 TWh, 35% less than in 2020. The decrease in national gas consumption is driven by lower demand from buildings, industry, and energy production. Gas demand from buildings and industrial processes is projected to drop by 60% and 62% respectively in 2050 compared to the 2020 level, as a result of greater energy efficiency and the transfer to electricity. The use of gas for power generation will decrease by 80%, following the gradual phase-out of thermal power plants. The transport sector is estimated to be the largest consumer of gas in 2050, accounting for 36.5% of total gas demand. An increase in gas consumption in the transport sector is driven by fast development of bioNGV²⁴. On the provision side of gas, the "TERRITOIRE" scenario foresees a fast development of the renewable gas industry, notably after 2030. The share of decarbonized gas is estimated at 20% in 2030, and in 2050 the production balance will be 100% of renewable gases. In 2050, biomethane produced from methanisation is the largest source of gas injection (130 TWh), followed by low-carbon hydrogen (77 TWh) and biomethane from pyro-gasification (57 TWh).

²² Térega: French gas transport network operator

²³ SPEGNN: Syndicat Professionnel des Entreprises Gazières Non Nationalisées (in French)

²⁴ bioNGV: Natural Gas Vehicles fueled by biogas

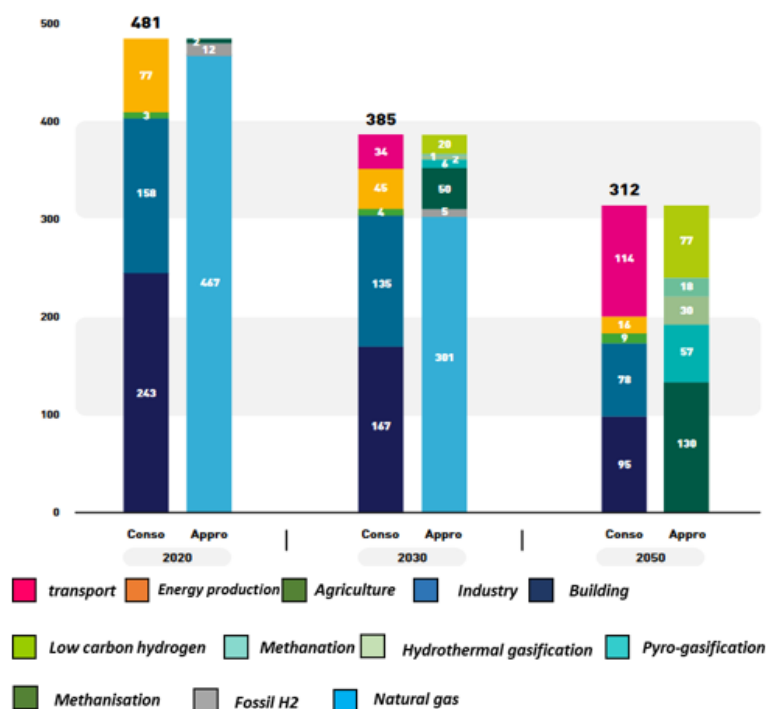


Figure 21 Production and consumption balance of gas projected by TERRITOIRE scenario of Gas Perspective (GRDF et al., 2022)

Energy pathways 2050 published in 2022 represents the vision of the electricity network operator (RTE) on possible solutions for the future electricity system in a carbon neutrality context. A number of scenarios are elaborated by crossing different hypotheses of final energy demand and new investments in power plants. These include six major scenarios (M0, M1, M23, N1, N2, N03) based on a reference consumption level which corresponds to an update of the SNBC final energy consumption trajectory. The reference consumption trajectory foresees 645 TWh of electricity consumption in 2050, higher than the volume indicated in SNBC. Besides, multiple variants interpreting different consumption levels are elaborated. The key element distinguishing the six principal scenarios is the possibility to invest in new nuclear power plants (RTE, 2022).

All of the RTE trajectories foresee that RES will play an important role in the future power generation mix. In 2050, the six scenarios estimate 70-208 GW of solar PV and 65-136 GW of wind power capacity. In a future without new nuclear power plants (scenarios beginning with “M”, M0, M1, M23), to satisfy electricity demand, more integration of RES power plants is required. In the case where France completely phases out nuclear power by 2050 (M0), the total required capacity of solar PV, onshore and offshore wind plants reach 344 GW, producing more 628 TWh of renewable electricity. As the future electricity mix is dominated by intermittent RES, more flexibility capacity will be mobilized to

guarantee the supply security. The solutions include batteries, decarbonized thermal plants and PSPs²⁵ (RTE, 2022).

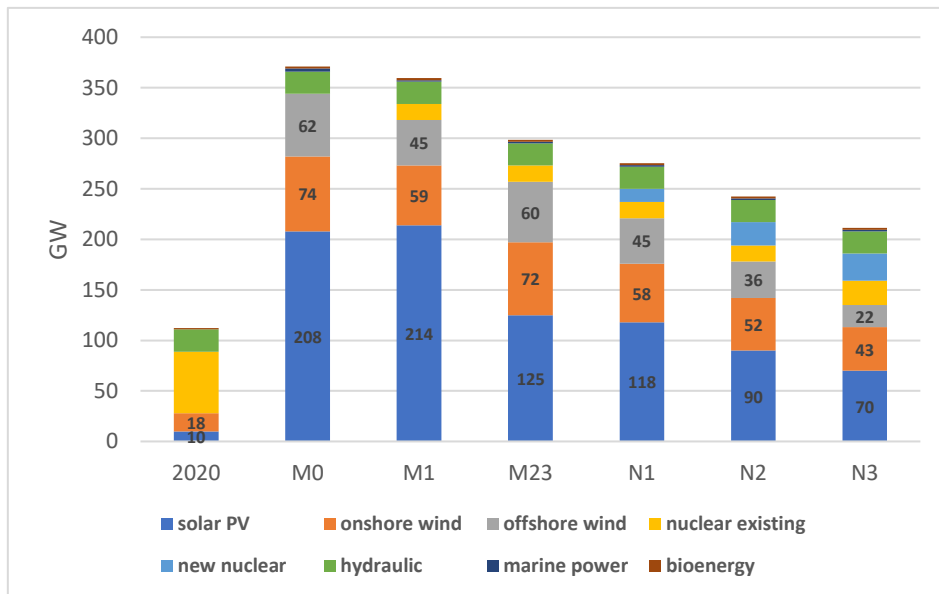


Figure 22 2050 Capacity of power plants in 2050 by RTE scenarios (RTE, 2022)

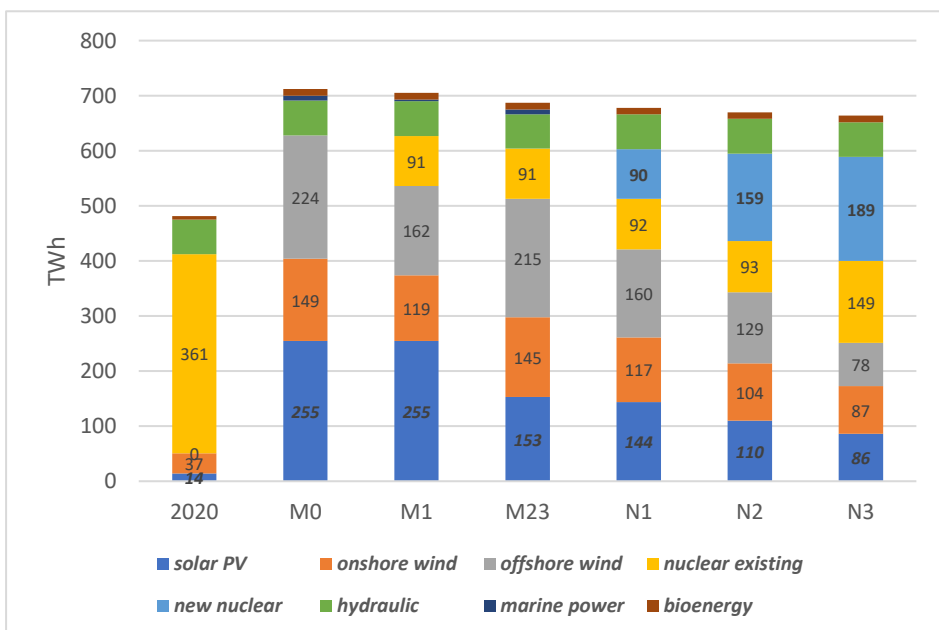


Figure 23 Balance of electricity production by RTE scenarios (RTE, 2022)

²⁵ PSP: Pumped storage power plants.

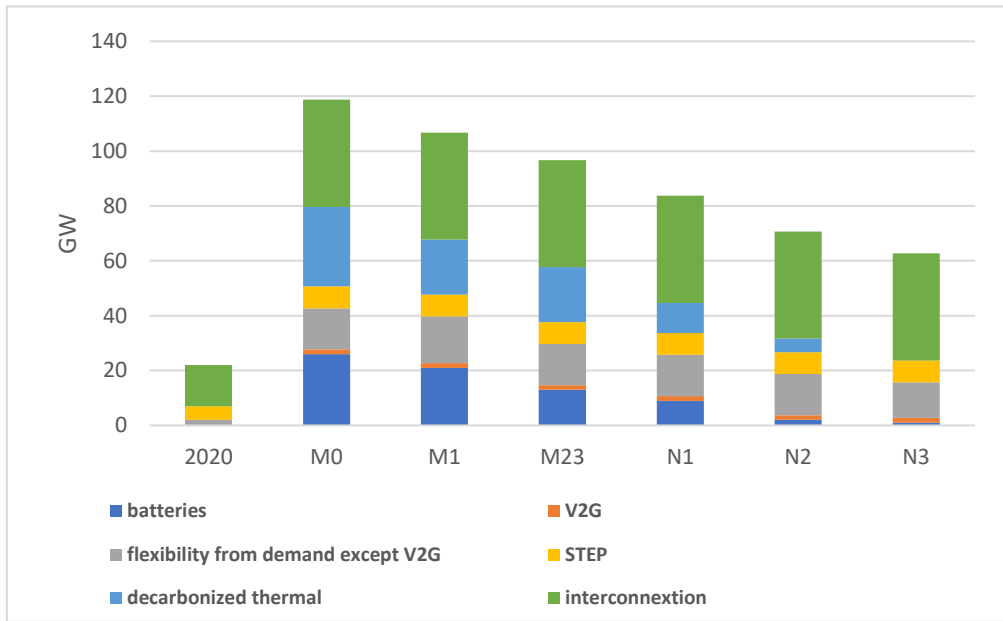


Figure 24 Flexibility of power system in 2050 by RTE scenarios (RTE, 2022)

1.3 Current state of residential building stock: large presence of buildings with low energy efficiency

Published energy perspective scenarios indicate multiple possibilities to reach a carbon-neutral system. Eligible solutions include decarbonizing electricity and the gas supply, bio-energies, the development of the CCS industry, and the widespread practice of more sober consumption. One important element to consider is that, compared with other sectors, decarbonizing residential buildings may present a higher level of complexity. This is because the housing stock contains a large variety of buildings with different features closely linked to energy consumption, including the climate zone, heating energy source, construction quality, etc. These features require careful consideration when making technology choices. In addition, a significant share of buildings is currently of low thermal quality and equipped with very carbon-intensive heating equipment. This constitutes a considerable challenge in achieving the carbon neutrality goal. In this section, we chiefly introduce these concerns.

1.3.1 Climate features and geographical location as important factors to consider

At the beginning of 2022, there were in total 37,553 thousand housing units in Metropolitan France, of which 81.9% were principal residences, 9.8% were secondary or occasional residences, and 8.3% were vacant, as suggested by INSEE²⁶ statistics (INSEE, 2022a)²⁷. Among the around 30.8 million principal residencies, 60% were individual houses and 40% were apartments.

Residential buildings present various features including geographical location, building quality, and heating equipment. Detailed information on the characteristics of housing stock can be found in the statistical results of previous housing surveys. These include the national housing surveys of 2020 (SDES, 2019b) and 2013 (INSEE, 2016) (ENL 2020, ENL 2013) by SDES²⁸, Phébus²⁹ 2012 (Ministère de la Transition écologique et de la Cohésion des territoires, 2018), and the Fideli database (INSEE, n.d.-b).

²⁶ INSEE: Institut national de la statistique et des études économiques (*in French*)

²⁷ Definitions of principal, secondary and vacant residence by INSEE (INSEE, n.d.-a):

Principal residence: dwelling principally occupied by one or several persons who constitute a household.

Secondary residence: accommodations used for weekends, leisure or vacations. Furnished accommodations rented (or to be rented) for tourist stays are also classified as second residences.

Occasional residence: accommodation or independent room occasionally used for professional reasons.

Vacant dwelling: unoccupied dwelling in one of the following cases: offered for sale, for rent; already assigned to a buyer or tenant and awaiting occupancy; awaiting estate settlement; kept by an employer for future use for the benefit of one of its employees; kept vacant and without a specific assignment by the owner.

²⁸ SDES : Service des données et études statistiques (*in French*)

²⁹ Phébus : Enquête Performance de l'Habitat, Équipements, Besoins et Usages de l'énergie (*in French*)

In addition, the CEREN and INSEE databases provides calibration of the main parameters of housing stock (number of dwellings, energy source, etc.) for intermediate years based on national housing surveys. The final result of ENL 2020 is not yet accessible online.

In terms of geographical location, residential buildings are unevenly distributed over climate zones and urban areas with different population densities. These geographical features are important factors to consider when making heating choices. Thermal regulation of 2012 (RT 2012) introduced the notion of climate zones (linked with heating need for buildings), according to which Metropolitan France is divided into zone H1, H2 and H3, depending on climatic rigor (Ministère de la Transition écologique et de la Cohésion des territoires, 2020c). Zone H1 corresponds to the coldest regions in the north and north-east of France, zone H2 are regions with a moderate climate in the west, and zone H3 is the Mediterranean coast with the warmest winter. Dwellings in the colder zone H1 in general have a longer, higher heating demand profile in winter, which may imply higher requirements for heating systems and thermal quality. This is the case for more than 55% of residential building stock in Metropolitan France³⁰. Concerning the distribution of dwellings over type of urban area, around 20.1% of principal residences are located in rural areas, and the majority are individual houses. Around 31.7% are in urban units of 100,000 inhabitants or more (excluding Paris) and 16% are located in the Paris region (INSEE statistics for early 2022) (INSEE, 2022b). Housing located in areas with different population densities may not have the same access to energy sources: district heating or natural gas networks may not be able to cover less populated zones.

³⁰ We can see that more than half of dwellings are located in zone H1. This can be explained by on the one hand the broad geographical extent of H1 (55 out of 96 *départements*), and on the other hand the high concentration of population in Ile-de-France and the Auvergne - Rhône-Alpes region.

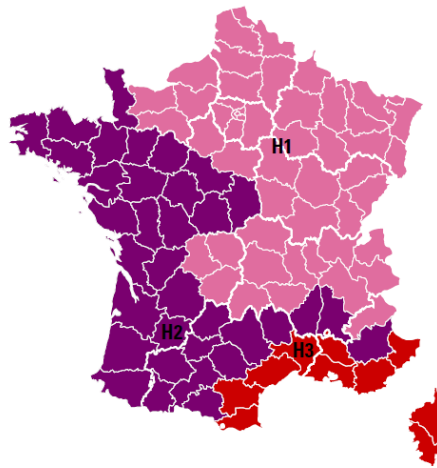


Figure 25 The three climate zones of Metropolitan France (PACTE, 2017a)

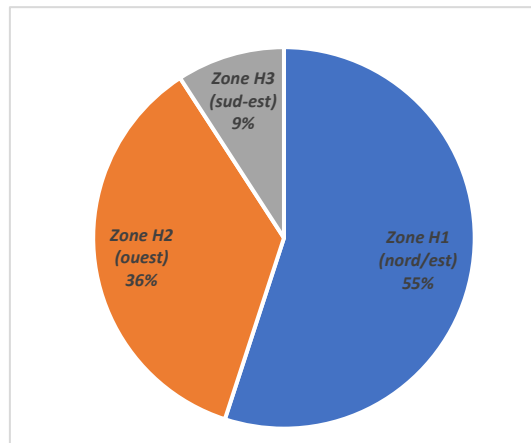


Figure 26 Housing stock by three climate zones, range: residencies in Metropolitan France (Ministère de la Transition écologique et de la Cohésion des territoires, 2018)

1.3.2 High presence of buildings with low thermal performance

Apart from geographical location, one important feature to consider is the thermal quality of a building, which is determined by its construction quality. The level of thermal quality differs greatly among existing residential buildings and is closely linked with the construction period. In general, recent buildings have a higher thermal quality than old buildings. This can be explained by the building styles employed during various periods. According to the studies by (PACTE, 2017a) and (Tabula, 2015)³¹, a significant differences can be observed between buildings constructed before 1948, between 1948-1975, and after 1975.

Dwellings constructed before 1948 mainly consist of old rural houses, and detached houses in urban and suburban areas. They are mainly wood or brick structures with poor thermal resistance. Moreover, the deterioration of construction material, which aggravates the loss of thermal quality, is very common among these old buildings. For a significant share of residential buildings constructed from 1946-1970 (reconstruction period), the priority was to accommodate the maximum number of people, with relatively little attention paid to thermal performance. Massive social housing projects implementing a standardized construction style and with low building quality were established during this period.

Buildings constructed after 1975 are in general of better thermal quality. This is partly explained by the implementation of building thermal regulations that set a minimum requirement for thermal quality. Effective insulation materials such as mineral wool and expanded polystyrene are commonly used. Moreover, new construction materials with very high thermal resistance have been applied since 2012, such as insulated bricks for houses and wooden frame walls clad in mineral wool for apartments (Tabula, 2015).

Considering the age structure of existing residential dwellings, a significant share of the building stock was constructed before 1975. According to statistics of CEREN³², a French organization dedicated to energy research and analysis (CEREN, 2022), around half of buildings were constructed before 1975, and buildings after 1999 represent 23% of the total stock. This suggests that a large share of residential buildings have relatively low thermal quality. These buildings may have very high energy demands, requiring much greater decarbonization efforts.

³¹ Detailed information on the construction characteristics of the French residential building stock is available in a study elaborated by (PACTE 2017a) which characterizes dwellings constructed in four major construction periods (before 1850, 1850-1948, 1948-1975, after 1975) into 14 archetypes. A similar methodology is applied in a study of building typology by Tabula/Episcopo (Tabula 2015).

³² CEREN: Centre d'études et de recherches économiques sur l'énergie (*in French*)

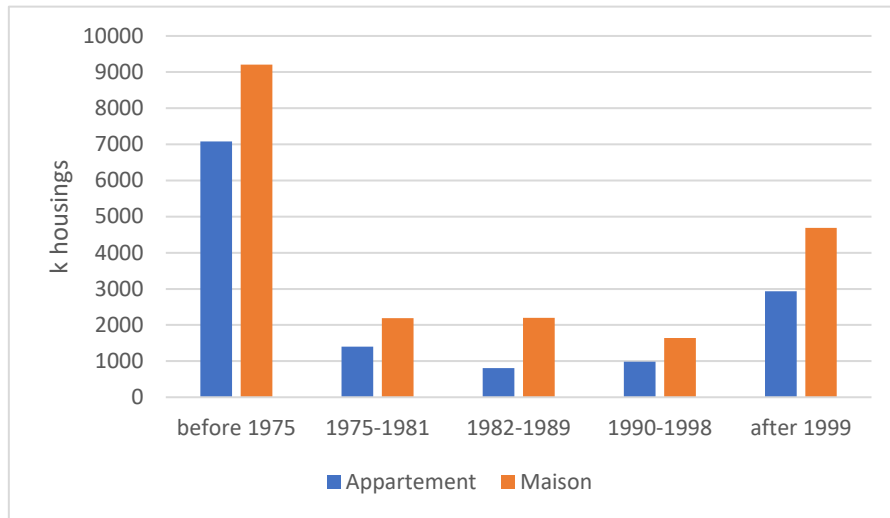


Figure 27 Age structure of housing stock of Metropolitan France (CEREN, 2022)

1.3.3 Overview of heating equipment stock: high presence of heating oil and natural gas

With regard to heating systems, the current housing stock relies on various energy sources. Gas and electricity are the dominant energy sources for both individual houses and apartments. In 2020, around 37% of dwellings were equipped with gas heating equipment and 36% with electric heating equipment. Gas heating was more widespread in apartments than individual houses at more than 52% compared to 27%. In addition, the integration rate of electric equipment was higher among individual houses (39%) than apartments (32%). Besides, we observe a significant presence (17%) of biomass heating equipment in individual houses, and district heating in collective buildings (10%). Note that a significant share of residential buildings still relies on very carbon-intensive heating oil (10% of total stock) and hard coal (1% of individual houses). The use of heating oil is much more common among individual houses (14%) than collective buildings (4%).

	<i>Solid biomass</i>	<i>Coal</i>	<i>Heating oil</i>	<i>Natural gas</i>	<i>LPG</i>	<i>DH</i>	<i>Electricity</i>	<i>total</i>
<i>apartment (k units)</i>	189.8	15.1	543	6839	10.3	1316	4291	13204.2
<i>% of housing stock</i>	1%	0%	4%	52%	0%	10%	32%	100%
<i>individual house (k units)</i>	3349	121.9	2879	5375	387	92	7710	19913.9
<i>% of housing stock</i>	17%	1%	14%	27%	2%	0%	39%	100%
<i>total (k units)</i>	3538.8	137	3422	12214	397.3	1408	12001	33118.1
<i>% of housing stock</i>	11%	0%	10%	37%	1%	4%	36%	100%

Table 1 Stock of heating equipment by energy source in 2020 estimated by CEREN, field: principal residences of Metropolitan France (CEREN, 2022)

1.3.4 Challenge of the future energy transition: illustration from DPE statistics

The overview above outlines that buildings with poor thermal quality and carbon-intensive heating equipment require significant efforts in the future energy transition. The statistics on EPCs³³ help us to better understand the difficulties faced by the residential sector. For a building, the EPC method estimates the amount of primary energy consumption per square meter, and thus constitutes an important measure of the energy performance of buildings. The EPC estimation is decided by multiple factors including the thermal quality of the building, the efficiency of energy equipment, climate features, and thermal quality, which is one of the most important factors. The EPC system ranks the energy performance of a building with one of seven ratings in alphabetic order (from A to G). Buildings ranked A and B are considered as energy efficient, while F and G buildings are “energy sieves”. EPC statistics suggests that, for principal residences in Metropolitan France, the share of dwellings with an A or B rating is only 7%, much lower than the share of “energy sieves” (class F and G, 11% and 7% respectively). The majority of dwellings present an energy performance level of D or E (34% and 24% respectively) (ONRE, 2022b). We can see that recent buildings in general have a better energy performance than old buildings: more than 40% of buildings built before 1948 are rated F or G, while this ratio decreases to 1.4% for housing built after 2000. The efficiency of very recent buildings is significantly higher: over 25% of dwellings built after 2000 dispose an energy label of A or B (ADEME, 2021a).

The statistical facts of EPC in France outline that, in the future, around one-fifth of residential buildings may require heavy decarbonization efforts. This suggests that important challenges lie ahead to achieve the objective of carbon neutrality.

³³ *Diagnostic de Performance Energétique* (DPE) in French– Energy Performance Certificate (EPC) in English

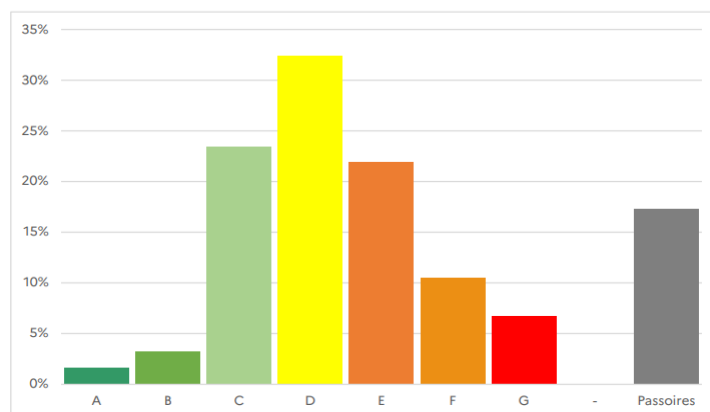


Figure 28 Energy performance of current dwelling stock from EPC statistics, range: Metropolitan France (ONRE, 2022b)³⁴

	A	B	C	D	E	F	G
before 1948	0.4%	0.4%	7.1%	23.9%	28.5%	21.0%	18.8%
1948-1974	0.2%	1.8%	14.7%	37.9%	28.6%	12.4%	4.4%
1975-2000	0.2%	2.4%	20.9%	39.6%	27.3%	7.9%	1.6%
after 2000	7.9%	17.2%	30.3%	33.0%	10.1%	1.2%	0.2%

Table 2 Distribution dwelling stock by EPC class and construction period (ADEME, 2021a)

³⁴ "Passoires" in French: rated F and G

1.4 An overview of eligible technology solutions for the future residential energy transition

The previous sections outlined the ambitions and challenges for residential buildings to reach carbon neutrality. The future energy transition of the residential sector needs to rely on a range of existing and emerging technologies. Solutions can be applied from both the energy demand and production sides of building. In this section, we provide an overview of eligible technologies to decarbonize the building energy system. We focus on thermal insulation to reduce the useful energy of buildings, and a range of efficient equipment including condensing boilers, electric heat pumps, solar thermal systems, fuel cells, and district heating as a solution for collective heating. Our review illustrates the technical-economic features, development status, and perspective of different technologies. This will allow us to better understand how these technologies work and contribute to carbon mitigation, and to identify the pros and cons for household investment, all of which are essential elements for understanding in our search for a future energy solution for residential buildings.

1.4.1 Thermal insulation as a key solution for existing residential buildings

1.4.1.1 Techniques for insulation retrofits

Thermal insulation is a solution to reduce the heating demand of a building. The principle is to slow down heat transfer through the building's thermal envelope using thermal resistant materials. The thermal envelope of a building represents all the building materials where a heat transfer occurs between the inside and outside environments, including the walls, windows, roofs and floors. By insulating the thermal envelope with materials with lower thermal conductivity or higher thermal resistance, buildings have a higher thermal quality. During winter, the speed of heat transfer from the heated interior to the colder external environment is lower, and the house will require less heat production to maintain the indoor temperature.

Along with the development of materials and building technology, an increasing number of insulation materials with high thermal quality are now available on the market, and a wide range of insulation techniques can be applied to different components of the building envelope. The PACTE³⁵ project (PACTE, 2017b) and Tabula (Tabula, 2015) present a detailed list of solutions according to typical French dwelling types. A common technique to insulate roofs, interior/exterior walls, and ground floors involves mechanically fixing one or several levels of insulation materials with a coating. Insulation materials include different insulation wools made from minerals, plant/animal-based products, as well as a range of synthetic products such as polystyrene foam, PUR, and fibrasylene. These insulation materials have a varied level of thermal performance. For windows, a common solution is to use double or triple glazing with lower thermal conductivity. The suitable insulation technique and the effect are highly dependent on the project.

1.4.1.2 Fabric retrofits as an important solution for existing housings and policy ambitions

Considering that a high number of buildings are of low thermal quality, renovating building fabrics is an important solution to reduce energy demand and carbon emissions from existing housing stock. In particular, for buildings ranked EPC F and G ("energy sieve"), important energy gains can be obtained by fabric renovation. An analysis based on the data from the PHEBUS housing survey provided by EDF (Milot, 2019) suggests that the technical potential (the total useful energy that can be gained from renovating current stock) of insulation is 84.12 TWh for individual houses and 58.82 TWh for apartments. This potential represents an important share of the current energy consumption of

³⁵ PACTE: Programme d'Action pour la qualité de la Construction et la Transition Energétique (*in French*)

buildings. Considering the 260 TWh of useful energy demand for space heating calibrated from the AME 2021 scenario, the estimated potential then represents around half of current useful consumption.

For existing buildings, the current energy policy framework, including the Law on Energy transition and Green Growth (LTECV), the national low-carbon strategy (SNBC) and the multi-annual energy program (PPE), has fixed multiple targets of energy retrofit for different time points in the future. In addition, the energy and climate policy in France considers energy renovation as one of the most important measures to achieve carbon neutrality in 2050. For the short term, the LTECV sets a goal to renovate a minimum of 500,000 dwellings (efficient renovation, rise of two energy ratings, and attainment of at least EPC label C) per year starting from 2017 and all “energy sieves” are expected to be renovated by 2025. Energy savings in the existing housing stock are estimated to be a major driver to reach the general abatement goal of reducing 20% of national final energy demand by 2030 (LTECV, all sectors). The PPE and SNBC, which detail the sectoral scenario objectives, give more precise targets of a 15% reduction of the total final energy demand of residential and tertiary buildings by 2023 and 28% by 2030 (both compared with 2010 levels). The energy renovation goal is to reach “BBC” level for the entire housing stock by 2050.

Along with the policy target of energy retrofits in the residential sector, various incentives take the form of specific financial aid. The list of major incentives includes MaPrimeRénov’, Certificats d’économies d’énergie (CEE), Chèque énergie, Éco-prêt logement social (Éco-PLS), Éco-prêt à taux zéro (Éco-PTZ) and Habiter mieux Agilité (Ministère de la Transition écologique et de la Cohésion des territoires, 2024). These incentives are proposed by public stakeholders and aimed at different types of household.

In addition, in order to support the policy ambition of widescale building renovation, the French government has introduced a national road map called the “Plan for Energy Renovation of Buildings”. This document outlines major objectives concerning renovation including increasing the number of renovation works, reducing energy poverty, and accelerating renovations of tertiary buildings especially the in public sector. A range of actions are proposed: in addition to multiple financial packages for both residential and public buildings in the coming years, efforts are expected from other aspects such as better communication of the benefits of energy renovation to households and territorial policies (Ministère de la Transition écologique et de la Cohésion des territoires, 2020b).

1.4.1.3 Current pace of renovation: unbalanced level between individual houses and apartments

The pace of energy renovations has tended to accelerate in recent years. According to ONRE³⁶ (ONRE, 2022a) statistics, the number of renovated dwellings and estimated energy savings from energy retrofits have increased since 2016. In 2019, more than 3 M dwellings underwent renovations that generated energy savings. These renovations achieved a total final energy gain of over 10 TWh. Compared with 2016, both the number of renovations and energy savings have increased by around 70%. We can see that financial incentives have played an important role in the recent growth: In 2019, around 77% (2.4M) of renovated dwellings benefited from financial aid.

The table below presents the details of energy savings according to four types of renovation: roof/walls/floors, windows/doors, energy equipment and ventilation. Renovating the thermal envelope contributes around 4.6 TWh of final energy savings, around half of the total energy gain of 2019. Note that, for insulation retrofits, the majority were carried out on individual houses. In 2019, more than 1.2 million individual houses renovated their roofs, walls or floors, bringing a total energy saving of 3.13 TWh. Both figures are around three times that of collective buildings. This may be explained by multiple factors, and we will develop this point in the following part.

	Number of dwellings	Final energy saving (TWh/year)
Roof, walls, floors	1605590	4.2
<i>Individual house</i>	1260117	3.07
<i>Apartment</i>	345473	1.13
Windows, doors	700726	0.43
<i>Individual house</i>	590826	0.37
<i>Apartment</i>	109900	0.06
Heating, DHW production	1099118	4.76
Ventilation	344333	0.76
All renovations	3057688	10.24
<i>Individual house</i>	2293223	8.11
<i>Apartment</i>	764465	2.13

Table 3 Number of dwellings receiving energy retrofits and estimated final energy savings in 2019 (ONRE, 2022a)

³⁶ ONRE: Observatoire national de la rénovation énergétique (*in French*)

1.4.1.4 Potential difficulties for insulation retrofits in buildings

As introduced above, the existing housing stock has a high potential for energy savings from energy renovations. However, it is still very uncertain whether the identified energy saving potential can be achieved in the future. At the current rate of investment, realizing such an ambitious goal before 2050 will require considerable efforts. Here we need to consider several elements that could create obstacles in a perspective of energy retrofits.

Firstly, despite increasing financial incentives, a considerable share of households, especially those with lower incomes, still encounter great difficulties in investing in renovation due to budget constraints. The statistics from the “TREMI³⁷” questionnaire suggest that, for individual houses, the share of households that have carried out an energy renovation is 36% among those with an annual consumption unit revenue below 14,130 euros, which is significantly lower than the share of households with an income above 30,810 euros per year (42%) (ONRE, 2022a).

Secondly, the increase in the marginal cost of energy savings makes it expensive to carry out a complete renovation, adding difficulties to reach the total insulation potential. For most dwellings, the first steps of renovation (for example, changing the windows), which require a low investment, can usually bring considerable energy savings. However, to reach a high thermal performance level (BBC consumption) requires the renovation of all components of the envelope. This might involve actions requiring heavy investments such as roof insulation with efficient materials. The case is similar when we consider the long-term pace to reach insulation potential. Taking the example of individual houses, the estimation of (Millot, 2019) gives a quasi-exponential increase in unitary investment costs and cumulative energy gains. The unitary investment cost remains relatively low (below €10/kWh) when the cumulative energy gain of the entire individual house stock is lower than 70 TWh (which is the case today³⁸); however, to reach the maximum potential of 84.12 TWh, the marginal cost increases to €43/kWh.

³⁷ TREMI: Enquête sur les travaux de rénovation énergétique dans les maisons individuelles (*in French*)

³⁸ In 2019, the total investment in thermal insulation (with tax) for individual houses was 19,540.39 M euros and the estimated useful energy saving was 2.75 TWh. The unitary investment cost of insulation was around 7.11 €/kWh (ONRE, 2022a)

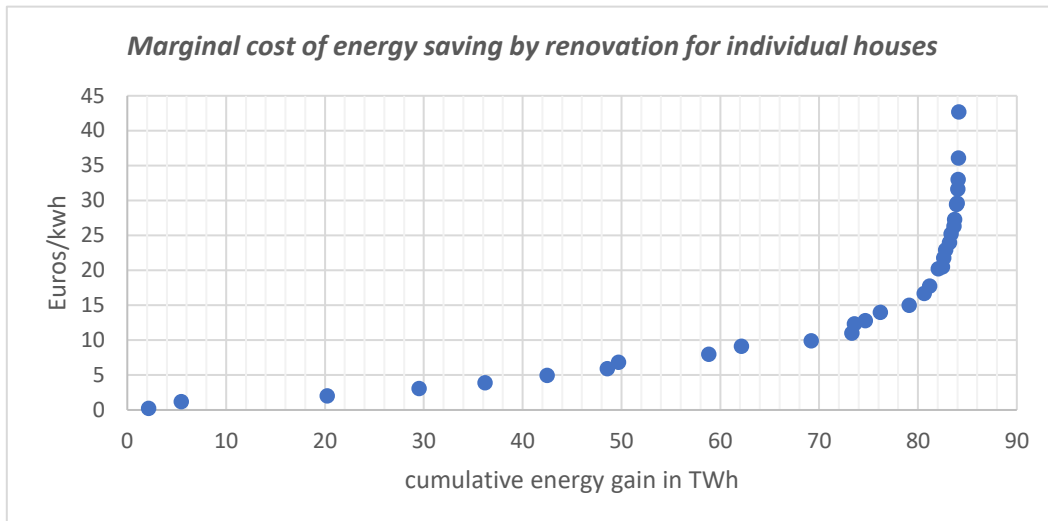


Figure 29 Marginal cost of energy retrofits (in KWh of energy saving) by cumulative energy gain for individual house stock (Millot, 2019)

Thirdly, the level of renovation is currently very low in collective buildings, and the over presence of tenant-occupied housing (over 50% of collective buildings) might increase the difficulties involved in mobilizing the collective stock. As energy renovation is usually a complicated project with a long amortization period, it is less economically feasible for tenant occupiers with short rental leases to invest. Besides, most financial aids are destined for owner occupiers or tenants with long rental leases (more than 5 years for Maprimerenov’).

Lastly, there is risk that investment in energy renovation may not bring the expected energy gain .In 2019, an estimated one-fifth of renovations (730,000 out of 3.3 M) in individual houses had no impact on final energy consumption, and a considerable number of dwellings had higher energy consumption after renovation (ONRE, 2022a). Another observation from the TREMI questionnaire suggests that, for all renovations of individual houses in 2019, around 11% of households claimed that the achieved renovation did not bring any improvement in thermal comfort and around 17% declared that the renovation had not reduced their energy consumption. This can be explained by several aspects including behavior factors (the rebound effect, which we develop in Chapter Six), technical failures, etc.

Complementary information 2 Regulation framework to guarantee thermal quality of buildings

Since 1974, a series of thermal regulations have been introduced. These regulations set requirements for energy performance and thermal comfort of buildings and are applied to both new constructions and existing housings. The first thermal regulation was enacted in 1974 (RT 1974), making a goal to reduce unit primary energy consumption in building sector to 225 kWh/m²/year, compared with the estimated consumption of 300 kWh/m²/year of buildings constructed during 1950-1974. RT 2005 fixed target to reduce primary energy consumption of new constructions to less than 90 kWh/m²/year, and in parallel created energy performance labels to make an improvement with respect to its objectives (Ministère de l'Emploi, de la Cohésion Sociale et du Logement, 2006). Thermal regulations have been applicable to buildings' renovations since 2007 and two energy labels for renovated constructs were then introduced in 2009: BBC renovation for maximum primary energy consumption of 80 kWh/m²/year and HPE renovation of 150 kWh/m²/year. RT 2012 are norms for all buildings constructed between 2013 and 2020. It also puts more efforts on enhancing the insulation of thermal envelopes and satisfying the heating demand more by passive loads (passive solar and internal heat), depending on implantation, compactness and bay orientation of the construction. Buildings of RT 2012 need to meet three criteria: Bbio (bioclimatic need) that explains the minimum energy efficiency requirement, Cep (primary energy consumption) which includes primary energy consumption for heating, cooling, lighting, DHW production and Tic (summer comfort) that expose the requirements for inside temperature during the hottest days in summer (AMORCE, 2019). In order to conform with RT 2012, the primary energy consumption cannot surpass a CepMax defined by a referential CepMoyen (value for an average building, depending on the usage or the part of building) of 50 kWh/(m².an) and a series of modulation factors including building type, geographical localization, altitude, surface area energy source. The newly introduced RE 2020 (Ministère de la Transition écologique et de la Cohésion des territoires, n.d.-a) (RE stands for environmental regulation, replacing the former acronym RT) is based on the three major criterions of RT 2012 (energy efficiency, thermal quality and summer comfort) and add additional requirement on environmental footprint of buildings (lifecycle analysis). The RE2020 imposes 9 indicators, with 5 of energy performance and 4 of carbon impact of buildings. Compared with RT2012, the newly introduced criteria are: ICconstruction, ICénergie, StockC and ICbâtiment that measures environmental performance of building, DH-incomfort (degree hours of discomfort) for summer comfort replacing indicator TIC in RT 2012. For primary energy consumption, RE 2020 disposes two indicators that define the maximum non-renewable and renewable primary energy consumption (Cep, nr_max and Cep Max), and the modulation factors to calculate the maximum energy consumption are slightly changed. The reference nonrenewable primary energy consumption (Cep_nr, maxmoyen) of apartment is 70 (kWh/m²/year) and of individual house 55 (kWh/m²/year).

	RT 1974	RT 1982	RT 2000	RT 2005	RT 2012 (Cep_Moyen)	RT 2020 (Cep, nr_max_moyen) individual house	RT 2020 (Cep, nr_max_moyen) apartment	RT 2020 (Cep, max_moyen) individual house	RT 2020 (Cep, max_moyen) apartment
Limit of Primary energy consumption (kWh/m ² /year)	225	170	130	90	50	55	70	75	85

Table 4 Standard of primary energy consumption from RT 1974 to RT 2020

Indicator	Description
ICénergie	Carbon emission of primary energy consumption CO ₂ /m ² kg
ICconstruction	Evaluation of the emission of all lifecycles of buildings: production of construction material, transportation, installation, repair, maintenance and end of life eq CO ₂ /m ²
StockC	the amount of carbon from the atmosphere stored in the building kgC/m ²
ICbâtiment	ICconstruction + ICenergy + carbon emission of water consumption and discharge during the building's operation.

Table 5 New parameters of RE 2020 (Ministère de la Transition écologique et de la Cohésion des territoires, n.d.-b)

1.4.2 An overview of efficient heating solutions for buildings

Currently, for residential buildings, a large range of equipment is available with different energy inputs and energy efficiency levels. In the future, the need for carbon mitigation will require more solutions with higher energy performance and lower carbon emissions. From our literature review, we have identified five technical solutions that may contribute to the future energy transition toward a carbon-free system: condensing boilers; multiple types of heat pump including air-sourced heat pumps, geothermal heat pumps and hybrid heat pumps; solar heating; residential fuel cells and district heating. In this section, we propose to review these four technologies.

These technologies have different degrees of maturity. The table below shows recent market data on the main energy equipment for housing. In 2021, air-sourced HP (air/air, air/water) accounted for more than 57% of the market, with around 0.75 million installations of air/air heat pumps and 0.25 million installations of air/water heat pumps. Condensing boilers accounted for around 36% of the market. The share of solar systems was relatively very low, while fuel cells still remained an emerging technology.

	2018	2021
Wood boiler	12135	36420
Geothermal heat pump	3080	3220
Air/water heat pump	93580	253140
Air/air heat pump	498120	758270
Conventional gas or fuel boiler	117000	81000
Condensing gas or fuel boiler	544000	634000
Individual water heater	4580	7800
Combined solar system	350	630

Table 6 Market share of residential heating equipment in 2021 (Observ'ER, 2022)

1.4.2.1 Condensing boiler

Condensing boilers are fuel combustion boilers with very high energy performance. Compared with conventional boilers, condensing boilers are much more efficient: the energy efficiency of condensing boilers can usually reach 100%, much higher than the 70% of conventional boilers. This is mainly because condensing boilers can capture the latent heat in a second heat exchanger from condensed flue gases (Techniques de l'ingénieur, 2014a).

The figure below describes the operating mechanism of a condensing boiler fueled by gas. When operating, a combustion boiler burns fuel in a closed combustion chamber, thus generating combustion gas which passes through a heat exchanger where the high temperature gas transfers heat to another fluid media (heat transferer) in the distribution network. Then the combustion gas passes through a second heat exchanger where the water vapor is condensed, and preheats the circulating water before it passes through the first heat exchanger. In this way the latent heat in the exhaust gas is reutilized for heat generation, significantly increasing the energy efficiency of the equipment. In addition, modern condensing boilers are fitted with an efficient combustion fan control and distribution system, both of which boost efficiency (MEP Academy, 2022).

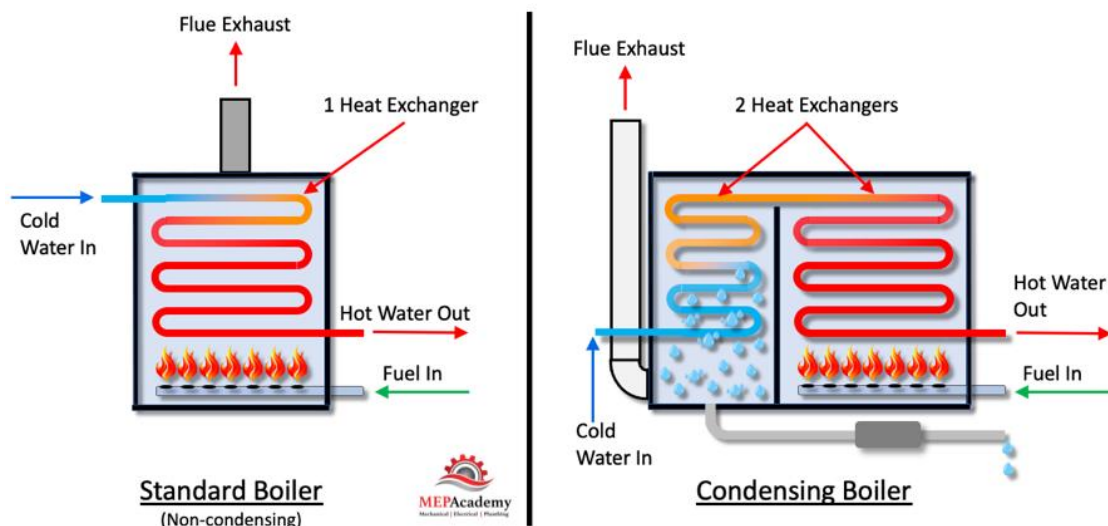


Figure 30 Operating principle of a condensing boiler (MEP Academy, 2022)

Apart from high energy efficiency, condensing boilers have several advantages. First of all, condensing boilers are a very reliable solution for heating. They can immediately and constantly provide heat for residential needs in all types of weather conditions. Secondly, condensing boilers have lower upfront costs than most efficient options. For example, (AMORCE, 2019) suggests that the total investment

cost (after taxes, in average) to install an individual gas heating system for an apartment in a collective building of 25 apartments³⁹ (surface area from 70-180 m²) is around 5000 €, 40% less than installing an individual electric heat pumps system, and only one third of the upfront cost to install a collective geothermal heat pump system (per apartment).

The major disadvantage of gas condensing boilers is that they are still a carbon-based solution as the current injection rate of biogas into the gas network is very low. If this situation persists, there will be strong constraints on the utilization of gas boilers under a stricter decarbonization context.

³⁹ A collective building constructed before 2005 in climate zone H1.

1.4.2.2 Electric heat pumps

Based on the thermodynamic cycle, heat pumps extract low-grade heat from water, air or the underground environment and convert the heat to a higher temperature for heating or hot water production. Most residential heat pumps use an electric compression cycle to produce heat, as demonstrated by the figure below.

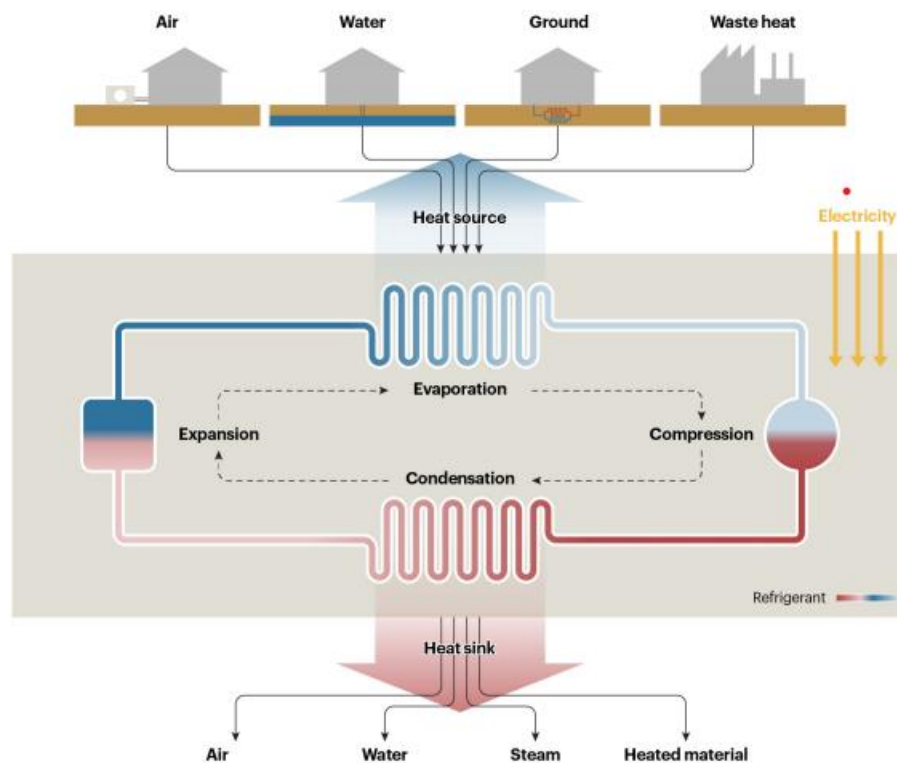


Figure 31 Operation principle of an electric compressor heat pump (IEA, 2022)

When the heat pump operates, the heat taken from the external environment is transferred to the refrigerant, and it is evaporated in the evaporator. Then the electric compressor draws in the vaporized refrigerant, raises its temperature to the required level, and transfers the heated refrigerant to the distribution circle. The refrigerant vapor is cooled down in the condenser and fed into the expansion valve, where a low pressure, low temperature refrigerant is prepared for repeating the refrigeration cycle. The heat distribution and emissions of the individual heat pump system can be operated either by a liquid-based distribution system or an air-based distribution system (IEA, 2022).

According to the type of heat source, we distinguish air source HP, water source HP and ground source HP. Heat pumps can also extract heat from industrial processes, buildings, and waste incineration plants, in which case, large-scale absorption heat pumps connected to the district heating network are

more commonly employed to cover greater heating demand. A heat pump can also cover cooling needs by reversing the thermodynamic cycle, in which case, we speak about reversible heat pumps.

The energy efficiency of HPs is measured by the coefficient of performance (COP), representing the quantity of useful heat produced by one unit of electricity input. The energy efficiency of HPs is highly dependent on the outside temperature of the heat source and the temperature requirement of the distribution circuit. When a heat pump is operating, we distinguish the inlet temperature as the temperature of the outside heating source, and the outlet temperature as the temperature at the beginning of distribution circuit (Techniques de l'ingénieur, 2024a).

A study of ADEME and RTE suggests that the COP of an air/water electric heat pump can reach over 3 when the outside temperature is above 6 degrees, with an outlet temperature of 45°C, while the COP decreases to 2 when the outside temperature is below 0. In case of a higher temperature requirement for heating (65°C), the COP can decrease to below 1.3 (ADEME & RTE, 2020). Compared to air-sourced heat pumps, ground sourced heat pumps have more stable performance, as they extract heat from underground geothermal reservoirs such as underground water or rocks where the temperature is less variable than outdoor air (Techniques de l'ingénieur, 2024a).

Installing a heat pump involves a relatively high cost to purchase and install equipment. As suggested by Observ'ER (Observ'ER, 2022), the average product price of an air-water electric heat pump with an electric capacity of 7-8 kW is around 9,000 euros with 1,700 euros for the installation. The price of a high performing product can reach 15,000 euros. The average price of geothermal (ground/water, 7-8 kW) heat pumps exceeds 13,000 euros with 2,360 euros for installation. These prices far exceed the cost of electric convectors or boilers.

Compared with gas/fuel combustion boilers, heat pumps can achieve considerable energy savings in normal operating conditions. When heat pumps operate with a relatively high COP, they can produce heat with a low energy input. However, this is not the case when the outside temperature drops. In very cold temperatures, heat pumps operate with very low energy efficiency and require a high electricity input. Geo-sourced HPs may provide a solution to this problem, although accessibility to underground heat is difficult for considerable share of households. Another inconvenience is that the installation of heat pumps requires a large space, making it less feasible to install them in small apartments.

1.4.2.3 Solar thermal systems

A more complete decarbonized solution for residential buildings is solar thermal systems. Solar energy can be used by buildings in either passive or active ways. Passive solar systems rely on the structure of the building to collect heat, for example, a trompe wall. An active solar heating system transforms solar energy into heat via mechanical devices including pumps or fans. Active solar systems can be used for DHW production, or combined usage of DHW and space heating. Here we focus on active solar thermal systems.

A solar thermal system is usually composed of a solar collector, pipelines, and a water tank. For a solar thermal system, a solar collector is the most important component, which is highly correlated with its performance. Commonly used solar collectors are flat-plate collectors and evacuated tube collectors. An evacuated tube collector operates in higher temperatures and is more efficient than flat-plate collector (Techniques de l'ingénieur, 2024b).

Currently, DHW production is the main usage of thermal solar systems. Thermosiphon systems, which are systems with forced circulation, are the most commonly used active solar thermal technologies for heating water. Thermosiphon systems are the simplest and most frequently installed solar system. The water tank in a thermosiphon system is always installed above the solar collector. The inlet pipeline provides cold water from a water tank to a solar collector, then the water in the collector is heated up with solar radiation. The heated water then moves towards the storage tank above, since its density is lower than the cold inlet. In this way the water in the storage tank is heated. As the water tank is placed outside on the roof, the water temperature inside is highly dependent on the outside situation. Thermosiphon systems can thus only be used in warm climates or during summer.

A more advanced technology is a solar thermal system with enforced circulation. The water storage tank placed inside the building is connected by two circuits: a primary circuit containing a heat transfer liquid and a second circuit containing domestic hot water. During operation, a water pump installed in the heat transfer liquid circuit mechanically enables the liquid to move from the water tank to the solar collector. The outlet of the solar collector then heats up the water stored in the tank, which is ready to be distributed by a secondary water circuit. Back-up equipment, such as an electricity convector, can be added to guarantee the hot water supply. Compared with a thermosiphon system, a system with enforced circulation is more efficient and adapted to cooler climates.

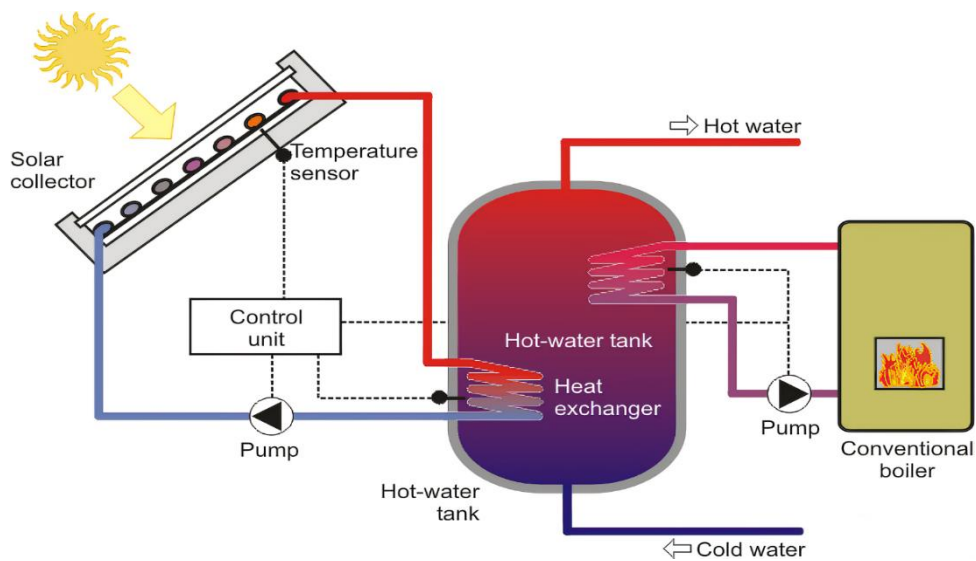


Figure 32 Operating principle of a solar thermal system with forced circulation (ADEME, 2019a)

Solar assisted heat pump (SAHP) systems and hybrid solar panels are emerging technologies that can achieve better efficiency. An SAHP is a heat pump coupled with a solar thermal system. In a SAHP, the working medium is preheated in the solar collector and transfers the heat to the heat pump evaporator through a heat exchanger in a water storage tank. In this case, the heat pump can efficiently work in environments with lower temperatures (Chwieduk, 2014). Hybrid solar panels simultaneously produce electricity and useful heat. The principle of this system is to add a photovoltaic overlay to thermal solar panels. In this way, the solar panel can benefit from the heat released by the photovoltaic cells, thus improving the overall efficiency of the system.

Residential buildings can use a combined solar thermal system to produce both DHW and space heat. This system works following the same principle as a solar thermal water heater with enforced circulation but adds another circulation unit to provide space heating. Solar systems used for heating have a larger water tank.

In terms of cost, compared with conventional water heaters, a solar thermal system is a much more expensive solution. According to a study by ADEME (ADEME, 2019a), the unitary cost of a thermal solar DWH system with enforced circulation is around 1,300 €/m² of solar collector (installation cost included), and similarly for a combined solar thermal system. For DHW production, the average size of a solar collector for a 100m² house is 4 m². For a combined solar system, the required size for solar panels is around 10-15m².

The main shortfall of solar thermal systems is that their performance is highly variable. On average, a solar water heater can cover 60% of annual demand from solar energy for an individual house. Its energy efficiency is highly dependent on solar conditions and temperatures and varies greatly across seasons. Solar heaters are significantly less efficient in winter with lower levels of solar radiation. A study by the producer Viessmann (Viessmann, n.d.) suggests that solar energy can cover nearly all hot water demand in summer (90%) while it is only capable of producing 26% of needs in winter. In this case, a backup water heater for winter is required.

1.4.2.4 Residential fuel cells for heating

A cogeneration system produces heat and electricity at the same time from natural gas, biogas, or hydrogen. Micro-CHP refers to systems with an electric capacity lower than 50 kW. For residential usage, the capacity of equipment usually ranges from 300W to 5KW, in which case we talk about a residential fuel cell. A typical fuel cell for residential heating is composed of a fuel cell module, a condensing boiler for supplementary heating (back-up boiler), a DHW storage balloon, a gas processing module, and multiple heat exchangers. Current available technologies are mainly based on solid oxide fuel cells (SOFC) made from ceramic materials capable of enduring high temperatures (600-850 degrees), and proton-exchange membrane fuel cells (PEMFC) produced from polymer materials (operating temperature between 20-100 degrees) (Techniques de l'ingénieur, 2022b).

When operating, a fuel cell heating system firstly transforms gas feedstock into hydrogen. Then the fuel cell module uses hydrogen to produce both heat and electricity. The produced electricity is then used by home appliances. If conditions allow, it is possible to sell back the surplus electricity production to the electricity grid. The heat produced from fuel cells is transferred to the distribution circuit and water tank to satisfy heating and DHW needs.

The overall efficiency of a fuel cell is calculated by adding together the thermal efficiency and electrical efficiency. The results of a laboratory test⁴⁰ indicate that micro-CHP with SOFC performs better in terms of electricity generation, while its thermal efficiency is lower than the PEM type. Real-life field trials give similar results: the thermal efficiency of PEM ranges from 48-66%, compared with 30-59% for SOFCs⁴¹ (ene.field, 2017).

	SOFC		PEM	
	Optimal conditions in laboratory test	Real-life data from the field trial	Optimal conditions in laboratory test	Real-life data from the field trial
Thermal efficiency, average	53%	46%	57%	57%
<i>St.dev. interval</i>		30 – 59%		48 – 66%
Electrical efficiency, average	42%	37%	32%	32%
<i>St.dev. interval</i>		28 – 47%		28 – 39%

Table 7 Comparison of thermal and electrical efficiency between SOFC and PEMFC (ene.field, 2017)

⁴⁰ Average results of 6 types of SOFC and 5 types of PEM.

Note that for the laboratory tests, the thermal and electric efficiencies cannot be added to calculate the total system efficiency, as the two efficiencies may not have been realized under the same test conditions.

⁴¹ Field test of over 1,000 units from September to December 2016, carried out by the “ene.field” project; the sample SOFC size is slightly higher than for the PEM.

Since it uses expensive materials such as platinum for electrode manufacturing, fuel cell micro-CHP remains an exorbitant heat solution compared with incumbent technologies such as gas boilers, pellet stoves, etc. For example, the upfront cost of a the Vitovalor PT2 proposed by Viessmann with an electric capacity of 750W can easily exceed 20,000 euros (purchase price, installation and possible connection to the gas grid) (Cegibat, 2018).

Residential usage of micro-CHPs is still in the emerging phase in most countries. Japan is the leading country, with more than 400,000 PEM fuel cells already in operation. In Europe, field tests in residential buildings have been elaborated since 2008, however, the scale of installation is still relatively small. The major projects are Callux (2008-2015) in Germany, Ene.field and Pace. The Ene.field project installed over 1,000 FC CHP units during 2013-2016 in 12 EU countries, including 603 SOFC units and 443 PEM units and has produced favorable test results in terms of real performance. This project was followed by the ongoing Project Pace with larger scale of installation (2,600 units) (Cegibat, 2018).

1.4.2.5 Efficient district heating (DH) networks

District heating (DH) networks are developed to cover the heating needs of multiple buildings. A district heating system consists of one or several central heating plants, a transmission and distribution network (pipelines), and heat end-users (buildings). The end-users of district heating can be residential buildings, factories, public utilities, etc. DH is an important solution to reuse recovered heat from waste incineration or industry processes, especially in urban areas where the heating demand from buildings is high (Techniques de l'ingénieur, 2014b).

Three generations of DH systems with different characteristics currently coexist, and a fourth generation is emerging. The main feature that distinguishes the four categories of DH networks is the operating temperature of the distribution system and heating energy sources. The first DH networks installed in France usually operate with high temperatures above 110 °C (first and second generation, pressurized steam or water). The third generation of DH systems (which is the current generation massively deployed in cities after 1980) can use a lower temperature distribution system of less than 100 °C. For DH systems, a lower distribution temperature on the one hand increases energy efficiency by reducing energy loss during heat transport, on the other hand allows for integrating more types of heat sources, especially RES, into the DH network. The first and second generation of DHs are mainly powered by CHP or heat plants powered by fossil energies, which produces high-temperature heat. With a lower operating temperature, the third generation integrates more energy sources including solar energy, biomass CHP and excess heat from industry. The emerging 4th generation can reduce the operating temperature to around 40-50 °C and enables integration of a wider range of RES in particular geothermal, and heat recovered from waste (ADEME, 2019c). The recent trend is to develop a “smart thermal grid” based on the 4th generation DH system that includes more production resources, heat storage, connection to the electricity system, and load management (Jiang, 2014; Lund, 2012, 2014). The first projects of the 4th generation DH system have been launched in the Netherlands (Zwetsloot, n.d.), Denmark and France.

	<i>1st generation</i>	<i>2nd generation</i>	<i>3rd generation</i>	<i>4th generation</i>
Period of best available technology	1880-1930	1930-1980	1980-2020	after 2020
Heat carrier	Steam	Pressurised hot water > 100 C	Pressurised hot water < 100	Low-temperature water 30-70C
Energy sources	Coal, MSW heating plant	CHP coal, CHP oil, heating plant with coal, MSW	large-scale solar, CHP biomass, industry excess heat, CHP waste, CHP coal, CHP oil, gas, MSW, oil, coal heating plant	geothermal, electricity surplus from PV and wind, heat pumps, large-scale solar, CHP biomass, industry excess heat, CHP waste

Table 8 Characteristics of four generations of DH networks (ADEME, 2019c; Lund, 2014)

The very first DH networks in France were established in large cities such as Paris, Lyon and Grenoble in the 1930s. During 1950-1970 (period of “reconstruction” after WW2), DH systems were massively implemented in residential districts. The Grenelle law introduced in 2009 considers DH as an important solution to use renewable energy sources for heating. Since the 2010s, a high quantity of more efficient DH networks has been developed.

According to statistics from SNCU⁴² (FEDENE SNCU, 2022), in 2021, around 900 DH systems were in place, with a total network length of 6,529 km and connecting around 45,000 buildings of different sectors. The total energy consumption is 38.2 TWh and the net delivery is around 29.3 TWh. Residential and tertiary buildings are the biggest consumer of district heat, representing respectively 52.7% and 35.8% of total heat production.

The DH system in France is fueled by various energy sources. Natural gas accounts for around one third of consumption (34.5%). The presence of renewables is significant: 62.5% of energy inputs are RRE⁴³ (Figure 33). This is the result of the rapid growth of green energy usage in DH systems after the Grenelle Law. Biomass and UVE (unit of waste valorization) are two major renewable energy sources, both representing 25.6% of total energy consumption. The great majority of DH networks in France are of the 2nd and 3rd generation with an operating temperature ≤ 110 °C.

District heat has an important role in current French energy policies. The objective of PPE is to reach 40 TWh of heat delivery by DH by 2023 and between 49-57 TWh by 2028. For the integration of RRE (renewable and recovered energy sources), the goal is to reach 31-36 TWh of heat delivery by 2028. The PPE guidelines are in line with LTECV goal of multiplying by 5 usage of RRE in heating and cooling networks by 2030 compared to 2012 (7.8 TWh of heat delivery by RRE in 2012) (FEDENE SNCU, 2022).

⁴² SNCU : Syndicat National du Chauffage Urbain et de la Climatisation Urbaine (*in French*). The SNCU produces annual statistics on existing DH networks based on surveys of DH network operators. The 2022 edition introduced here covers more than 95% of operators in France.

⁴³ RRE: Renewable and Recovered Energies

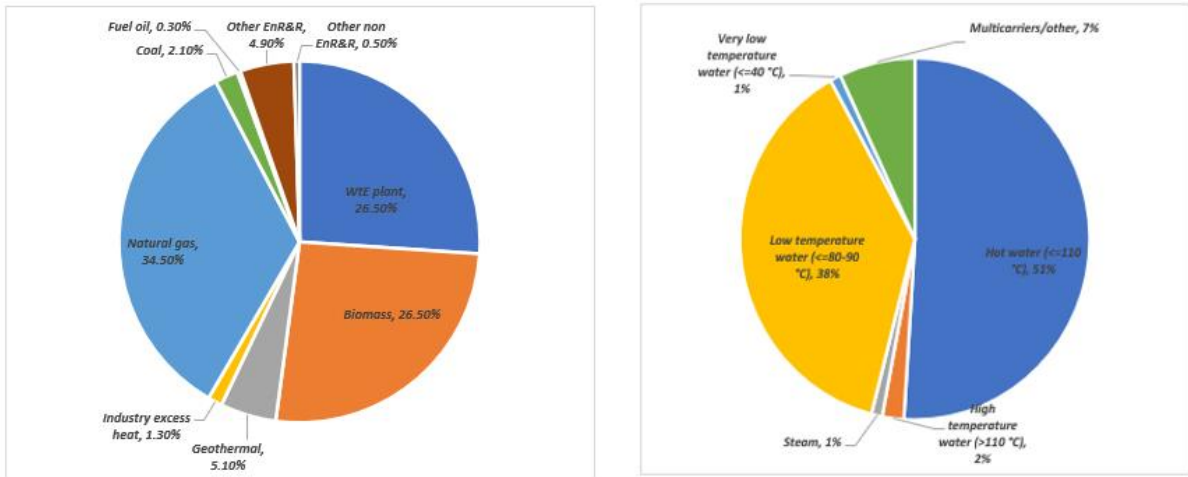


Figure 33 Energy balance (input energy) and temperature level (in number of networks) of French DH systems (FEDENE SNCU, 2022)

Conclusion

This first section highlights the main elements that we need to consider and understand in our research to establish a residential energy perspective. Reaching carbon neutrality by 2050 is a very important objective for the energy system. By observing current energy and emission balances, we are able to understand that the ambition of carbon neutrality involves challenges to decarbonize the energy system, and massive efforts are required from residential buildings.

The review of published energy prospective scenarios provides us with insights on potential solutions to reach a low-carbon energy system in the future. The AMS scenario allows us to understand the official vision of France and the rationale behind the country's current energy policies such as SNBC and PPE. This review illustrates the existence of more than one answer to the question of the energy transition. Multiple solutions could make contributions in the future, including decarbonized gas, renewable electricity, biomass, the CCS industry, and efforts from the energy demand side.

The review of the characteristics of housing stock allows us to understand that decarbonizing the residential sector is a complicated issue. Various features linked with heating including climate conditions and geographical location (access to energy source), and the thermal quality of buildings require consideration when applying technical solutions. The high number of existing buildings with low thermal quality and heated by fuel oil brings challenges for achieving the carbon neutrality goal.

The future transition of residential buildings will rely on a range of technical solutions. Thermal insulation that reduces useful energy demand by improving the energy performance of buildings is one such solution, and especially pertinent for old buildings. We have reviewed the policy ambitions, current pace and future difficulties of building fabric renovation. This allows us to understand the important role of insulation and its uncertainties in the future. We provide an overview of the technical-economic features of multiple low-carbon and efficient heating solutions for residential buildings. This helps us to better understand how these technologies work and contribute to decarbonizing the building energy system. This literature review for technologies provides valuable elements for our analysis for a future energy solution.

Chapter One has illustrated well the complexity of the question concerning the residential energy perspective. For our study, we propose to use a modeling approach. The elements introduced in Chapter One call for a model capable of in-depth analysis by considering the requirements for decarbonization, the role of residential buildings in global efforts, the specificities of residential energy consumption, and the presence of multiple technical solutions and their features. In the following section, we will develop in detail our study approach.

Chapter Two Exploring an energy solution for a future decarbonized residential system: a TIMES approach

Introduction

Various efficient technologies and renewable energy sources provide a broad range of solutions to decarbonize residential buildings. In this thesis work, we explore the technical choices of the residential energy system to achieve carbon neutrality by 2050, taking a prospective energy modeling approach. The role of various technical solutions for buildings will be investigated in detail.

The first chapter described the place of the residential sector in France's energy system and why its contribution in terms of the low-carbon transition should be assessed relatively to the options in the other sectors. We thus propose to investigate the energy prospective of residential buildings with a view of the global energy system. We try to reply to the question of how mitigation efforts are distributed among end-use sectors in the pathway to reach carbon neutrality, and the role that residential buildings could play in global efforts. We will also apply a scenario approach that enables us to interpret the transition pathways under different conditions.

In our research, we propose to account for a range of elements that may have a strong effect on investment choices. We focus on variables related to both energy supply and the demand side of residential buildings. On the supply side, one concern is the supply availability of biomass and district heating, which may play a critical role in the future. Solid biomass energy for households is supplied in various ways with highly differentiated costs and availability. Besides, access to biomass energy is geographically disparate. Concerning the supply of district heating, its potential is highly dependent on demand density. All these elements must be accounted for. Another element is the perspective of renewable gas as a solution to decarbonize gas usage. Currently, various technologies exist, including methanization, pyro-gasification, hydrothermal gasification and power-to-gas, with different levels of maturity. Their potential for development could be a major element restricting investment in gas equipment in a carbon-free system. On the demand side, a very important element to consider is the evolution of future demand for energy services and commodities. This shapes the production requirements of the energy system, which has a critical effect on the technology choice. Apart from demand scenarios, we focus on the effect of electric heat pumps in the energy system. One particular aspect to consider is that, during extreme cold periods, residential buildings could generate high electricity demand due to the reduced energy efficiency of installed heat pumps. This could lead to a problem of supply security. Another focus is the role of thermal insulation. Achieving the identified potential of insulation can bring significant energy savings. However, as multiple difficulties exist (as

we argued in the first chapter), the risk of a lower contribution from insulation linked with lower efficiency or renovation work or a slower investment pace needs to be considered.

We use a prospective modeling approach to explore this question of the future technology choices for residential buildings and the global energy system. Our energy modeling approach is based on a prospective model that represents the entire energy system of France with a bottom-up perspective, TIMES-FR. In order to account for the key elements introduced above, we make multiple improvements on the modeling side.

Chapter Two introduces our modeling approach. We have organized this chapter in two sections. The first section presents the main features of TIMES and how the French energy system is represented in the TIMES-FR model. The second section focuses on our contributions on the modeling side.

TIMES is a model generator that can be applied to represent different types of energy system. In the first part of section one, we provide an overview of the key features of TIMES. We present how an energy system is represented by process, commodity and commodity flows in TIMES. This illustrates the capacity of TIMES to provide a detailed representation of a complicated energy system. Next, we present the optimization paradigm of TIMES based on minimizing the total discounted cost of the entire energy system and partial equilibrium. This shows that TIMES is an adequate modeling tool for our research, and helps us to understand how TIMES obtains a future energy solution and to identify the major drivers of the optimization process. All the features presented in section one allows us to understand how TIMES works and why TIMES is a pertinent modeling method.

The second part of section one presents how the French energy system is modeled in TIMES-FR, which constitutes the model basis of our study. The TIMES-FR model was originally developed by (Assoumou, 2006) at the Center for Applied Mathematics, MINES Paris PSL and has since been used further in other doctoral work. To focus on our contributions, we present the main features of the model. We introduce how different energy sectors including primary energy production, power generation, and energy uses are represented and the links between them. This helps to better understand the systemic modeling approach of TIMES-FR. We further develop the advantages of using a prospective energy model to study the question of residential heating. A review of several other modeling approaches will be given for comparison.

Section two then presents in detail our contributions to TIMES-FR. We focus on six major contributions on both the supply and demand sides of the building energy sector: for the supply side these are renewable gas supply, district heating and biomass supply; for demand side they are building technology stock calibration, the electric heat pump sector and a review of demand scenarios.

On the supply side, for the renewable gas sector, the previous exercise developed a detailed structure in TIMES. Our contribution is to complete the given structure by modeling the hydrothermal gasification industry, and reviewing the production cost and supply potential for all of the technologies. A bibliographical review of the key features of available technologies will help us achieve this objective. For biomass supply, we propose a disaggregated structure that is able to capture differences in terms of supply potential and cost for different regions, supply modes and biomass products. We present in detail how we calibrate the potential of different biomass supply processes from the existing literature. A disaggregated structure is as usefully applied to the sector of district heating supply, allowing to differentiate the investment choice of a district heating system and its potential.

On the demand side, for building energy systems, we recalibrate the technical-economic parameters of the entire energy process using recent bibliographical resources and a projection of the demand profile of all technologies in buildings based on the situation in 2014-2020. This provides improvements in representing the building energy system in TIMES-FR. For electric heat pumps, a detailed modeling of their operation mode and energy efficiency over three temperature ranges is introduced. This enables us to capture the fluctuation of energy performance with temperature conditions and provides better grounds to explore the long-term role of electric heat pumps and their impacts on the electric system.

Lastly, we introduce our work on the future demand of energy services and commodities. This aspect is essential to consider. Our concern is to model the future demand of all end-use sectors in TIMES-FR, including industry, transport, residential, tertiary and agriculture. Four demand scenarios, D1-D4, with decreasing demand level are introduced. They are inspired from hypotheses of published energy prospective scenarios. We first present a review of demand trajectories proposed by the DGEC's AME and AMS scenarios, S1-S4 of ADEME and NégaWatt 2022. We then provide the details of our hypotheses for future demand and how they are inspired from the review of existing trajectories.

Résumé

Diverses technologies efficaces et sources d'énergie renouvelables offrent un large éventail de solutions pour décarboner les bâtiments résidentiels. Dans ce travail de thèse, nous explorons les choix techniques dans le secteur résidentiel pour atteindre la neutralité carbone d'ici 2050, en adoptant une approche de modélisation prospective pour le système énergétique. Le rôle des diverses solutions techniques pour les bâtiments sera étudié en détail.

Le premier chapitre décrit la place du secteur résidentiel dans le système énergétique français et explique pourquoi sa contribution en termes de transition bas-carbone doit être évaluée relativement aux options disponibles dans les autres secteurs. Nous proposons ainsi d'examiner les perspectives énergétiques des bâtiments résidentiels dans leur interdépendance avec le système énergétique global. Nous essayons de répondre à la question de savoir comment les efforts d'atténuation sont répartis entre les secteurs de consommation finale pour tendre vers la neutralité carbone, et le rôle que les bâtiments résidentiels pourraient jouer dans les efforts globaux. Nous appliquerons également une approche par scénarios qui nous permet d'interpréter les trajectoires de transition dans différentes conditions.

Dans notre recherche, nous proposons de tenir compte d'un ensemble d'éléments susceptibles d'influencer fortement les choix d'investissement. Nous nous concentrons sur les variables liées à l'offre et à la demande énergétiques des bâtiments résidentiels. Du côté de l'offre, une préoccupation est la disponibilité de la biomasse et du chauffage urbain, qui pourraient jouer un rôle crucial à l'avenir. L'énergie issue de la biomasse solide pour les ménages est fournie par divers circuits avec des coûts et une disponibilité très différenciée. De plus, l'accès à la biomasse énergie est géographiquement disparate. En ce qui concerne l'approvisionnement en chauffage urbain, son potentiel dépend fortement de la densité de la demande. Tous ces éléments doivent être pris en compte. Un autre élément est la perspective du gaz renouvelable comme solution pour décarboner les usages du gaz. Actuellement, diverses technologies existent, dont la méthanisation, la pyro-gazéification, la gazéification hydrothermale et le Power-to-Gas, avec des niveaux de maturité différents. Leur potentiel de développement pourrait constituer un élément majeur limitant l'investissement dans les équipements fonctionnant au gaz dans un système sans carbone.

Du côté de la demande, un élément très important à considérer est l'évolution future de la demande des services énergétiques et des commodités. Elle façonne les besoins de production du système énergétique, ce qui a un effet critique sur le choix des technologies. En plus des scénarios de demande, nous nous concentrons sur l'effet des pompes à chaleur électriques dans le système énergétique. Un aspect particulier à prendre en compte est que, pendant les périodes de froid extrême, les bâtiments

résidentiels pourraient générer une forte demande en électricité en raison de la baisse de l'efficacité énergétique des pompes à chaleur installées. Cela pourrait poser un problème de sécurité d'approvisionnement. Un autre point d'attention est le rôle de l'isolation thermique. Atteindre le potentiel identifié en matière d'isolation peut générer des économies d'énergie importantes. Cependant, comme de nombreuses difficultés existent (comme argumenté dans le premier chapitre), le risque d'une contribution moindre de l'isolation, liée aux travaux de rénovation peu efficaces ou à un rythme d'investissement plus lent, doit être pris en compte.

Nous utilisons une approche de modélisation prospective pour explorer cette question des choix technologiques futurs pour les bâtiments résidentiels et le système énergétique global. Notre approche de modélisation énergétique est basée sur un modèle prospectif qui représente l'ensemble du système énergétique français avec une perspective ascendante, TIMES-FR. Afin de tenir compte des éléments clés mentionnés ci-dessus, nous apportons de multiples améliorations sur le plan de la modélisation.

Le deuxième chapitre présente notre approche de modélisation. Nous avons organisé ce chapitre en deux sections. La première section présente les principales caractéristiques de TIMES et comment le système énergétique français est représenté dans le modèle TIMES-FR. La deuxième section se concentre sur nos contributions en matière de modélisation.

TIMES est un générateur de modèles qui peut être appliqué pour représenter différents types de systèmes énergétiques. Dans la première partie de la première section, nous donnons un aperçu des principales caractéristiques de TIMES. Nous présentons comment un système énergétique est représenté par des process, des commodités et des flux de commodités dans TIMES. Cela illustre la capacité de TIMES à fournir une représentation détaillée d'un système énergétique complexe. Ensuite, nous présentons le paradigme d'optimisation de TIMES basé sur la minimisation du coût total actualisé de l'ensemble du système énergétique et l'équilibre partiel. Cela montre que TIMES est un outil de modélisation adéquat pour notre recherche et nous aide à comprendre comment TIMES obtient une solution pour le futur système énergétique et à identifier les principaux moteurs du processus d'optimisation. Toutes les caractéristiques présentées dans la section 1 permettent de comprendre comment fonctionne TIMES et pourquoi TIMES est une méthode de modélisation pertinente.

La deuxième partie de la section 1 présente comment le système énergétique français est modélisé dans TIMES-FR, qui constitue la base de modèle de notre étude. Le modèle TIMES-FR a été initialement développé par (Assoumou, 2006) au Centre de Mathématiques Appliquées, MINES Paris PSL, et a depuis été utilisé dans d'autres travaux doctoraux. Pour nous concentrer sur nos contributions, nous ne présentons que les principales caractéristiques du modèle. Nous introduisons la manière dont les

différents secteurs énergétiques, y compris la production d'énergie primaire, la production d'électricité et les usages énergétiques, sont représentés et les liens entre eux. Cela aide à mieux comprendre l'approche de modélisation systémique de TIMES-FR. Nous développons également les avantages d'utiliser un modèle énergétique prospectif pour étudier la question du chauffage résidentiel. Un examen de plusieurs autres approches de modélisation sera fourni à titre de comparaison.

La section deux présente ensuite en détail nos contributions à TIMES-FR. Nous nous concentrons sur six contributions majeures tant du côté de l'offre que de la demande dans le secteur énergétique des bâtiments : pour l'offre, il s'agit de l'approvisionnement en gaz renouvelable, du chauffage urbain et de l'approvisionnement en biomasse ; pour la demande, il s'agit du calibrage du stock technologique des bâtiments, du secteur des pompes à chaleur électriques et d'une revue des scénarios de demande.

Du côté de l'offre, pour le secteur du gaz renouvelable, les travaux antérieurs avaient développé une structure détaillée dans TIMES. Notre contribution consiste à compléter cette structure en modélisant l'industrie de la gazéification hydrothermale et en examinant les coûts de production et le potentiel d'approvisionnement pour toutes les technologies. Un examen bibliographique des principales caractéristiques des technologies disponibles nous aidera à atteindre cet objectif. Pour l'approvisionnement en biomasse, nous proposons une structure désagrégée capable de capturer les différences en termes de potentiel d'approvisionnement et de coût pour différentes régions, modes d'approvisionnement et produits de biomasse. Nous présentons en détail comment nous calibrons le potentiel des différents processus d'approvisionnement en biomasse à partir de la littérature existante. Une structure désagrégée est également utilement appliquée au secteur des réseaux de chauffage urbain, permettant de différencier le choix d'investissement dans un système de chauffage urbain et son potentiel.

Du côté de la demande en énergie pour les bâtiments, nous recalibrons les paramètres technico-économiques de l'ensemble des processus énergétiques en utilisant des ressources bibliographiques récentes et une projection du profil de demande de toutes les technologies dans les bâtiments basée sur la situation en 2014-2020. Cela apporte des améliorations à la représentation du système énergétique des bâtiments dans TIMES-FR. Pour les pompes à chaleur électriques, une modélisation détaillée de leur mode de fonctionnement et de leur performance sur trois plages de température est introduite. Cela nous permet de capturer la fluctuation de la performance énergétique en fonction des conditions de température et de mieux explorer le rôle à long terme des pompes à chaleur électriques et leurs impacts sur le système électrique.

Enfin, nous introduisons notre travail sur la demande future de services et de commodités énergétiques. Cet aspect est essentiel à considérer. Notre objectif est de modéliser la demande future de tous les secteurs de consommation finale dans TIMES-FR, y compris l'industrie, le transport, le résidentiel, le tertiaire et l'agriculture. Quatre scénarios de demande, D1-D4, avec des niveaux de demande décroissants, sont introduits. Ils sont inspirés des hypothèses des scénarios prospectifs énergétiques publiés. Nous présentons d'abord une revue des trajectoires de demande proposées par les scénarios AME et AMS de la DGEC, ainsi que les scénarios S1-S4 de l'ADEME et Négawatt 2022. Nous détaillons ensuite nos hypothèses pour la demande future et comment elles sont inspirées de la revue des trajectoires existantes.

2.1 A prospective modeling approach: TIMES

TIMES (an acronym for The Integrated MARKAL-EFOM1 System) is a bottom-up model generator which provides a technology-rich basis for representing energy systems of different scales over a multi-period time horizon. It achieves a linear optimization for the modeled energy system. TIMES belongs to the family of “bottom-up” MARKAL models developed by ETSAP⁴⁴ since the 1980s. It is the successor of the MARKAL and EFOM models. Currently TIMES is a widely used modeling tool for energy perspective. The users of TIMES include more than 150 research teams from over 50 countries (Doudard, 2018; ETSAP, 2016).

In this section, we will firstly explain how an energy system is modeled by TIMES and how TIMES uses an optimization method to provide future energy solutions. Next, we present how the French energy system is represented by TIMES-FR, the main modeling tool of the thesis. The logic of TIMES has been discussed in detail in documentation by ETSAP (ETSAP, 2016) and a series of previous works (Assoumou, 2006; Doudard, 2018; Millot, 2019; Siggini, 2021). Here we propose to provide a simplified description that covers the essential aspects of TIMES and makes it easier to understand our contributions.

2.1.1 Key features of TIMES

2.2.1.1 Energy system in the view of TIMES

A TIMES model is composed of three basic elements: process, commodity, and commodity flow. A commodity can represent energy carriers, energy services, materials, or emissions. A process in TIMES represents a step of energy production or consumption, taking one or several commodities as input and producing other commodity outputs. Processes in TIMES are described by a set of technology and economic parameters. Important parameters are efficiency, availability factor, share of input/output, technical life, investment cost and variable cost. TIMES allows for modeling a wide range of processes over different sectors and functions, including process of primary energy mining, energy import and export, final energy production, energy end-use and energy storage with different periods of energy production and consumption. Commodity flows are the links between processes and commodities attached to processes (ETSAP, 2016). For illustration, the figure below presents an example of a process

⁴⁴ ETSAP (The Energy Technology Systems Analysis Program) is a technology collaboration program elaborated by International Energy Agency (IEA). It focuses on providing solutions for energy scenario modeling. The community currently comprises 21 countries (ETSAP, n.d.).

modeled in TIMES with one input and one output. This process represents a gas boiler in buildings that uses gas from the network to produce useful heat.

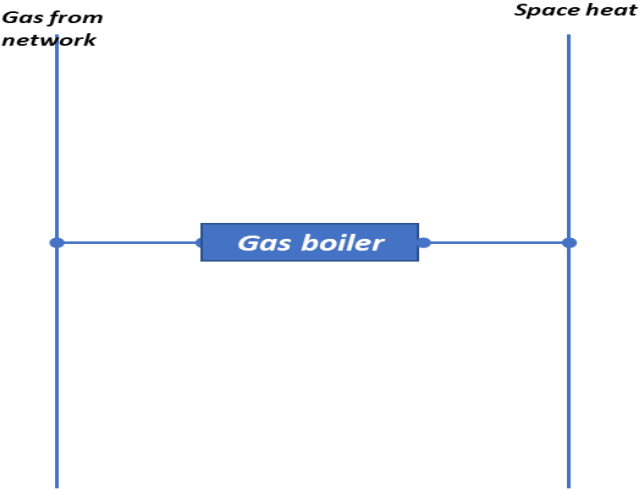


Figure 34 Schema of a process with one input and one output in TIMES

TIMES can also present a system with multiple processes and commodities. Figure 35 describes an example of a building energy system with three input energy sources that can be modeled by TIMES. The schema represents three types of heating equipment: gas boiler, biomass boiler, and electric heat pump, and a distribution network of the input energy sources for the building. Following the same logic, TIMES can represent a complex energy system with multiple energy sectors and hundreds of processes and commodities.

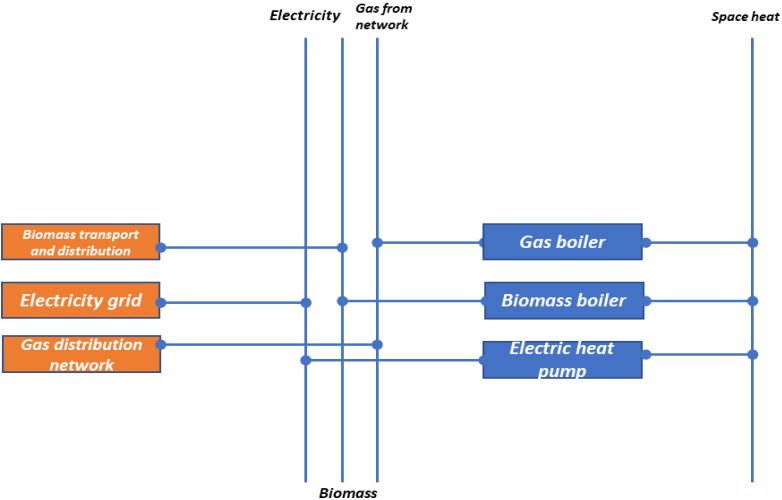


Figure 35 Schema of an energy system with multiple processes and commodities in TIMES

2.2.1.2 Optimization paradigm of TIMES

TIMES is based on a linear cost minimization with partial equilibrium of the energy system. Under a partial equilibrium, supply matches demand in energy markets, primary energy, final energy, and energy services. The function below presents the optimization paradigm of TIMES. When optimizing, TIMES makes decisions on all the decision variables, such as equipment investments and operations, primary energy supply and energy trade. In the linear optimization program of TIMES, the objective is to minimize the cost of all decision variables, on the condition that all constraints written in linear form linked with decision variables are satisfied. TIMES minimizes the discounted annual cost of all regions and all time periods in the energy system. The annual cost is the difference between cost (investment cost, fixed cost and variable cost) and revenue. The revenue in TIMES is defined as the discounted value of assets or commodities at the end of the horizon (salvage cost), subsidies, and income from commodity exports.

$$\text{Min } \sum_{r=1}^R \sum_{t=t_0}^T (1 + d_{r,t})^{t_0-t} * \text{Annual cost } (r, t)$$
$$\sum_i b_{ij} x_i \geq d_i$$

Equation 1

With

$i = 1, \dots, n$, n : number of decision variables

$j = 1, \dots, k$ k : number of constraints

b_{ij}, d_i : coefficient linked with constraints

r : region, $r = 1, \dots, R$

t : year, $t = 1, \dots, T$

Annual cost (r, t) : total annual cost in region r and year t

t_0 : reference year

$d_{r,t}$: discount rate of region r and year t

2.2.1.3 Temporal definition

TIMES has flexible temporal definition, as time periods and time slices (time divisions over a year) may be defined by users. The time horizon for a model solution is divided into a user-chosen number of time-periods containing one or several years. Within the same time period, all the parameters remain the same, except for the cost objective function which differentiates between payments in each year of a period. As the length of time period is variable, the users are free to choose the resolution of the optimization solution for the future. Besides, users of TIMES can define times-slices, which are time divisions within a year. Any commodity and process may have its own, user-chosen time-slices. These flexible time-slices are segregated into three groups: seasonal (or monthly), weekly (weekday vs. weekend), and daily (day/night or hourly), where any level may be expanded (contracted) or omitted. The parameters of commodity or process can be time-slice dependent. It is thus possible to differentiate the demand profile or technical-economic parameters of processes over specified time slices. This enables the model to better interpret variations in the demand and supply situation throughout the year.

2.2.2 TIMES-FR, a detailed representation of the French energy system

Our research is based on TIMES-FR, which models the French energy system. TIMES-FR was developed by the Center for Applied Mathematics at PSL University by the PhD thesis of Edi Assoumou (Assoumou, 2006). This work proposed a systemic model for France and investigated with more detail the structure of the power generation sector. It was followed by multiple efforts that brought more detail to the modeling structure of TIMES-FR, including (Doudard, 2018; Maïzi & Assoumou, 2007; Millot, 2019). (Doudard, 2018) used a TIMES approach to explore the long-term flexibility of the electricity and gas system for France. In his work, the renewable gas sector of France was modeled in detail. This structure was then adopted in TIMES-FR. The doctoral thesis of (Millot, 2019) developed a more detailed structure for end-use demand and recalibrated the technology stock of electricity and heat production. All of the abovementioned modeling efforts provide a solid basis to understand the French energy system with TIMES.

2.2.2.1 General description of model structure

TIMES-FR is a multi-sector, multi-energy model that represents the entire energy system of France, including the steps of primary energy production or importation, energy transformation, and energy end-use. The primary energy supply sector includes provision (through mining or importation) of biomass, crude oil, coal natural gas and intermittent renewables such as solar, wind, and geothermal. The extraction of crude and natural oil is not included in the French model.

The energy transformation sector in TIMES-FR represents processes to produce final energies or energy products available for energy end-uses. It includes the processes of oil refining, electricity and heat production, and biogas production. The module of electricity generation in TIMES-FR represents in detail the current stock of power plants in Metropolitan France by type of equipment, and a complete list of available technologies for future investment. In addition, it models electricity imports/exports through an interconnection grid. For the current stock, (Millot 2019) calibrates a total stock of 126.5 GW including 63.1 GW of nuclear capacity for 2018, derived from database of RTE. The closure of two nuclear reactors at Feissenheim (1.76 GW) in 2020 is considered: by 2021 the capacity of nuclear stock is reduced to 61.4 GW. For future investments, the model contains more than 30 technology types including 3rd and 4th generation nuclear power plant, the new generation of solar/wind power plants, decarbonized thermal power plants (combined cycle with CCS, IGCC⁴⁵ with CCS), and fuel cells. The

⁴⁵ IGCC: integrated gasification combined cycle

range of flexibility choices, including various type of batteries and hydraulic plants are also described. The hypotheses of the technical-economic parameters of these new technologies are based on the World Energy Outlook New Policies Scenario of 2016 (International Energy Agency 2016). For the gas system, TIMES-FR presents in detail the various branches of renewable gas production. We will describe its structure in the next section.

For energy end-use, TIMES-FR includes five sectors: residential, tertiary, industry, transport and agriculture. It covers 6 residential and tertiary energy demands, 23 industry demands, 15 transport demands and 4 agricultural demands. TIMES-FR models a large choice of end-use technologies to produce these demands for energy services and commodities, including various industrial processes, the transport of equipment, and building of energy equipment. The choice of demand type modeled in TIMES-FR is principally based on the 2014 energy balance by Eurostat (Eurostat, 2024), and the 2018 CEREN database (for residential and tertiary buildings) (CEREN, 2022). The parameters of industrial processes and transport equipment are calibrated from reports of the JRC⁴⁶ including BAT (best available technologies) reference documents (European Commission, n.d.) and (Simões et al., 2013). In the next section, we will make a detailed description of a residential energy system modeled in TIMES-FR.

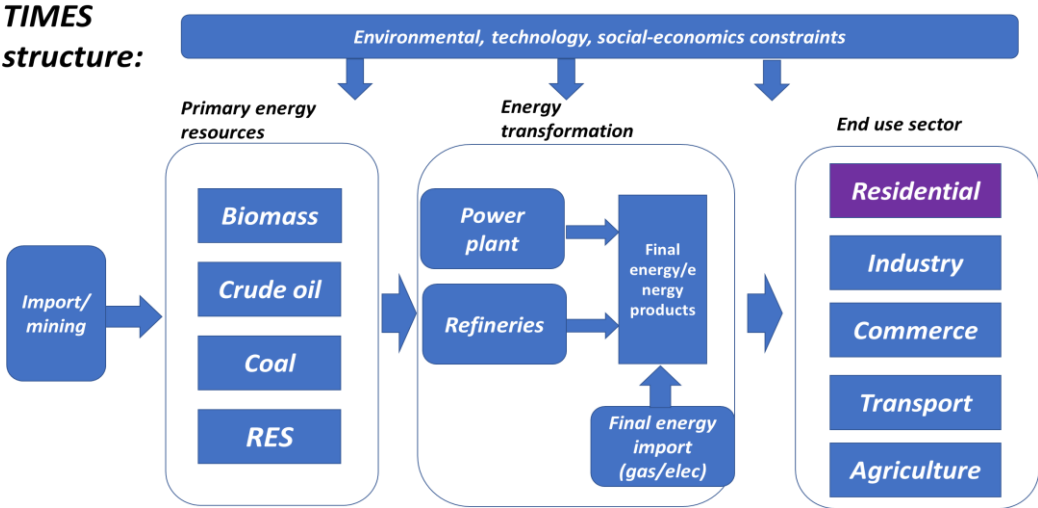


Figure 36 Simplified structure of TIMES-FR

⁴⁶ JRC: Joint Research Center of the European Commission.

2.2.2.2 Time slices and time periods

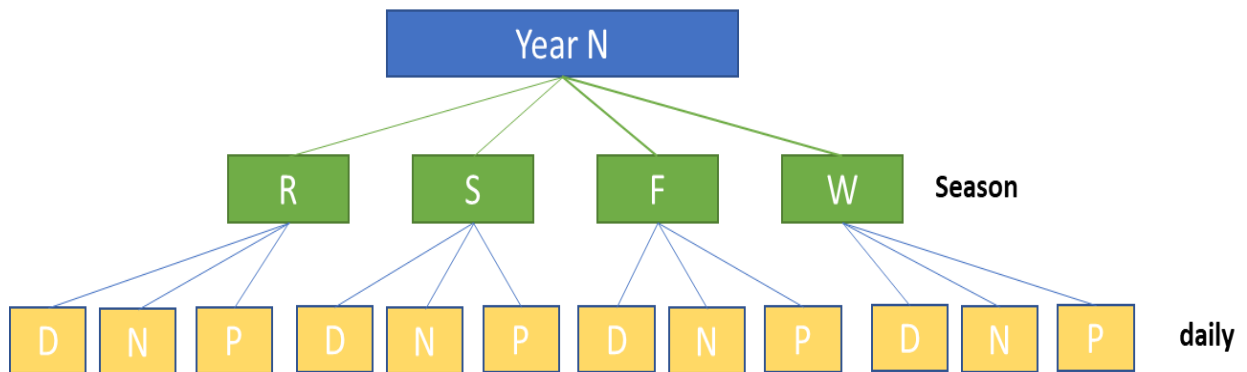


Figure 37 Schema of time slices in TIMES-FR

The time horizon for our study is 2050, but this timeframe can be easily extended. In our analysis, the period of 2020-2050 is divided into 7 time periods: the first time period is defined as one year and after 2021 each time period has a range of five years. Note that the horizon of 2050 can be extended to 2100. Each year is then divided into 12 time slices with four seasonal levels and three intra-day levels. The presence of different time slices allows the model to consider variations of multiple important parameters of the energy system, including demand profile, performance of energy equipment, and resource availability. Four seasons correspond to winter (W), spring (R), summer (S) and autumn (F). The duration of winter is longer than other seasons (16/11-14/03, four months). Three intra-day levels include day (from 8h-18h), peak (19h) and night (20h-7h) of a working day and this ratio is constant over four seasons. The peak hour represents the moment when the usage intensity of energy equipment reaches the highest level during a day. The figure above (Figure 37) presents a breakdown of 12 time slices through a year: winter night has the highest share with a total duration of 21.1%.

2.2.3 Representing the building energy system: TIMES compared with other solutions

Apart from TIMES, which is a more generic purpose model, a variety of dedicated methods exist to model buildings and residential heating. These methods can bring different levels of representation of specific features of residential buildings, such as envelope geometrics, building orientation, occupation of householders, outside temperature, etc., and are able to capture different degrees of the dynamics of energy consumption (hourly, daily, weekly or monthly time resolutions).

In order to better understand their features and compare them with the TIMES approach, we reviewed the range of existing programming tools for modeling building energy consumption. Here we chiefly introduce several types of model. One of the most commonly used methods comprises dynamic thermal simulation models, such as Pleiades+Comfie, Energy+, Simbad, TRNSys, Virtual Environment, and Modelica Building Systems. A dynamic thermal simulation model can give a realistic and accurate representation of the thermal status of a building and its temporal evolution throughout a year. Taking an example from Pleiades+Comfie, a building and its energy consumption is represented in detail by an accurate description of building materials (with a large choice from the material library), envelope geometrics (with a detailed building plan), occupation, consumption pattern, solar radiation, etc. The time resolution of dynamic thermal simulation models ranges from several minutes to one hour (IZUBA Technologies, n.d.). These models can help to guide usage patterns and dimensioning of energy equipment. Another type of model is the family of physics-based simulation tools, for example Simscape. Simscape can represent in detail the behaviors of a power system in a building by modeling its physical components and connections. It can be used for testing the performance of a system (Mathworks, n.d.). In addition to thermal simulation and physics-based models, load curve generation models interpret in detail the consumption pattern of individual households and its impact on energy demand, for example LoadProfileGenerator (LoadProfileGenerator, n.d.).

Here we illustrate how dynamic thermal simulation method can be applied to the issue of residential heating with several examples of studies. We focus on studies exploring the role of electric heat pumps. (Saffari et al., 2023) examine the effectiveness of energy savings and carbon footprint reduction made by a hybrid heat pump compared to a conventional combustion boiler with different fabric retrofit scenarios. They are based on a building energy simulation model IESVE (Integrated Energy Modeling Software) where a typical two-story detached house built in 1999 (160 m²) in Ireland is represented in detail. The results suggest that, under the condition of high insulation, installing a hybrid heat pump can save up to 128 (kWh/m²/year) (72%) of primary energy for the same house, including a considerable volume of electricity. The study by (GRDF & Artelys, 2022) analyses the effect of a hybrid heat pump on reducing peak electricity demand by simulating the operation of a hybrid heat pump

composed of a 4.5 kW electric heat pump and a 25 kW condensing boiler, and a 6 kW standalone electric heat pump in an average new single family house in France. The simulation results suggest that the installed hybrid heat pump can reduce peak electricity demand by more than 30% compared to a standalone electric heat pump (from 5.2 kW to 3.6 kW).

The methods reviewed above are pertinent solutions to represent the building energy system. Compared with these solutions, TIMES can model different energy equipment and load curves, but with a less detailed granularity. However, the contribution of TIMES as a multi-sector prospective model is that it treats these questions from the point of view of a broader system. TIMES focuses on the entire building sector and its interaction with other parts of the energy system. For example, when we study the role of electric heat pumps in buildings, TIMES allows us to analyze the impact of an increased usage of heat pumps, not only on the residential energy balance, but also on the electricity production system, and the variation of electricity demand by other end-use sectors including industry, transport. This brings a more complete explanation of the specific question and its implication for the global energy transition taking a systemic approach.

2.2 Our contributions on the modeling side

In this section, we introduce our contributions on the modeling side in order to better reply to the research question. Based on the existing structure of the French model developed in earlier work, multiple improvements on both the supply and demand sides of the building energy sector are proposed. Our contributions include not only an improvement of the modeling structure, but the calibration of important technical-economic parameters, the supply potential for existing technologies in the model, and a review of the hypotheses of useful demand. We focus on six major improvements comprising, for the supply side: renewable gas supply, district heating, and biomass supply; and for the demand side: calibration of the building technology stock, the electric heat pump sector, and a review of demand scenarios. For each contribution, we will firstly introduce its context to help us to understand its importance and our starting point for the modeling exercise. The introduction will be followed by a detailed description on how we interpret these aspects in the model and our hypotheses.

2.2.1 Improvement of supply side

2.2.1.1 Renewable gas supply

One element that may make important contributions to decarbonize the energy system is a range of technologies to produce renewable gases, including biomethane, hydrogen, and biogas/syngas. The production of renewable gases is able to valorize various types of waste and provides a decarbonized solution for multiple energy usages. Biomethane and hydrogen can be injected to the gas network, and biogas/syngas are eligible fuels for direct utilization by consumers, such as power generation, transport and heating. The main technologies for renewable gas production include methanization, gasification, power-to-gas, and hydrothermal gasification.

We will firstly present an overview of the existing technologies to produce decarbonized gases. The purpose of this review is to better understand the key features of these technologies, including their technical parameters, production costs, maturity level, and development potential. This provides essential elements for us to complete our modeling of the renewable gas sector.

2.2.1.1.1 Overview of technologies to produce renewable gases

Methanization

Methanization is based on the degradation of organic matter by micro-organisms under controlled temperature and pressure conditions and in anaerobic conditions. It is a way to recover organic industrial and agriculture residues, municipal waste (MSW), sewage sludge. During methanization, a mixture of waste is heated slightly in a digester to produce biogas composed of 50-70% CH₄, 20-50% CO₂, and several other gases. Biogas can be used directly for power generation. Another output of the digester is a “digestate” comprising humid organic material that can be used as a fertilizer. Pure methane (biomethane) is then produced by a purification process and can be directly injected into the gas distribution/transport network (ADEME, 2023). The energy yield of biomethane purification/injection from biogas is around 94%, taking into account the heating needs of the methanizer. For a recovery for the production of electricity, the electrical output is approximately 35% (Ministère de la Transition écologique et de la Cohésion des territoires, 2019).

The production cost of biomethane depends on several characteristics of the project, especially the type of input and the capacity of the methanizer. A study by ADEME (ADEME et al., 2018) analyses 12 representative methanizers in France with biomethane debits from 173-756 m³/h and indicates that the LCOE of biomethane ranges from €81 to €107/MWh (10% of discount rate). The same analysis also

concludes that small scale methanizers treating agricultural effluents (manure and slurry) tend to have higher investment costs but lower input costs, while large-scale treating energy plants run by industry-territorial operators (CIMSEs) (GRDF, 2020) present the reverse situation. The buy-back tariff of biomethane ranges from €45 to €125 /MWh depending on the input and the quantity injected. This buy-back tariff benefits from financial support and largely exceeds the price of natural gas (ADEME, 2022).

The methanization industry has grown rapidly since the first injection of biomethane in the gas network in 2011. By the end of 2021, the 365 biomethane production sites accounted for in total 4.3 TWh of injection into gas network and 6.4 TWh of injection capacity. Compared with the previous year (2020), the installed capacity and the volume of biomethane injection both increased by nearly 100% (SDES, 2022b). The objective of the energy policy (PPE) is to reach 6 TWh of network injection per year by 2023 and 22 TWh by 2028 (Ministère de la Transition écologique et de la Cohésion des territoires, 2019). If the current growth rate is maintained, the objective of PPE will be achieved well in advance.

Methanization presents significant potential to provide decarbonized gas for the energy system. As estimated by a study by ADEME, the maximum volume of primary energy valorizable by methanization reaches up to 150 TWh, including 122 TWh of agricultural inputs and 29.5 TWh of non-agricultural inputs (ADEME et al., 2018). In an optimistic future, if all available inputs are mobilized, the total injection could reach up to 130 TWh per year (GRDF Perspective Gaz, Scenario 2050) (GRDF et al., 2022).

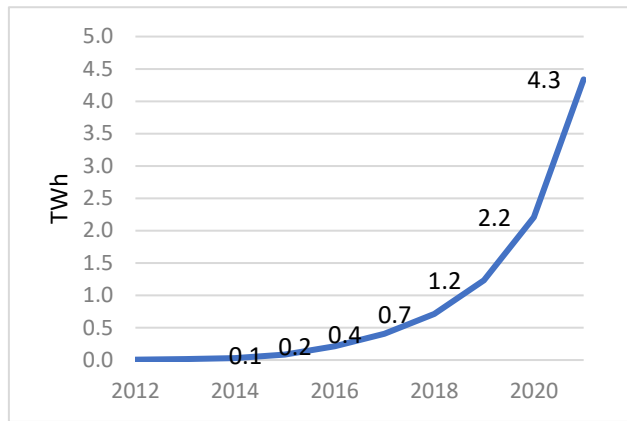


Figure 38 Evolution of injected volume of biomethane to gas network in France since 2012 (SDES, 2022b)

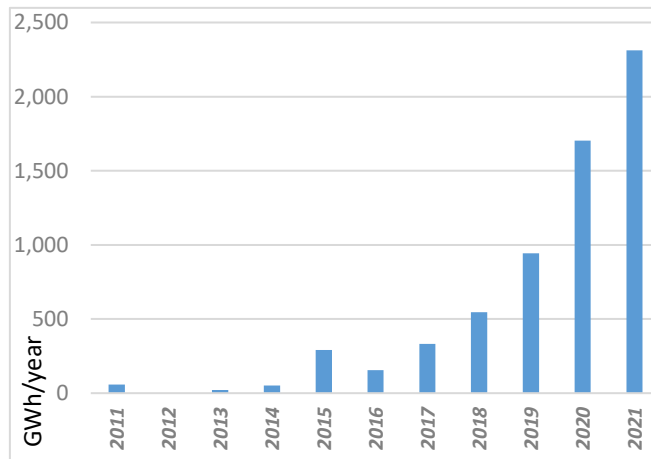


Figure 39 Evolution of new biomethane injection capacity since 2011 in GWh/year (SDES, 2022b)

Pyro-gasification and hydrothermal gasification

Pyro-gasification consists in decomposing solid, carbonaceous materials with high temperature/pressure into a mixture of combustible gases. The inputs can be lignocellulose biomass, coal, solid recovered fuels and sorting refusals. It is an alternative to incineration and landfill for materials that are more difficult to treat and that have been little or poorly recovered up to now, especially refuse-derived fuel (RDF) and sorting refusals. The gasification process comprises drying, pyrolysis, partial oxidation and reduction steps under different temperatures and catalytic conditions. The product of gasification is a mixture of CO (20-30%), H₂ (30-45%), CO₂ (15-25%), and CH₄ (10%) called "Syngas". Syngas has a higher calorific value than biogas and can also be used directly in power generation for industry. Besides, gasification produces a considerable amount of heat. With further steps of methanization and epuration, the CO and H₂ component of syngas can produce pure biomethane (ADEME, 2019b). The average yield of biomethane from gasification is around 50-60% with 20% of recoverable heat (ADEME, 2022). One ton of dry biomass can produce around 2 MWh of biomethane by gasification.

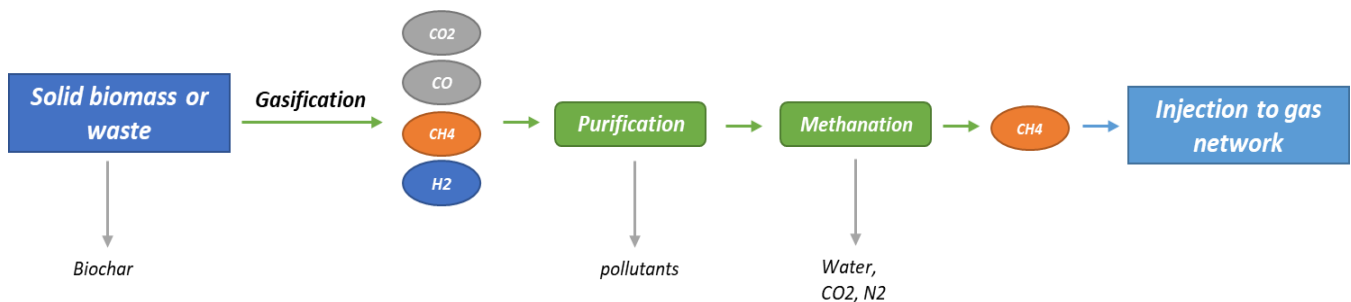


Figure 40 Biomethane production from the pyro-gasification process

Pyro-gasification has a high requirement for input materials and usually needs a preliminary drying process to reduce the humidity rate to less than 10%. Besides, to acquire injectable biomethane, the syngas needs to be treated in multiple further steps including washing, epuration, methanization and CO₂ removal. These auxiliary steps prolong the conversion process and require extra energy input.

A more advanced hydrothermal gasification process provides an efficient solution for these difficulties. Different from pyro-gasification, hydrothermal gasification degrades organic matter under supercritical conditions (>221bar, >375°C). It uses liquid inputs with low dry matter content (15-20%), but rich in organic matter; this includes all types of biomass waste, industrial or agricultural effluents, sludge from wastewater treatment plants and digestate of methanization. Compared with pyro-

gasification, the output from a hydrothermal gasification reactor has a richer CH₄ content (25-40%). After the epuration process, the CH₄, H₂ and CO₂ are separated. Hydrothermal gasification can reach a higher energy yield (70%) in a faster time and using a more compact reactor (ADEME et al., 2018).

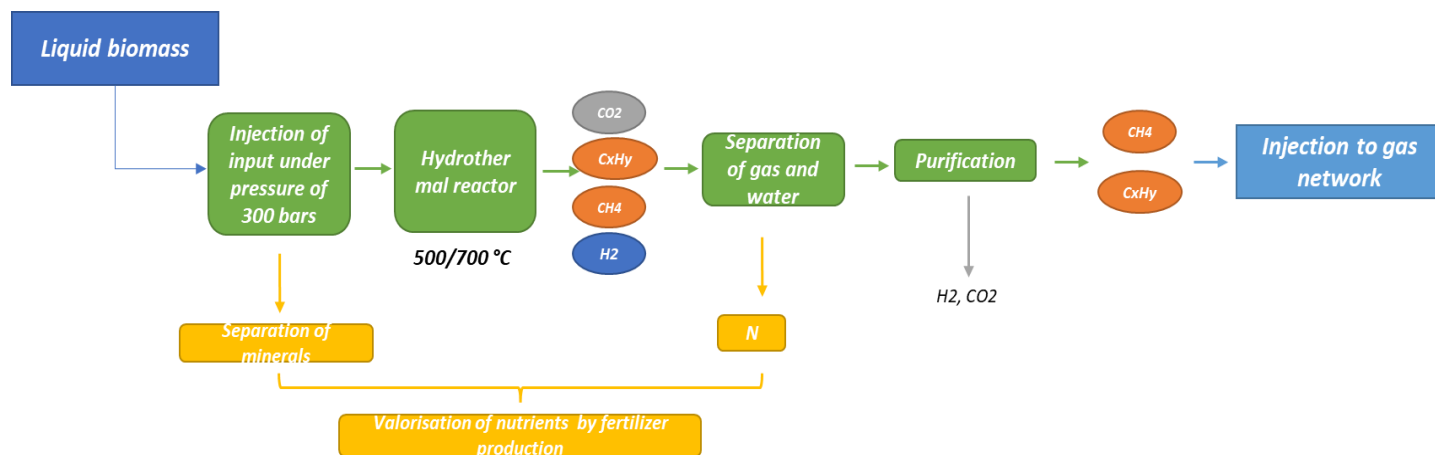


Figure 41 Biomethane production from the hydrothermal gasification process (ADEME et al., 2018)

In terms of cost, existing bibliographies suggest that the LCOE of biomethane from pyro-gasification is higher than from methanization. The 2018 ADEME study estimates that the LCOE ranges between €90-125 /MWh (10% of the discounting rate) and a considerable share of the production cost comes from the input provision. The LCOE is significantly reduced when the pyro-gasification unit uses CSR (solid recovered fuels) and receives subsidies for waste treatment. For hydrothermal gasification, there are less available data on its cost. It is estimated that the production cost of injectable biomethane from hydrothermal gasification could reach around €110 /MWh for France by 2030 under a scenario of scale effect and technology progress (Groupe de Travail Gazeification Hydrothermale, 2023). In the Netherlands, the purchasing tariff proposed for biomethane produced by hydrothermal gasification is €75 /MWh, which enables the industry to compete in the market. One important element to be considered is that, by taking non-recyclable waste as input, hydrothermal gasification can avoid a significant share of the waste treatment cost. As estimated by (Groupe de Travail Gazeification Hydrothermale, 2023), the cost of treating waste from sewage ranges from €23-150 /t depending on the method (landfill, composting, incineration).

At the current stage, nearly all of the existing pyro-gasification projects in Europe are in the demonstrator phase, except the Höganäs project in Sweden. Höganäs has been in industrial usage since 2018 with an annual solid biomass input capacity of 6 MWh (IEA, 2019). Previous to Höganäs, Sweden elaborated a GoBiGas project with larger scale of 20 MW biomethane production capacity (IEA, 2020); however this project was stopped in 2018 due to the high production cost of biomethane

(ADEME, 2022). In France, the pyro-gasification industry is developing rapidly. The first R&D platforms are already in operation, including the projects GAYA (first pyro-gasification project in France) and Synthane (Doudard, 2018). In addition to the R&D demonstrators, around 50 industrial-scale projects are under development. The main ongoing projects are Metropole Limoges with a 100 GWh/year biomethane output capacity, and Green Gas Provence with a 125 GW/year biomethane output capacity. Both are planned to achieve their first injection into the network by 2026 (GRDF, 2021).

As for the hydrothermal gasification industry, the Netherlands is the leading country in terms of technology maturity and installation scale. A project at the industrial stage with a capacity of 20 MW (thermal) by the SCW Systems company is already in operation (Alkmaar 1). The project to develop another industrial demonstrator with a larger capacity (40 MW, Alkmaar 2A) has already been launched. It is estimated that the hydrothermal gasification industry will be able to cover 57% of demand for renewable gas in the Netherlands by 2030. Compared to the Netherlands, the current development level of hydrothermal gasification is much lower in France. However, the branch of hydrothermal gasification is very dynamic, with active participation from industries including Leroux & Lotz Technologies and VINCI Environment, and development of the first pilot projects. The first prototype constructed by CEA with an input of 10kg per hour has been in operation since 2015. For the same project, demonstrators with a larger input capacity (0.5-1 t/h) are currently under construction. At the current stage, the most advanced project in France is a 2 MW demonstrator planned to be finished in 2024 by Leroux & Lotz Technologies at Montoir-de-Bretagne (GHAMa). The installation in Brittany mainly treats sludge from wastewater treatment plants.

Country	Project/actor name	Project stage	Project status	Capacity	Input	Technology
Pyro-gasification						
France	Gaya	R&D demonstrator	in operation since 2018	0.4 MW of CH ₄ production capacity per year	CSR, solid biomass, solid biomass waste	Dual Fluidized Bed Biomass Gasification
France	Limoges Metropole	Under construction	planned first injection to network in 2026	100 GWh of CH ₄ production per year	Solid biomass, solid biomass waste	Dual Fluidized Bed Biomass Gasification
Sweden	Höganäs	industrial stage	in operation since 2018	6 MWth/year	solid biomass	Staged gasification with heated rotating drum (Woodroll technology)
UK	ABSL (Swindon)	R&D demonstrator	operation planned S1 2023	3 MW of CH ₄ production capacity per year	solid biomass waste	Bubbling fluidized bed + plasma cracking of tars (RadGas technology)
hydrothermal gasification						
France	GAZHYVERT	prototype	prototype since 2015, demonstrator of 0.5/1 t/h under construction, 2026 towards	biomass input 10 kg/h	sludge	
France	Gama	Industrial demonstrator	Under construction, planned to be in operation since 2024	2t/h of input (2MW)	sludge	
Netherlands	SCW Systems	Industrial stage	in operation since 2022	biomass input 4t/h		
Switzerland	Paul Scherrer Institut (PSI) + TreaTech	pilot	in operation since 2022, plan for commercial unit 2024	biomass input 110 kg/h		

Table 9 Overview of existing projects of pyro-gasification and hydrothermal gasification (Bioenergy International, 2024; Doudard, 2018; GRDF, 2021; Groupe de Travail Gazeification Hydrothermale, 2023; IEA, 2019)

According to a study elaborated by the working group of hydrothermal gasification⁴⁷, the biogas potential from hydrothermal gasification in France could reach 63.2 TWh per year by considering 18 types of input (Groupe de Travail Gazeification Hydrothermale, 2023). According to the same report, hydrothermal gasification industries in France can include three categories of input with different degrees of priority for valorization. The first type of input for the branch of hydro gasification (inputs of primary priority) mainly includes sludge from wastewater treatment, industrial processes, and digestate. These materials are difficult to recover by other solutions. The total biogas potential of inputs of primary priority is 37.5 TWh. Inputs of the second and third degree of priority correspond to materials eligible for hydrothermal gasification but already with a high degree of recovery using other processes, for example different types of organic waste from households and agriculture. The prospective of developing hydrogen gasification for these inputs remains highly uncertain and faces strong competition from other renewable energy branches. The potential of inputs of secondary priority is estimated at 25.7 TWh per year.

⁴⁷ Groupe de Travail national Gazéification Hydrothermale (in French): A working group launched by GRTGaz with 26 partners from multiple sectors including technology developers, equipment manufacturers, waste and wastewater treatment specialists, gas companies, network operators, industrial customers, local authorities, associations and consulting companies.

Priority 1 inputs	<i>TWh/year</i>
<i>urban sludge from WWTP</i>	3.3
<i>sludge from food industry</i>	3.9
<i>sludge from chemical, paper, pharmaceutical industry</i>	1.2
<i>dredging sludge</i>	5.5
<i>digestates</i>	20.8
<i>beet vinasse</i>	0.5
<i>distillers grains</i>	0.8
<i>carcasses</i>	1.5
Priority 2 inputs	
<i>black liquor</i>	3.1
<i>beet pulp</i>	3.5
<i>abattoir waste</i>	0.4
Priority 3 inputs	
<i>slurry</i>	1.4
<i>manure</i>	15.2

Table 10 Estimated biogas potential from multiple resources in 2050 (in TWh) (Groupe de Travail Gazeification Hydrothermale, 2023)

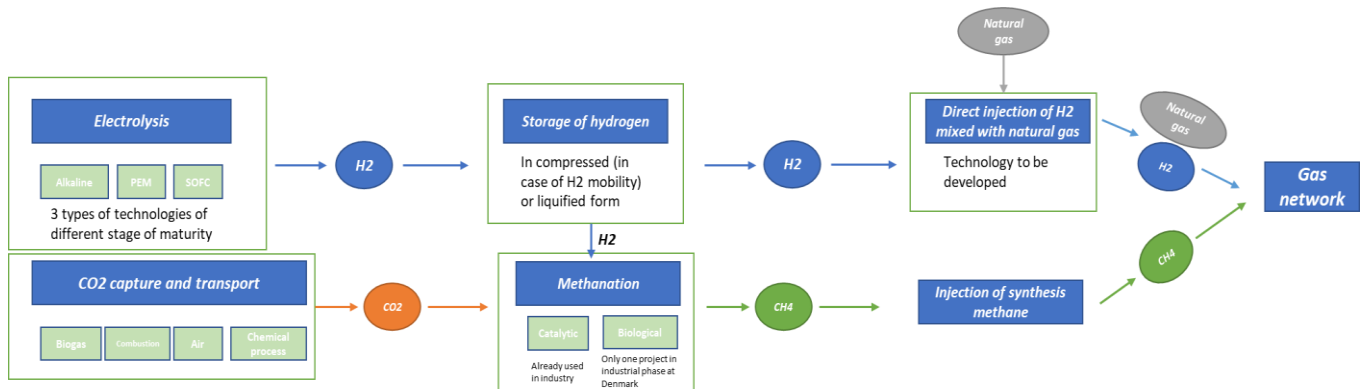


Figure 42 Technologies of power-to-H₂ and power to CH₄ (ADEME et al., 2018)

Another solution to produce renewable gas is power-to-gas (P2G) technology. Here we distinguish power-to-H₂ and power-to-CH₄ processes with different gas outputs. Electrolysis of water into hydrogen is the first step for both technologies. With power-to-H₂, the produced hydrogen can be stored (in compressed or liquefied form) or injected into the gas network mixed with methane. The stored hydrogen can also be recombined with captured CO₂ to form synthetic methane (CH₄). The sources of CO₂ are industrial processes, power generation and methanization. These CO₂ emissions are valorized thanks to power-to-CH₄ (ADEME et al., 2018). Currently, the following three electrolyzing technologies with different levels of maturity are identified: alkaline, PEM (proton exchange membrane), and SOEC (solid oxide electrolyzer cell) (ADEME, 2014).

The alkaline method inserts two electrodes into a potassium hydroxide (KOH) solution. With a continuous electricity current, oxygen is produced at the anode and hydrogen at the cathode. A diaphragm is placed between the electrodes in order to separate the produced gas. To acquire pure hydrogen requires further treatment of the gas acquired from the cathode (“washing”, removal of KOH, water, oxygen). The energy efficiency of the alkaline method is around 70%⁴⁸, and larger-scale projects can achieve greater efficiency. Alkaline is a mature technology (developed at the beginning of the 20th century) and already used in industrial processes. The advantage of alkaline technology lies in its long lifespan (50000-60000h). However, its capacity to work with a varied load stills needs to be developed (Doudard, 2018).

PEM technology follows the same chemical principle as the alkaline method. The specificity lies in the use of a membrane serving to channel both the electrolyte and two gas flows. Compared with the

⁴⁸ Efficiency = H₂ flow rate [Nm³/h] x H₂ HCV (3.55 kWh/Nm³) / Electrical power [kW]

alkaline method, the PEM electrolyzer is more compact and requires less purification efforts to obtain hydrogen. The energy efficiency of PEM is comparable with that of the alkaline method (70%, laboratory results). The lifespan of PEM is shorter than that of an alkaline electrolyzer (around 20000h). The development of PEM dates from the 1960s and technical improvements are still required in order to increase its lifetime and energy efficiency.

SOEC technology carries out electrolysis at high temperatures (700-800°C) with a heat input. Electricity consumption can thus be significantly reduced. The production of hydrogen in an SOEC electrolyzer is easily reversible, and the device serves in this case as a fuel cell that uses hydrogen to produce electricity and heat. SOEC can achieve high energy efficiency (100% from H₂ to electricity), however, this technology is still in the laboratory phase.

According to an estimation by ADEME (ADEME, 2014), the LCOE of hydrogen produced from a power-to-H₂ process ranges from €120-140 /MWh (10% of discounting rate). Provision of electricity accounts for around 70-80% of the complete cost. The production of CH₄ using power-to-gas technology involves a higher cost of around 155 à 170 €/MWh, depending on capacity of electrolyzer (ADEME et al., 2018).

Uncertainty remains regarding the development model of power-to-gas. For the near future, the feasible solution is direct usage of hydrogen in the transport sector and injection of methane produced from methanization into local distribution network. Techniques to inject hydrogen directly into the gas network are still under development. The results of existing R&D projects suggest that injecting up to 20% of hydrogen into the gas network is feasible, however this technique is only compatible with a new distribution network. The vision of the gas network operator in France (GRDF) for the long term consists in developing an exclusive hydrogen distribution and transport network. The current available demonstrators in France are GRHYD (Engie, n.d.), Jupiter 1000 (Jupiter 1000, n.d.) and ENERGO (Techniques de l'ingénieur, 2022a). Apart from the R&D demonstrators, several industrial-scale projects are under development. All of them are based on a power-to-methane development model.

Country	Project/actor name	Project stage	Project status	Capacity	Technology
France	GRHYD	R&D demonstrator	in operation since 2014		Production of hydrogen by electrolysis – storage- injection of H2 into distribution network with a ratio of 20%
France	Jupiter 1000	Industrial demonstrator	In operation since 2020	1 MW	Test direct hydrogen injection and methanation with CO2 capture for industrial customers
Germany	Audi e-gas	industrial stage	in operation since 2013	300Nm3/h (<2% vol. H2)	Power-to-CH4 for transport (bio GNV), electrolyzer: alkaline 6,3MWe (McPhy)

Table 11 Overview of existing power-to-gas and power-to-methane projects (Engie, n.d.; Jupiter 1000, n.d.; Power Technology, 2021; Techniques de l'ingénieur, 2022a)

2.2.1.1.2 Representation of the renewable gas sector in TIMES-FR

For exploring the long-term flexibility and interaction of the gas and electricity system in France, the work of (Doudard, 2018) has developed a detailed structure for renewable gas production from technologies of methanization, pyro-gasification, power-to-gas, and the link between the gas sector and electricity system with the CCS industry (TIMES-FR-GAZEL). This provided inspiration for (Millot, 2019) to represent these technologies in TIMES-FR. For this study, the modeling structure for the renewable gas sector is based on the given framework. Here we briefly present how these technologies are modeled in TIMES-FR.

For the branch of methanization, TIMES-FR uses five different processes to differentiate the production cost of biogas linked with the level of resource mobilization. The hypotheses of cost and potential are based on (ADEME et al., 2018). Biogas produced by the five processes of methanization can be directly consumed by CHP plants or injected into the gas network through purification with or without capture of CO₂. The captured CO₂ is stored in carbon sinks. For pyro-gasification, the model uses four different processes to present technologies that take different types of solid biomass input. The model also presents the pyro-gasification process with CO₂ capture. The intermediary steps between gasifiers and biomethane purification are not presented. In TIMES-FR, the usage of solid biomass for pyro-gasification is in competition with other usages of biomass such as direct heating consumption via CHP plants and boilers. For the power-to-gas sector, the model considers a small electrolyzer and a large electrolyzer with different production costs and efficiency for hydrogen production. Multiple options exist after the production of hydrogen from electrolysis: methanization for biomethane production, direct injection into the network, and direct usage. Currently, the process of methanization of H₂ is presented at an aggregated level. For all the processes of renewable gas production in TIMES-FR, the usage of captured CO₂ (for methanation, industrial processes, etc.) is not modeled.

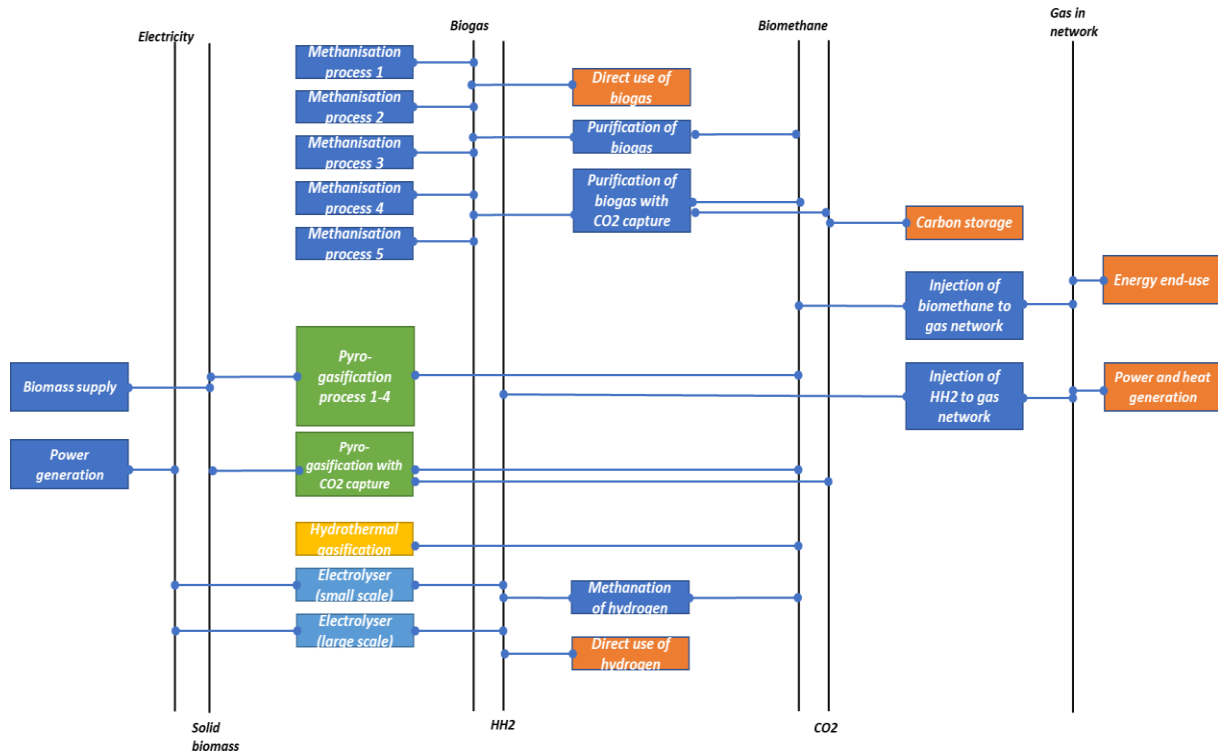


Figure 43 Structure of the renewable gas sector and its interaction with the electricity system in TIMES-FR

Our contribution is to complete the representation of the renewable gas sector in TIMES-FR by adding a hydrothermal gasification module to produce biomethane, and review the production cost, energy efficiency and supply potential of all the technologies involved in renewable gas production.

For the current stage, we represent various processes of hydrothermal gasification with different technical principles and inputs at an aggregated level. We presume that the production cost of biomethane by hydrothermal gasification is €110 /MWh in 2050, and the potential of biomethane supply reaches 63.2 TWh. Both follow the hypotheses of (Groupe de Travail Gazeification Hydrothermale, 2023).

As for the technical-economic parameters of other renewable gas technologies, we retain a considerable part of the hypotheses adopted by (Doudard, 2018). For methanization, in case of purification without CO₂ capture, the hypothesis of biomethane production cost is €90 /MWh (ENEA Consulting, 2017) in 2018, and the total cost is decomposed into a biogas production share (€60 /MWh) and a purification/injection share (€30 /MWh). Both the investment cost of purification and the variable cost of biogas production are presumed to decrease in the future. We distinguish four levels of variable biogas production cost by the range of biomass resources mobilized for methanization. The variable cost increases with the mobilization rate of the biomass resource. This is in line with

hypotheses of ADEME (ADEME et al., 2018). The extra cost of purification with CO₂ capture is €9/t of CO₂ following the study of (Reiter & Lindorfer, 2015). We consider the efficiency of biomethane injection to be 94%. The technical potential of biogas production from methanization is 90 TWh in 2030 and 152 TWh in 2050 (ADEME et al., 2018). For pyro-gasification, the retained investment cost for gasifiers is €3000 /kWCH₄ in 2030 and €2500 /kWCH₄ in 2050. The yield is 63%. For processes with SRF input, the provision cost is €40/MWh and the technical potential is 1 TWh in 2030, and 9 TWh in 2050 (ADEME et al., 2018).

2.2.1.2 District heating supply

2.2.1.2.1 Context: disparity of development potential for district heat linked with demand density

As discussed in the first chapter, district heating is one of the major solutions for heating in the building sector. With the development of an efficient low-temperature heating network, DH is a viable solution to recover several renewable heat sources such as geothermal energy, industrial excess heat, and heat from waste incineration. District heating is thus of interest to our analysis for the long-term energy choice of the residential sector. One important aspect that we need to consider is that areas with different densities of heating demand have different conditions to develop a district heating system. A major element is the delivery cost linked with network investments which are decisive for the economic viability of projects.

District heat systems are usually projects that require high upfront expenditure. They are usually developed in densely populated areas with a high heating demand density such as city centers, and the suburban districts of large cities. In these areas, installed district heat facilities can deliver high volumes of heat, and the fixed costs for a unit of heat delivery can be reduced to a low level, making it a more economically viable solution. However, in rural areas where the heat demand is relatively low, developing a large-scale district heating network may generate high fixed costs for limited heat delivery. A district heat system seems to be a less convenient solution here. An important feature to assess the technical dimensioning and economic viability of a district heat network is thermal density, calculated by annual delivered heat quantity (MWh) divided by the length of network (m). A high thermal density means that the same distance of pipeline can cover more heating demand, thus lowering the unitary fixed network cost of delivered heat, which constitutes a major part of the total cost of heat delivery. It is estimated that, for existing projects in France, the annualized CAPEX (Capital Expenditure) for primary distribution ranges from €10 /MWh for low thermal density networks to €27 /MWh for high thermal density networks. According to ADEME (ADEME, 2019c), the weighted average thermal density (by energy delivery) of the French DH network was 4.7 MWh/ml in 2018, and 1.5 MWh/ml is the economically viable threshold for French DH networks.

The national heat map developed by CEREMA illustrates the disparity between conditions to develop district heat among the different zones in France. The heat map projects yearly residential heating demand of the entire territory of Metropolitan France in 2030 with a resolution of 1 hectare (100*100m). The heating demand in the CEREMA map is estimated by a simulation method taking into account a series of factors such as climate features and building types. The main data sources for simulation are open data from GRDF, a 2016 population survey by INSEE, the CEREN database, the DDH of France Météo and Fichers Fonciers. A detailed presentation of the calculation method is given by

(Cerema, 2020). The plots of 100*100 m are further classified into 10 categories based on demand scale, from less than 30,000 kWh to more than 1,200,000 kWh per year (with different colors on the map). Parcels with high demand density are colored red and usually correspond to densely populated, central areas of cities where DH with a high thermal density and a lower unitary fixed cost of heat delivery can be developed.

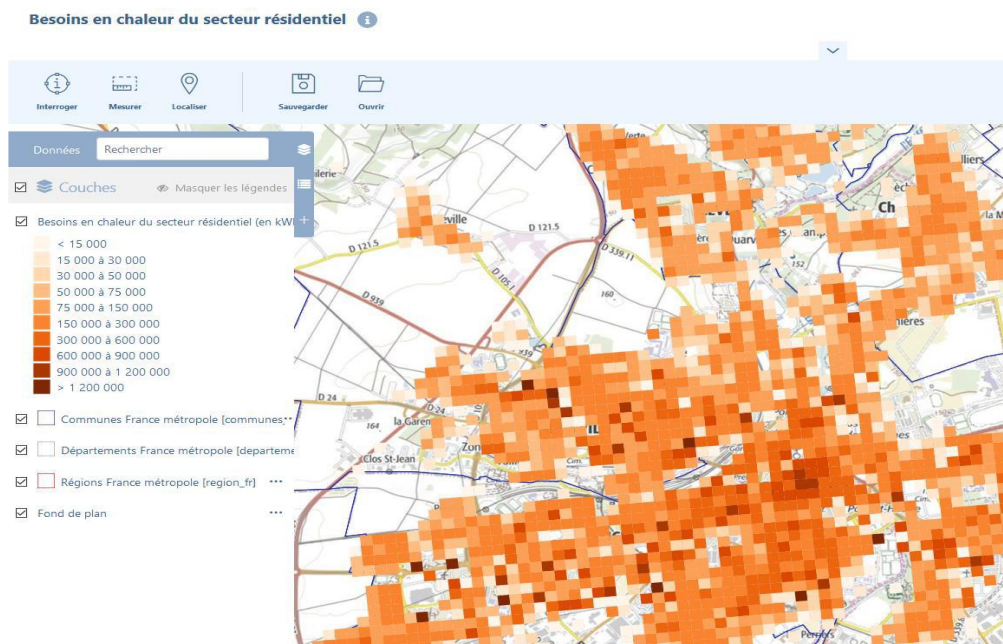


Figure 44 Example of the national heat map produced by Cerema (Cerema, 2020)

The information given by the heat map suggests that the demand potential of areas with favorable investment conditions for district heating is limited. For each category of density, we aggregate the estimated heating demand of all the parcels and obtain an estimation of its demand potential in useful energy. The figure below presents the distribution of national demand by areas of demand density calculated from the heat map. We note that the heating demand of parcels with relatively high demand density where the annual demand is above 0.9 GWh (parcels with the highest and second highest demand density) represents only around 14% of national demand, while a significant share of heat demand is located in areas with low demand density and low economic viability to invest in a district heating system.

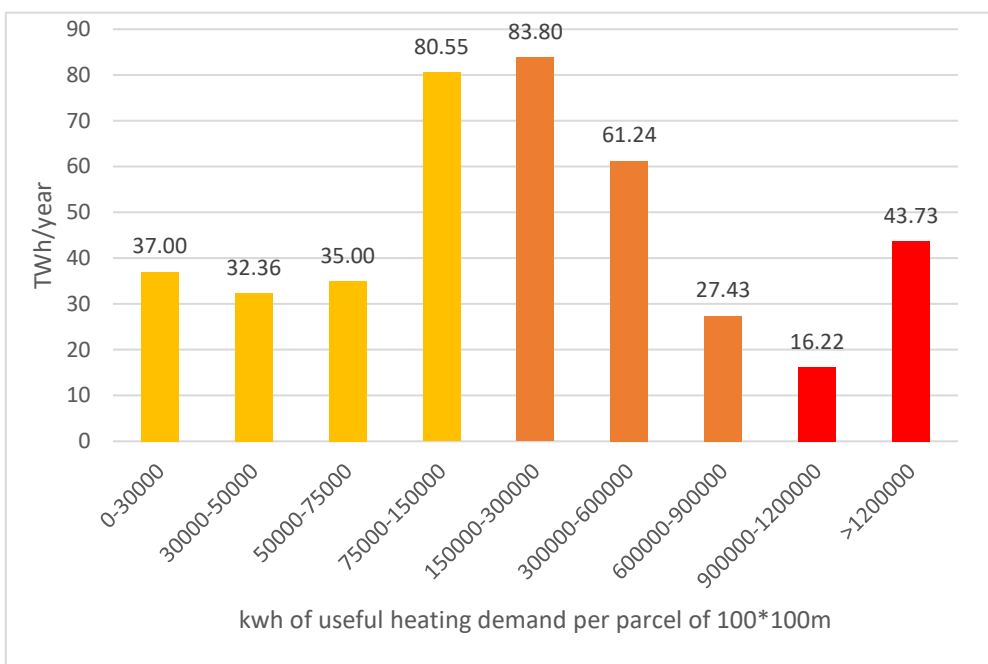


Figure 45 heating demand by level of demand density, estimated by the national heat map

2.2.1.2.2 Improved modeling structure for residential district heating distribution

In the modeling of energy systems, it is important to consider the disparity in investment conditions and the supply potential of district heating for areas with different levels of heating density. We thus elaborated an improved model structure for to supply district heat to residential buildings. We separately represent three types of district heating system with high, medium and low thermal densities. The disaggregated structure enables a better accounting for cost and potential for investments in district heating.

The figure below (Figure 46) presents a simplified structure for representing the sector of primary distribution of district heat developed in TIMES-FR. The three types of network (high, medium, low density) are described by three independent processes. Each type of network is decomposed into two successive technologies: pipeline networks and substations along with other equipment. The two-step method allows for a more precise presentation of annual fixed investment costs of different network components with different estimated lifetimes. We consider that the physical lifetime of pipelines is 40 years, and that of the other equipment is 20 years. The annual investment cost (CAPEX) is respectively 27, 19, 10 (€/MWh) for low, medium and high-density networks, and the share of CAPEX related to canaling is fixed at 70%. These hypotheses are based on (ADEME, 2019c).

The investment eligibility of a district heat network with different thermal densities depends on the density of heating demand. We calibrate the supply potential of three types of district heat network by estimating the demand potential using the national heat map. We suppose that the provision potential of a high-density network corresponds to the estimated heating demand of all the parcels in the map with an annual demand above 0.9 GWh per year (in red), a medium density network for parcels with an annual demand between 0.15-0.9 GWh per year, and a low-density network for parcels with an annual demand below 0.15 GWh per year. The supply potential of a high thermal density network is 60 TWh, medium density 172 TWh, and low density 185 TWh.

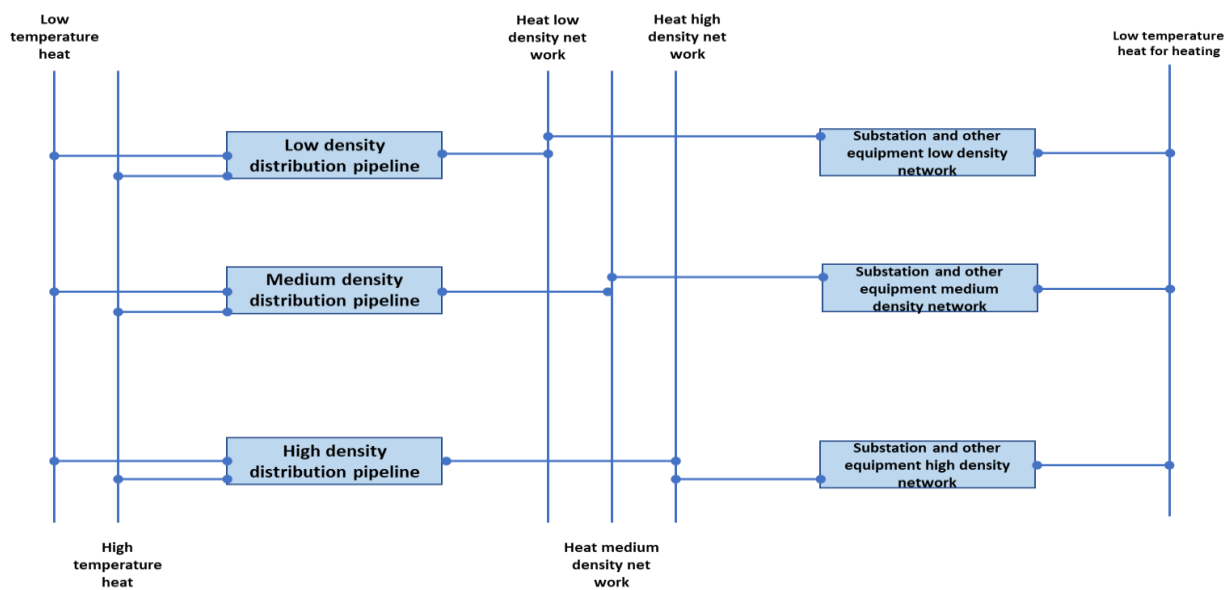


Figure 46 Disaggregated structure of residential district heating supply in TIMES-FR

	Low density network	Medium density network	High density network
canaling (€/MWh)	18.9	13.3	7
other equipment (€/MWh)	8.1	5.7	3
Total annual CAPEX (€/MWh)	27	19	10
Total annual OPEX (€/MWh)	9.7	9	9.3

Table 12 Estimated annual investment cost and operation cost DH networks of different thermal density (for the primary distribution circuit)

thermal density	level of annual heating demand (MWh)	estimated total residential demand (TWh)
low	< 150	185
middle	150-900	172
high	> 900	60

Table 13 Estimated supply potential of low, middle and high thermal density DH network covering areas of different demand density

2.2.2 Improvement in supply side: the case of biomass

2.2.2.1 Context: current biomass supply in France presents high complexity

Forestry biomass is currently an important energy source for heating. As a decarbonized energy source, biomass may play a vital role in the future energy transition. Solid biomass energy has multiple advantages that facilitate its usage in the building sector and make it a convenient decarbonized energy solution for households. Firstly, forest biomass is easy to acquire, transport and store, thus allowing for a low production cost. Some households have access to short cycle supplies with inexpensive purchase prices. Secondly, forestry biomass can be directly used in various types of heating equipment, including open fireplaces, stoves, and boilers. Some emerging biomass heating technologies, especially automatic pellet stoves, can provide high levels of energy efficiency and thermal comfort for households. Apart from its direct usage, developing biomass transformation technologies enables biomass to be presented in different physical forms (biogas, biofuel), which makes biomass more competitive in terms of adapting to increasing types of energy demand.

It is thus necessary to consider the role of biomass in our energy prospective study. For energy modeling, one thing that cannot be ignored is that the forestry biomass supply system presents a high level of complexity, leading to difficulties in identifying future supply availability and provision cost. Several aspects require attention.

Firstly, although France has an abundant forest stock, the exploitable part of forest for biomass energy is very limited. According to an estimation from IGN⁴⁹, France has around 2,500 Mm³ of wood stock, while the average extraction rate on stock is around 1.6%, accounting for 50% of the total annual biological production (2016 data) (ADEME & IGN, 2016). The exploitability of forest stock is highly dependent on a range of factors including forest management policies, environmental and social concerns (biodiversity, landscape conservation, and public access), technical conditions for exploitation and economic profitability. All these concerns reduce the availability of biomass energy to a very low level compared to wood stock.

Secondly, for forest biomass, usage for energy competes with demands from industry and construction material. According to statistics from the Ministry of Agriculture and Food Sovereignty⁵⁰ (Agreste⁵¹) (Agreste, 2020), in 2019, including all supply cycles, energy wood accounted for around 46% of the total wood harvest, industry wood for 19%, and wood timber for construction for 35%. Stronger

⁴⁹ IGN : Institut national de l'information géographique et forestière (in French)

⁵⁰ Ministère de l'Agriculture et de la Souveraineté alimentaire (in French)

⁵¹ Agreste : La statistique, l'évaluation et la prospective agricole du ministère de l'Agriculture et de la Souveraineté alimentaire

competition comes from the usage of wood in industrial processes such as paper production, production of wood board, for both energy wood and industrial usage of wood targeting materials with a smaller diameter (lower than 20cm). Besides, the wood industry provides various types of products such as wood logs, forest chips, and sawmill by-products eligible for different energy usages. The major steps of processing wood raw materials include a first and a second transformation. Best-quality wood logs are products of the first transformation and can be directly used by households. A considerable volume of sawmill by-products, such as saw-mill dust, wood bark and wood chips can be collected during both the first and second transformation of wood. These sawmill by-products can be reprocessed into wood pellets and briquettes, both of which are expensive wood fuels with high calorific value and used for domestic purposes, or consumed by large boilers for district heating, electricity production and industrial usage.

Thirdly, biomass supply for households has various supply cycles, and their cost and availability are not the same. Households can acquire biomass energy (wood logs) from both short cycles and market sales. The short cycles include auto-supply (harvest from private property for free) and direct sales from wood producers with a much lower prices than on the market. The price of direct sales is close to the production cost of wood logs. With easy accessibility and very low production costs, the short cycles are important supply mode of forest biomass for the residential sector. However, they are accessible to only some households, mostly living in rural areas. A statistic report by ADEME (ADEME, 2018c; SDES, 2019a) indicates that around 40% of domestic wood fuel is provided by auto-supply, and 20% by direct sales. Nevertheless, it is hard to precisely estimate annual consumption and supply potential. Market sales are the most expensive supply mode and accessible to all households. In 2020, the national average retail price of wood logs was around 32 euros/MWh (VAT included) (SDES, 2021).

Fourthly, the supply potential and cost of forest biomass differs across geographical regions. This is mainly explained by the uneven distribution of forest resources among regions. The figure below illustrates an estimation of the technical-economic availability of energy and industry wood in 2035 according to a study by ADEME (for commercial exploitation). Nouvelle Aquitaine, Grand Est, and Bourgogne-Franche-Comté are estimated to be the regions with the highest technical economic availability, with respectively 1,428, 1,372 and 1,216 kTEP⁵² of commercial production potential. The retail price of wood logs ranges from 56 to 88 euros/stere. Brittany, Provence-Alpes-Côte d'Azur & Corsica and Pays de la Loire are the regions where wood energy prices are the highest, while households in Bourgogne-Franche-Comté benefit from the lowest wood fuel prices in Metropolitan France (ADEME, 2018a). Moreover, a difference in the provision mode of domestic wood fuel can be

⁵² kTEP: kilotonne of oil equivalent

observed: In Auvergne-Rhône-Alpes, more than 50% of residential wood energy is supplied by auto-provision, compared with 15% in IDF (ADEME, 2018c, 2018b).

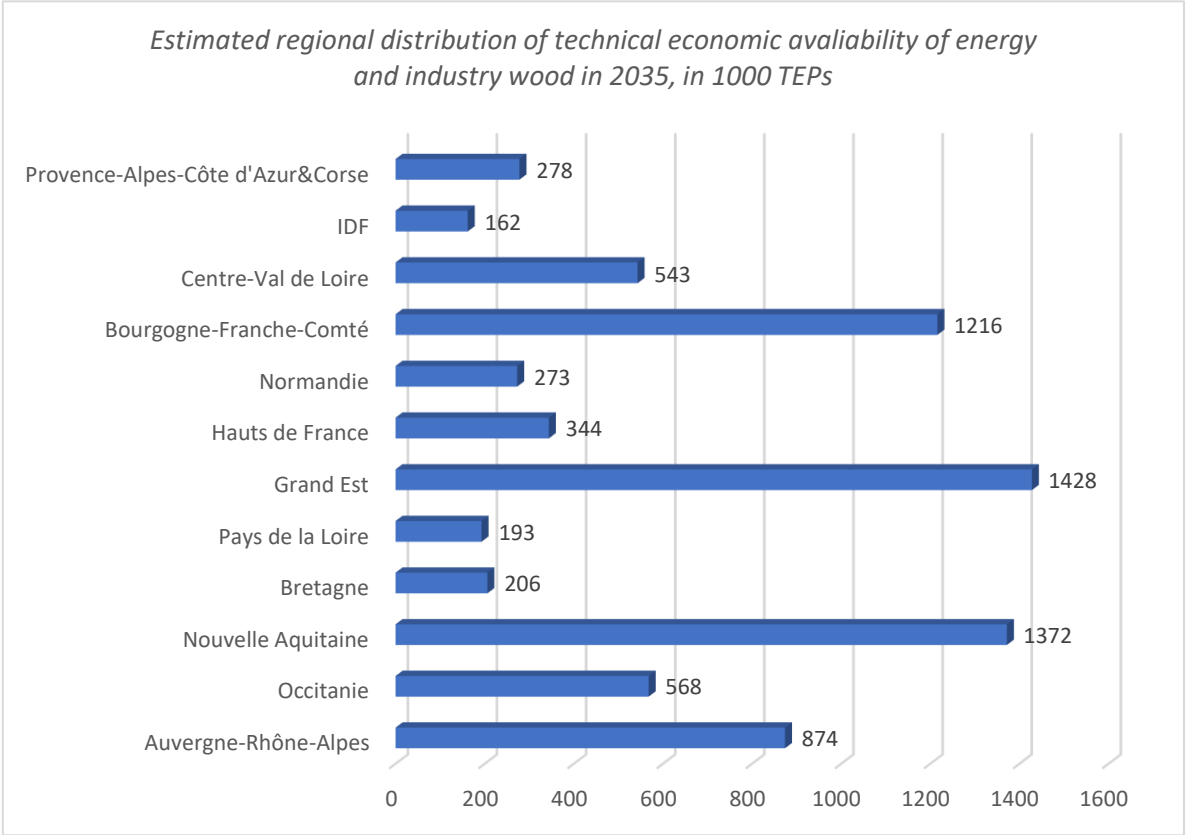


Figure 47 Estimated technical economic availability of energy and industry wood in 2035 per region, under constant forest management scenario of ADEME and IGN (Source: IGN, ADEME, 2016)

2.2.2.2 Disaggregated structure for the biomass supply sector

All of the elements introduced above present the complexity of biomass supply to the energy system. They are important to consider when modeling the energy system. The previous model structure of TIMES-FR used a simplified aggregated method to represent solid biomass supply; however, this method may not be sufficient to capture the heterogeneity of the supply situation. Based on this, we have elaborated a modeling structure for biomass provision that presents in detail the various supply cycles of biomass energy sources. The improved modeling of the biomass energy sector enables us to better quantify the supply availability and costs of various biomass energy sources. This helps us to understand its role in the future energy transition.

The new structure accounts for provisions of multiple biomass energies in solid, gaseous and liquid forms (Figure 48). For solid biomass, the provision of products from different geographical regions and supply cycles is included. We decompose solid biomass supply into two steps: forestry exploitation (mining) and all the steps related to transport, reprocessing and distribution that make solid biomass available for end-use. We consider four types of forestry biomass including wood logs, sawmill chips, sawdust, forest chips; wood logs are further specified by three supply cycles (market sales, short cycles and auto-supply) for the residential sector. The three supply cycles of wood logs for households and forest chips are further disaggregated into 12 independent processes corresponding with 12 administrative regions of France. In this way, the solid biomass mining sector in TIMES-FR is disaggregated into 51 processes. Cost hypotheses of these provision processes are calibrated from multiple studies elaborated by ADEME and Agreste (ADEME, 2017b, 2018c; ADEME & IGN, 2016; Agreste, 2019). The table below summarizes the default assumptions retained for production costs (market sale) of wood log and wood pellets for 12 administrative regions. The price of wood logs ranges from €20 to €36 /MWh and the Bourgogne-Franche-Comté region has the lowest provision cost. The supply of solid biomass to residential buildings is due more to high transport and distribution costs. We consider an additional distribution cost of €5 /MWh for wood logs. The production costs of forest chips, sawmill chips and sawdust are respectively €21.7, €15 and €14.9 /MWh.

Region	wood logs (€/MWh)	pellets (€/MWh)
Auvergne-Rhône-Alpes	25.50	42.11
Occitanie	28.50	41.50
Nouvelle Aquitaine	26.50	44.80
Bretagne	36.00	38.35
Pays de la Loire	32.50	41.63
Grand Est	27.00	38.87
Hauts de France	26.00	41.61
Normandie	25.50	45.59
Bourgogne-Franche-Comté	20.00	48.26
Centre-Val de Loire	25.00	46.52
IDF	27.00	46.04
Provence-Alpes-Côte d'Azur & Corse	32.00	41.04

Table 14 Production cost of wood logs and pellets

For liquid biomass, TIMES-FR allows for the usage of first- and second-generation biofuel. Both can be either locally produced or imported into the energy system. However, for the production of first-generation biofuel, the type of input and technology still remains unprecise. Second-generation biofuel technology can use all types of solid biomass available for market sale in TIMES.

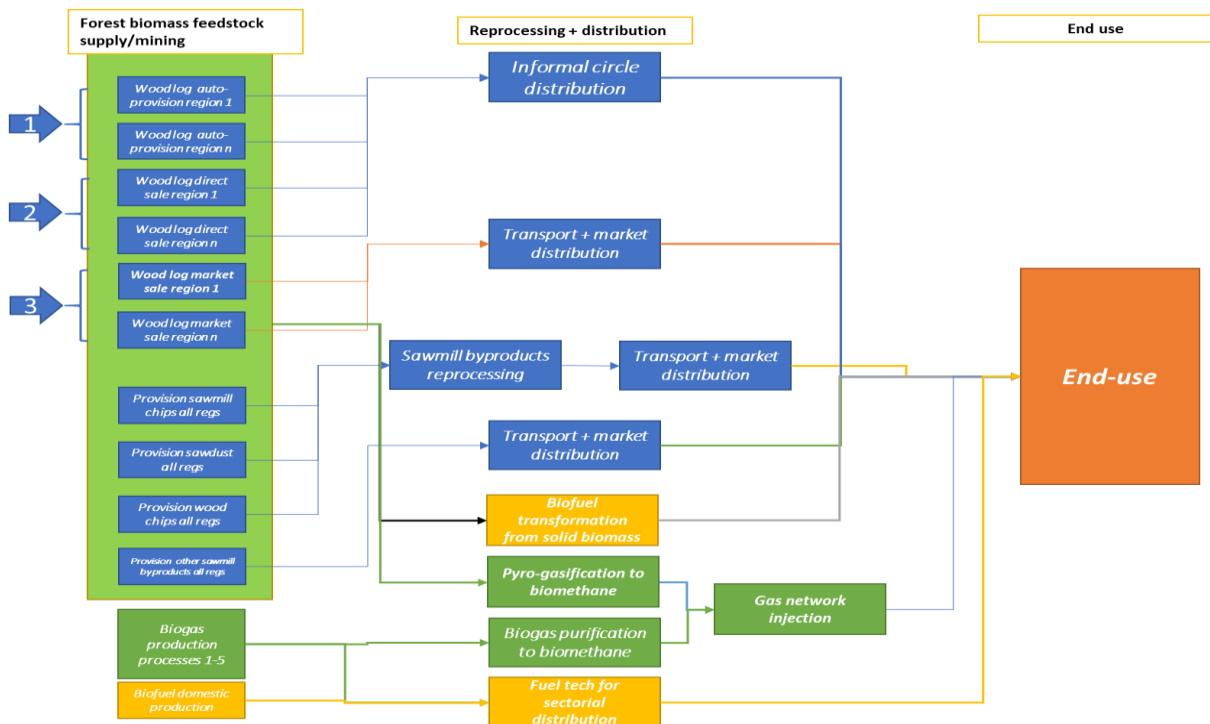


Figure 48 improved modeling structure for biomass energy supply in TIMES-FR

2.2.2.3 Stock of solid biomass energy supply and two scenarios of future availability

The stock of various solid biomass supplies for the base year is calibrated from a range of data sources accessible online, including (ADEME, 2018c, 2018b; ADEME & IGN, 2016; Agreste, 2019). The adopted values of regional availability of forest biomass for market sale are based on a report published by (ADEME & IGN, 2016) that estimates the supply availability of energy wood and industry wood according to the forest stock of 13 administrative regions of Metropolitan France from 2016 to 2035. Biomass supply by auto-supply and direct sales is estimated from statistics on the number of households and average biomass consumption by provision mode by administrative region (ADEME, 2018b). The stock of second-transformation wood by-products (sawmill wood chips, sawdust, bark) is based on annual statistics of wood production from Agreste (Agreste, 2019).

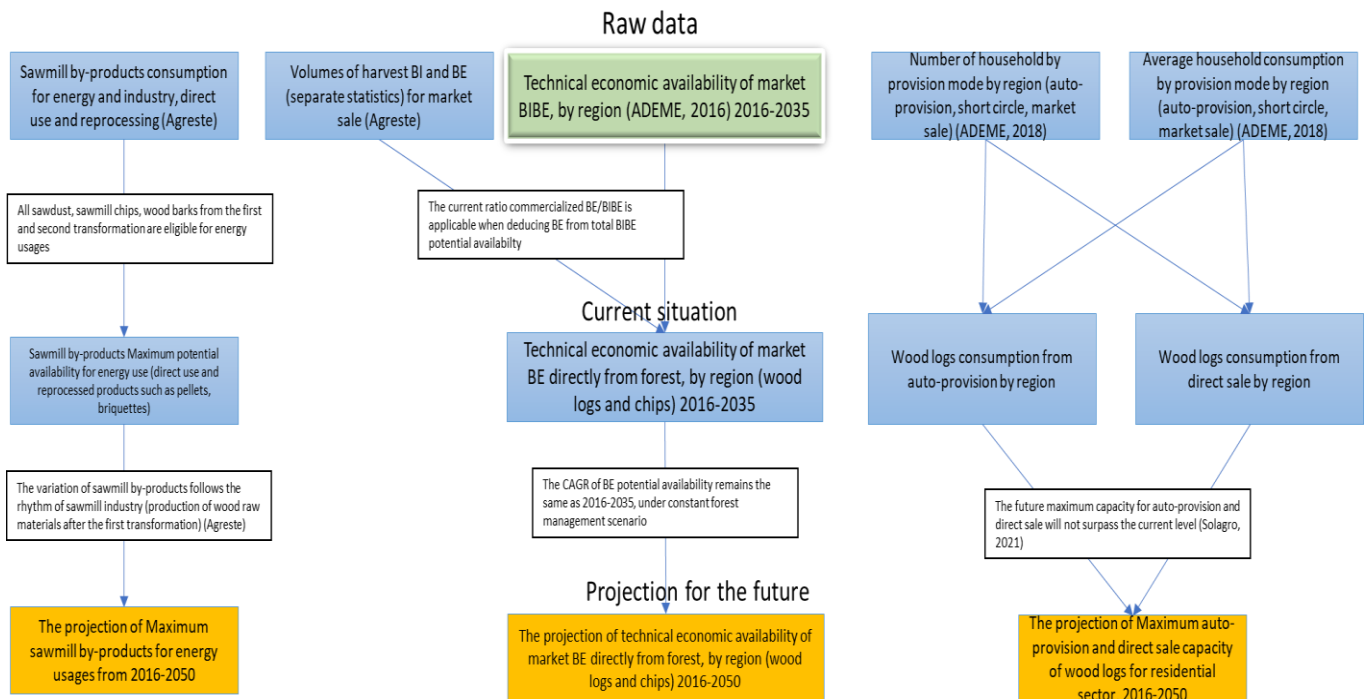


Figure 49 Hypotheses for calibrating current stock and future supply potential of solid biomass energy

For the base year, we define a total solid forest biomass supply availability of 105.87 TWh, including 41.96 TWh of nonmarket wood logs (auto-provision and direct sale), 28.88 TWh of wood logs for commercial sale, 13.59 TWh of wood chips from forests, and 21.43 TWh of second-transformation wood by-products. The availability of forest-origin biomass differs considerably across regions. Grand Est, Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté and Nouvelle Aquitaine are the regions with the highest stock, disposing respectively of 16.65, 11.47, 10.55 and 9.87 TWh of solid biomass energy

potential (all provision cycles included). Besides, the ratio of wood energy provided by nonmarket mode varies greatly across regions: In Auvergne-Rhône-Alpes, more than 50% of residential wood energy is supplied by auto-supply, compared with 15% in Île-de-France. The stock of various solid biomass supplies in 2020 is calibrated from various data sources accessible online.

With regard to the future supply availability of solid biomass, we elaborate two scenarios with different growth rates of biomass stock potential: the high biomass scenario, which simulates a rapid growth of available wood energy till 2050, and the low biomass scenario with a constant stock in the future. These two scenarios are inspired from the vision of ADEME and IGN on future forest management (ADEME & IGN, 2016). In the study of 2016, a dynamic silviculture scenario and a constant silviculture scenario are published. From the high biomass potential scenario, we interpret an optimistic future for forest exploitation: technology progress increases the feasibility of exploitation; a favorable silviculture policy unlocks the exploitation in forests of multiple types of ownership status currently underdeveloped, especially private forests without PSG⁵³. In 2050, the supply potential of both commercial wood logs and forest chips will be double that of 2020. Besides, we consider an additional provision potential of wood-waste, non-forest wood and solid agricultural residue available for biomethane production by pyro-gasification. We take the ADEME estimation that the supply potential of waste wood, non-forest wood and solid agricultural waste in 2050 will be respectively 19, 36, and 5 TWh (ADEME et al., 2018). If all these resources are mobilized, there will be around 42 TWh additional production of biogas (the yield of pyro-gasification is 0.7). For the share of solid biomass from the nonmarket cycle, we suppose that its availability remains constant in the future, based on the estimation of (Solagro, 2021).

The low biomass potential scenario foresees a much slower increase in forest mobilization from 2020 to 2050. The supply availability of forest biomass can hardly surpass 410 PJ and there will be no possibility of using additional provision potential for pyro-gasification.

⁵³ PSG : Plan Simple Gestion (CNPFP, n.d.)

Region	Supply availability 2020				High wood potential 2050		Low wood potential 2050	
	Auto-provision	Short circle	Wood chips from forest	Wood logs commercial circle	Wood chips from forest	Wood logs commercial circle	Wood chips from forest	Wood logs commercial circle
Auvergne-Rhône-Alpes	3.49	1.68	2.02	4.29	4.07	8.66	2.28	4.86
Occitanie	2.38	1.28	0.91	1.93	2.63	5.59	1.73	3.67
Nouvelle Aquitaine	3.26	1.71	1.57	3.34	2.00	4.26	1.79	3.80
Bretagne	1.65	1.35	0.43	0.91	1.10	2.34	0.74	1.57
Pays de la Loire	1.40	0.82	0.41	0.87	0.82	1.74	0.61	1.29
Grand Est	3.31	4.90	2.70	5.74	6.06	12.88	4.26	9.05
Hauts de France	1.65	0.96	0.88	1.86	1.62	3.44	1.25	2.66
Normandie	1.41	1.54	0.63	1.35	0.98	2.08	0.82	1.73
Bourgogne-Franche-Comté	1.41	2.75	2.04	4.34	4.28	9.09	3.11	6.61
Centre-Val de Loire	1.10	1.26	0.96	2.04	1.81	3.85	1.42	3.02
IDF	0.37	0.51	0.44	0.93	1.05	2.23	0.73	1.54
Provence-Alpes-Côte d'Azur & Corse	1.05	0.71	0.60	1.28	1.47	3.11	1.02	2.16
total	22.48	19.48	13.59	28.88	27.89	59.28	19.74	41.95

Table 15 Estimated supply availability of wood logs and wood chip supply and hypotheses for the high and low supply potential scenario (in TWh)

	2020	2050
Sawmill wood chips	11.23	9.12
Sawdust	4.69	3.60
Bark	2.04	1.34
Other products	3.47	3.00
Wood waste (available from 2025)	36.42	60

Table 16 Availability of wood by-products (second transformation) and wood waste

2.2.3 Improving the demand side

2.2.3.1 Updating the building energy system

Previous studies by (Assoumou, 2006; Millot, 2019) elaborated a detailed structure in TIMES-FR to represent energy end-use in the building sector. Multiple types of useful demand and the set of available technologies of different energy inputs are modeled. Based on the developed structure, we carry out several updates: firstly, we review and update all the technical-economic parameters of available technologies of buildings based on a review of recent published works. This allows us to consider the recent evolution of features in the building technology stock. Secondly, we recalibrate the projection of the demand profile of all technologies in buildings based on the situation in 2014-2020. This allows for a higher level of accuracy in considering the dynamics of building demand, in particular the level of peak demand. Besides, time-slice-specified availability factors for all processes are calibrated based on the demand profile, reflecting the required dimensioning of equipment adapted to peak demand. All these efforts provide solid improvements in the TIMES representation of the building energy system in France. In this section, we start with a short description of the model structure for residential and tertiary buildings, including a thermal insulation module. Then we introduce in detail the three major improvements elaborated in this study.

2.2.3.1.1 Building energy system in TIMES-FR and modeling of thermal insulation

For both residential and tertiary buildings, TIMES-FR represents 4 types of useful demand: space heating, domestic hot water (DHW), cooking and other electricity usages. The demand for space heating and DHW is further disaggregated into two residential building types and eight tertiary building types: apartment, individual house, office, hospitality (café/restaurant/hotel), commerce, community housing, healthcare, education, transport, sport/leisure. In TIMES-FR, the energy system for buildings contains the range of processes that transform primary and final energy sources into these energy services. As an illustration, the figure below presents a simplified structure of the energy system of individual houses with part of the processes modeled in TIMES-FR. For each type of building, the modeling structure is the same. For demand for space heating, DHW production and cooking, TIMES-FR models a technology stock that contains various equipment items, taking different energy inputs and with different levels of energy efficiency. The sector of specific electricity demand is represented at an aggregated level. We will make a more detailed description of the available technologies for buildings in the following part.

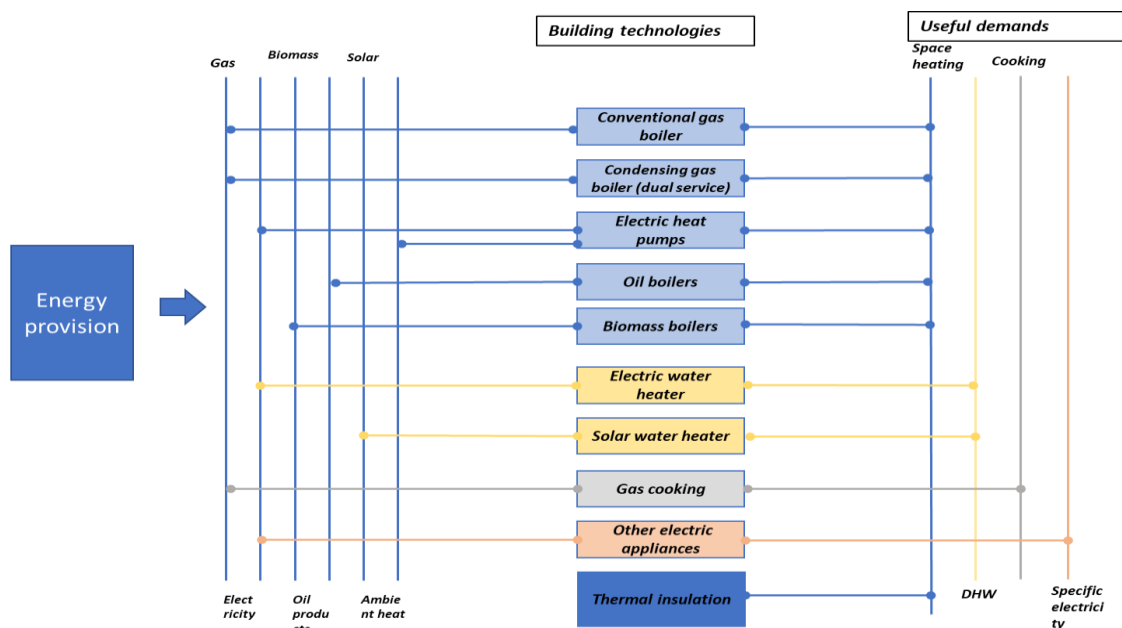


Figure 50 Illustration of residential energy system in TIMES-FR

Thermal insulation is modeled as positively producing space heat for buildings. Investment in thermal insulation in year N constantly “produces” a certain volume of useful heating (in PJ) in the following years, representing the energy saving generated by insulation. The technical lifespan of insulation investment is 50 years, longer than its economic life (30 years).

For residential buildings, TIMES-FR describes 32 types of insulation technology, distinguished by the items renovated (windows, roof, exterior wall, etc.). The technical potential and cost of each level of insulation is calibrated from statistical results of the Phébus housing survey in 2012 by (Millot, 2019). The total potential of residential thermal insulation defined in the model is 84 TWh for individual houses and 59 TWh for collective buildings (as discussed in the first chapter). Thermal insulation in the tertiary sector is presented at an aggregated level by 8 processes corresponding to 8 categories of tertiary buildings (office, commerce, hospitality, education, community housing, healthcare, sport/leisure, transport). The potential of tertiary thermal insulation is defined as 40 TWh, following the hypothesis of (Millot, 2019). The insulation potential of each category of tertiary building is proportional to its level of final energy consumption.

	Potential yearly useful energy saving (TWh)
Office	10.13
Hotel/restaurant	4.38
Commerce	9.07
Education	4.66
Community housing	2.41
Healthcare	4.81
Sport, leisure, culture	3.11
Transport	1.44

Table 17 Adopted hypotheses of tertiary insulation potential

2.2.3.1.2 Review of technical-economic parameters for building energy systems

The energy efficiency values and the unitary investment cost of energy equipment are chosen and calibrated from producer data, various bibliographical resources, and previously defined price ranges in TIMES-FR. In order to ensure that the adopted values of investment cost in the model are in line with the real situation, for each process, we compare the value with price ranges provided by other information sources. Our main data sources include ADEME, Amorce, and a number of online information sources from energy suppliers such as Engie, EDF and GRDF. More details are given in Annex 1. For some equipment for which we could not find available data, especially emerging technologies such as hydrogen burners and gas heat pumps, we assume that their cost follows a fixed ratio compared to other equipment with the same energy input.

The table below summarizes the adopted values of lifespan, efficiency, unitary fixed operation cost, and unitary fixed investment cost of all available technologies for heating, DHW production and cooking. For space heating, we model 28 types of heating equipment with seven different energy inputs, including biomass, electricity, gas, geothermal, heating oil, hydrogen, LPG, and solar. For biomass, electricity, gas, oil and LPG heating, we model various types of equipment. The technology stock covers almost all investment options available in the market or to be developed in the future. For gas heating, the building energy system in TIMES-FR contains conventional gas stoves, single or dual service low temperature and condensing boilers, and gas heat pumps. For electric heating, we model conventional electric radiators, two types of standalone heat pump with different energy efficiencies and two types of hybrid heat pump. For biomass heating, the model presents open fireplaces, conventional biomass boilers and wood pellet boilers. In terms of cost, the most expensive technologies are fuel cells, gas heat pumps and geothermal heat pumps with very low market maturity. The unitary investment cost of all these technologies exceeds €2,500/kW. The investment cost of renewable solutions including solar thermal systems and heat pumps in general exceeds €1,500/kW, which is significantly more expensive than biomass, gas and LPG boilers with an investment cost of around €200-400 /kW.

<i>Energy source</i>	<i>equipment name</i>	<i>lifespan</i>	<i>efficiency</i>	<i>Unitary Fixed OM⁵⁴ cost (€/kW)</i>	<i>Unitary capacity cost (installation included) (€/kW)</i>	<i>Data source</i>
Space Heating						
Biomass	Open fireplace	15	0.51	0	240	existing in TIMES
	Biomass boiler	20	0.77	0	274	Producer data
	Biomass boiler dual service	20	0.77	15	301	Producer data
	Wood-pellet boiler high performance	20	0.9	23	468	Producer data
Electricity	Air source hybrid heat pump	20	0.93	87	1737	Producer data
	Air heat pump with electric boiler	20	0.93	74	1479	Producer data
	Advanced air heat pump with electric	20	0.93	91	1829	Producer data
	Electric radiator	20	0.93	3	312	Producer data
	Advanced air source hybrid heat pump	20	0.95325	101	2014	Producer data
Gas	gas stove	15	0.85	5	100	Bibliographical
	low-temperature gas boiler		0.9	6	120	Producer data
	low-temperature gas boiler dual service	20	0.9	7	132	Producer data
	condensing gas boiler	20	0.97	14	271	Producer data
	condensing gas boiler dual service (high		1.1	18	355	Producer data
	Gas heat pump	15	0.93	159	3179	existing in TIMES
Geotherma	Ground heat pump with electric boiler	20	0.93	125	2500	Bibliographical
Heating oil	Oil stove	20	0.70	7	142	Producer data
	Oil boiler (low temperature)		0.90	8	158	Producer data
	Dual oil boiler		0.90	11	211	Producer data
	Condensing dual oil boiler	20	1.00	15	304	Producer data
Hydrogen	Hydrogen burner	20	0.9	232	4637	Producer data
LPG	LPG stove	15	0.70	7	142	Producer data
	LPG boiler	20	0.90	8	158	Producer data
	Dual LPG boiler	20	0.90	11	211	Producer data
	LPG heat pump	20	0.93	103	2062	existing in TIMES
Solar	Solar collector with diesel backup dual	20	0.93	48	2382	existing in TIMES
	Solar collector with electricity backup dual	20	0.93	46	2303	existing in TIMES
	Solar collector with gas backup dual	20	0.93	48	2382	existing in TIMES
DHW						
Biomass	Biomass hot water heater	20	0.45	12	239	existing in TIMES
Electricity	PAC water heater	15	0.9	9	935	existing in TIMES
	Electric boiler water heater resistance	15	0.9	3	69	Bibliographical
Gas	Fuel cell on gas for water and electricity,	15	0.4	646	12914	existing in TIMES
	Gas boiler water heater	15	0.68	10	198	existing in TIMES
Geotherma	Geothermal heat exchanger water heater	20	0.9	67	1334	existing in TIMES
Heating oil	Oil boiler water heater	15	0.63	11	220	existing in TIMES
LPG	LPG boiler water heater	15	0.66	11	220	existing in TIMES
Solar	Solar water heater with diesel backup	15	0.9	44	2200	Bibliographical
	Solar water heater with electricity backup	15	0.9	44	2200	Bibliographical
	Solar water heater with gas backup	15	0.9	44	2200	Bibliographical
cooking						
electricity	electricity plaque	15	1	9	450	Bibliographical
gas	gas stove	15	1	10	500	Bibliographical
LPG	LPG stove	15	1	7	500	Bibliographical

Table 18 Adopted technical economic parameters for building technologies in TIMES-FR

⁵⁴ Operation & Maintenance

2.2.3.1.3 Calibrating useful demand profiles for buildings and availability factors for building processes

For all demands from residential and tertiary buildings in TIMES-FR, including space heating, DHW production, cooking and other electricity usages, we specify their distribution over 12 time slices (as mentioned above, four seasons and three daily time slices). Our projections of demand profiles for residential and tertiary energy usages are calibrated from hypotheses of both seasonal and daily distribution. The projection of seasonal demand is based on an estimation of monthly degree days for 2020-2040 and 2040-2070 by the European Centre for Medium-Range Weather Forecasts (ECMWF) (ECMWF, 2023). We suppose that the distribution of heating demand over four seasons is purported with the number of Degree Days of Heating (DDH). The intraday profiles are built by time series of residential and tertiary useful energy demand provided by the When2Heat project (Ruhnau et al., 2019). The When2Heat dataset is part of the Open Power System Data (*Open Power System Data*, n.d.) project, a publicly accessible data platform for electricity system modeling research. When2Heat data comprises space heating and DHW production demand for 28 European countries from 2008 to 2020 in an hourly resolution. Demand profiles by When2Heat are simulated from gas load profiles, temperature and population data.

<i>Time slice</i>	<i>Individual house heating 2020-2040</i>	<i>Individual house heating after 2040</i>	<i>Apartment heating 2020-2040</i>	<i>Apartment heating after 2040</i>	<i>Individual house water</i>	<i>Apartment water</i>	<i>Tertiary heating 2020-2040</i>	<i>Tertiary heating after 2040</i>	<i>Tertiary water</i>
<i>RD</i>	6.7%	6.5%	6.5%	6.3%	12.0%	10.9%	6.6%	6.4%	9.8%
<i>RN</i>	5.8%	5.6%	6.0%	5.8%	9.1%	10.3%	6.1%	5.9%	11.5%
<i>RP</i>	0.7%	0.7%	0.7%	0.7%	1.1%	1.0%	0.6%	0.5%	0.8%
<i>SD</i>	1.6%	1.3%	1.6%	1.3%	13.4%	12.3%	1.6%	1.3%	11.3%
<i>SN</i>	1.4%	1.1%	1.4%	1.2%	10.2%	11.5%	1.4%	1.2%	13.2%
<i>SP</i>	0.2%	0.1%	0.2%	0.1%	1.3%	1.1%	0.1%	0.1%	0.9%
<i>FD</i>	10.1%	9.9%	9.9%	9.7%	11.7%	10.7%	9.9%	9.7%	13.6%
<i>FN</i>	8.8%	8.7%	9.1%	8.9%	9.0%	10.1%	9.2%	9.0%	16.0%
<i>FP</i>	1.1%	1.0%	1.0%	1.0%	1.1%	1.0%	0.8%	0.8%	1.1%
<i>WD</i>	32.6%	33.3%	32.0%	32.7%	16.7%	15.3%	31.9%	32.6%	9.6%
<i>WN</i>	27.8%	28.4%	28.4%	29.0%	12.8%	14.3%	29.1%	29.8%	11.3%
<i>WP</i>	3.3%	3.4%	3.2%	3.3%	1.6%	1.4%	2.7%	2.7%	0.8%
<i>total</i>	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 19 Adopted hypotheses for residential and tertiary useful demand profiles

	<i>Historical 2014-2020</i>		<i>Projection 2020-2040</i>		<i>Projection 2040-2050</i>	
	<i>Seasonal level</i>	<i>Intraday level</i>	<i>Seasonal level</i>	<i>Intraday level</i>	<i>Seasonal level</i>	<i>Intraday level</i>
Space heating IH	projection DDH scenario RCP4.5 2011-2040	project when2heat heating profile	projection DDH scenario RCP4.5 2011-2040	project when2heat heating profile	projection DDH scenario RCP4.5 2040-2070	idem projection 2020-2040
Space heating Apt	projection DDH scenario RCP4.5 2011-2040	project when2heat heating profile	projection DDH scenario RCP4.5 2011-2040	project when2heat heating profile	projection DDH scenario RCP4.5 2040-2070	idem projection 2020-2040
Space heating Tertiary	projection DDH scenario RCP4.5 2011-2040	project when2heat heating profile	projection DDH scenario RCP4.5 2011-2040	project when2heat heating profile	projection DDH scenario RCP4.5 2040-2070	idem projection 2020-2040
DHW IH	project when2heat heating profile	project when2heat heating profile	project when2heat heating profile	project when2heat heating profile	idem projection 2020-2040	idem projection 2020-2040
DHW Apt	project when2heat heating profile	project when2heat heating profile	project when2heat heating profile	project when2heat heating profile	idem projection 2020-2040	idem projection 2020-2040
DHW Tertiary	project when2heat heating profile	project when2heat heating profile	project when2heat heating profile	project when2heat heating profile	idem projection 2020-2040	idem projection 2020-2040

Table 20 Projection of the impact of weather conditions on building energy demand in the long-term

Table 19 presents the yearly breakdown of space heating and DHW demand for the building sector defined in TIMES-FR for 2020-2040 and after 2041. For space heating, tertiary and residential buildings present parallel profiles: “winter day” is the time slice with the highest demand load at around 32% of total yearly demand. With a 1% duration over a year, “winter peak” represents around 3.3% of yearly demand for residential heating and around 2.7% for tertiary heating. This allows us to capture the effect of the peak period. Compared to space heating, demand for hot water is more evenly distributed over the year. For all time slices, the demand share does not exceed 17%, and the load of peak DHW demand is significantly lower than space heating.

The availability factor (AF) of an energy equipment item is the amount of time that it can operate over a certain period. We define an AF for all end-use processes and power plants in TIMES-FR. The AFs of residential and tertiary processes for space heating, DHW production, cooking and specific usages are time slice specified. The adopted values of AFs are estimated from calibrated demand distribution over 12 time slices (from When2Heat dataset and monthly DDH) and their durations. In addition, the level of availability factors reflects the dimensioning requirement per time slice to satisfy annual useful energy production. For each time slice, its AF is calculated from the average load (GW) required for this time slice to produce 1 PJ of useful energy for one year. As dimensioning of the heating system is based on the load requirement of peak demand, we apply a correction factor, defined as the ratio of the highest average load among time slices over the highest hourly load within a day, to all the AFs.

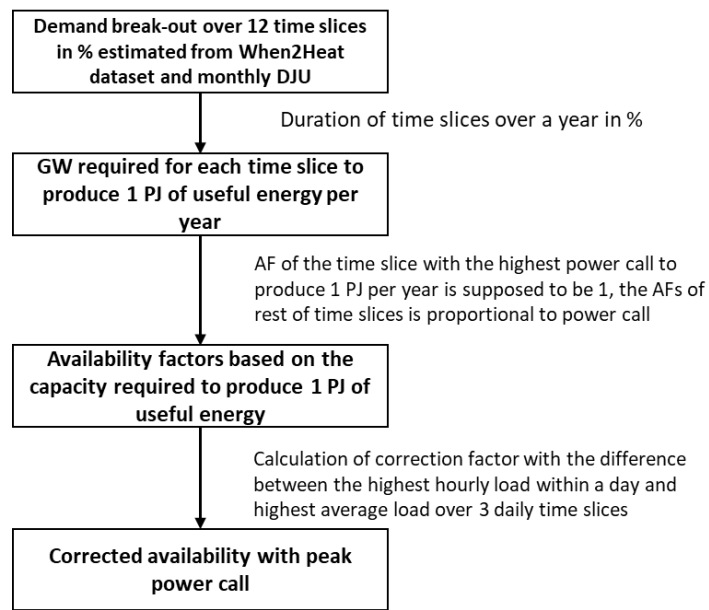


Figure 51 Adopted hypotheses to calibrate availability factors for modeled building energy equipment

	<i>RD</i>	<i>RN</i>	<i>RP</i>	<i>SD</i>	<i>SN</i>	<i>SP</i>	<i>FD</i>	<i>FN</i>	<i>FP</i>	<i>WD</i>	<i>WN</i>	<i>WP</i>
Space heating individual house 2020-2040	0.27	0.12	0.33	0.05	0.02	0.07	0.41	0.18	0.50	0.84	0.37	0.92
Space heating individual house after 2041	0.26	0.11	0.31	0.04	0.02	0.05	0.39	0.17	0.48	0.84	0.37	0.92
Space heating apartment 2020-2040	0.28	0.13	0.33	0.06	0.03	0.07	0.42	0.20	0.50	0.87	0.40	0.95
Space heating apartment after 2041	0.26	0.12	0.32	0.04	0.02	0.05	0.40	0.19	0.48	0.87	0.40	0.95
DHW individual house	0.50	0.19	0.54	0.47	0.18	0.52	0.49	0.19	0.53	0.45	0.17	0.45
DHW apartment	0.77	0.37	0.82	0.73	0.35	0.79	0.76	0.36	0.81	0.69	0.33	0.69
Space heating tertiary 2020-2040	0.27	0.13	0.26	0.06	0.03	0.05	0.41	0.19	0.40	0.83	0.39	0.76
Space heating tertiary after 2040	0.26	0.12	0.25	0.04	0.02	0.04	0.39	0.18	0.38	0.83	0.39	0.76
DHW tertiary	0.38	0.23	0.36	0.37	0.22	0.35	0.53	0.32	0.50	0.24	0.14	0.21

Table 21 Retained availability factors of residential and tertiary technologies

2.2.3.2 Improved modeling structure for electric heat pumps

2.2.3.2.1 Context: energy efficiency of electric heat pumps is highly variable

As introduced in Chapter One, electric heat pumps are an efficient solution to decarbonize space heating, and are increasingly present in the housing stock. The role of heat pumps in future energy transition thus merits our attention.

One aspect that cannot be ignored is that the energy efficiency of air-sourced electric heat pumps is highly dependent on external temperatures. The COP (coefficient of performance) of electric heat pumps drops during cold weather. The variation of energy efficiency and electricity demand by heat pumps may have a high impact on electricity and the building energy system. One particular case is during extremely cold periods, when the energy efficiency of heat pumps drops to a very low level, and heat pumps rely almost only on electricity input to produce heat. An energy system with a high share of electric heat pumps may generate very high electricity power demand, leading to supply security issues. We will provide a detailed introduction to this energy security concern linked to investment in electric heat pumps in Chapter Four. The variation in heat pumps' performance and its implication for the energy system thus requires consideration in future investment choices. In our exercise, this calls for a modeling structure able to capture the fact that installed heat pumps operate differently over varied temperature ranges.

2.2.3.2.2 Detailed modeling of electric heat pumps for space heating

We have proposed an improved modeling structure for all types of heat pump, including hybrid heat pumps, in the residential and tertiary sectors in TIMES-FR. In the new modeling method, a heat pump is separately modeled in three independent processes corresponding to equipment during warm periods, cold periods and extremely cold periods. The disaggregated structure for electric heat pumps enables a detailed representation of the variation in energy efficiency and operating mode for HP technologies through different temperature ranges. The improved model structure allows us to better account for the role of heat pumps in the future energy system.

We define that warm periods correspond to the time span when the outside temperature is above 3 degrees Celsius, cold periods are between 0 and 3 degrees Celsius, and extremely cold periods represent the length of time when the outside temperature is below 0 degrees. We have chosen these temperature ranges to describe HP technologies in our model since, based on our experiment results, the COP of HP varies greatly across these three temperature conditions.

The performance (COP) of the heat pump process during warm, cold and extremely cold periods follows a decreasing order. For hybrid heat pumps, the three independent processes take different energy inputs: We suppose that an HHP in warm periods uses only HP to provide heat, that an HHP in extremely cold periods completely switches to gas, and that during the cold periods, both a combustion boiler and a heat pump contribute 50% to the heat production. In this way, TIMES interprets the fact that the HHP can flexibly change its operating mode. Standalone heat pumps can only use electricity for all three periods. The products of the three independent processes, representing space heating during warm, cold and extremely cold periods, will then be transformed into a single demand commodity (space heat) by a virtual process.

Five types of electric heat pump are modeled, including two types of air-sourced heat pump, a geothermal heat pump and two types of air-sourced hybrid heat pump. Table 22 summarizes the adopted parameters of energy efficiency and operating mode for the modeled electric heat pumps. The value of energy efficiency is based on the hypotheses of ADEME/RTE (ADEME & RTE, 2020) elaborated from data on real performance provided by (PACTE, 2013). Note that we use the COP of regime W45 (temperature of water outlet 45 degrees) and some buildings with poor thermal insulation might require a higher level. The COP of an air-water heat pump is between 1.7 and 3.5, and between 1.3 and 2.9 for an air-air heat pump. The performance of HPs significantly drops when outside temperatures decrease, while the COP of ground-sourced heat pumps remains relatively constant because they extract heat from underground structures where there is less temperature variation (ADEME & RTE, 2020).

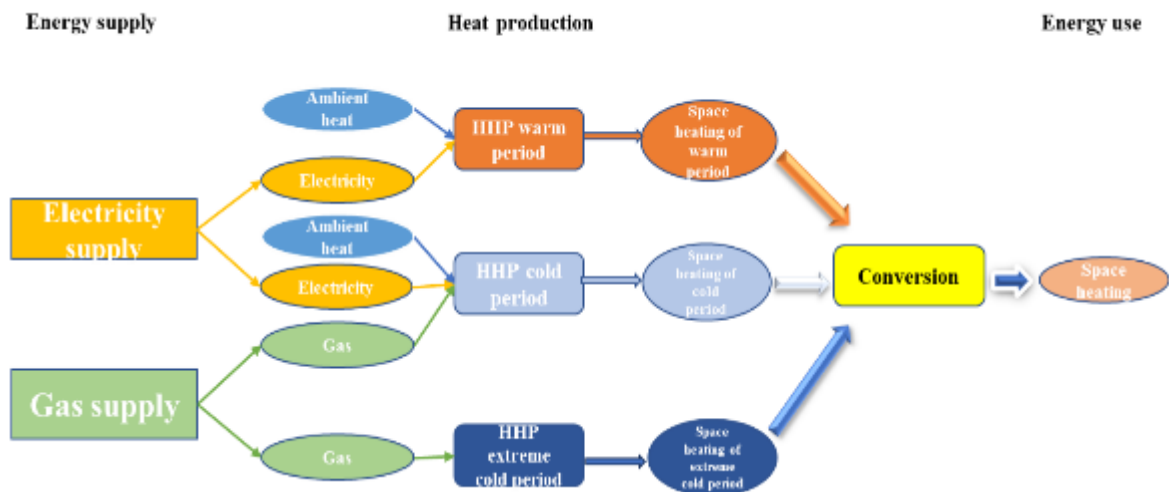


Figure 52 Improved modeling structure for HHP in TIMES

Tech type	Period	Value taken in model	Operating mode (HHP)
<i>Air-sourced HHP air to air</i>	Warm (3°C)	2.45	HP alone
	Cold (0°C - 3°C)	1.95	HP 50%, gas boiler 50%
	Extreme cold (-0°C)	1.6	Gas boiler 100%
<i>Air-sourced HHP advanced (air to water)</i>	Warm	2.875	HP alone
	Cold	2.125	HP 50%, gas boiler 50%
<i>Air-sourced HP air to air</i>	Extreme cold	1.85	Gas boiler 100%
	Warm	2.45	
	Cold	1.95	
<i>Air-sourced HP advanced air to water</i>	Extreme cold	1.6	
	Warm	2.875	
<i>Ground-sourced HP</i>	Cold	2.125	
	Extreme cold	1.85	
	Warm	4.35	
	Cold	3.5	
	Extreme cold	2.65	

Table 22 Retained hypotheses of technical economic parameters of modeled heat pumps

2.2.4 Improvement on the demand side: calibrating demand scenarios

The first three contributions that we have previously introduced focus on improving the model structure to better represent the French energy system. Another aspect essential to consider is the future demand of the energy service and commodities. In this part, we present the construction of our assumptions and scenarios relating to future energy demand. Our concern is not only residential buildings, but also other sectors including transport, industry, tertiary and agriculture. These sectors, in particular transport and industry, have high energy demand. Their demand in the future may be a main driver of the energy transition.

Based on the review of existing trajectories, we calibrated core parameters and established several scenarios of the future demand trajectory. These scenarios allow us to explore the reaction of the energy system under different demand conditions. This is an important part of the prospective analysis for the French energy system. In order to elaborate these demand scenarios, we investigate existing energy prospective scenarios.

In this part, we will firstly describe the range of possible demand pathways proposed by the existing literature. We focus on how future useful demand for energy services and commodities is treated in the long-term studies reviewed in the Chapter One, including the AME, AMS scenario of DGEC, the S1-S4 of ADEME, and NégaWatt 2022. The purpose is firstly to identify the range of factors decisive to future energy demand and understand how they are connected, and secondly to apprehend various visions of the evolution of future energy demand driven by different hypotheses. All these elements provide important insights for constructing our demand hypotheses. For the review of existing demand trajectories, we focus on their macro-economic framework which is the central hypothesis of a demand scenario, and visions for sectorial trajectories.

We will then present our hypotheses for future demand and how they are inspired from the review of existing trajectories. We propose to introduce four demand trajectories, D1-D4, with decreasing demand levels. We will present in detail the key assumptions and adopted values for buildings, transport, industry and agriculture demand through different scenarios.

2.2.4.1 Review of published scenarios of demand

2.2.4.1.2 Overview of macroeconomic framework of reviewed scenarios

The macroeconomic framework of a demand scenario includes assumptions on long-term demographic trends, the economic situation, climate and international environment. These are important factors related to the future demand of all end-use sectors. The reviewed scenarios are based on varied macroeconomic tendencies.

Population is a very important factor in energy demand. It is directly linked to future housing needs, traveling needs, and demand for agricultural and industrial products. Regarding the future evolution of the demographic structure, official statistical offices in France and Europe have elaborated several projections. These provide important references for estimating future demand for useful energy, goods and services. The population hypotheses adopted in the reviewed scenarios are mainly based on these projections. INSEE in France has established 27 scenarios of future population growth by varying assumptions on three main elements that decide future population levels, fertility rates, life expectancy, and immigration flows. For each of these factors, there is a high, central and low hypothesis. INSEE's reference scenario makes central hypotheses for all demographic factors. In the projection for 2007-2060 (INSEE, 2022c), the central scenario retains a fertility rate of 1.95 since 2015, a female life expectancy of 91.1 years, male life expectancy of 86.6 years in 2060, and a positive migration flow of 100,000 since 2007. It anticipates a total of 72.27 million inhabitants in Metropolitan France and DROM⁵⁵. The population projection of Eurostat uses a similar method as INSEE and produces six scenarios (one baseline, five sensitivity tests by crossing assumptions of migration, fertility and mortality) (Eurostat, n.d.). The Eurostat baseline scenario projects a lower population growth than INSEE's central scenario as it adopts a lower fertility rate.

The table below summarizes the hypotheses adopted on future demographic structure and economic growth by the reviewed demand scenarios. Scenario AMS 2018 interprets relatively fast growth of the economy and population. For the population, AMS 2018 is based on the INSEE central scenario: the French population increases 0.3% per year and reaches over 72 million in 2050. In terms of economic growth, AMS 2018 assumes that the economic growth trend prior to 2018 will continue in the future, and that the level of GDP in 2050 will increase by 65% compared with the 2018 level. This is an optimistic assumption of productivity growth, given the slowdown observed since the 1980s (DGEC, 2020b).

⁵⁵ DROM: Départements et Régions d'Outre-Mer (in French)

Compared to AMS 2018, AME 2021 considers slower population growth and economic development. The total population in 2050 is forecast at 71.78 M, corresponding to the Eurostat trajectory. AME 2021 makes a smaller estimation to INSEE's central scenario as the recent trend during 2013-2018 is lower than expected. In terms of economic growth, AME 2021 takes into account the impact of the Covid crisis on the French economy in 2020 (-8.25% GDP decrease) and foresees a rapid recovery of GDP growth from 2021, also based on the hypothesis of the European Commission. Nevertheless, AME foresees a long-term impact of the 2020 economic recession: the total growth rate of national GDP between 2018 and 2050 is 50%, significantly lower than the AMS scenario produced in 2018 (65%) (DGEC, 2021a).

Four ADEME and NégaWatt 2022 scenarios are based on a low estimation of population growth corresponding to INSEE's "low fertility, central life expectancy and central immigration flow" scenario and an optimistic vision of future economic growth. The recently observed slowdown in the fertility rate will continue in the future, and the current level of immigration will remain constant with a net immigration balance of 70,000 people per year. In 2050, the population of France is estimated at 69.7M, much lower than the hypotheses of AME 2021 and AMS 2018. Under the ADEME scenarios, economic growth will follow a constant increase of 1.3% per year until 2050, the same as in AMS 2018.

	2018	2020	2030	2050	
	AME 2021				Hypothesis
Population	<i>total inhabitants (M)</i>				
		65.27		71.78	EUROSTAT
	<i>fecundity rate</i>				
	<i>immigration flow</i>				
GDP growth	100	91.75	110	150	European Commission
	AMS 2018				
Population	<i>total inhabitants (M)</i>				INSEE Central scenario INSEE 2007-2060
		65.27	68.53	72.27	
	<i>fecundity rate</i>	1.95	1.95	1.95	
	<i>immigration flow (person)</i>	100000	100000	100000	
GDP growth	100	105	119	165	
	ADEME				
Population	<i>total inhabitants (M)</i>				scénario fécondité basse, espérance de vie centrale et migration centrale) INSEE 2007-2060
		65.27	67.4	69.7	
	<i>fecundity rate</i>	1.80	1.80	1.80	
	<i>immigration flow (person)</i>	100000	100000	100000	
GDP growth	1.3% per year				idem to AMS 2018
	NégaWatt 2022				
Population	Idem to ADEME				"Fécondité basse, espérance de vie centrale, flux migratoire central" INSEE 2007-2060

Table 23 Main macro-economic hypotheses by reviewed scenarios (ADEME, 2021b; DGEC, 2020b, 2021a; négaWatt, 2022)

2.2.4.1.2 Visions of sectorial energy demand in the future

Residential buildings

The reviewed scenarios are based on varied hypotheses on future housing needs, consumption behavior and climate change, factors that are closely related with energy demand from residential buildings. The evolution of housing needs is a key element to consider for the future demand of space heating. We need to consider not only the number of dwellings required, but other elements that are correlated with the total surface area to be heated, in particular surface area requirements for new constructions, the ratio of individual houses to larger surface area in new constructions, and requirements for secondary residencies. These features are linked with population growth and housing habits (cohabitation, preference for individual house, etc.).

AME 2021 foresees an increase in heating needs and specific electricity usages, and a decrease in cooking and DHW needs in the future. Under AME 2021, the demand for space heating in France increase significantly by 2050 following greater housing needs. The number of dwellings (principal residences in Metropolitan France) will reach over 34 million by 2050, around 13% more than the current stock. This is related to population growth and de-cohabitation trends. The number of people per dwelling will decrease from 2.17 in 2020 to 2 in 2050. Concerning climate conditions, the AME considers an effect of global warming that reduces heating needs in the future. It considers a CAGR⁵⁶ of climate factor to heating demand of -0.11% from 2020 to 2030, and -0.19% from 2030. It refers to the RCP2.6 scenario of IPCC⁵⁷ by which the global temperature rise is limited below 2 °C by 2100 compared to 1990 (DGEC, 2021a).

For other energy usages of residential buildings, demand for DHW and specific electricity consumption will remain relatively constant in the future. Specific electricity demand in buildings increases 5% compared to 2015, while demand for DHW decreases by 5%. There will be a significant decrease in cooking demand of 10% by 2050. AME 2021 foresees a higher specific electricity demand of 5% for residential buildings, a variation opposite to current trend (-8.4% in 2030 if the current trend continues).

Compared to AME, the AMS scenario estimates a slower increase in surface area to be heated for the residential building stock. The pace of new constructions will slow down from 324,000 dwellings in 2016 to 205,000 in 2050 due to a slowdown in population growth. Besides, for new constructions, inhabitants will tend to choose more apartments with smaller surface areas. The percentage of collective buildings in new constructions will increase to 75% in 2050, compared with 61% in 2015. Besides, the AMS scenario supposes that future inhabitants will adopt more sober energy consumption

⁵⁶ CAGR: Compound Annual Growth Rate.

⁵⁷ IPCC: Intergovernmental Panel on Climate Change

behavior by reducing the setpoint temperature for heating by 1 degree for all buildings. This reduces demand for space heating (DGEC, 2020b).

ADEME's S1 and S2 describe a future with lower housing needs, while S3 and S4 present the opposite case. Under S1, the growth rate of housing units in the future is much slower than the current level. The number of new constructions (until 2050) is limited to 4 M. This is much lower than the case where the current trend continues in the future (10M). This is linked with the tendency for cohabitation: the number of people in housing units is 2.1 in 2050, higher than the level if the current trend continues. The ratio of secondary residences drops from 9% to 2.5%. Besides, only 15% of new dwellings are individual houses; this ratio is much lower than current level (45%). ADEME's S2 presents similar dynamics of housing stock to S1, with only a slight increase in new constructions during 2015-2050 (5M compared to 4M), equivalent to around 150,000 dwellings constructed per year. S3 and S4 foresee a continuous increase in the size of housing stock until 2050 as a result of rapid population growth and a tendency for de-cohabitation. Under S3, around 12 million new dwellings will be constructed between 2015-2050. Nonetheless, the ratio of collective buildings with smaller surface areas in new constructions will be lower than nowadays (25% vs 45%). Under S4, 10 million of new dwellings are constructed between 2015-2050. However, the proportion of apartments remains at 45% in the future. This leads to a rapid growth in the surface area to be heated (ADEME, 2021b).

The NégaWatt 2022 scenario presents a very slow increase in housing needs in the future, as residents will adopt more sober housing consumption patterns. The average number of people per dwelling remains at the current level (2.2). As a result, the number of housing units in 2050 will not be far from the current level. The ratio of individual houses in new constructions will decrease to 20% by 2050 compared to 40% in 2017 (négaWatt, 2022).

	2015	AME 2021	AMS 2018	ADEME Trend	ADEME S1	ADEME S2	ADEME S3	ADEME S4	Négawatt 2022
Number of people per dwelling	2.21	2	2.02	2.02	2.12	2.12	2.02	2.02	2.2
Proportion of individual houses in new constructions	42.80%	41.50%	25%	45.00%	15.00%	15.00%	25%	45%	20%
Number of constructions	324.5k dwellings per year	198k dwellings per year			4 M new dwellings between 2015-2050	5 M new dwellings between 2015-2050	12 M new dwellings between 2015-2050	10 M new dwellings between 2015-2050	

Table 24 Hypotheses of housing stock by reviewed scenarios, comparison between 2015 and 2050

Tertiary demand

Similar to residential buildings, the reviewed scenarios adopt various hypotheses on the future growth of the tertiary surface area, which is decisive to heating needs. AME 2021 projects a significant rise in the size of tertiary building stock in the future. The total surface area of tertiary buildings will increase by 30% in 2050 compared with 2010, reaching 1,197 Mm²⁵⁸ in 2050. Rapid growth of the tertiary surface area is a result of population growth and a higher employment rate in the tertiary sector. However, the rapid expansion of the tertiary building stock, and demand for energy usages including space heating, DHW and specific electricity, will both decrease. Both DHW demand and specific electricity usages will drop by 5% in 2050 compared with 2015, as the tertiary sector will adopt more sober energy consumption patterns (DGEC, 2021a). Under AMS 2018, the growth rate of the surface area of tertiary buildings is lower (7Mm² new construction per year, constant till 2050) (DGEC, 2020b). This is explained by more efficient usage of offices by companies. For the four ADEME scenarios, the estimated total surface area of tertiary buildings in 2050 ranges from 995 Mm² in S1 to 1,133 Mm² in S4 (ADEME, 2021b). All these scenarios present a slower growth rate than the AME scenario. Under the négaWatt 2022 scenario, there will be an increase in health care facilities due to the aging French population. Besides, an increase in teleworking as a consequence of the Covid crisis has the effect of reducing office demand (négaWatt, 2022).

	2020	2050	2050	2050	2050	2050	2050
		AME	ADEME	ADEME	ADEME	ADEME	ADEME S4
		2021	Trend	S1	S2	S3	
<i>office and administration</i>	247	279					
<i>hospitals</i>	74	82					
<i>commerce</i>	229	244					
<i>research and education</i>	190	213					
<i>community housing</i>	70	77					
<i>healthcare</i>	125	189					
<i>sport, culture</i>	76	85					
<i>transport</i>	25	28					
<i>new constructions (net)</i>			261	130	132	166	261
<i>total surface</i>	1036	1197	1133	995	997	1030	1133

Table 25 Hypotheses of tertiary demand by reviewed scenarios, in Mm² of construction (ADEME, 2021b; Association négaWatt, 2022; DGEC, 2021b; Ministère de la Transition Ecologique et de la Cohésion des Territoires, 2023)

⁵⁸ Mega Square Meters (Mm²)

Transport demand

The reviewed scenarios present different futures for mobility demand for France by taking different hypotheses regarding influential factors on both passenger mobility and merchandise transport. Demographic and economic growth are certainly major drivers of future mobility demand. Apart from the general macro-economic tendencies, a very important factor is travelling habits including the frequency of long/short distance travel, a preference for public transport, and the willingness to practice carpooling or hitchhiking. It is also important to consider the mode of economic development, in particular for the local economy.

Under AME 2021, all types of mobility needs will constantly increase in the future, following rapid population growth and economic development. The total passenger and merchandise traffic demand will increase by 30% and 48% in 2050 compared to 2015. There will be a high increase in demand for public transport in 2050: train travel demand nearly doubles and bus demand also sees a significant increase (33%). This is the result of policy measures in favor of public transport. The increase in the usage of public transport reduces the share of personal cars in the total mobility demand. In 2050, 73.6% of passenger travel demand is by car and 22.6% by public transport, compared with 79.7% and 17% in 2018 (DGEC, 2021b).

AMS 2018 foresees a slightly slower increase than AME 2021 for both passenger transport and merchandise transport for the period 2015-2050. Demand for passenger and merchandise transport will increase by 26% and 40%, compared with 30% and 48% under the AME scenario. The AMS trajectory presents varied growth rates among different types of travel demand. For car travel, the growth rate of long-distance travel is far greater than for short distance travel (45% vs 12%). In 2050, demand for long-distance travel reaches 364,551 M.P.km⁵⁹, compared with 251,258 M.P.km in 2014. For public transport, the growth rates of bus travel (urban and intercity) and travel by train all surpass 50% in 2050 (DGEC, 2020b). We can also see a significant increase in merchandise transport by LUV⁶⁰ as a result of fast development of circular/short cycle economics.

The four ADEME scenarios describe different trajectories for future mobility demand. S1 and S2 present a future where travel demand is significantly reduced as French society adopts more sober travelling habits. S3 and S4 present a continuous increase in travel demand where current traveling habits, such as high usage of individual cars and airplane travel, are maintained in the future. Under S1, passenger travel demand decreases by 26% in 2050. This is based on the assumption that more inhabitants will choose to walk or use a bike for short travel distances. At the same time, in a more

⁵⁹M.P.km: Million Passenger Kilometers

⁶⁰LUV: Light Utility Vehicle

socially responsible society, carpooling and hitchhiking develop in rural areas. The demand for airplane travels significantly decreases (50% of the 2015 level). Demand for merchandise transport will decrease by 45%, as the relocation of the economy reduces the required distance of freight traffic. S2 foresees a case featuring fewer frugality measures for transport in the future. Demand for passenger and merchandise mobility will drop by 10% and 35% compared with 2015, and the decrease rates are lower than in S1. Under S3, demand for passenger mobility is 23% higher than in 2015, and merchandise mobility remains at the same level. Travel by airplane will increase by 65% in 2050. Under S4, there will be a higher increase (39% compared with 2015) in passenger mobility demand, led by more demand for long-distance travel, in particular by car and airplane. The level of merchandise mobility is also much higher than in 2015 (30%). The main contributor to merchandise mobility is the development of e-commerce, which requires a more connected logistic network (ADEME, 2021b).

NégaWatt 2022 foresees a strong decrease in future mobility demand, as a result of frugal mobility patterns and a change of economic mode. For future passenger mobility, the NégaWatt scenario envisages a reduction in road and airplane transport, and an increase in train transport. The average travel demand by car will decrease from 11,000 km/p/y⁶¹ to around 8,000 km/p/y. Airplane travel demand will be divided by 2.5 from 4,000 km/p/y to 1,500 km/p/y. These changes are explained by several factors: Firstly, the French population will reduce the frequency of travel as teleworking becomes more common. NégaWatt 2022 estimates that, in 2050, 40% of workers will work remotely for half of the time. Secondly, the travel distance will significantly reduce, as future inhabitants will prefer to do activities locally. Thirdly, there will be more car sharing. Under NégaWatt 2022, the average number of people per private vehicle increases from 1.7 today to 1.85 in 2030 and to 2 in 2050. Demand for merchandise transport both by road and by ship will be divided by two in 2050 compared with 2019, as a result of the growth of local economy

⁶¹ km/p/y: kilometers per person per year

	2015	AME 2021	AMS 2018	Negawatt 2022
Passenger traffic (Gpkm)				
private car	723	873	812	488.6
train	105	191	188	209.4
bus	58	78	94	69.8
airplane	14	22	16	69.8
motorbike	14	11	14	69.8
bicycle	5	17	34	
Total passenger traffic	919	1192	1158	907.4
merchandise (Gt)				
truck	258	400	358	150
train	34	35	52	110
ship	7	8	10	290 (including international transport)
total merchandise traffic	299	443	420	550

Table 26 Hypotheses of transport demand according to AME, AMS and négaWatt 2022 scenarios, comparison between 2015 and 2050 (DGEC, 2020b, 2021a; négaWatt, 2022)

	2015	ADEME trend	ADEME S1	ADEME S2	ADEME S3	ADEME S4
Total passenger traffic (including international flights) (Gpkm)	1136.7	1534.545	841.158	1023.03	1398.141	1580.013
Total merchandise traffic (in Gt)	323	374.68	177.65	209.95	323	419.9

Table 27 Hypotheses of transport demand according to ADEME scenarios, comparison between 2015 and 2050 (ADEME, 2021b)

Industry demand

AME 2021 presents a varied trajectory for energy-intensive industry (IGCE) and diffuse Industry. There will be a reindustrialization in the future and an increase in industrial activities, mainly driven by diffuse industries which are less energy-intensive and have higher added value. The production level of IGCE will not change significantly in 2050 compared with 2015. The level of steel, ethylene, and paper production will be slightly lower than in 2015. For diffuse industries, we expect to see a high increase in food & beverage, machine and chemical products. This is due to higher demand for consumer goods led by economic growth (DGEC, 2021b).

AMS 2018 projects a similar demand trend as AME 2021 for two types of industry in the future. The activities of energy-intensive industries will be lower than currently, since on the one hand, citizens adopt more a sober consumption behavior towards these products, on the other hand, the development of circular economics (recycling) reduces demand for new products. In 2050, the production of steel, aluminum, ammonia and paper will be respectively 16%, 7%, 3% and 3% lower than the 2015 level (DGEC, 2020b).

ADEME S1 foresees a significant reduction in industrial demand as future inhabitants will adopt much more frugal lifestyles. The need for construction material, transport equipment and synthetic fertilizers will be much lower than the current level as citizens will tend to construct smaller houses, and reduce their usage of personal cars and consumption of agricultural products. Besides, the demand for consumer goods decreases as inhabitants get used to repairing and reusing objects in daily life (circular economy). S2 describes a future with significant reindustrialization efforts, and the development of a circular economy. Efforts are put on increasing the added value of industrial products. Although production drops due to a decrease in market demand, the trade balance is improved for multiple industry branches. The development of a circular economy allows for lower demand for raw industrial materials. S2 estimates that, in 2050, more than 80% of raw material for industry process is of recycled material. Under S3, industrial demand is slightly lower than the current level. However, certain sectors such as aluminum or ammonia see their volumes increase, as there will be more demand for transport equipment. Contrary to S1-S3, S4 foresees a much higher demand for nearly all types of industrial products including construction materials, transport equipment, and agricultural products in a society in favor of consumption. It should be noted that domestic production will not be able to cover all demand, and France will largely rely on imports under this scenario (ADEME, 2021b).

The future French industry under NégaWatt 2022 will feature low production and low exportation, and a high level of recycling. Demand for consumption goods and equipment will be significantly reduced as inhabitants tend to demand fewer new products with the development of a circular economy.

Besides, the production surplus of most industrial branches will largely decrease as the industry will be reoriented to produce what is required rather than the opposite (production driven by consumption in the future instead of consumption driven by production) (Association négaWatt, 2022).

			AME 2021	AME 2018	ADEME S1	ADEME S2	ADEME S3	ADEME S4
	2015	2020	2050		2050	2050	2050	2050
IGCE (Mt)								
steel	15.01	14.39	14.96	12.6084	-54%	-41%	-10%	4%
aluminum	0.89	0.87	0.91	0.8277	-19%	0%	55%	88%
ethylene	2.51	1.99	2.27		-65%	-71%	-47%	-28%
chlorine	1	0.96	1.1	1.0379	-38%	-44%	-14%	-8%
ammonia	1.07	1.02	1.17		-33%	-44%	7%	21%
clinker	12.51	11.85	13.18					
glass	4.1	4.08	4.24	4.1	-38%	-46%	2%	14%
paper	7.99	6.72	7.65	7.7503	-3%	6%	2%	3%
sugar	4.52	4.55	5.18					
diffuse industry (€ billion Added value)								
primary metals	25.6	24.7	38.3					
chemicals	41.4	41.1	63.7					
nonmetal minerals	8	7.9	12.2					
food and beverage	43.5	41.1	63.6					
equipment	60.2	54.2	83.9					
other (textiles)	23.3	21.5	33.4					

Table 28 Hypotheses of industrial demand by reviewed scenarios (ADEME, 2021b; DGEC, 2020b, 2021a; négaWatt, 2022)

Demand for agricultural products

All of the reviewed scenarios except ADEME S4 foresee a considerable reduction in agricultural product demand, as future residents tend to change food regime and reduce food waste. This enables a reduction of the required surface area for livestock and crops. Under the AME scenario, the total surface area for agricultural activities decreases by 3% in 2050 compared with 2020. AMS adopts similar hypotheses as AME. Under ADEME S1, per capita meat consumption is estimated to be 33% of the current level in 2050. Besides, food waste drops by around 50%. As a result, the total surface area for agricultural activities will decrease by 12% in 2050 compared with 2015. Negawatt 2022 also estimates significant changes in agricultural demand: average consumption of animal products and food waste will be divided by 2, following the hypothesis of Afterres2050 by Solagro (Solagro, 2016).

2.2.4.2 Retained hypotheses for future demand by our exercise

Although the scenarios reviewed above elaborate varied hypotheses in a macro-economic context and various drivers of sectorial useful demand, shared visions can be observed. For residential demand, most scenarios project an increase in the number of dwellings as a result of population growth and a tendency to decohobitation. The AME 2021 and ADEME S4 scenarios foresee a rapid expansion of the construction surface area of residential buildings due to a high proportion of individual houses with larger surface areas remaining in the housing stock. This leads to a much higher heating demand. AMS 2018 and other ADEME scenarios (S1-S3) are based on a future housing stock with a lower proportion of individual houses and average surface area. For tertiary demand, AME 2021 and ADEME S3-S4 estimate a rapid expansion of tertiary constructions, while ADEME S1-S2 present the opposite trend. For transport demand, AME 2021, ADEME S4 and AMS 2018 foresee a considerable increase in passenger and merchandise mobility demand by 2050. Contrary to the DGEC scenarios, ADEME S1, S2 and NégaWatt 2022 describe a future where travel demand is lower than the current level. They are based on the strong hypothesis that future inhabitants will adopt much more frugal lifestyles thus reducing their travel demand by energy-intensive transport including by private car and airplane.

We may further conclude three visions of future demand from these trajectories. The AME 2021 and ADEME S3-S4 scenarios describe a high perspective of energy demand linked to assumptions of rapid population growth and a consumerist lifestyle. Scenario AMS describe a slower growth of energy demand in the future linked with additional efforts on energy saving. The ADEME S1-S2 and négaWatt 2022 scenarios represent a very low demand perspective based on a deep transition of consumption patterns in society.

The reviewed scenarios are important references for constructing our demand trajectories. For our study, we propose to elaborate three scenarios in line with the three visions proposed in the existing literature. We propose a high demand trajectory calibrated from the hypotheses of the AME scenario, a second high demand trajectory based on the AMS scenario, and a low demand trajectory calibrated from the S1 of ADEME. Since there is a significant difference in transport and industry demand between the second high demand scenario and the low demand scenario, we introduce a medium demand scenario between the two cases. This allows us to cover more possibilities of future energy demand. We name the four trajectories with a decreasing level of demand as D1, D2, D3, D4.

For our demand scenarios, the adopted values of residential, tertiary and agricultural demand are calibrated from various hypotheses. We will present them in the following parts.

2.2.4.2.1 Hypotheses of building and agricultural demand trajectories

For the residential sector, national useful heating demand is calculated by aggregating the demand of existing stock and new constructions of both collective buildings and individual houses. For each building type (apartments and individual houses), the total space heating demand of a year in the future is the multiplication of the total surface area to be heated and unitary useful demand. The unitary useful demand in the future is a factor of climate change. For all scenarios, we retain a climate factor of -0.11% per year from 2020-2030, -0.19% from 2030-2050 (central scenario of global warming by Météo France). The surface areas of existing stock and new constructions are estimated from hypotheses including the destruction rate, target housing unit, and average surface per dwelling. The calibration of tertiary heating demand follows a similar method as for residential buildings. For each type of tertiary building, the total useful heating need includes that of existing and new stock, and the heating need is the product of the surface area, unitary useful demand, and a climate factor. The surface area is calculated from the population and per capita tertiary surface. We assume that per capita tertiary surface remains constant in the future (2020 level, 14.6m² per person).

$$E_{utn} = E_{utn \text{ existing stock}} + E_{utn \text{ new constructions}}$$

$$E_{utn \text{ existing stock}} = S_{tn \text{ existing stock, LC}} * E_{ut0, specific, LC} * C_{tn} + S_{tn \text{ existing stock, SFH}} * E_{ut0, specific, SFH} * C_{tn}$$

$$S_{tn \text{ existing stock, LC}} = S_{t0 \text{ existing stock, LC}} * (1 - (1 + x)^{(tn-t0)})$$

$$S_{tn \text{ existing stock, SFH}} = S_{t0 \text{ existing stock, SFH}} * (1 - (1 + x)^{(tn-t0)})$$

$$E_{utn \text{ new constructions}} = S_{tn \text{ new constructions, LC}} * E_{ut0, specific, LC} * C_{tn} + S_{tn \text{ new constructions, SFH}} * E_{ut0, new constructions, SFH} * C_{tn}$$

$$S_{tn \text{ new constructions, LC}} = \frac{Population_{tn}}{Number \text{ of person per housing}_{tn} * average \text{ surface area of new LC}_{tn}} - Number \text{ of existing housings}_{tn} * \% \text{ of LC in new constructions}_{tn}$$

$$S_{tn \text{ new constructions, SFH}} = \frac{Population_{tn}}{Number \text{ of person per housing}_{tn} * average \text{ surface area of new SFH}_{tn}} - Number \text{ of existing housings}_{tn} * \% \text{ of SFH in new constructions}_{tn}$$

Equation 2

With t0 = current year (2020)

tn, future year, n = 2021, 2022, ..., 2050

x, constant destruction rate

E_{utn}, useful demand for heating in year n, n = 2021, 2022, ..., 2050

E_{utn existing stock}, heating demand of existing stock of year n

E_{utn new constructions}, heating demand of new constructions of year n

S_{tn existing stock, LC}, surface area of apartments in existing stock in the future year n

C_{tn}: climate factors in future year n (CAGR of demand variation)

Formula 1 hypotheses for calibrating residential useful demand

$$E_{utni} = E_{utni \text{ existing stock}} + E_{utni \text{ new constructions}}$$

$$E_{utni \text{ existing stock}} = S_{tn \text{ existing stock, i}} * E_{ut0, specific, i} * C_{tn}$$

$$S_{tn \text{ existing stock},i} = S_{t0 \text{ existing stock},i} * (1 - x_i)^{(tn-t0)}$$

$$E_{utn \text{ new constructions},i} = S_{tn \text{ new constructions},i} * E_{ut0 \text{ specific},i} * C_{tn}$$

$$S_{tn \text{ new constructions},i} = \text{per capita tertiary surface}_{tni} * \text{Population}_{tn} - S_{tn \text{ existing stock},i}$$

Equation 3

With t_0 = current year (2020)

t_n , future year, $n = 2021, 2022, \dots, 2050$

i : type of tertiary buildings, $i = 1, 2, \dots, 8$

x_i , constant destruction rate of tertiary building type i

E_{utni} , useful demand for heating in year n for building type i , $n = 2021, 2022, \dots, 2050$

$E_{utn \text{ existing stock},i}$, heating demand of existing stock of year n for building type i

$E_{utn \text{ new constructions},i}$, heating demand of new constructions of year n

a_{tni} , ratio of energy frugality for building type i , $a_{tn} \in (0,1)$

$S_{tn \text{ existing stock},i}$, surface area of building type i in existing stock in the future year n

C_{tn} : climate factors in future year n (CAGR of demand variation)

Formula 2 hypotheses for calibrating tertiary useful demand

Agricultural demands, including energy demand from buildings, agricultural processing, tractors and other usages, are indexed by variation of total surface area used by agricultural activities (farming and cultivation). The adopted hypotheses of agricultural demand for high, medium and low demand scenarios are as follows:

	AME 2021 (D1, D2)		ADEME S1 (D4)	
	total surface (ha)	compared to 2020	total surface (ha)	compared to 2020
2020	28582003	100%	28582003	100%
2025	28385470	99%	28001953	98%
2030	28212616	99%	27421902	96%
2035	28072401	98%	26841852	94%
2040	27906600	98%	26261801	92%
2045	27761183	97%	25681751	90%
2050	27641085	97%	25101700	88%

Table 29 variation of total surface area used by agricultural activities by AME 2021 and ADEME S1 source: (ADEME, 2021b; DGEC, 2021a)

2.2.4.2.2 Retained demand trajectories

The table below presents the retained values for all energy service demands modeled by TIMES-FR for four demand scenarios.

Under D1, we suppose that space heating demand will increase significantly by 2030 and 2050. By 2030, the space heating demand from apartments and individual houses will be 29% and 21% higher than in 2015, and by 2050, demand from apartments and individual houses will be 67% and 56% higher. For the transport sector, both short- and long-distance travel by car will increase by around 21%. Passenger mobility demand by bus or train has a higher growth rate of 34% and 82%. For industry demand, D1 presents a contrasted future for energy-intensive industries and diffuse industries: demand for steel, metal, glass, and paper remains relatively constant in the future, while demand for textiles, food & beverage, and chemicals increases significantly.

The second high demand trajectory (D2) following AMS 2018 adopts the same hypotheses as D1 for industrial and agricultural demand, and assumes lower demand from the residential and transport sectors. For residential buildings, demand from individual houses increases at a much lower rate than from apartments (20% compared with 75%). All mobility demands except bus and road freight will increase in the future yet with lower growth rates than in the high demand scenario (D1). Short- and long-distance travel by car will increase by 12%, compared with 21% in D1. Freight transport will rely more on trucks and rail: demand for road freight and rail freight increases by 39% and 53% in 2050, accompanied by a sharp decrease in demand from utility cars (-45%).

Contrary to D1 and S2, the D4 scenario in line with ADEME S1 simulates a future with a much lower demand level, especially from the industry and transport sectors. For energy-intensive industries, production in 2050 drops from 24% (aluminum) to 51% (steel) compared with 2015. Demand for most branches of diffuse industry increases. However, their growth rate is lower than in D1 and D2. For the transport sector, D4 supposes that demand for all types of passenger mobility decreases by 37% in 2050, and 40-50% for freight mobility. For all branches of transport, demand in D4 is less than a half that of the highest demand trajectory (D1).

We will further explore another scenario (D3) with an intermediary demand level between D2 and D4. All types of energy demand in D3 are calculated from the average of D2 and D4. D3 allows us to explore a future with a more moderate decrease in industrial and transport demand.

For all the demand scenarios, we adopt the same hypothesis for tertiary demand due to a lack of available information from the reviewed scenarios. Heating demand from tertiary buildings is indexed by projected surface area (see the previous section) by AME 2021. Demand from all types of buildings, except education, will see a slight increase (from 5% to 10%) in 2050.

		D1				D2				D3				D4				
Unit		2015	2030	±%	2050	±%	2030	±%	2050	±%	2030	±%	2050	±%	2030	±%	2050	±%
Residential																		
Apt heating	PJ	270.4	348.7	29%	450.4	67%	340.0	26%	474.3	75%	333.3	23%	449	66%	326.6	21%	424.1	57%
IH heating	PJ	580.7	703.3	21%	908.7	56%	650.8	12%	698.6	20%	640.1	10%	675	16%	629.4	8%	650.9	12%
DHW Apt	PJ	23.3	23.4	0%	22.6	-3%	23.7	2%	22.1	-5%	23.5	1%	22	-4%	23.4	0%	22.6	-3%
DHW IH	PJ	66.4	64.2	-3%	62.0	-7%	67.7	2%	63.1	-5%	66.0	-1%	63	-6%	64.2	-3%	62.0	-7%
Cooking	PJ	84.9	81.9	-4%	77.6	-9%	101.9	20%	101.9	20%	91.9	8%	90	6%	81.9	-4%	77.6	-9%
specific electricity usage	PJ	260.7	265.2	2%	274.0	5%	265.2	2%	274.0	5%	265.2	2%	274	5%	265.2	2%	274.0	5%
Tertiary																		
Space heating Office	PJ	78.8	87.8	12%	88.9	13%	87.8	12%	88.9	13%	87.8	12%	88.90	13%	87.8	12%	88.9	13%
Space heating Café, hotel, restaurant	PJ	19.9	22.1	11%	22.2	12%	22.1	11%	22.2	12%	22.1	11%	22.15	12%	22.1	11%	22.2	12%
Space heating Commerce	PJ	56.4	61.6	9%	61.8	10%	61.6	9%	61.8	10%	61.6	9%	61.81	10%	61.6	9%	61.8	10%
Space heating Education	PJ	50.7	50.4	-1%	47.9	-5%	50.4	-1%	47.9	-5%	50.4	-1%	47.92	-5%	50.4	-1%	47.9	-5%
Space heating Communal tertiary habitat	PJ	19.8	20.6	4%	20.6	4%	20.6	4%	20.6	4%	20.6	4%	20.63	4%	20.6	4%	20.6	4%
Space heating Healthcare	PJ	38.8	42.1	8%	42.2	9%	42.1	8%	42.2	9%	42.1	8%	42.20	9%	42.1	8%	42.2	9%
Space heating Leisure	PJ	24.5	25.7	5%	25.8	5%	25.7	5%	25.8	5%	25.7	5%	25.80	5%	25.7	5%	25.8	5%
Space heating Transport	PJ	9.8	9.9	1%	9.9	1%	9.9	1%	9.9	1%	9.9	1%	9.89	1%	9.9	1%	9.9	1%
DHW Office	PJ	4.1	4.1	0%	3.9	-5%	4.1	0%	3.9	-5%	4.1	0%	3.85	-5%	4.1	0%	3.9	-5%
DHW Café, hotel, restaurant	PJ	7.0	7.0	0%	7.0	0%	7.0	0%	7.0	0%	7.0	0%	7.02	0%	7.0	0%	7.0	0%
DHW Commerce	PJ	8.3	8.3	0%	8.3	0%	8.3	0%	8.3	0%	8.3	0%	8.28	0%	8.3	0%	8.3	0%
DHW Education	PJ	6.7	6.7	0%	6.7	0%	6.7	0%	6.7	0%	6.7	0%	6.69	0%	6.7	0%	6.7	0%
DHW community housing	PJ	6.5	6.5	0%	6.5	0%	6.5	0%	6.5	0%	6.5	0%	6.48	0%	6.5	0%	6.5	0%
DHW Healthcare	PJ	11.3	11.3	0%	11.3	0%	11.3	0%	11.3	0%	11.3	0%	11.33	0%	11.3	0%	11.3	0%
DHW Leisure	PJ	11.5	11.5	0%	11.5	0%	11.5	0%	11.5	0%	11.5	0%	11.49	0%	11.5	0%	11.5	0%
DHW Transport	PJ	1.3	1.3	0%	1.3	0%	1.3	0%	1.3	0%	1.3	0%	1.32	0%	1.3	0%	1.3	0%
Cooking	PJ	38.5	38.5	0%	36.6	-5%	38.5	0%	36.6	-5%	38.5	0%	36.56	-5%	38.5	0%	36.6	-5%
Other electricity demand	PJ	212.6	202.0	-5%	204.1	-4%	202.0	-5%	204.1	-4%	202.0	-5%	204.14	-4%	202.0	-5%	204.1	-4%
Public lighting	PJ	203.1	20.1	-90%	20.3	-90%	20.1	-90%	20.3	-90%	20.1	-90%	20.30	-90%	20.1	-90%	20.3	-90%
Other sectors	PJ	20.2	34.7	72%	37.6	86%	34.7	72%	37.6	86%	34.7	72%	37.59	86%	34.7	72%	37.6	86%
Transport																		
Road.Car.Short Distance. Gpkm		499.1	553.6	11%	602.6	21%	509.4	2%	560.5	12%	459.7	-8%	436.40	-13%	409.9	-18%	312.3	-37%
Road.Car.Long Distance. Gpkm		257.0	256.5	0%	310.3	21%	262.3	2%	288.6	12%	236.7	-8%	224.72	-13%	211.1	-18%	160.8	-37%
Road.Motorbike Gpkm		13.9	11.9	-14%	10.9	-21%	13.9	0%	13.9	0%	12.8	-8%	11.40	-18%	11.7	-16%	8.9	-36%
Road.Vul.Passenger Gpkm		76.8	85.2	11%	92.8	21%	78.4	2%	86.3	12%	71.3	-7%	67.63	-12%	64.3	-16%	49.0	-36%
Road.Vul.Freight Tt		23.1	28.0	21%	35.8	55%	18.4	-20%	12.7	-45%	18.4	-20%	12.65	-45%	18.4	-20%	12.7	-45%
Road.Bus.Urban. Gpkm		18.7	19.3	3%	25.1	34%	15.7	-16%	12.0	-36%	15.7	-16%	11.96	-36%	15.7	-16%	12.0	-36%
Road.Bus.Intercity. Gpkm		35.3	36.5	3%	47.5	34%	29.7	-16%	22.6	-36%	29.7	-16%	22.60	-36%	29.7	-16%	22.6	-36%
Road.Freight. Tt		264.0	320.3	21%	409.3	55%	308.0	17%	366.3	39%	260.2	-1%	256.18	-3%	212.4	-20%	146.0	-45%
Rail.Freight. Tt		34.3	25.2	-26%	35.3	3%	40.3	18%	52.4	53%	33.0	-4%	35.05	2%	25.8	-25%	17.7	-48%

Rail.Passengers.Light.	Gpkm	10.5	13.5	29%	19.1	82%	13.3	27%	18.8	79%	11.0	4%	12.70	21%	8.6	-18%	6.6	-37%
Rail.Passengers.Heavy.	Gpkm	93.9	120.7	29%	170.8	82%	118.9	27%	168.1	79%	98.1	4%	113.46	21%	77.2	-18%	58.8	-37%
Domestic flight	PJ	33.3	40.3	21%	52.3	57%	38	14%	38	14%	32.3	-7%	26.6	-20%	24	-28%	15.3	-54%
International flight	PJ	234.9	296	26%	439.5	87%	268	14%	268	14%	221	-6%	190.4	-19%	174	-26%	112.8	-52%
Inland navigation	PJ	20.3	17.5	-14%	23.1	14%	23.1	14%	29	43%	19.3	-5%	19.2	-4%	15.4	-24%	9.9	-51%
Offshore navigation	PJ	75.7	63.6	-14%	86.3	14%	86.3	14%	108.2	43%	73.4	-3%	75	-1%	61.3	-19%	41.6	-45%
Industry																		
Iron and Steel	Mt	15.0	16.4	9%	15.0	0%	16.4	9%	15.0	0%	14.3	-5%	11.19	-25%	12.3	-18%	7.4	-51%
Aluminum	Mt	0.6	0.7	12%	0.6	2%	0.7	12%	0.6	2%	0.6	-1%	0.54	-11%	0.5	-14%	0.5	-24%
Copper	Mt	0.0	0.0	8%	0.0	2%	0.0	8%	0.0	2%	0.0	-4%	0.04	-16%	0.0	-15%	0.0	-33%
Other Non-Ferrous Metals	PJ	18.2	19.7	8%	18.6	2%	19.7	8%	18.6	2%	17.6	-4%	15.36	-16%	15.4	-15%	12.1	-33%
Ammonia	Mt	0.9	1.0	9%	1.0	9%	1.0	9%	1.0	9%	0.9	-1%	0.79	-11%	0.8	-12%	0.6	-31%
Chlorine	Mt	1.0	1.1	10%	1.1	10%	1.1	10%	1.1	10%	1.0	-4%	0.86	-14%	0.8	-17%	0.6	-38%
Other Chemicals	PJ	154.8	184.0	19%	238.2	54%	184.0	19%	238.2	54%	155.4	0%	168.87	9%	126.8	-18%	99.6	-36%
Cement	Mt	15.9	18.0	13%	16.8	5%	18.0	13%	16.8	5%	16.0	1%	13.88	-13%	14.0	-12%	11.0	-31%
Lime	Mt	2.9	3.2	8%	3.0	2%	3.2	8%	3.0	2%	2.8	-4%	2.49	-16%	2.5	-15%	2.0	-33%
Glass Hollow	Mt	3.8	4.3	13%	3.9	3%	4.3	13%	3.9	3%	3.6	-6%	3.02	-21%	2.8	-26%	2.1	-45%
Glass Flat	Mt	0.8	0.9	13%	0.8	3%	0.9	13%	0.8	3%	0.7	-6%	0.63	-21%	0.6	-26%	0.4	-45%
Other Non-Metallic Minerals	PJ	57.0	67.0	18%	86.9	53%	67.0	18%	86.9	53%	57.7	1%	62.45	10%	48.4	-15%	38.0	-33%
Extraction	PJ	10.3	11.5	12%	14.1	37%	11.5	12%	14.1	37%	10.1	-2%	10.46	2%	8.7	-15%	6.8	-34%
Food and Beverages	PJ	171.4	193.9	13%	250.6	46%	193.9	13%	250.6	46%	199.0	16%	239.65	40%	204.1	19%	228.7	33%
Textile and Clothes	PJ	10.7	11.8	10%	15.3	43%	11.8	10%	15.3	43%	12.1	13%	14.84	39%	12.3	15%	14.4	35%
High Quality Paper	Mt	3.2	3.0	-4%	3.0	-4%	3.0	-4%	3.0	-4%	3.2	2%	3.22	1%	3.5	9%	3.4	7%
Low Quality Paper	Mt	4.8	4.6	-4%	4.6	-4%	4.6	-4%	4.6	-4%	4.6	-4%	4.58	-5%	4.6	-4%	4.5	-5%
Transport Material	PJ	34.5	37.1	7%	48.0	39%	37.1	7%	48.0	39%	37.5	9%	46.64	35%	37.9	10%	45.3	31%
Mechanical Construction	PJ	67.7	72.9	8%	94.4	39%	72.9	8%	94.4	39%	73.6	9%	91.59	35%	74.3	10%	88.8	31%
Wood	PJ	18.7	20.9	12%	25.7	37%	20.9	12%	25.7	37%	21.6	15%	25.67	37%	22.2	19%	25.6	37%
Other Industries	PJ	93.6	104.7	12%	128.6	37%	104.7	12%	128.6	37%	108.0	15%	128.47	37%	111.3	19%	128.3	37%
Non-Energy Consumption - Chemicals	-PJ	450.7	504.2	12%	619.4	37%	504.2	12%	619.4	37%	488.9	8%	476.24	6%	473.6	5%	333.1	-26%
Non-Energy Consumption - Others	-PJ	142.7	159.7	12%	196.1	37%	159.7	12%	196.1	37%	154.8	8%	150.80	6%	150.0	5%	105.5	-26%
Agriculture																		
Agriculture Building	PJ	48.3	47.9	-1%	46.9	-3%	47.9	-1%	46.9	-3%	46.8	-3%	39.01	-19%	45.6	-5%	31.1	-36%
Agriculture Processing	PJ	5.9	5.9	-1%	5.8	-3%	5.9	-1%	5.8	-3%	5.7	-3%	4.79	-19%	5.6	-5%	3.8	-36%
Agriculture Tractor	PJ	107.6	106.8	-1%	104.7	-3%	106.8	-1%	104.7	-3%	104.3	-3%	86.97	-19%	101.7	-5%	69.3	-36%
Agriculture Other	PJ	27.5	27.3	-1%	26.8	-3%	27.3	-1%	26.8	-3%	26.7	-3%	22.26	-19%	26.0	-5%	17.7	-36%

Table 30 Retained hypotheses per sector for four scenarios of future energy service and commodity demand

Conclusion

In Chapter Two, we chiefly introduce the research question by presenting the methodology of the thesis and our contributions. We focus on the energy prospective of residential buildings in France faced with the challenge of carbon neutrality. We use a systemic approach for our analysis. Our research is based on a prospective modeling approach using the TIMES-FR model which represents the entire energy system of France.

We introduce the main features of TIMES, including its model structure, optimization paradigm and temporal definition. In addition, we explain how the different energy sectors in the French energy system are represented by TIMES-FR, thus illustrating how our energy model works. To study the question of residential heating, compared with other modeling solutions, the advantage of TIMES is that we are able to explain the technology choice from a broader system point of view.

In order to better reply to our research question using TIMES-FR, we make multiple improvements to both the supply and demand sides of the building energy system:

- for the supply side: renewable gas supply, district heating, biomass supply;
- for the demand side: calibration of building technology stock, electric heat pump sector, review of demand scenarios.

We present in detail how these contributions are devised for the model.

The modeling approach developed in Chapter Two is key to providing a solid basis to answer various questions about energy prospective. In Chapters Three and Four, we will provide answers to our research question using the improved TIMES-FR model.

Annex Technical-economic parameters of residential technologies and detailed hypotheses

Energy source	equipment name	lifespan	efficiency	Unitary Fixed OM cost (euros/kW)	Unitary capacity cost (euros/kW)	Data source	Range to compare	Reference
Space Heating								
Biomass	Fireplace	15	0.51	0	240	existing in TIMES		
	Biomass boiler	20	0.77	0	274	Producer data	biomass boiler with "reversed" combustion, € 5,000-12,000 (Hellowatt) Prix des chaudières à bois : coût moyen, pose et entretien (hellowatt.fr)	Cast iron PACCO woodburning stove - horizontal – not airtight - 10kW
	Biomass boiler dual service	20	0.77	15	301	Producer data		10% more expensive than equipment of single service (model hypothesis)
	Wood-pellet boiler high performance	20	0.9	23	468	Producer data	High performance wood boiler, €10,000 - €20,000 , 90% energy efficient (Hellowatt) Prix des chaudières à bois : coût moyen, pose et entretien (hellowatt.fr)	Chaudière Granulés CPA Evolution De Dietrich 24 kW avec Silo
Electricity	Air source hybrid heat pump	20	0.93	87	1737	Producer data		atlantic alfea hybrid duo gaz 11
	Air heat pump with electric boiler	20	0.93	74	1479	Producer data	Range 1: air-sourced electric heat pumps, €11,000 HT, installation included for an individual house of 110 m2 (Amorce) Range 2: individual heat pump for apartment of 70 m2, €7,918 inc. tax (Amorce)	Daikin Altherma 3H HT- Bi-Bloc
	Advanced air heat pump with electric boiler	20	0.93	91	1829	Producer data		Atlantic alféa Extensa Duo A.I
	Electric radiator	20	0.93	3	312	Producer data	Conventional electric inertia convector , capacity ranges from 0.5 - 2 kW, purchase price ranges from 30 - 500 euros, installation ranges from 50 - 200 euros (EDF izi) Pose d'un radiateur électrique : prix et tarifs (izi-by-edf-renov.fr)	Radiateur électrique à inertie fluide 1500 W SAUTER Orosi horizontal blanc
Gas	Advanced air source hybrid heat pump gas stove	20	0.95325	101	2014	Producer data		bosch hybrid condense AW
	low-temperature gas boiler	15	0.85	5	100	Bibliographical sources	Purchasing price 500-2500 euros, installation price 500-1000 euros, average required capacity for an individual house of 100m2 is 20-25 kW, energy efficiency 80-90% (Engie)	
	low-temperature gas boiler dual service	20	0.9	6	120	Producer data	Purchasing price 1000-3000 euros, installation price 500 -1000 euros, energy efficiency 90-95% (Engie)	Chaudière murale gaz Acléis BAS NOx NGLM23-8XN5
	condensing gas boiler	20	0.9	7	132	Producer data		
	condensing gas boiler dual service	20	0.97	14	271	Producer data	Range 1: individual condensing gas boiler 5000 euros inc. tax (Amorce) Range 2: 3000-5000 euros of purchasing price, 500-1000 euros installation cost, energy efficiency 100-110% (Engie)	Chaudière gaz condensation chauffage seul SAUNIER DUVAL Thema fit 15 kW
	condensing gas boiler dual service (high performance)	20	1.1	18	355	Producer data		Chaudière Bosch 9000i Wm 20kw/ 100l Au Sol. Gaz À Condensation + Eau Chaude Sanitaire
	Gas heat pump	15	0.93	159	3179	existing in TIMES		

Geothermal	Ground heat pump with electric boiler	20	0.93	125	2500	Bibliographical sources	Range 1: €14,857 inc. tax per installation for collective buildings, low efficiency (Amorce) Range 2: additional cost of 1500-3000 euros for a geothermal heat pump (ADEME)	Engie fourchette de prix PAC sol-eau de 6 à 8 kW, 18000 euros hors la pose, 4000 euros prix d'installation	
Heating oil	Oil stove	20	0.70	7	142	Producer data			
	Oil boiler (low temperature)		0.90	8	158	Producer data	3500-6000 euros for a low-temperature oil boiler, a storage tank is needed. For installation, average cost is 1000 euros, 20kW for individual house of 120 m2 (Engie) Guide de prix d'une chaudière fioul : achat et installation ENGIE		
	Dual oil boiler		0.90	11	211	Producer data			
	Condensing dual oil boiler	20	1.00	15	304	Producer data	Purchasing price for a condensing oil boiler: between 4,500-8000 euros(Engie) Guide de prix d'une chaudière fioul : achat et installation ENGIE		
Hydrogen	Hydrogen burner	20	0.9	232	4637	Producer data	Les premières chaudières à hydrogène domestiques sont en service - Cache Climatation - AIR3D		
LPG	LPG stove	15	0.70	7	142	Producer data		identical with oil boiler	
	LPG boiler	20	0.90	8	158	Producer data		identical with oil boiler	
	Dual LPG boiler	20	0.90	11	211	Producer data		identical with oil boiler	
	LPG heat pump	20	0.93	103	2062	existing in TIMES			
Solar	Solar collector with diesel backup dual	20	0.93	48	2382	existing in TIMES	Price range 14,000-18,000 euros (Hellowatt)		
	Solar collector with electricity backup dual	20	0.93	46	2303	existing in TIMES			
	Solar collector with gas backup dual	20	0.93	48	2382	existing in TIMES			
DHW									
Biomass	Biomass hot water heater	20	0.45	12	239	existing in TIMES			
Electricity	PAC water heater	15	0.9	9	935	existing in TIMES	Price range 3,000-4,000 euros inc. tax (ADEME)		
	Electric boiler water heater resistance	15	0.9	3	69	Bibliographical sources	Purchasing price ranges between 200-1,500 euros, depending on capacity, type of thermostat and brand. Installation price between 350-500 euros (Engie) required capacity: 17-20 kW if the electric water heater needs to supply a wash basin and bath at the same time (EDF izi)	Prix d'un ballon d'eau chaude : combien ça coûte vraiment ? ENGIE	
Gas	Fuel cell on gas for water and electricity, micro-cogeneration	15	0.4	646	12914	existing in TIMES			
	Gas boiler water heater	15	0.68	10	198	existing in TIMES	Purchasing price for gas water heater ranges from 400-3,000 euros, installation costs between 600-1,000 euros (Engie)		
Geothermal	Geothermal heat exchanger water heater	20	0.9	67	1334	existing in TIMES			
Heating oil	Oil boiler water heater	15	0.63	11	220	existing in TIMES			
LPG	LPG boiler water heater	15	0.66	11	220	existing in TIMES	Range 1: purchasing price for solar gas water heater ranges between 3000-6500 euros, installation cost between 500-1000		

Solar	Solar water heater with diesel backup	15	0.9	44	2200	Bibliographical sources	euros (Engie) Range 2: upfront cost between 5000-7000 euros (Hellowatt) Range 1: purchasing price for solar gas water heater ranges between 3000-6500 euros, installation cost between 500-1000 euros (Engie) Range 2: upfront cost between 5000-7000 euros (Hellowatt)
	Solar water heater with electricity backup	15	0.9	44	2200	Bibliographical sources	Range 1: purchasing price for solar gas water heater ranges between 3000-6500 euros, installation cost between 500-1000 euros (Engie) Range 2: upfront cost between 5000-7000 euros (Hellowatt)
	Solar water heater with gas backup	15	0.9	44	2200	Bibliographical sources	Range 1: purchasing price for solar gas water heater ranges between 3000-6500 euros, installation cost between 500-1000 euros (Engie) Range 2: upfront cost between 5000-7000 euros (Hellowatt)
Cooking							
electricity	electricity plaque	15	1	9	450	Bibliographical sources	Prix et pose d'une plaque à induction (travauxbricolage.fr)
gas	gas stove	15	1	10	500	Bibliographical sources	Prix et tarifs 2023 d'une gazinière (m-habitat.fr)

Chapter Three Transition to a future carbon-free heating system – an in-depth analysis

Introduction

The question of how to undertake the energy transition for space heating is complex. As discussed in the second chapter, a wide range of factors need to be considered. One important element is supply security during peak demand and extreme cold periods for heating, and this is a major concern for the integration of electric heat pumps: the energy efficiency of electric heat pumps drops significantly in extreme cold weather, which may generate high electricity demand. Hybrid heat pumps can reduce this problem by using gas during cold temperature situations. Other important elements include thermal insulation and the availability of gas. A significant share of useful demand can be shaved by retrofitting building fabrics. However, there is possibility that the energy gain by retrofit is lower than the expected level. This needs to be considered in the design of future heating systems. Gas is an important energy source for heating and its supply availability may have strong implications on future investment choices for the building system. Besides, the efforts for buildings are driven by emission targets. For different time steps in the future, the technology solution may be highly dependent on the pace of carbon mitigation.

In this section, we propose to make a complete analysis of the future transition of space heating to carbon neutrality. We focus on the multiple key elements mentioned above, including the presence of extreme cold situations, the efficiency of thermal insulation, the pace of carbon mitigation, and the opportunity cost of gas. We study the reaction of the energy system under different scenarios. In this exercise, we bring an improved modeling structure for the heating sector by introducing extreme cold periods into heating demand and hybrid heat pumps. Our study approach will focus on both the building sector and the role of buildings in the global energy transition and on the interaction between this sector and other sectors in the energy system. We focus on these key questions: what is the role of various energy sources in the global effort to achieve carbon neutrality? What is the optimal distribution of mitigation efforts among end-use sectors, and how will the building sector contribute? How will the transition of the gas system take place? What is the optimal investment choice for heating and the role of electric heat pumps and gas in the future heating system? What is the effect of standalone and hybrid heat pumps on the electricity system? How do these solutions vary under different cases of gas supply and mitigation targets? What are the costs of the energy system for these different solutions?

Chapter Three is organized into three sections. Section One introduces in detail why it is important to consider these scenarios for each dimension and the key hypotheses. For the thermal insulation dimension, we present in detail the major impediments to renovating the building sector, in particular the financial constraints of households and renovation efficiency based on evidence from the TREMI survey. This allows us to better understand the risks regarding the effectiveness of insulation retrofits in terms of energy gains. In order to take into account this aspect, we construct a high and a low scenario concerning building insulation. In addition to the effectiveness of insulation, we elaborate a scenario that interprets the influence of extreme cold events on heating. This scenario focuses on the impact of extreme cold temperatures on electric heat pumps. We present in detail how we characterize the level of extreme cold from available data on temperature and thermal sensibility. We then introduce the hypotheses for multiple scenarios elaborated for the dimension of the mitigation trajectory between 2030 and 2050 and the opportunity cost of gas, including multiple cases of anticipated or late mitigation efforts between 2030 and 2050, cases with limited gas consumption in 2030 and 2050 following the SNBC scenario, and cases with the presence of emerging hydrothermal gasification technology for renewable gas production in the future.

14 study scenarios are elaborated taking different cases from the four dimensions. The second section of this chapter sets out the hypotheses featured in each scenario in order to clarify the purpose of these scenarios for our study.

Section Three presents our modeling results and the discussion. The analysis is based on both technical and economic criteria. Regarding the technical side, we focus on the evolution of the energy balance for the global energy system and for different end-use sectors, the mitigation pace, and the evolution of equipment heating capacity. Regarding the economic side, we illustrate the evolution of annual cost. These analyses allow us to reply to various research questions in detail. Section Three is divided into five parts. We firstly present the results of the contrafactual scenario without extreme cold events. The contrafactual scenario serves as a reference to compare with other scenarios and to illustrate the effects of different variables. Next, we present two scenarios featuring extreme cold events and different investment conditions for hybrid heat pumps. This allows to answer the question about the impact of extreme cold events and long-term role of electric heat pumps. Part Three focuses on the scenario featuring low insulation and helps to outline the solution for heating systems in case of a lower contribution from thermal insulation. Part Four presents the reactions of the energy system under different paces of mitigation between 2030 and 2050. The last part presents the scenarios with limited usage of gas following the SNBC and scenarios with hydrothermal gasification. We will then be able to understand the opportunity cost of gas in achieving the neutrality target, and the impact when considering the presence of an emerging renewable gas technology.

Résumé

La question de la transition énergétique pour le chauffage des bâtiments est complexe. Comme discuté dans le deuxième chapitre, un large éventail de facteurs doit être pris en compte. Un élément important est la sécurité d'approvisionnement durant les périodes de forte demande et de froid extrême pour le chauffage, ce qui constitue une préoccupation majeure pour l'intégration des pompes à chaleur électriques : l'efficacité énergétique des pompes à chaleur électriques diminue considérablement par temps très froid, ce qui peut entraîner une forte demande d'électricité. Les pompes à chaleur hybrides peuvent atténuer ce problème en utilisant le gaz lors de températures froides. D'autres éléments importants incluent l'isolation thermique et la disponibilité du gaz. Une part significative de la demande utile peut être réduite par la rénovation de l'isolation des bâtiments. Cependant, il existe une possibilité que le gain énergétique obtenu grâce à la rénovation soit inférieur au niveau souhaité. Cela doit être pris en compte dans la conception des futurs systèmes de chauffage. Le gaz est une source d'énergie importante pour le chauffage et sa disponibilité peut avoir de fortes implications sur les choix d'investissement futurs pour le système de bâtiment. De plus, les efforts concernant les bâtiments sont guidés par des objectifs d'émission. Pour différentes échéances dans le futur, la solution technologique peut dépendre fortement du rythme de décarbonation (rythme de réduction de CO₂ souhaité).

Dans cette section, nous proposons de réaliser une analyse complète de la transition future du chauffage des espaces vers la neutralité carbone. Nous nous concentrons sur les multiples éléments clés mentionnés ci-dessus, y compris la présence de situations de froid extrême, l'efficacité de l'isolation thermique, le rythme de décarbonation et le coût d'opportunité du gaz. Nous étudions la réaction du système énergétique sous différents scénarios. Dans cet exercice, nous améliorons la structure de modélisation pour le secteur du chauffage en introduisant des périodes de froid extrême dans la demande de chauffage et des pompes à chaleur hybrides. Notre approche d'étude se concentrera à la fois sur le secteur du bâtiment et sur le rôle des bâtiments dans la transition énergétique mondiale, ainsi que sur l'interaction entre ce secteur et d'autres secteurs du système énergétique. Nous nous penchons sur ces questions clés : quel est le rôle des différentes sources d'énergie dans l'effort global pour atteindre la neutralité carbone ? Quelle est la distribution optimale des efforts d'atténuation parmi les secteurs d'utilisation finale, et comment le secteur du bâtiment contribuera-t-il ? Comment se déroulera la transition du système gaz ? Quel est le choix d'investissement optimal pour le chauffage et quel sera le rôle des pompes à chaleur électriques et du gaz dans le futur système de chauffage ? Quel est l'effet des pompes à chaleur autonomes et hybrides

sur le système électrique ? Comment ces solutions varient-elles selon différents cas d'approvisionnement en gaz et d'objectifs d'atténuation ? Quels sont les coûts du système énergétique pour ces différentes solutions ?

Le chapitre trois est organisé en trois sections. La première section introduit en détail pourquoi il est important de considérer ces scénarios pour chaque dimension et les hypothèses clés. Pour la dimension de l'isolation thermique, nous présentons en détail les principaux obstacles à la rénovation du secteur du bâtiment, en particulier les contraintes financières des ménages et l'efficacité de la rénovation, en nous basant sur les données de l'enquête TREMI. Cela nous permet de mieux comprendre les risques concernant l'efficacité des rénovations d'isolation en termes de gains énergétiques. Pour tenir compte de cet aspect, nous construisons un scénario haut et un scénario bas concernant l'isolation des bâtiments. En plus de l'efficacité de l'isolation, nous élaborons un scénario qui interprète l'influence des événements de froid extrême sur le chauffage. Ce scénario se concentre sur l'impact des températures de froid extrême sur les pompes à chaleur électriques. Nous présentons en détail comment nous caractérisons le niveau de froid extrême à partir des données disponibles sur les températures et la sensibilité thermique. Nous introduisons ensuite les hypothèses pour plusieurs scénarios élaborés pour la dimension de la trajectoire d'atténuation entre 2030 et 2050 et le coût d'opportunité du gaz, incluant plusieurs cas d'efforts de décarbonation anticipés ou tardifs entre 2030 et 2050, des cas avec une consommation limitée de gaz en 2030 et 2050 suivant le scénario SNBC, et des cas avec la présence d'une technologie émergente de gazéification hydrothermale pour la production de gaz renouvelable à l'avenir.

Quatorze scénarios d'étude sont élaborés en prenant différentes hypothèses des quatre dimensions. La deuxième section de ce chapitre expose les hypothèses figurant dans chaque scénario afin de clarifier l'objectif de ces scénarios pour notre étude.

La section trois présente nos résultats de modélisation et la discussion. L'analyse est basée à la fois sur des critères techniques et économiques. Sur le plan technique, nous nous concentrons sur l'évolution de l'équilibre énergétique pour le système énergétique global et pour différents secteurs d'usages finaux, le rythme de décarbonation souhaité et l'évolution de la capacité de chauffage des équipements. Sur le plan économique, nous illustrons l'évolution des coûts annualisés. Ces analyses nous permettent de répondre en détail à diverses questions de recherche. La section trois est divisée

en cinq parties. Nous présentons d'abord les résultats du scénario contrefactuel sans événements de froid extrême. Le scénario contrefactuel sert de référence pour comparer avec d'autres scénarios et illustrer les effets de différentes variables. Ensuite, nous présentons deux scénarios présentant des événements de froid extrême et différentes conditions d'investissement pour les pompes à chaleur hybrides. Cela permet de répondre à la question de l'impact des événements de froid extrême et du rôle à long terme des pompes à chaleur électriques. La troisième partie se concentre sur le scénario présentant une faible isolation et aide à esquisser la solution pour les systèmes de chauffage en cas de contribution moindre de l'isolation thermique. La quatrième partie présente les réactions du système énergétique sous différents rythmes de décarbonation entre 2030 et 2050. La dernière partie présente les scénarios avec une utilisation limitée du gaz suivant le SNBC et des scénarios avec gazéification hydrothermale. Nous serons alors en mesure de comprendre le coût d'opportunité du gaz pour atteindre l'objectif de neutralité, et l'impact de la présence d'une technologie émergente de gaz renouvelable.

3.1 Key dimensions for low-carbon building construction and hypotheses for scenario definition

In the previous chapter, we outlined the political ambition to achieve carbon neutrality for France and the important role of the residential sector in global efforts. We introduced how the prospective energy model, TIMES-FR, can reply to the question of future technology choices for residential buildings by considering various important elements. In this study, we rely on the improved structure of TIMES-FR to explore four key dimensions identified by us, i.e., the presence of extreme cold events, the effectiveness of thermal insulation, the pace of decarbonization, and the opportunity cost of gas. This allows us to explore the future challenges of the residential energy transition. For each dimension, we establish several scenarios. With TIMES-FR, we compare the difference between energy balance, emission trajectory, cost, and the capacity of future technology stock. In this section, we introduce why these dimensions are important to consider and our hypotheses for scenario definition.

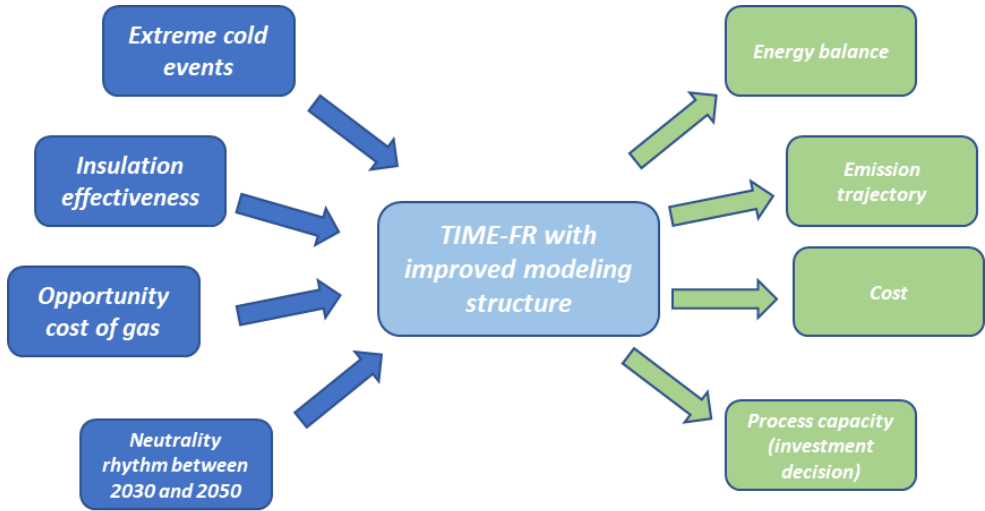


Figure 53 Schema of study

3.1.1 Effectiveness of thermal insulation

The availability of thermal insulation is an important element to consider, as it contributes to reducing the share of energy demand from heating equipment. This might be a strong influential factor in investment choices for residential buildings. As we discussed in Chapter Two, major impediments still exist to renovating the building sector, in particular the financial constraints of households and the efficiency of renovation.

Evidence of the effect of these influential factors is provided by the statistical results of the “TREMI” survey led by SDES and ADEME. The “TREMI” survey is based on a sample of 100,000 individual houses representative of French households. The main objective of the survey is to measure the current pace of renovation, and identify the motivations and setbacks facing households and their awareness and use of financial aids (SDES, 2020a).

As energy renovation involves relatively high investment costs, financial reasons may constitute a major barrier for households to invest. The results of the TREMI survey suggests that, among those households that had not renovated their house in 2019, 30% declared that this was due to their unfavorable financial situation. The barrier may be higher for lower income households with more budget constraints. According to TREMI statistics, among those households belonging to the first quintile of per consumer unit revenue (less than €14,310 per person), around 36% had renovated their house. This ratio is significantly lower than for households in the last quintile (more than 30,810 euros per person) (42%). In terms of energy gain, for all the individual houses renovated from 2017-2019, the total final energy gain by households in the first revenue quintile is around 1.1 TWh, compared with 1.9 TWh for households in the last quintile.

For energy renovation, a range of financial aids can help households to cover the high investment costs and encourage them to take action. However, households’ awareness of these financial aids is still low, in particular for those who have not renovated their house and declare financial reasons⁶². The cognitive barrier reduces the effect of these subsidies. The results of the TREMI survey suggest that around 35% of households in this situation are not aware of at least one type of financial aid, compared to 24% among those who undertook an energy renovation during 2017-2019. For five major national

⁶² “My financial situation does not allow me to carry out the work” or “I’m not sure that the expected energy gain can match the investment” or “I’m certain that the energy gain will not match the investment in energy retrofits”.

financial aids⁶³, none of them has an awareness rate higher than 50% among households who did not carry out energy renovation during 2017-2019.

Another concern is the efficiency of renovation work. As suggested by the TREMI survey, among all the renovations for individual houses achieved in 2019, around 22% (730,000 out of 3.3 M) had no effect in reducing energy consumption, and around 18% even led to higher energy demand. This can be explained by both technical and behavior factors. For some buildings, especially those with poor thermal performance, several parts of the building need to be renovated in order to efficiently reduce the global consumption. In this case, carrying out work on only one part may not have a significant effect. The evidence can be found in the statistics regarding the energy gains of renovated individual houses in 2019 (ONRE, 2022a) (Table 31). We can note that dwellings that have undergone one renovation represent 64% of total surface area, and only 39% of total energy gain. For households that have renovated more than three parts, they represent around 30% of total energy gain and only 13% of surface area. Another technical issue for renovation is the quality of work. Sometimes, a lack of renovation expertise may lead to work with very low energy gains. This is more likely to happen when the renovation is carried out by individuals.

Concerning the behavior aspect, low energy gains from renovations can be linked to a rebound effect. Householders may use energy equipment more intensively after investing in energy efficiency. We will develop this aspect in detail in Chapter Five.

<i>Number of renovated places</i>	<i>Number of dwellings</i>	<i>Total energy gain (TWh)</i>	<i>Average energy gain (MWh)</i>	<i>Share of total energy gain (%)</i>	<i>Share of renovated surface area (%)</i>
1	1481488	3.2	2.1	39%	64%
2	528970	2.5	4.7	31%	23%
More than 3	282765	2.4	8.6	30%	13%

Table 31 Final energy gain by number of renovated parts of a building, all individual houses renovated in 2019 (ONRE, 2022a)

Considering the elements argued above, there is a possibility that the building sector follows a slow renovation pace and that a large share of the potential energy savings estimated at present cannot be achieved. We propose to compare high and low insulation scenarios. The high insulation pace is based on an optimistic vision: it allows for a rapid increase in renovation so that all the potential of individual houses, apartments, tertiary buildings can be achieved in 2035. Under the high insulation scenario, the

⁶³ *In French* “Les crédits ou réductions d’impôts spécifiques à la rénovation”, “L’éco-prêt à taux zero”, “La TVA à 5,5 %”, “Les certificats d’économies d’énergie”, “Habiter mieux”

maximum potential for energy gain by building fabric retrofit is 130 TWh for residential buildings and 42 TWh for tertiary buildings. The low insulation scenario represents a pessimistic vision of building renovation in the future: only half the estimated availability can be achieved, and not before 2050. This simulates the case where the target of building renovation cannot be achieved due to major difficulties mentioned above.

The figure below describes the maximum annual investment pace of individual houses (MI) and collective buildings (LC) defined for three insulation scenarios. We translate the investment pace by annual additional energy saving due to insulation. Under the high insulation scenario, the maximum level of yearly investment can be doubled by around 2028 for individual houses and 2023 for apartments. In 2035, the upper bound for useful energy gains by individual houses in the model is set at 7.76 TWh per year and by apartments at 6.40 TWh per year. In the case of the low insulation scenario, the maximum additional energy gain per year that can be provided by insulation remains at the current level (2.75 TWh) till 2050 for individual houses. The maximum yearly additional energy gain follows a slow growth rate till 2050.

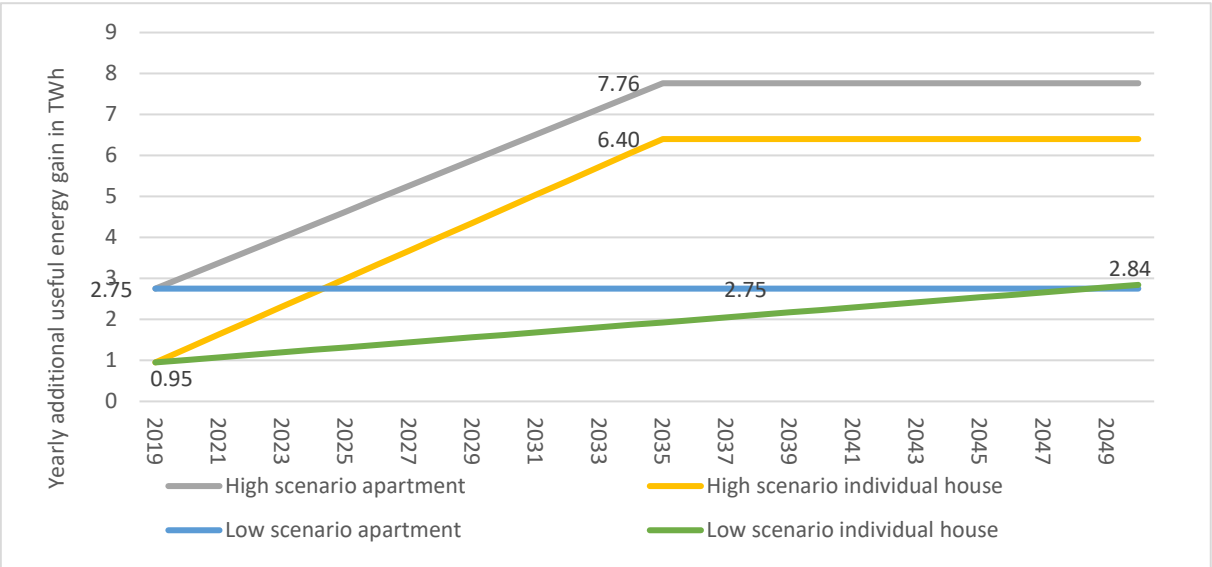


Figure 54 Potential of energy saving by residential buildings under the high and low insulation scenario (yearly rhythm)

Scenario name	Residential hypothesis	Tertiary hypothesis
Low insulation pace	The estimated technical insulation potential for both individual houses and apartments can only be achieved after 2050. Yearly investment in thermal insulation cannot surpass 2.75 TWh till 2050 for individual houses. For apartments, the maximum yearly investment potential follows a linear growth till 2050, and in 2050, the potential reaches 2.84 TWh.	The estimated insulation potential for all types of tertiary buildings can only be achieved after 2050. The maximum yearly potential of investments in tertiary insulation remains constant at 1.6 TWh till 2050.
High insulation pace	The estimated insulation potential for both individual houses and apartments can be achieved sooner, in 2035. For both individual houses and apartments, maximum yearly new investments follow linear growth from 2019 to 2035. In 2035, the yearly investment potential reaches 7.76 TWh for individual houses and 6.4 TWh for apartments.	The estimated insulation potential for all types of tertiary buildings can be achieved by 2035. The maximum yearly potential of investment in tertiary insulation remains constant at 4 TWh till 2050.

Table 32 Hypotheses for future investment rhythm of thermal insulation under the high and low insulation pace scenario

3.1.2 Extreme cold events

According to the Météo France definition, a cold wave signifies a period of cold weather of high persistence, intensity and geographical extent. It endures more than two days with a temperature significantly lower than the normal level of the region (MÉTÉO France, n.d.). Extreme cold events occur frequently in France and can have a major impact on the energy system, especially the electricity and gas supply. In very cold situations, households tend to generate high heating demand. This can be a challenge for supply security. In extreme cases, a system failure can take place (for example, a “black-out” of the electricity grid). Taking the example of the cold wave that happened in France in the last week of February 2018 can further illustrate this effect on the power grid. On the 27th and 28th of February, the national average temperature dropped to $-3.2\text{ }^{\circ}\text{C}$, compared to a $2\text{ }^{\circ}\text{C}$ historical average, making it the most severe cold wave in recent years. For a major part of north-east France, the lowest temperature was -10 to $-15\text{ }^{\circ}\text{C}$ (Météo France, 2018). For the same period, the electricity demand surged due to heating demand as France is characterized by a high share of electric radiators (30% of households in 2022) which was historically enabled by a large nuclear power fleet. The peak power demand from the electric grid reached 96 GW. This value is much higher than the observed historical values in February (81.9 GW at 2017, 86.5 GW in 2019) (RTE, 2024).

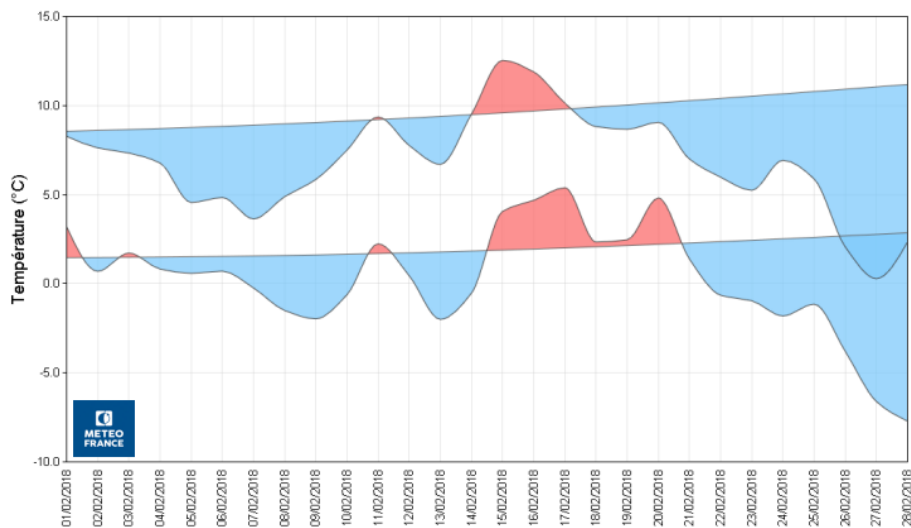


Figure 55 Evolution of average minimal and maximal daily temperature in February, 2018 for France (Météo France, 2018)

The energy security risk could be higher when households use electric heat pumps for heating. As introduced in Chapter Two, the energy efficiency of electric heat pumps is highly dependent on outside temperature conditions, and the COP drops significantly when the outside temperature is low. During extreme cold weather when the COP is very low, heat pumps generate high electricity demand when

operating. This may not be a major concern if the electric heat pumps are installed in only a few buildings. However, in low-carbon scenarios, we have to consider this aspect when focusing on the entire energy system with a significant number of installations.

The potential pressure on the electricity supply system may be reduced by using hybrid heat pumps (HHP). When the outside temperature is very low, a HHP can switch to gas boiler or mixed mode to produce space heat. In this case, the equipment's contribution to peak electricity power demand is significantly reduced. As suggested by the simulation of (GRDF & Artelys, 2022), for the same demand profile⁶⁴, a hybrid heat pump generates over 30% less power demand during peak periods compared with a standalone heat pump, thus reducing a considerable amount of system costs associated with the purchase of electricity and the network. The prospective report published by ADEME and RTE for the building sector suggests that when taking HHP as an alternative solution to standalone HP to electrify residential buildings, the future peak power demand from the French residential system will be significantly reduced (ADEME & RTE, 2020). If the SNBC and PPE electrification trajectories in residential buildings were to be retained, replacing 2.5 million conventional heat pumps that need to be installed by 2035 with hybrid heat pumps could reduce around 3 GW of peak demand and 1.7 TWh of annual electricity consumption compared to the case without.

Considering these elements, when modeling the energy system, it is important to account for the presence of extreme cold events and their impact. We propose to introduce a scenario that interprets the presence of extreme cold periods for heating. We focus on the impact of extreme cold on the performance of electric heat pumps. As discussed in Chapter Two, we have elaborated an improved structure in TIMES-FR that can be used to interpret the variation in energy efficiency of electric heat pumps in different temperature ranges and the existence of multiple investment choices including hybrid heat pumps. Here we present how we characterize the extreme cold situation in TIMES.

We propose to represent the temperature situation of a year by the percentage of heat demand in warm, cold and extreme cold periods to be produced by electric heat pumps. As we have defined different energy efficiencies for heat pumps over the three temperature ranges (by the disaggregated model structure), this approximates the operating conditions of a heat pump through a year. To characterize the demand situation in the future, our scenario is based on available data of 2018-2022. We estimate the level of heat demand for different temperature ranges through a year from the data on temperature and thermal sensitivity. The data sources are departmental temperature chronicles by INSEE/METEO France (Météo France, n.d.) and a database elaborated by the Strategy Department of

⁶⁴ individual house of 110 m², intermediate insulation level, climate zone H2, temperature set for heating between 16-19 °C, climate data from 2005-2014.

GRDF to estimate the thermo-sensitive share of gas and electricity consumption for heating for each IRIS⁶⁵ of France.

These available data are processed by us in order to obtain an accurate estimation of national heating demand for France. We firstly estimate the proportion of heating demand over three periods for each department⁶⁶ in Metropolitan France except Corsica (95 departments in total), and the French national average is then deduced from departmental statistics. Here we present the main hypotheses for data calibration.

For each department, the calibration of heat demand consists of two major steps: firstly, classification of daily demand type by efficient temperature; secondly, estimation of daily demand with chronicles of efficient temperature and thermal sensitivity.

Efficient temperature is derived from the temperature of the two previous days (as illustrated by the formula below). We see that the efficient temperature chronicle lists fewer “extreme” cases except for consecutively very cold periods. This is a more pertinent method recognized by gas/electricity network operators for estimating the residential energy demand profile: due to the thermal inertia of buildings, the heating needs do not increase immediately following a temperature drop.

$$T_{eff}(J) = 0.64 T(J) + 0.24 T(J - 1) + 0.12 T(J - 2) \quad \text{Equation 4}$$

We suppose that a day is classified as extremely cold if the efficient average temperature is lower than 0, as cold if the efficient average temperature is between 0 and 3, and as warm if the efficient average temperature is above 3.

Thermo-sensitivity for heating is the variation in energy consumption following a change in the outside temperature. We can assume that the heating demand is thermo-sensitive from a certain threshold temperature, depending on energy sources and climate situations. For the entire temperature range below the threshold, the variation in heat demand upon temperature follows a gradient, as suggested by user data provided by electricity network operators (GRDF et al., 2018). In our exercise, we define a unique threshold temperature of 18 degrees for all regions in Metropolitan France.

Then, for each department, the daily heat consumption is calculated from the production of the difference between ET and threshold temperature (18 °C), and thermo-sensitivity (MWh/°C). The level

⁶⁵ IRIS, « îlots regroupés pour l'information statistique », is a sub-municipal statistical division for France. France currently has 50800 IRIS, including 700 for overseas departments (DOM).

⁶⁶ “département”, French administrative areas

of thermal sensitivity for one department is the addition of all IRISs located in this department. We suppose that the entire heating demand on an extremely cold day is heating demand for extreme cold periods, in the same manner as for cold and warm days. At the end, we have an estimation of heat demand for all extreme cold, cold, and warm days for each department.

$$C_{extreme_cold} = \sum_{x=1}^X \sum_{n=1}^N C_{n,x} \quad \text{Equation 5}$$

$$C_{n,x} = \sum_1^i (ET_x - T) * TS_i \quad \text{Equation 6}$$

With

$C_{extreme_cold}$: Heat demand of extreme cold period for Metropolitan France

$C_{N,x}$: Energy consumption of day n for department x

x is the index of department, $x = 1, 2, \dots, X, X = 95$

n is the index of extreme cold day in department $x, i = 1, 2, \dots, N, N = \text{number of extreme cold days in } x$

i is the index of IRIS in $x, i = 1, 2, \dots, I, I = \text{number of IRIS in department } x$

ET_x : Efficient temperature of department x

TS_i : thermosensibility of IRIS i ($\frac{MWh}{^\circ C}$)

T : threshold temperature (18 °C)

The table below presents the obtained values for heating distribution over four seasons and three temperature ranges for 2018-2022. The heat demand for winter is constituted by 80.2% of warm demand, 15.6% of cold demand and 4.2% of extreme cold demand. The presence of cold and extreme cold demand is very low in other seasons. These values are retained in our exercise to represent future demand in the presence of extreme cold situations.

	cold	extreme cold	warm	total
autumn (31/08-15/11)	0.47%	0.00%	99.52%	100.00%
spring (15/03-31/05)	2.23%	0.18%	97.59%	100.00%
summer (01/06-30/08)	0.00%	0.00%	100.00%	100.00%
winter (16/11 -14/03)	15.61%	4.24%	80.15%	100.00%

Table 33 Retained hypotheses on the distribution of heating demand over four seasons and three temperature ranges

3.1.3 Neutrality and mitigation pace between 2030 and 2050

The global objective for the French energy system established by the energy law is to reach carbon neutrality by 2050. There are various possible pathways to achieve this objective: the mitigation pace can be linear; the decarbonization efforts can also be faster or slower than the linear pace for certain time steps before 2050. The changes in global mitigation pace may have important impacts on the energy system including on residential and tertiary buildings. Given this context, apart from the case of a linear mitigation pace, we propose to explore five cases by varying the pace of carbon mitigation. For all five variants, the carbon emissions target is strictly in line with SNBC ambitions: carbon emissions in 2030 are 40% lower than in 1990, and in 2050, the goal of zero net emissions is achieved. The difference is only the required mitigation efforts of the three time steps between 2030 and 2050. We study three variants, named anticipated 1-3, with different levels of effort ahead of the linear schedule, and two late decarbonization variants, named late 1-2. The goal here is to assess the sensitivity of the building sector’s low-carbon choices in a fast or slow transition to a carbon neutral system. The descriptions of these variants are as follows:

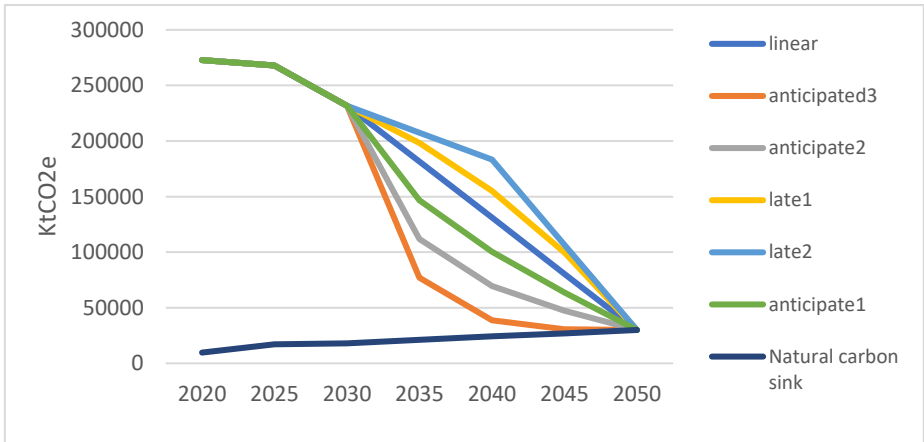


Figure 56 Proposed carbon emission trajectories of the five variants of mitigation pace between 2030 and 2050

3.1.4 Opportunity cost of gas

We explore here another interesting contribution that a comparative analysis of scenarios with the TIMES model can bring. As an important guideline for future energy transition in France, the SNBC proposes a relatively constrained future for gas. In 2050, gas consumption in the carbon neutral energy system under SNBC drops to 158 TWh, less than half of gas consumption in 2021 (336 TWh) (Ministère de la Transition écologique et de la Cohésion des territoires, 2020a). The vision of SNBC is important to consider but it was designed with an iterative and negotiated process without a systemic modeling exercise. SNBC has the advantage of resulting from a large consultation process, while TIMES has the flexibility to explore trajectories and technology developments in a systemic way. We have tried to combine the information that can be extracted from both approaches, and we are interested in identifying the alternative solutions to gas in TIMES-FR when its usage is limited in the future, as by the SNBC.

Another element for gas is the possibility to produce renewable gases from emerging technologies, in particular hydrothermal gasification. As introduced in the first chapter, hydrothermal gasification is a reliable technology to produce carbon-free renewable gas. Although currently with very low level of installation in France, it may be one of the major solutions in the future. Considering this, the question arises of how alternative solutions will evolve in the presence of these emerging renewable gas industries in the future.

By answering the abovementioned questions, we are able to better understand the opportunity cost of gas, an essential element to apprehend the prospective of the energy system in France. This is also a major concern for gas network operators. In our study, we propose to study three cases. We study two variants that follow the SNBC gas consumption trajectory. For the first variant, gasSNBC1, we suppose that the global gas consumption cannot surpass the level of SNBC in 2030 and 2050. For the intermediary time steps, we suppose that the gas trajectory is linear. The second variant, gasSNBC2, sets a stricter limit than the gasSNBC1. Apart from the global consumption, the usage of gas by the industry, transport and building sectors in 2030 and 2050 cannot exceed the SNBC scenario.

The details of the gas trajectory proposed by SNBC are presented by the table below.

	SNBC trajectory (AMS 2018) (TWh)			
Year	Industry	Transport	Building	Total
2030	101	14	149	356
2050	30	42	37	158

Table 34 Trajectory of gas consumption according to the SNBC (DGEC, 2020b)

We also consider the opportunities resulting from a variant of a high perspective for hydrothermal gasification. This technology is at a pilot stage in France and its contribution is only allowed in dedicated exploratory scenarios. Assuming successful first industrial demonstrators (2026) in France, and progress in the technology, this scenario allows the development of hydrothermal gasification after 2030. The integration of hydrothermal gasification technology provides higher availability for the future gas supply by enlarging the range of accessible sources for renewable gas production. We include the possibility of producing 63.8 TWh of biomethane from hydrothermal gasification in 2050. The maximum potential is in line with estimation of the white book published by the working group of hydrothermal gasification (Groupe de Travail Gazeification Hydrothermale, 2023).

3.2 Scenario design

We propose to study 14 scenarios established from the four key dimensions introduced above. We construct four central scenarios, named from S1 (contrafactual) to S4, with a linear mitigation pace and no particular limits on gas usage. The contrafactual scenario (S1) is the case when there is no presence of extreme cold situations for future demand. The contrafactual scenario serves as a reference to compare with other scenarios and to illustrate the effects of different variables. S2 introduces the presence of extreme cold events and allows for investing in HHP. It helps to illustrate the effect of the presence of extreme cold situations on building investment choices for heating and responds to the question of the role of hybrid heat pumps. S3 is the case with the presence of extreme cold demand and prohibited investments in HHP. By comparing S2 and S3, we can further explore the effect of hybrid heat pumps on the electricity system. S4 explores the case featuring low availability of thermal insulation, with the presence of extreme cold events. Under S4, the lower availability of energy gains by insulation brings another challenge to the building heating system: the higher heat demand profile induced by lower thermal quality requires more energy production by heating equipment, which increases the competition of energy sources in the carbon neutrality context. In scenario S4, we explore the reaction of the heating system to this situation, in particular the varying contributions of key heating solutions such as electric heat pumps and gas boilers.

Scenario	Possibility to invest in HHP	Presence of extreme cold	of Insulation potential	Gas usage	Mitigation pace between 2030-2050
<i>S1 (contrafactual)</i>	No	No	High	No particular limit	Linear
<i>S2</i>	Yes	Yes	High	No particular limit	Linear
<i>S3</i>	No	Yes	High	No particular limit	Linear
<i>S4</i>	Yes	Yes	Low	No particular limit	Linear

Table 35 Hypotheses of four central scenarios

To study the case of different mitigation paces, we introduce three variants of anticipated paces between 2030 and 2050 and two variants of late mitigation pace. They are based on a future with the presence of extreme cold and high insulation potential.

By comparing these scenarios with S2, we aim to answer several questions: for the intermediary time steps, which sector will endure a greater mitigation burden in case of an anticipated mitigation pace or a lower burden in the contrary case? What are the implications for the pace of energy transition in the building sector, especially the role of gas and electricity? What is the cost surplus in the case of anticipated pace?

Scenario	Possibility to invest in HHP	Presence of extreme cold	Insulation potential	Gas usage	Mitigation pace between 2030-2050
<i>S2_advanced 1</i>	yes	yes	High	No particular limit	Anticipated mitigation pace between 2030-2050, level 1
<i>S2_advanced 2</i>	yes	yes	High	No particular limit	Anticipated mitigation pace between 2030-2050, level 2
<i>S2_advanced 3</i>	yes	yes	High	No particular limit	Anticipated mitigation pace between 2030-2050, level 3
<i>S2_late 1</i>	yes	yes	High	No particular limit	Late mitigation pace between 2030-2050, level 1
<i>S2_late 2</i>	yes	yes	High	No particular limit	Late mitigation pace between 2030-2050, level 2

Table 36 Hypotheses of five variants of mitigation pace between 2030 and 2050

In order to reply to the question about the opportunity cost of gas, we present five study scenarios. By comparing scenario *S2_gasSNBC1* and *S2_gasSNBC2* with *S2*, we will be able to firstly understand how the target neutrality can be achieved in case of more constrained usage of gas, and secondly the alternative solutions to replace gas. Comparing the three scenarios with a high perspective of hydrothermal gasification, *S2_gasHigh*, *S2_gasHighSNBC1*, *S2_gasHighSNBC2*, will allow us to evaluate the variation of opportunity costs in the case of developing an emerging renewable gas technology.

Scenario	Possibility to invest in HHP	Presence of extreme cold	Insulation potential	Gas consumption	Mitigation pace between 2030-2050
<i>S2_gasSNBC1</i>	yes	yes	High	Constrained usage of gas for global system in 2030 and 2050	linear
<i>S2_gasSNBC2</i>	yes	yes	High	Constrained usage of gas for global system in 2030 and 2050	linear
<i>S2_gasHigh</i>	yes	yes	High	High perspective for hydrothermal gasification	linear
<i>S2_gasHighSNBC1</i>	yes	yes	High	High perspective for hydrothermal gasification	linear
<i>S2_gasHighSNBC2</i>	yes	yes	High	High perspective for hydrothermal gasification	linear

Table 37 Hypotheses of five variants to study opportunity cost of gas

Concerning other important hypotheses, our exercise retained a high scenario of energy service demand and a trajectory of carbon emissions to achieve carbon neutrality. The high demand scenario simulates a continuation of the current demand trend till 2050, which leads to a high increase in residential, industry and transport demand. In 2050, demand from residential space heating is 46% higher for individual houses than the 2015 level, and 55% for collective residences. The potential of natural carbon reservoirs dedicated to energy consumption and CCS is respectively 30 MtCO₂e and 15 MtCO₂e.

3.3 Results and discussion

3.3.1 The contrafactual scenario

3.3.1.1 Pathway of the global energy system

Figure 57 presents the trajectory of the French energy balance for the contrafactual scenario S1. For the global energy system, the optimal solution includes a significant increase in electricity consumption complemented by the use of various decarbonized energy sources including bio-energies, ambient heat, and solar power. Carbon-intensive oil products and coal are gradually replaced. In 2020, oil products are the biggest energy source for the French energy system, with a share of 38% of total energy consumption. The shares of gas and electricity are also high, however much lower than that of oil products (26% and 22.7%). By 2050, the presence of oil products reduces to 3.3%. Electricity consumption by the French energy system increases from 333 TWh in 2020 to around 546 TWh in 2050, equivalent to an augmentation of around 64%. The direct usage of bio-energies also increases from 139 TWh in 2020 to 266 TWh to 2050. Consumption of bio-energies includes biofuel, various types of solid biomass and recycled biomass from the paper industry. The total consumption of gas is 302 TWh in 2050, lower than in 2020 (389 TWh). In 2050, electricity is the biggest energy source, representing 32.2% of total consumption. Following electricity, direct bio-energy consumption represents 20.6%, while gas from various production sources amounts to 19%.

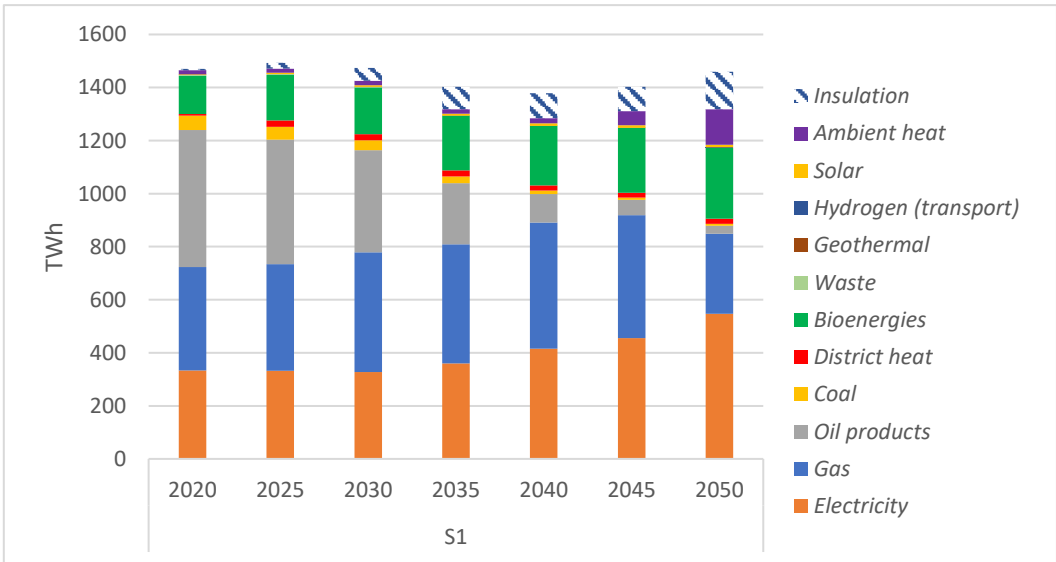


Figure 57 Evolution of final energy consumption by all end-use sectors for the contrafactual scenario (S1)

Gas production in the future will be highly dependent on renewable sources. The rapid development of renewable gas industries begins in 2040, and in 2050, the production of decarbonized gases increases to 220 TWh, representing more than 60% of the gas balance. Biomethane produced from methanization or pyro-gasification (for injection) and hydrogen produced from electricity are the biggest sources. Note that 116 TWh of fossil-based natural gas consumption remains in 2050, representing around 36% of global gas consumption. Emissions from natural gas in 2050 are estimated to be neutralized by various carbon sinks.

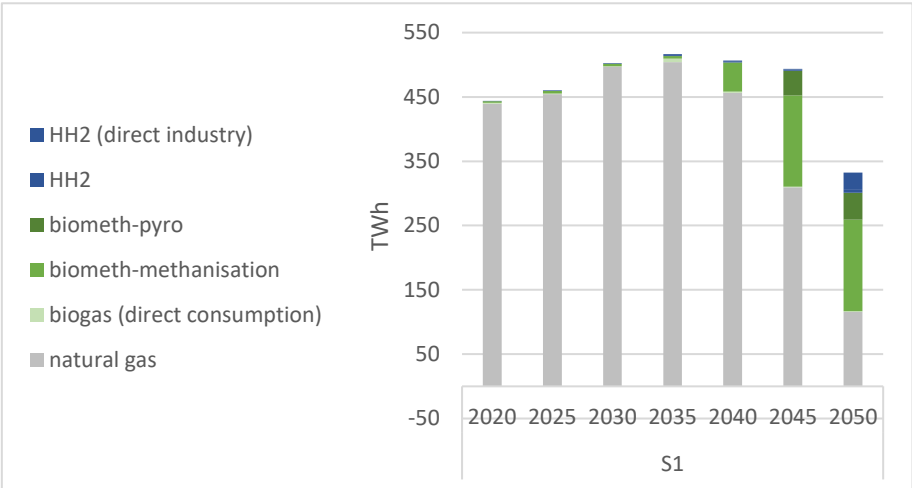


Figure 58 Evolution of energy balance of gas production for the contrafactual scenario

3.3.1.2 Mitigation burden share

Figure 59 presents the trajectory of carbon emissions generated by the global energy system in the contrafactual scenario (S1). We can see that this scenario allows the objective of carbon neutrality to be reached by 2050. In 2050, around 30 MtCO₂e of positive emissions remains, which is expected to be neutralized by natural carbon sinks (SNBC hypothesis). In achieving the global objective, the end-use sectors take different shares of the mitigation burden.

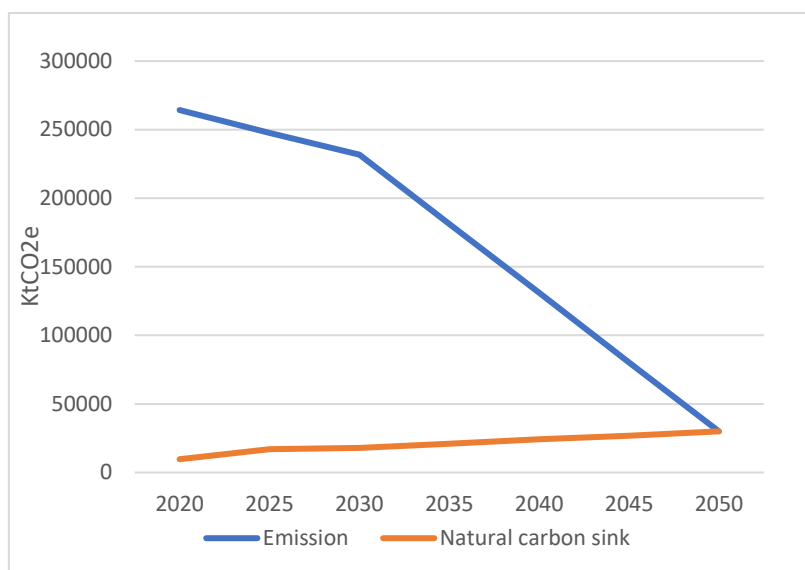


Figure 59 Overall trajectory of carbon emissions⁶⁷

Figure 60 presents the emission trajectories of the industry, transport, agriculture and building sectors. We can see that, in achieving the global objective, the end-use sectors take different shares of the mitigation burden. The transport sector takes the largest burden share of carbon mitigation in the short and middle terms. For the 2025-2040 period, emissions by the transport sector decrease by 60%, which is faster than the pace of overall energy consumption (47%) and far ahead of the industry and building sectors. The carbon mitigation in transport is driven by replacing carbon-intensive oil products by energy sources with a lower emission factor, including biofuel, gas and electricity (Figure 61). After 2025, there is a significant increase in the use of biofuel and gas. By 2040, the consumption of biofuel in transport reaches 69 TWh (first- and second-generation biofuels)⁶⁸. Electrification of transport begins in 2030, and by 2050 electricity consumption reaches 106 TWh. Another important factor that

⁶⁷ Natural carbon sink: the amount of CO₂ neutralized by natural carbon sinks. It is represented as a negative emission in the carbon accounting

⁶⁸ To be noticed that we define the emission factor for first-generation biofuel production as 63.4% lower than conventional oil products, following hypothesis of (DGEC, 2020a). The usage of biofuel which replaces oil products represents very important part of contribution to emission cut in transport.

contributes to mitigating transport emissions is improved fuel efficiency. Although the demand scenario simulates higher mobility needs in the future, especially for travel by private car, the total final energy demand reduces by around 25% in 2050. Fuel demand is reduced due to the massive deployment of more energy-efficient electric and hybrid cars.

For industry, a 26% cut in emissions is achieved between 2020 and 2045 (35 years), a mitigation rate lower than in the transport sector. This involves replacing the consumption of oil products and hard coals with gas and electricity. We can observe an important increase in final energy demand after 2025 due to the assumed growth of diverse industrial branches. After 2045, there is a significant increase in electricity consumption, which replaces part of the share of gas, leading to an acceleration in mitigation. By 2050, gas and electricity explain most of the final energy demand in industry. Consumption of gas and electricity reaches 174 TWh and 165 TWh, representing 42% and 40% of total energy demand. The simulated trajectory of carbon emissions suggests that the industry sector has the lowest direct mitigation rate of energy consumption: by 2050, 20 MtCO_{2e} of carbon emissions remains for the industry sector, representing around one third of its emissions in 2020. These emissions originate from the use of natural gas and are estimated to be neutralized by CCS.

For residential and tertiary buildings, significant carbon mitigation efforts are achieved after 2030: in 2030, emissions from the building sector remain at 85% of the 2020 level, while in 2050, the sector is nearly carbon free. Efforts to decarbonize the building sector after 2030 mainly consist in an acceleration in building renovation, more usage of solid biomass, and electrification by heat pumps. We observe a sharp decrease in carbon emissions between 2040 and 2045. This is explained by the integration of decarbonized biomethane in the gas supply network for buildings. The consumption of renewable gases (biomethane from methanization and gasification) reaches 132 TWh in 2045, which is relatively around 4 times their level in 2040. For the period 2045-2050, there is also a significant increase in the usage of heat pumps and thermal insulation which replaces the share of gas. This allows the building sector to achieve the last step of mitigation to attain a carbon-free system. For the agriculture sector, emissions reduce steadily until 2050. By 2050, emissions from agricultural usage decrease to around half of the 2020 level. This is achieved by replacing a significant part of oil product consumption by bio-energies. Note that the model treats only the share of emissions from the agriculture sector that is linked with energy usage.

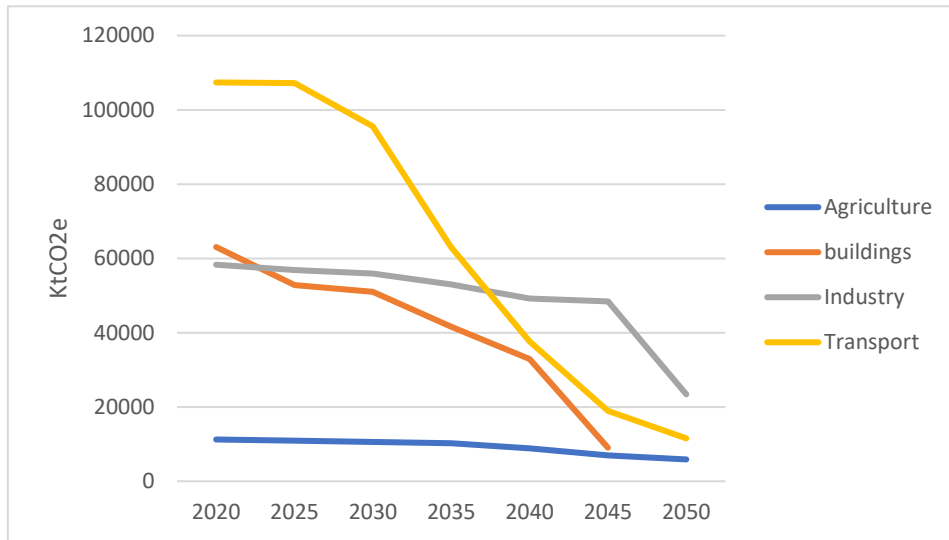


Figure 60 Mitigation trajectory of the industry, transport, and building sectors⁶⁹

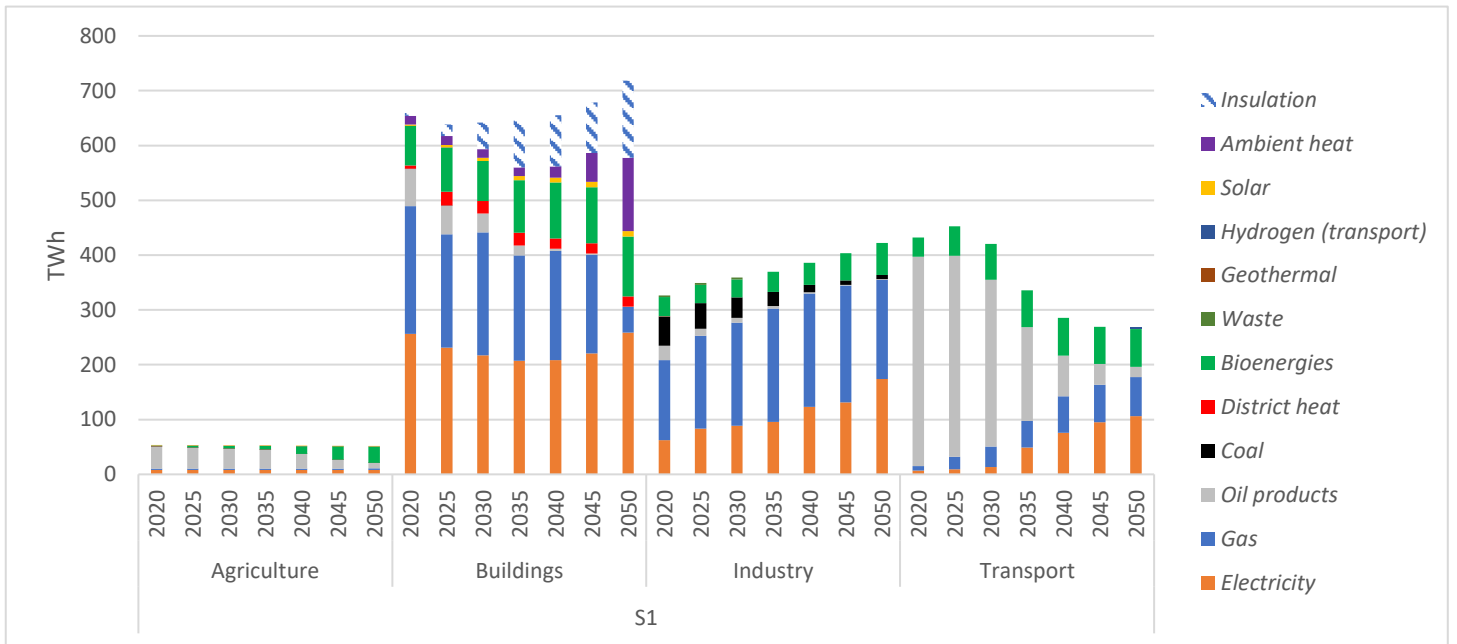


Figure 61 Evolution of final energy balance per sector, the contrafactual scenario

⁶⁹ Emission from buildings reduce to 0 by 2050

3.3.1.3 Solution for space heating

Figure 62 and Figure 63 present the evolution of the energy balance for space heating and the installed capacity of heating equipment for residential and tertiary buildings. Space heating represents the largest share of energy demand from buildings. The energy transition for space heating features two phases. In the middle term (before 2040), carbon-intensive energies, and especially oil heating, will be replaced by gas, solid biomass, and energy savings from thermal insulation. In the long term, as discussed in the previous section, the share of gas reduces significantly, and will be replaced by heat pumps and thermal insulation.

By 2040, oil products will nearly disappear in the energy balance of space heating. We can see a considerable increase in the number of gas boilers in the heating equipment stock before 2040, replacing a large share of oil boilers. The total installed capacity of gas boilers reaches 92 GW, compared with 55 GW in 2020. The investment choice for gas as a heating system might be explained by several reasons: firstly, the emission factor of gas is considerably lower than that of oil products, and the emission target in the middle term still allows for the usage of gas; secondly, low-temperature and condensing boilers are solutions requiring relatively low investment costs among the range of high-performance equipment, such as electric heat pumps and solar heating.

In the long term (2040-2050), especially in the five years after 2045, we observe a sharp decrease in gas consumption in the building sector. Gas consumption for heating will reduce to 22 TWh by 2050, compared with 168 TWh in 2040. As gas demand reduces to a very low level in 2050, a considerable quantity of gas boilers remains in the equipment stock (46GW, around half of the 2040 level). This means an anticipated renewal of heating equipment.

After 2045, there is a significant increase in heat pump usage (electricity and ambient heat), a renovation that replaces the share of gas in the energy balance. The total energy consumption by heat pumps reaches 197 TWh (64 TWh of electricity and 132 TWh of ambient heat), compared to 77 TWh in 2045. In 2050, the installed capacity of electric heat pumps reaches 76 GW.

If we suppose a unitary electric capacity of 7 kW (estimation of required HP capacity for an individual house of 100 m² located in the île-de-France region, according to hypotheses of gas supplier (Engie) (Engie, 2022)), the result of the baseline scenario suggests that there will be around 10 million air-source electric heat pumps installed in residential and tertiary buildings. We also note that air-sourced heat pumps (Air/water heat pump, AWHP, and air/air heat pump) will constitute the total market share of electric heat pumps in the future, and that geothermal heat pumps with a higher upfront cost and a less accessible heating source will not be the future investment choice of the residential building

system. Thermal insulation efforts in the five years leading up to 2050 to avoid residual emissions leads to around 40 TWh of additional energy savings, equivalent to a 43% increase.

One possible explanation of the significant changes in the energy balance after 2045 is stronger competition for gas and electricity usage among end-use sectors due to a tighter emission constraint in order to achieve carbon neutrality. In 2050, gas supply is significantly reduced with a decrease in natural gas imports, and more than 60% of gas production is based on renewable sources.

While gas demand is significantly reduced in buildings, its share in transport and industry remains high. Technologies for industry and transport demand are highly fuel dependent. This creates a stronger need for renewable gas for carbon mitigation since these technologies have fewer alternatives. For residential and tertiary buildings, carbon mitigation can be less dependent on gas thanks to other efficient solutions, including heat pumps and thermal insulation. For the electricity system, the supply potential from nuclear and renewable power plants is limited. Faced with higher demand, investments are required in equipment with high electric efficiency.

In 2050, electric heat pumps become the first heating source, representing around 40% of total final energy demand (electricity and ambient heat). Solid biomass also represents a considerable share of the energy balance (100 TWh, 21% of total consumption), while gas only concerns around 4.3% of the total energy demand for heating. The other heating solutions include electric convectors and district heating. Continuous renovation efforts that improve thermal quality lead to a final energy saving of 140 TWh, representing 28% of total consumption for heating in 2050.

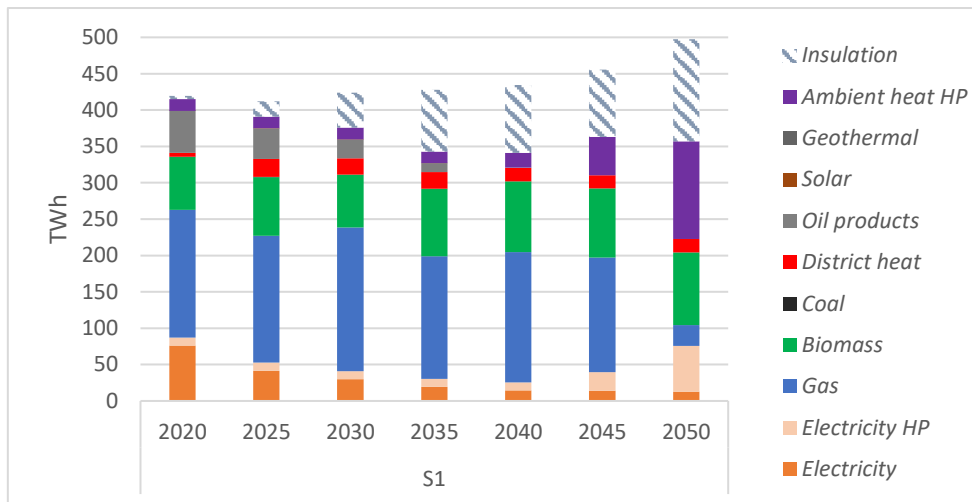


Figure 62 Evolution of final energy balance for space heating under S1

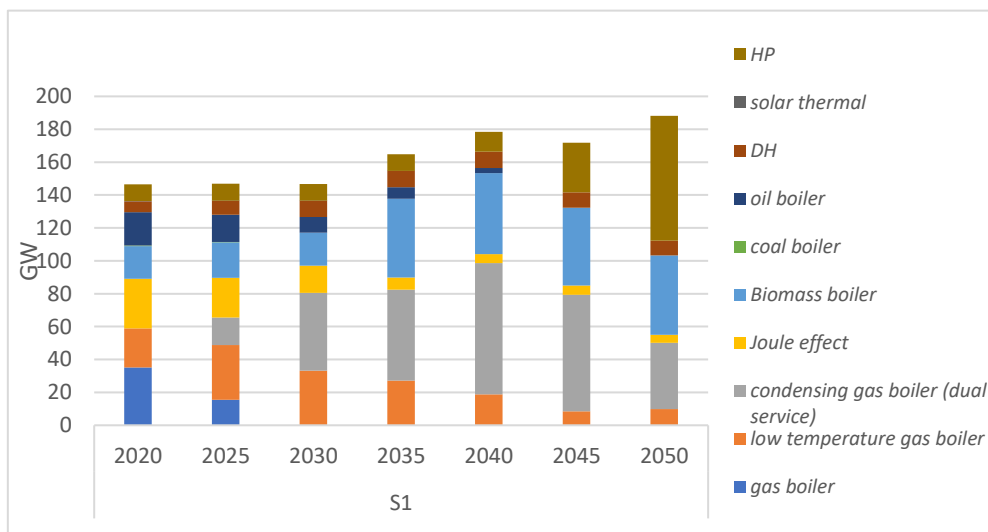


Figure 63 Evolution of installed capacity of heating equipment, S1

3.3.2 Impact of extreme cold demand situation and the role of HHP

The contrafactual scenario introduced above provides us a reference to compare with other cases in order to better reply to our research question. In this part, we present the modeling results of S2 and S3, two scenarios that interpret an extreme cold situation, while simulating different investment conditions for hybrid heat pumps. By studying these two cases we will better understand the long-term effect of extreme cold events and the role of hybrid heat pumps.

3.3.2.1 Choice for space heating with the presence of extreme cold

Figure 64 and *Figure 65* present the evolution of final energy consumption and the equipment stock for heating under scenarios S2 and S3. In S3, when introducing an extreme cold situation, the building sector presents a globally similar heating solution structure in 2050. However, observable changes occur in the energy balance of heat pumps and gas. The energy system continues to invest in a large quantity of standalone heat pumps. As the overall energy efficiency of electric heat pumps is lower, with the same volume of electricity consumption, their contribution to heat production is reduced. Under scenario S3, installed HPs consume 67 TWh of electricity and 124 TWh of ambient heat. With higher electricity consumption, the contribution to heat production of installed electric heat pumps in S3 is 5% lower. The additional part of energy demand that is not satisfied by electric heat pumps is compensated by greater gas usage: under S3, gas consumption in 2050 is 41 TWh, 15 TWh more than in S1.

In S2 where investment in HHPs is allowed, the building sector chooses to integrate a large quantity of hybrid heat pumps that replaces the share of standalone heat pumps. Under S2, the total installed capacity of HPs is 70 GW, similar to the level of S3. The HHP capacity reaches 24 GW in 2050, which is 34% of the total installed capacity of electric heat pumps. We note that the entire new installation of HHPs takes place between 2045 and 2050. HHPs become a competitive option only at the end of the period, when competition between energy resources reaches a higher level. Installed HHPs present an annual consumption of 17 TWh of electricity, 35 TWh of ambient heat, and 5 TWh of gas. Final energy demand from standalone heat pumps is 48 TWh of electricity and 88 TWh of ambient heat.

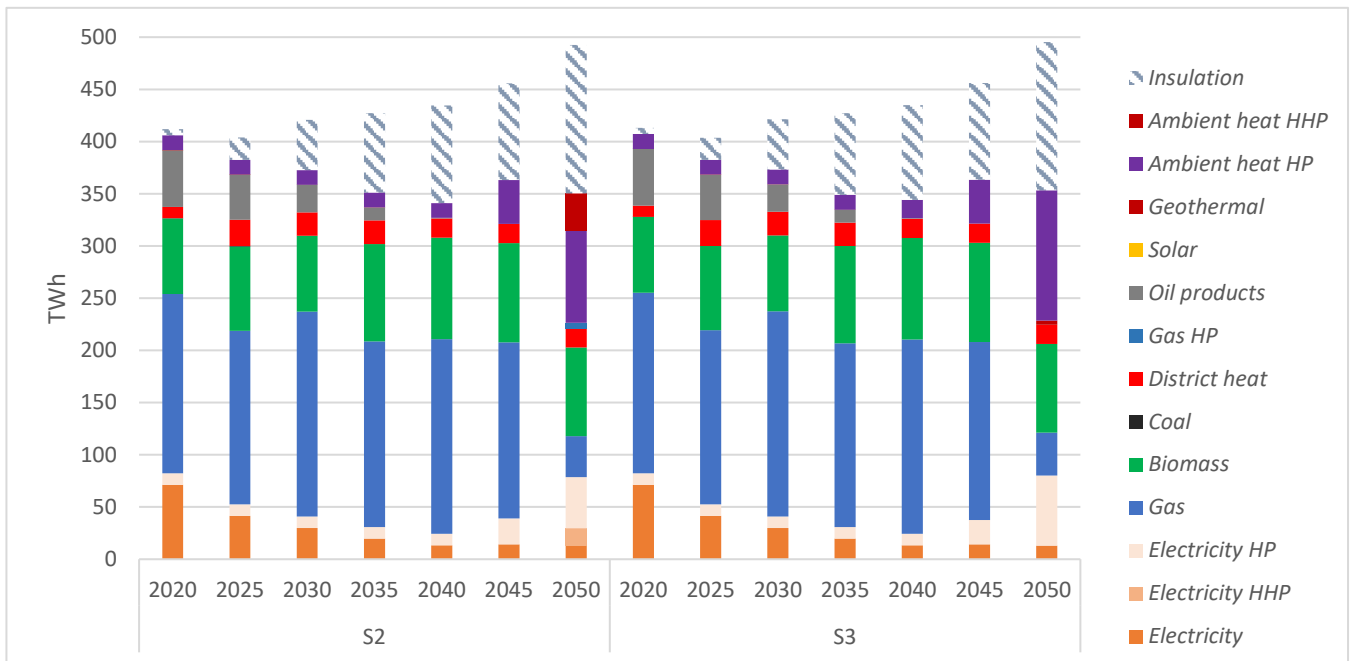


Figure 64 Final energy balance for residential and tertiary space heating under S2 and S3

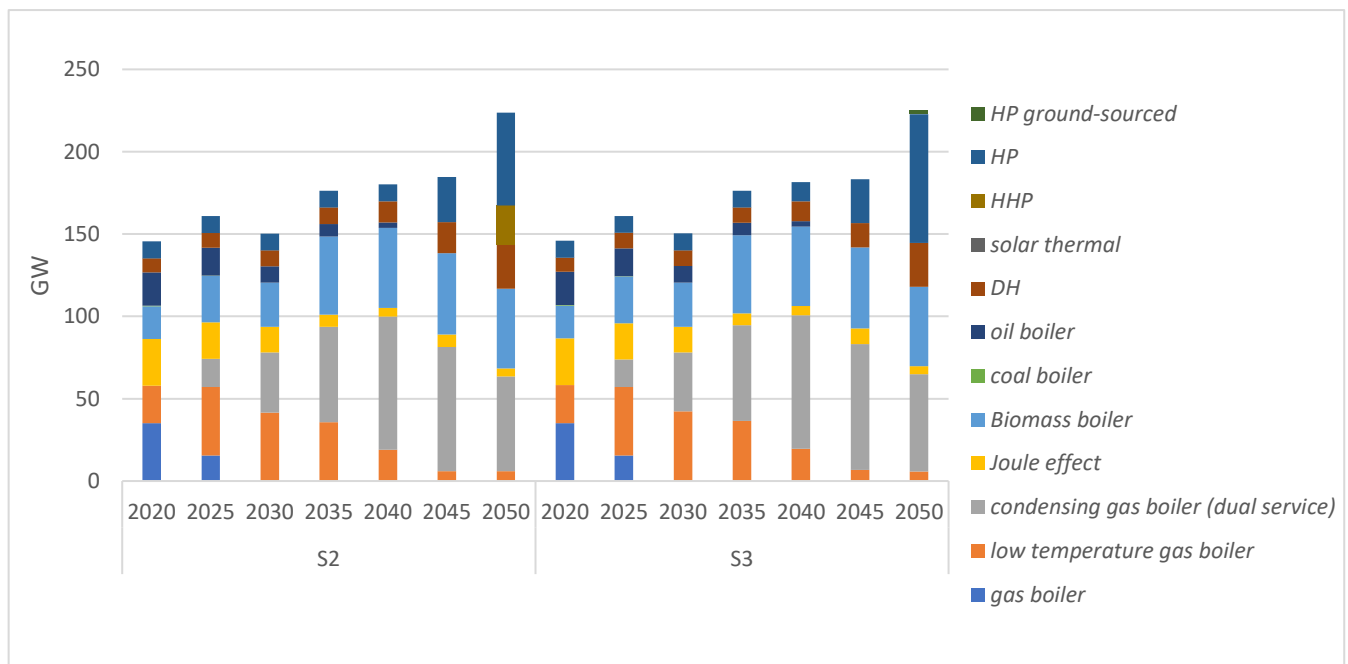


Figure 65 Installed capacity of heating equipment under S2 and S3

3.3.2.2 Effect of hybrid heat pumps on the electricity system

Figure 66 presents in detail the energy consumption of installed HHPs and HPs during extreme cold and cold periods under S2. We observe that the installed HHPs use gas boilers to produce heat during cold and extreme cold periods, while standalone HPs operate only with electricity. The final energy balance of standalone HPs for cold and extreme cold periods is composed of 11 TWh of electricity and 12 TWh of ambient heat. For the same period, installed HHPs consume 5 TWh of gas, replacing the major part of electricity consumption. These results suggest that hybrid heat pumps have a positive effect in reducing electricity demand for heating in cold weather. Besides, as HHPs avoid operating with electric heat pumps in extreme cold situations, they have higher yearly energy efficiency: the yearly COP of HHPs reaches 3.09, significantly higher than HPs (2.84).

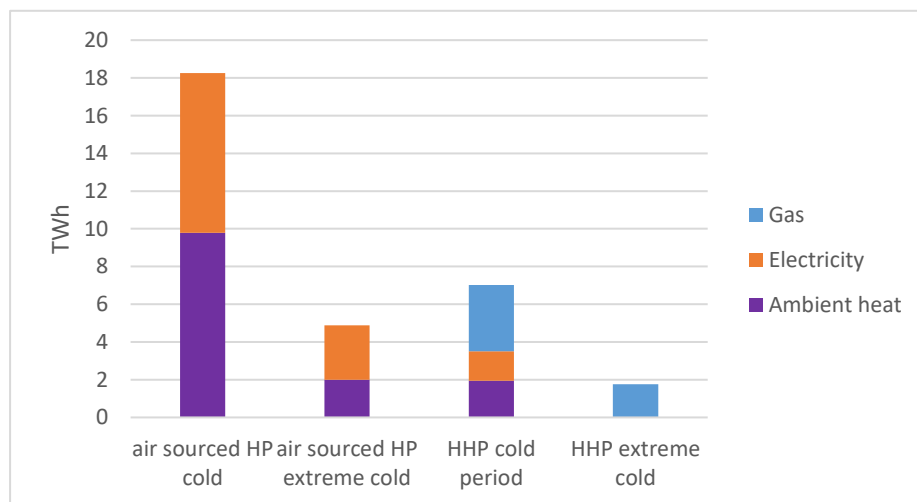


Figure 66 Details of energy consumption of HPs and HHPs under S2 for 2050

In order to better illustrate the effects of hybrid heat pumps, we compare the balance of electricity consumption and production between S2, a scenario featuring high investment into hybrid heat pumps, and S3, which features only standalone heat pumps. Figure 67 details the electricity consumption by end-use branches for S2 and S3. We note that integration of HHPs has an impact on the structure of electricity consumption. The total electricity demand under scenarios with HHP (S2) is 583 TWh, slightly lower than S3 (588 TWh). Compared with a scenario without HHP, electricity demand from the building sector is slightly higher in S2 (6 TWh). This is explained by more usage of electricity for cooking, which replaces the use of gas (around 10 TWh). Apart from buildings, electricity demand from industry and transport remains the same in S2 and S3. However, the consumption of electricity for hydrogen production (electrolysis) is significantly lower in S2 (13 TWh). Additional hydrogen production in S3 mainly contributes to industrial production. This is because, in S2, when gas demand for the building

sector is lower, more gas can be used to satisfy industrial demand, thus reducing the need for hydrogen. This may have a positive effect on reducing the system’s cost as hydrogen production features high upfront and operational costs.

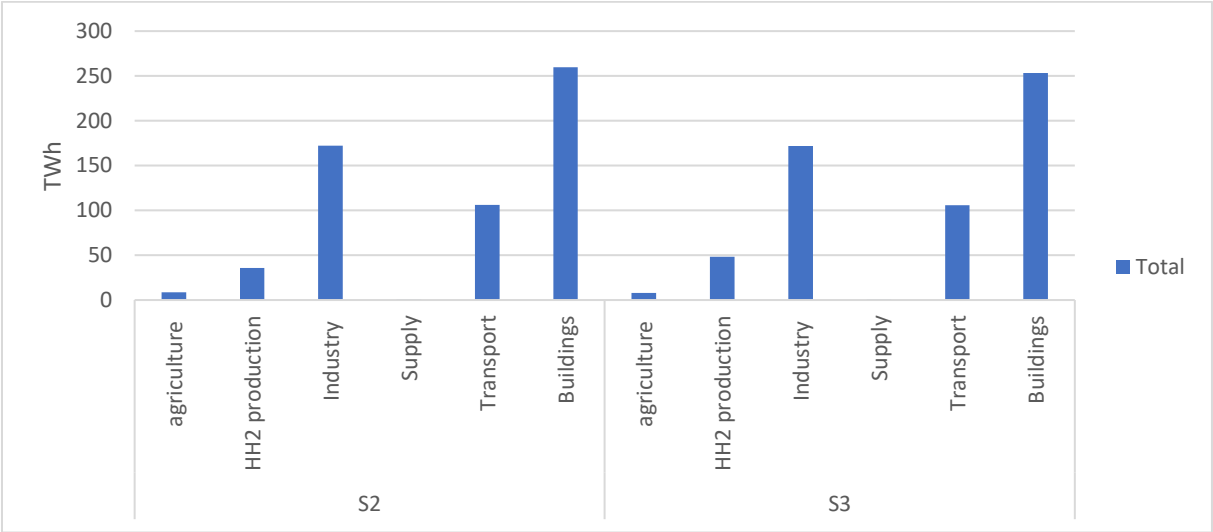


Figure 67 Electricity consumption by end-use sector in 2050, comparison between S2 and S3

As for electricity supply system, nuclear power, solar, wind and hydraulic are the main energy sources for electricity production in 2050. By comparing S2 and S3 in Figure 68, we can see that the changes in electricity demand do not have a significant impact on the energy balance.

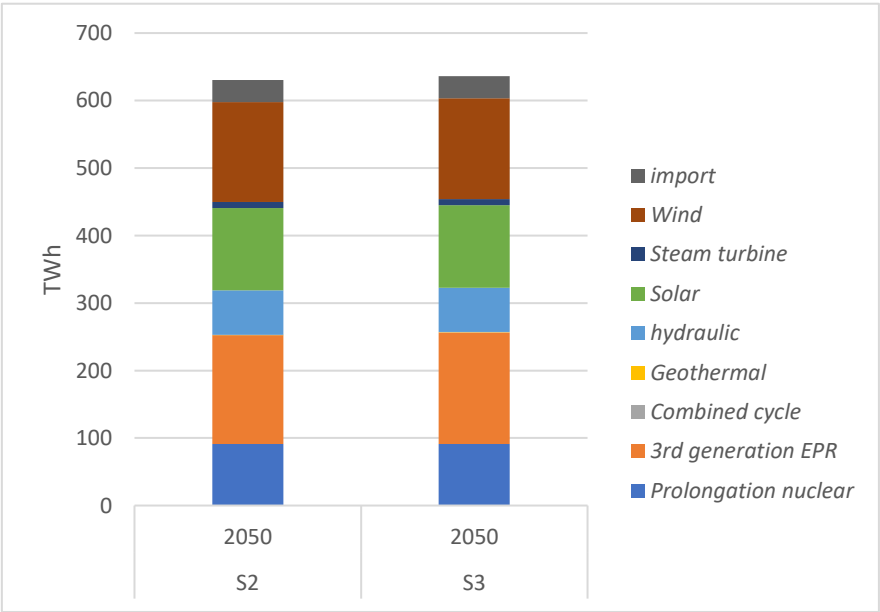


Figure 68 Electricity production mix under S2 and S3 in 2050

3.3.2.3 Economic analysis

Thanks to its cost minimization approach, TIMES also gives a consistent economic balance for each scenario. The figure below presents the differences in the annual cost of the building energy system for S2 and S3 compared with the contrafactual scenario. It corresponds to all the fixed and variable expenditures, including the annual investment cost, fixed and variable operation and maintenance costs, and the fuel cost. The difference in cost for the three scenarios is relatively low. We note that for time steps before 2050, the cost of the building energy system in S2 and S3 is slightly lower than for the contrafactual scenario. This is explained by lower levels of investments in electric heat pumps at a higher cost. In 2050, the scenarios with the presence of extreme cold events have a more significant cost surplus than the contrafactual scenario. When accounting for extreme cold situations, installed electric heat pumps are less energy efficient. The building energy system requires an equipment stock with a larger capacity to cover the heating demand. Additional gas boiler and district heating capacities are required for S2 and S3, generating a higher investment cost. We also observe that the cost of the building energy system in S2 is higher than in S3, due to investments in hybrid heat pumps at a higher cost. However, the difference is relatively small considering the absolute value of annual costs for building sector: for scenario S2, the building system requires around 48,000 million euros of annual costs in 2050.

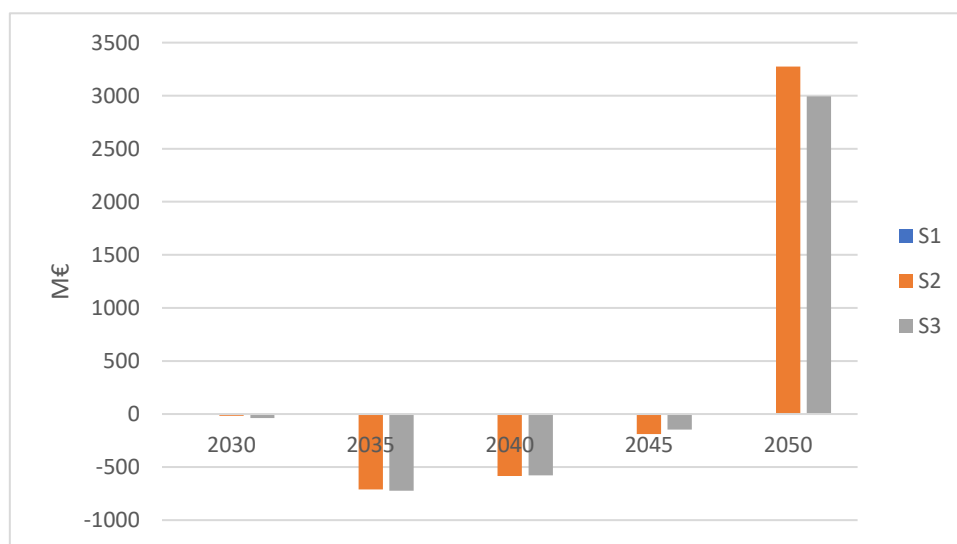


Figure 69 Evolution of annual costs for the building sector for S2 and S3 (difference compared with S1)

3.3.3 The role of insulation in the future building sector

Scenario S4 represents the case when the theoretical energy gain by insulation retrofit cannot be reached due to impediments in the future. By comparing the results of S2 and S4, we will be able to illustrate how the building energy system will react in an unfavorable case of thermal insulation. [Figure 70](#) and [Figure 71](#) present the evolution of the energy balance and the installed equipment capacity for space heating for these two scenarios. The simulation results of S4 show a significantly lower contribution of thermal insulation for heating in both the medium and long terms. In 2040, energy savings amount to 65 TWh in S4, 25% lower than in S2, while in 2050, the thermal insulation difference between S2 and S4 reaches 52 TWh, which is more than 10% of total final demand. A lower contribution of insulation induces a higher consumption of gas after 2035: in 2040, gas consumption in S4 is 208 TWh, around 12% higher than S2 (186 TWh); in 2050 around 46 TWh of gas remains in the energy balance in S4, compared to 39 TWh in S2. Apart from gas, after 2040, we observe a significant increase in HP production in S4. In 2050, the total final energy consumption by heat pumps under S4 reaches 217 TWh (electricity, ambient heat and gas), around 12% higher than S2 (193 TWh). We observe that in S4, the energy system chooses to invest much more in standalone heat pumps than in HHPs. In 2050, the Installed capacity of HHPs under S4 is 13 GW, only around half of the installed capacity in S2. The share of HHPs in overall HP capacity is 28%, and lower than 43% in S2. This could be explained by the fact that, as HHP becomes a competitive option only after 2045, the building system has already invested in a significant volume of standalone HPs and condensing boilers in the periods before, meaning that there is less need for integration of HHPs in 2050. Besides, due to the lower level of thermal insulation, the building sector requires an equipment stock with a higher capacity. Under S4, the total installed capacity of heating equipment is around 235 GW, 19% higher than in S2.

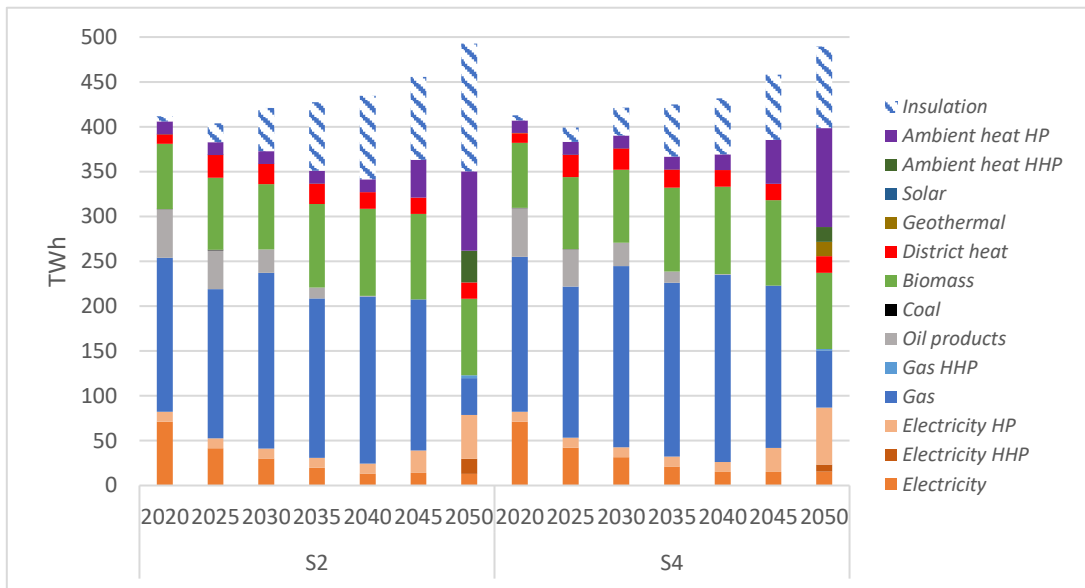


Figure 70 Evolution of energy balance of space heating under S2 and S4

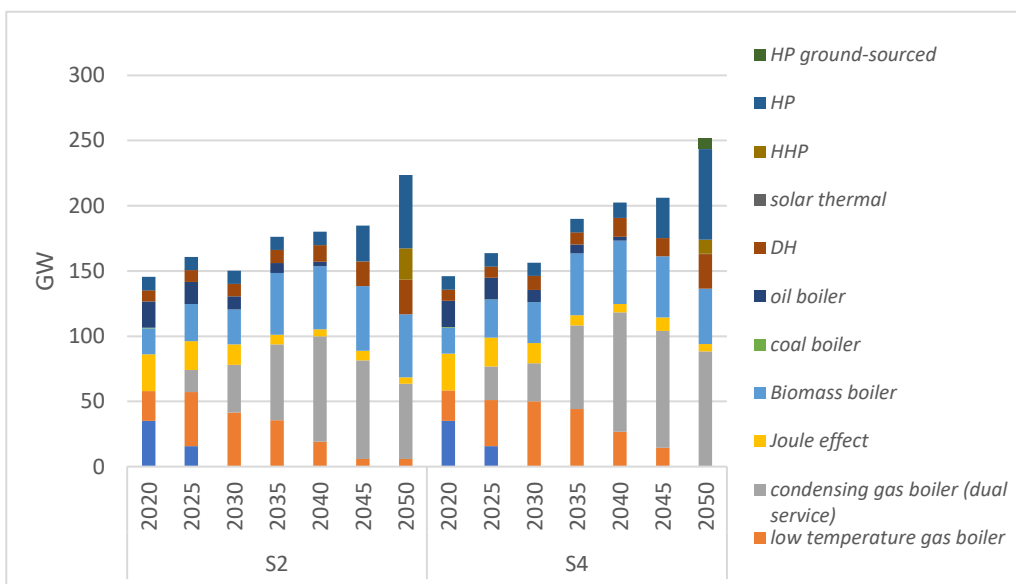


Figure 71 Evolution of building equipment stock under S2 and S4

A lower level of insulation in the building sector induces significant changes in the total cost required by the French energy system to reach carbon neutrality. Figure 72 presents the difference of annual costs between S4 and S2 for buildings, energy supply, industry, and the transport sector. In 2050, the cost for the building sector is significantly lower in S4. This is explained by the fact that the building energy system reduces investments in thermal insulation and invests in more gas boilers and heat pumps with lower upfront costs as replacements. However, the increased use of gas in buildings induces, firstly, a cost surplus in the transport sector due to more investment in electric vehicles to replace gas, and secondly, a higher gas supply cost linked with more production of renewable gases. Compared with S2, S4 requires significantly higher expenditure from the global system as the cost surplus in the energy supply and transport sectors is much higher than the difference in the building sector.

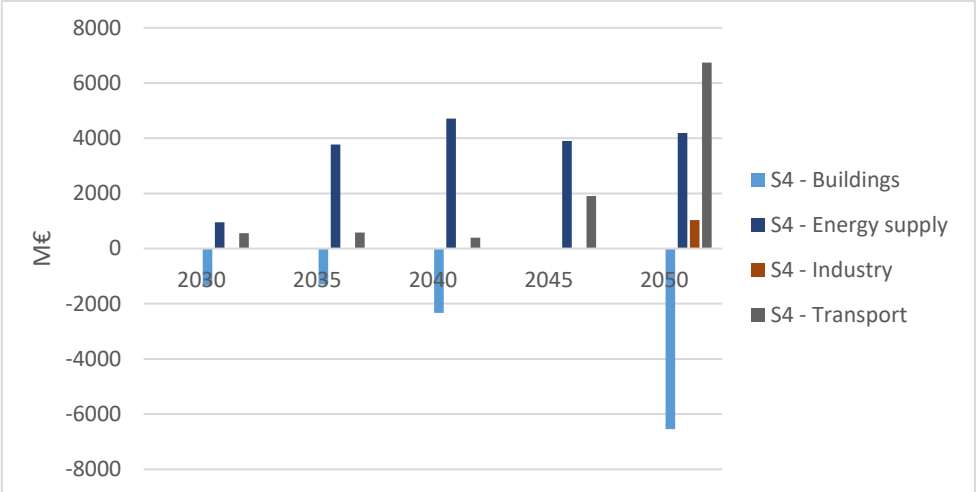


Figure 72 Difference in annual cost per energy sector between S4 and S2

3.3.4 Proposed solutions for various mitigation paces between 2030 and 2050

The previous sections are based on a linear mitigation pace between 2030 and 2050. However, various possibilities exist for the intermediary time steps. It is important to consider these situations and understand how the energy system reacts. As introduced in the second section, in order to reply to this question, five variants of mitigation pace are elaborated, including three variants with an increasing level of anticipation for carbon mitigation before 2050, and two variants of a late mitigation pace. Here we make an analysis of the results obtained from these five scenarios.

3.3.4.1 Scenarios with anticipated mitigation efforts between 2030 and 2045

Figure 73 illustrates the simulated trajectories of total final energy consumption for scenario S2 and three variants of anticipated decarbonization after 2030. We note that, for the global energy system, no significant differences in the proposed solution for 2050 can be observed between the three variants and the S2. However, the different mitigation pace greatly changes the solutions for intermediary time steps between 2030 and 2050. The results suggest that, compared to S2, a mitigation pace ahead of schedule before 2050 leads to an earlier decrease in gas consumption, as well as earlier electrification of the energy system. In 2040, the usage of gas in the energy system decreases from 473 TWh in S2 to 303 TWh to S2_advanced3 (34% lower) with the highest mitigation rate level in 2040, while electricity consumption follows an increasing order from S2 to S2_advance3, from 423 TWh under S2 to 532 TWh under S2_advanced3 (around 32% higher).

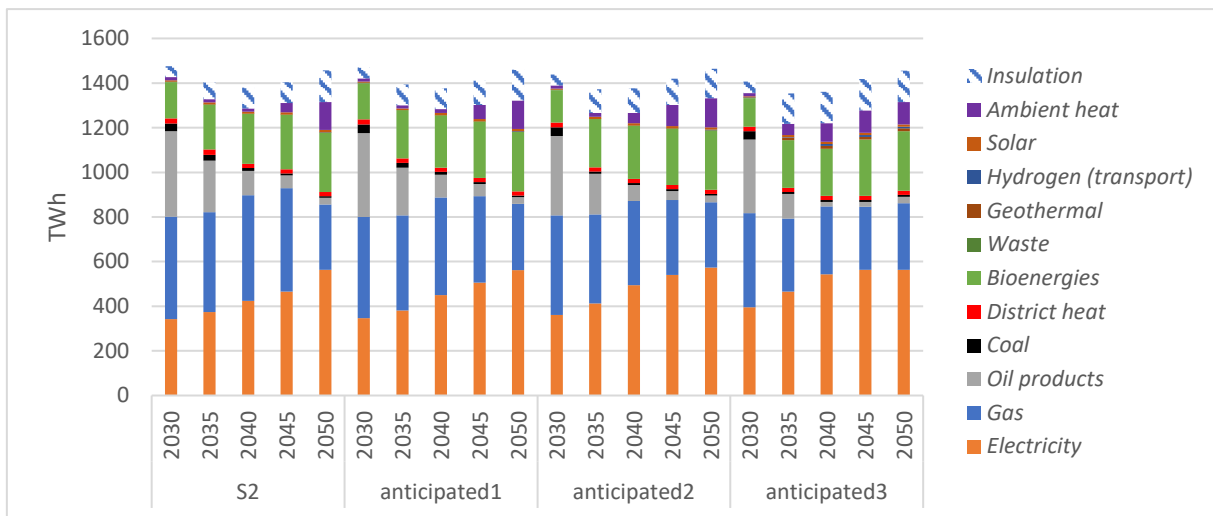


Figure 73 Trajectory of final energy demand between 2030 and 2050 under 3 variants of advanced mitigation target

From the evolution of the sectorial energy balance, we observe that additional efforts to achieve the advanced mitigation goal are required for all end-use sectors including building, transport, and industry. [Figure 75](#) and [Figure 76](#) compare the evolution of the final energy balance under S2 and S2_advanced3. For the building sector, under S2_advanced3, a significant reduction in gas consumption takes place between 2030 and 2035, much earlier than in S2. For the transport sector, the decline of oil products follows a faster pace. To replace oil products, electricity consumption increases between 2035 and 2045. For industry, the level of electrification is significantly higher for the intermediary time slices: in 2040, electricity consumption in industry reaches 168 TWh, compared with 128 TWh in S2 (31% higher).

[Figure 74](#) illustrates the details of gas production for the three variants and scenario S2. We note that a stricter emission constraint during previous periods before 2045 induces earlier integration of renewable gases as well in the gas supply mix. Under S2_advanced3, the total gas production by renewable sources reaches 209 TWh by 2040, around 4 times that of S2, and other branches of new gas other than methanization, such as hydrogen and pyro-gasification, begin to develop earlier.

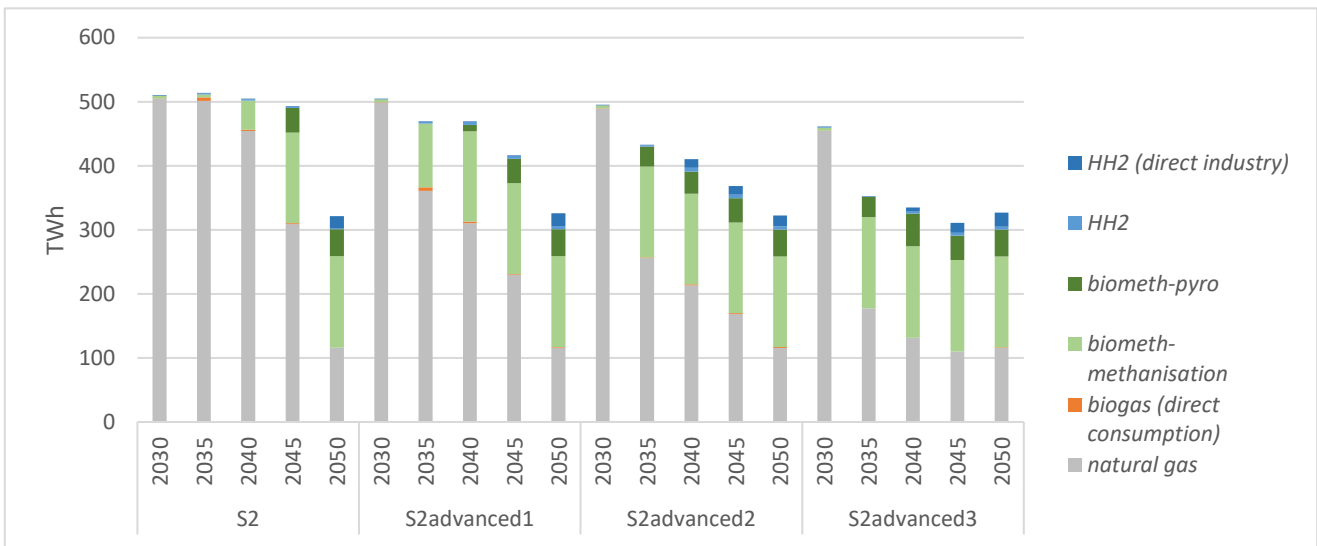


Figure 74 Evolution of balance of gas system (HH2 included) for three variants of anticipated mitigation pace

Figure 75 and Figure 76 compare the evolution of the sectorial energy balance for 2030-2050 between scenario S2_anticipated3 (with the highest level of anticipation for carbon mitigation) and scenario S2. We observe that additional efforts to achieve an anticipated mitigation goal are required for all end-use sectors including building, transport and industry.

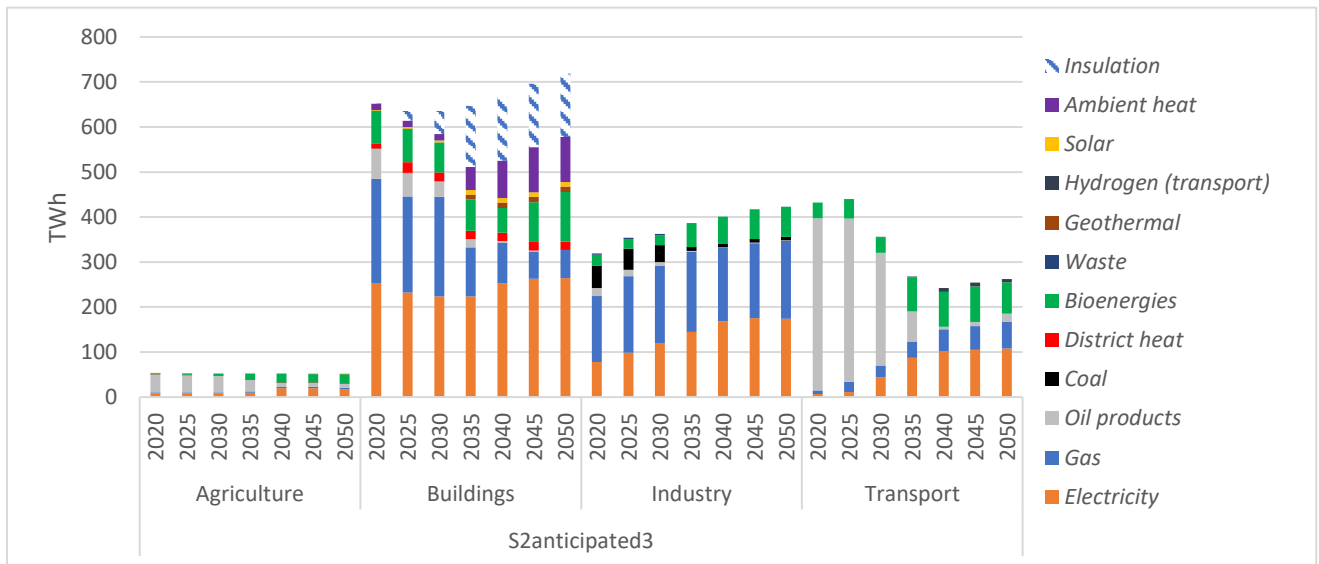


Figure 75 Trajectory of final energy consumption by end-use sector for S2_anticipated3

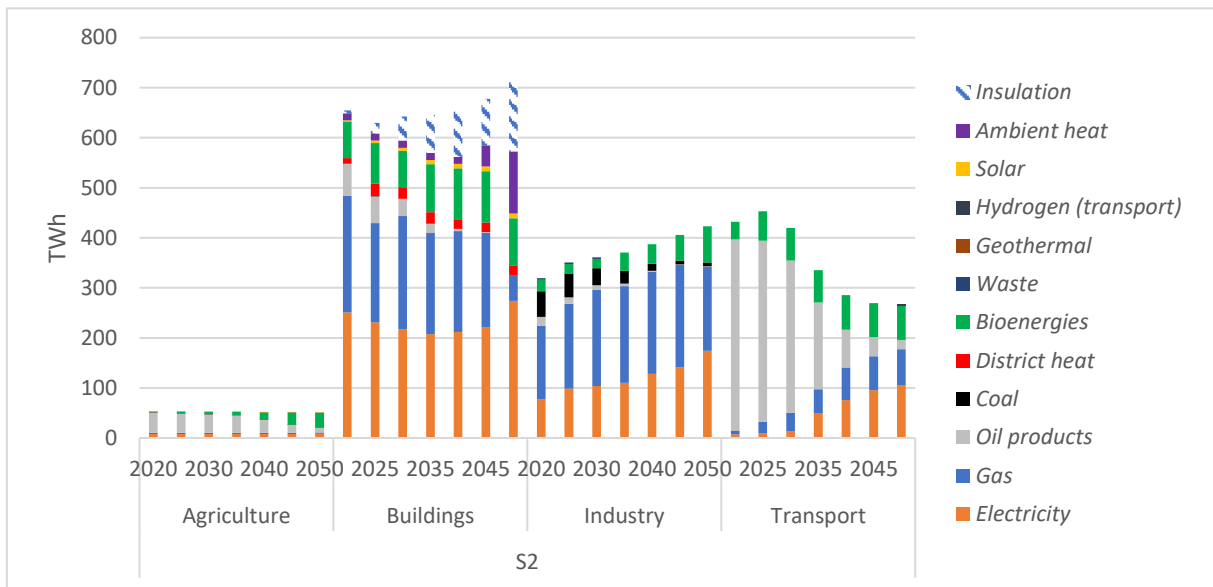


Figure 76 Trajectory of final energy consumption by end-use sector for S2

Figure 77 presents the details of space heating options for S2 and the three variants of advanced mitigation. With the anticipated mitigation goal, the integration of high volumes of electric heat pumps is achieved earlier. Under S2_advance3, electricity consumption by HPs and HHPs reaches 30 TWh by 2035, almost three times their level in S2 for the same period (11 TWh). By 2050, final energy demand from electric heat pumps remains almost the same as S2 for all variants with advanced mitigation efforts, while for all the variants, the share of HHP is lower than in the reference case (S2). This may be for the same reason that we put forward for the low insulation scenario. Apart from electricity, the consumption of gas in 2050 under variants of advanced mitigation (advance2 and advance3) is slightly higher than in S2 (10 TWh), as lower demand from the industry and transport sectors generates less competition for gas usage.

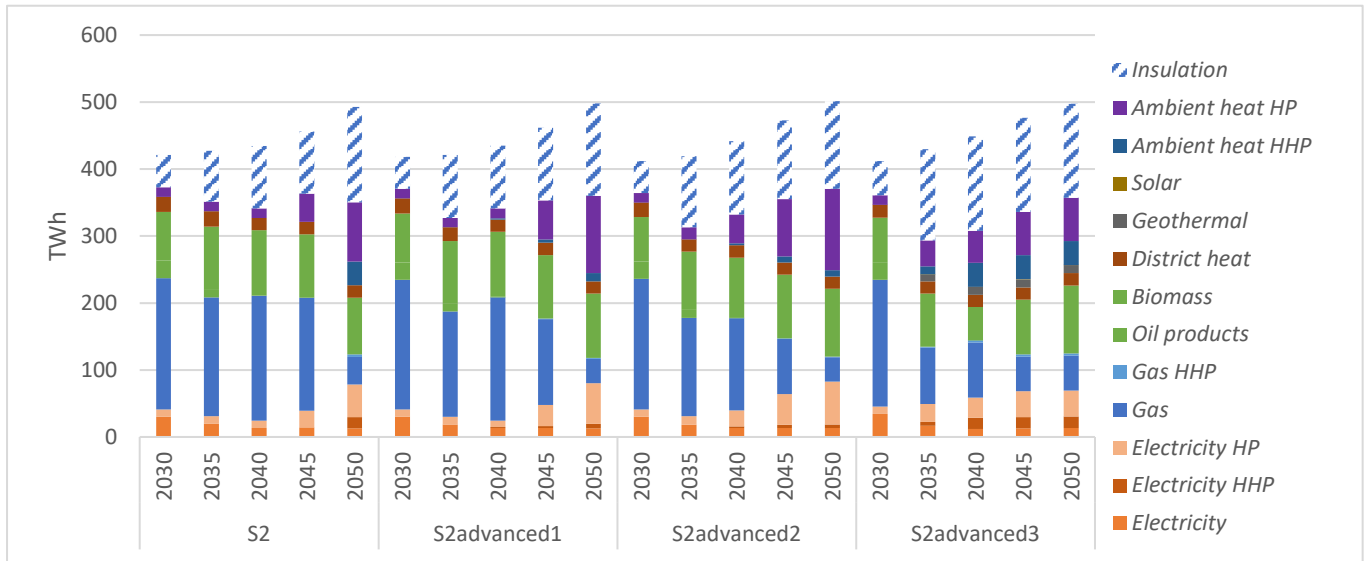


Figure 77 Final energy balance of space heating for 3 variants of anticipated mitigation

3.3.4.2 Scenarios of late achievement of mitigation target between 2030 and 2050

Compared with scenarios of advanced mitigation between 2030 and 2045, scenarios of late mitigation present reverse tendencies for the pace of gas and electricity consumption (Figure 78). As a lower requirement for carbon mitigation is required for the first years, the consumption of gas remains at a higher level. Following the pace of carbon emission, a more drastic transition of the final energy balance takes place in the last five years before 2050. For both the building and industry sectors, compared to S2, a higher volume of gas remains in the energy balance till 2045 (Figure 79).

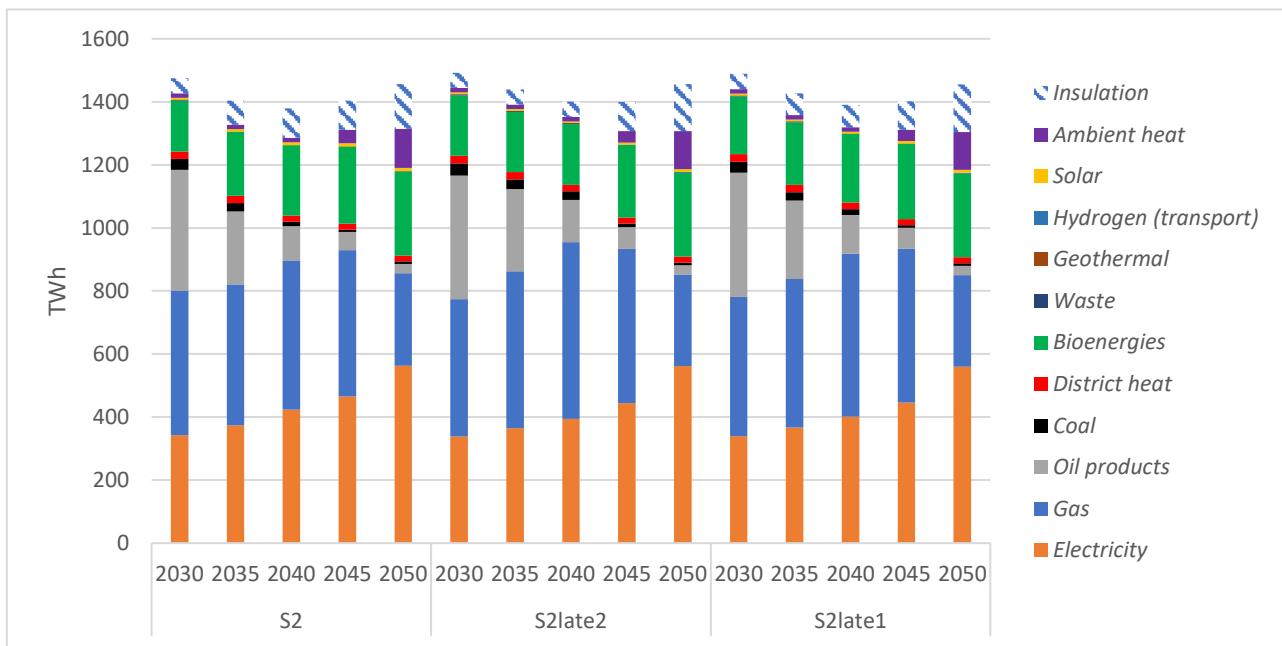


Figure 78 Trajectory of final energy demand between 2030 and 2050 under 2 variants of late achievement of mitigation target

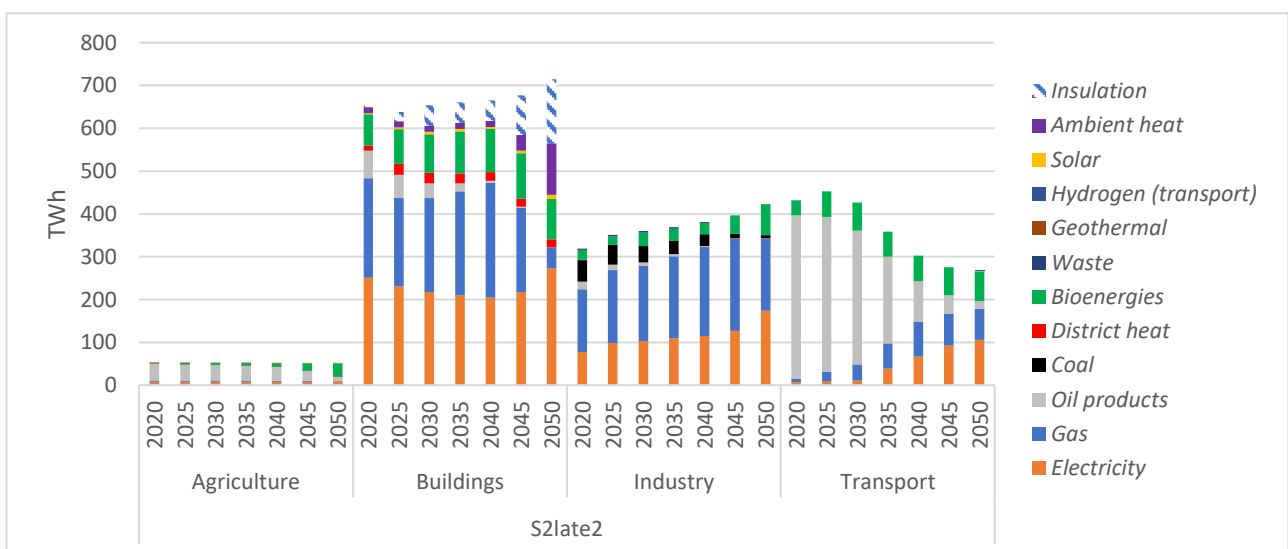


Figure 79 Trajectory of final energy consumption by end-use sector for S2_late2

As for the energy choice for space heating, the late mitigation pace variants present a significantly higher demand for gas for the intermediary periods. Under S2late2, gas consumption for heating reaches 239 TWh in 2040, around 28.5% higher than in S2. As more gas heating is allowed, there is less requirement for thermal insulation with higher investment costs between 2030 and 2040.

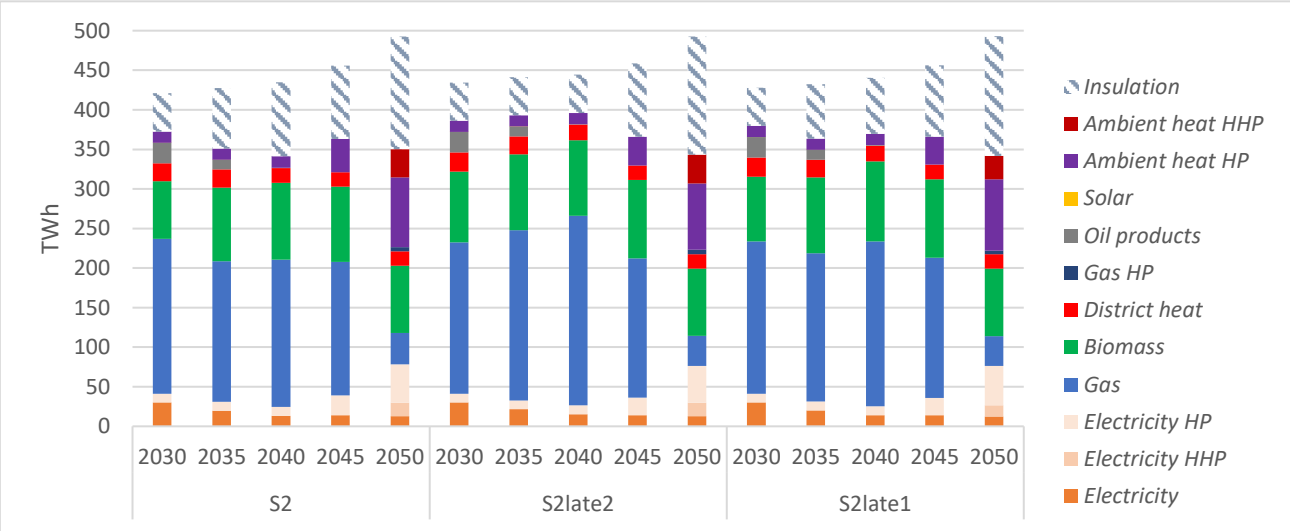


Figure 80 Final energy balance of space heating for S2 and 2 variants of late mitigation

3.3.4.3 Economic analysis

Figure 81 presents the difference between the total annual cost for the five mitigation pace variants compared with scenario S2. For the intermediary time steps before 2050, a significant cost surplus compared to S2 can be observed for all three anticipated mitigation pace variants. We also note that the cost surplus may not follow a linear growth with the level of additional efforts to cut emissions. To abate carbon emissions to a low level before 2045 incurs much higher costs. Scenario S2_anticipated3 requires around a 40% cut in additional emissions compared with scenario S2_anticipated2 in 2040, while its annual cost surplus is more than twice the cost of S2_anticipated2, far exceeding the additional mitigation rate.

The higher annual cost of the energy system for time steps before 2050 is induced by additional efforts from several sectors: firstly, for the building sector (Figure 82), the advanced mitigation target requires anticipated investment (compared to S2) in electric heat pumps with higher costs; secondly, in order to decarbonize the gas supply, the energy system opts to invest in renewable gases at an earlier stage, which increases the cost of the energy supply

(Figure 83). Under scenario S2_anticipated3, in 2040, buildings account for around 43% of the total cost surplus, 37% for the energy supply, and 15% for transport.

In 2050, all the variants of anticipated carbon mitigation have a lower cost than in the S2. However, the gap in absolute value is much lower than for the previous time steps. The global cost of all the periods is significantly higher. This suggests that imposing an anticipated mitigation target is a more expensive solution to reach carbon neutrality, due to the high additional cost required for time steps before 2050.

For the two late mitigation pace scenarios, the cost trajectories present a reverse trend. For the three time steps between 2035 and 2045, the annual cost of the energy system is significantly lower than in S2. This is logically explained by the lower investment in electric heat pumps for buildings and decarbonized gas for the energy supply. In 2050, a higher annual cost is required due to additional efforts to reach carbon neutrality.

Compared to the linear mitigation pace, making greater efforts when approaching 2050 seems a more optimal solution in terms of cost. However, establishing a huge decarbonization challenge for the last five years before 2050 may bring higher risks of not achieving the mitigation goal.

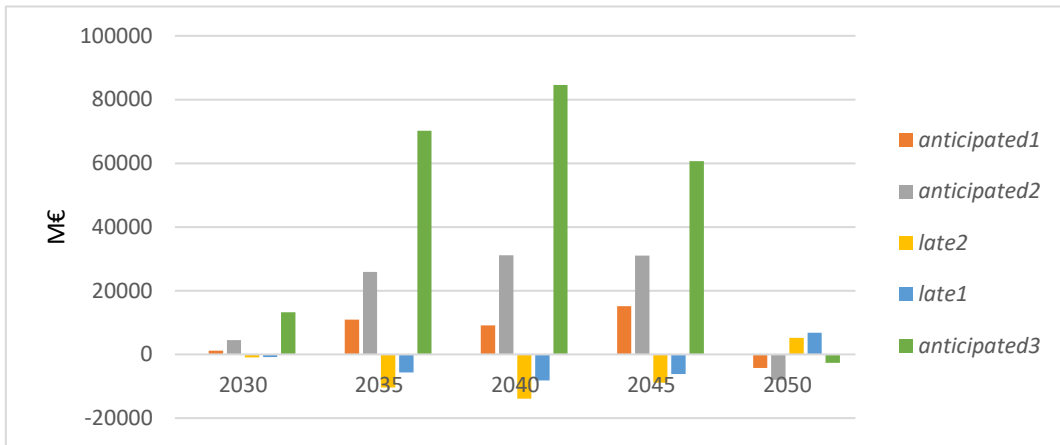


Figure 81 Difference of total annual cost between five variants of mitigation pace and scenario S2 per time step

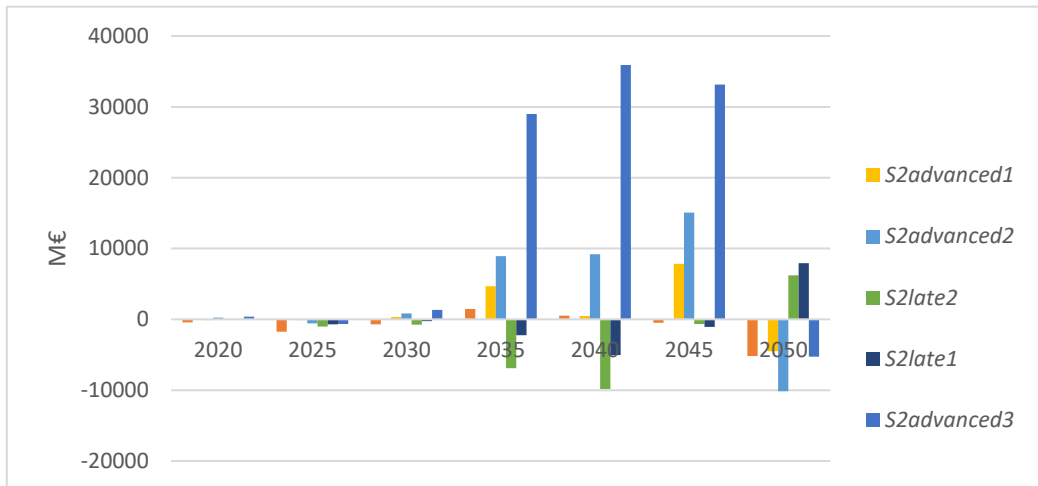


Figure 82 Difference of annual cost of building energy system between five variants of mitigation pace and scenario S2 per time step

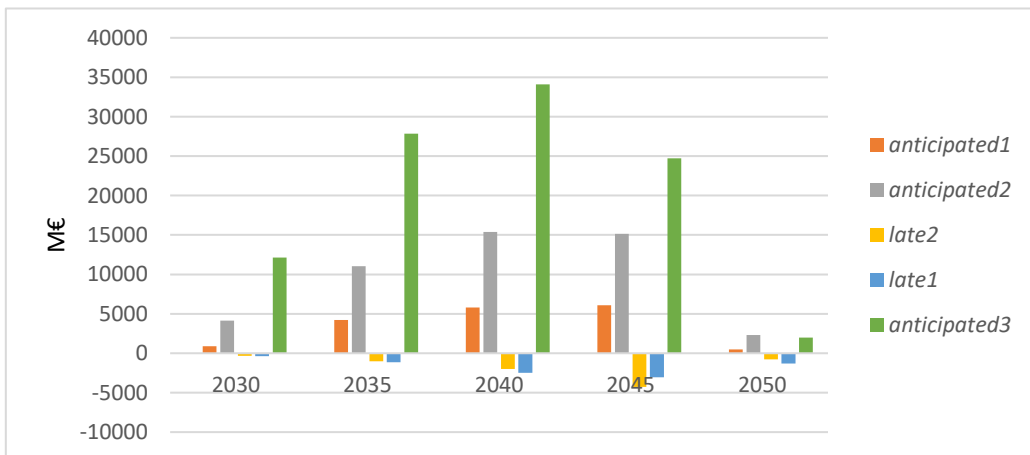


Figure 83 Difference of annual cost of energy supply between five variants of mitigation pace and scenario S2 per time step

3.3.5 Opportunity cost of gas

We have introduced multiple variants that are in line with the SNBC scenario for gas consumption in 2030 and 2050. The SNBC proposes a relatively constrained usage of gas by the energy system in the future. By exploring these scenarios, we are able to better understand the opportunity cost of gas in the energy transition. [Table 38](#) compares gas consumption in the SNBC trajectories and in our modeling result with no particular constraint on gas usage (S2). Following the SNBC trajectory, gas consumption is significantly lower than the proposed solution in scenario S2. In 2050, global gas consumption reduces to around 150 TWh under the SNBC, half the level of S2.

All end-use sectors also have a lower level of consumption in SNBC. Usage of gas in industry has the highest gap: In 2050, gas consumption in industry is only 30 TWh under SNBC, around one fifth of S2 (150 TWh). Note that the limit for gas usage is only for consumption of gas from the gas network, while direct usage of hydrogen by industry and direct consumption of biogas are not included (the same hypotheses as SNBC).

Year	<i>SNBC trajectory (AMS 2018)</i>				<i>S2 model result</i>			
	Industry	Transport	Building	Total	Total	Industry	Transport	Building
2030	101	14	149	356	500	187	37	222
2050	30	42	37	158	298	150	72	53

Table 38 Comparison between simulated pace of gas and SNBC

We will firstly compare scenario S2 with S2_gasSNBC1 and S2_gasSNBC2. The first scenario sets constraints on the global consumption of gas in 2030 and 2050, and the second scenario is based on a stricter constraint by limiting the usage of gas for each end-use sector. Next, we introduce three scenarios that consider an emerging technology for decarbonized gas production, i.e., hydrothermal gasification, and explore how the opportunity cost will change.

3.3.5.1 Alternative solutions to gas for different energy sectors

Figure 84 compares the final energy demands from 2030 to 2050 between S2_gasSNBC1, S2_gasSNBC2 and S2. Note that a limited usage of gas has a significant impact on the proposed energy solution. The energy system will be more dependent on oil products, coal and electricity.

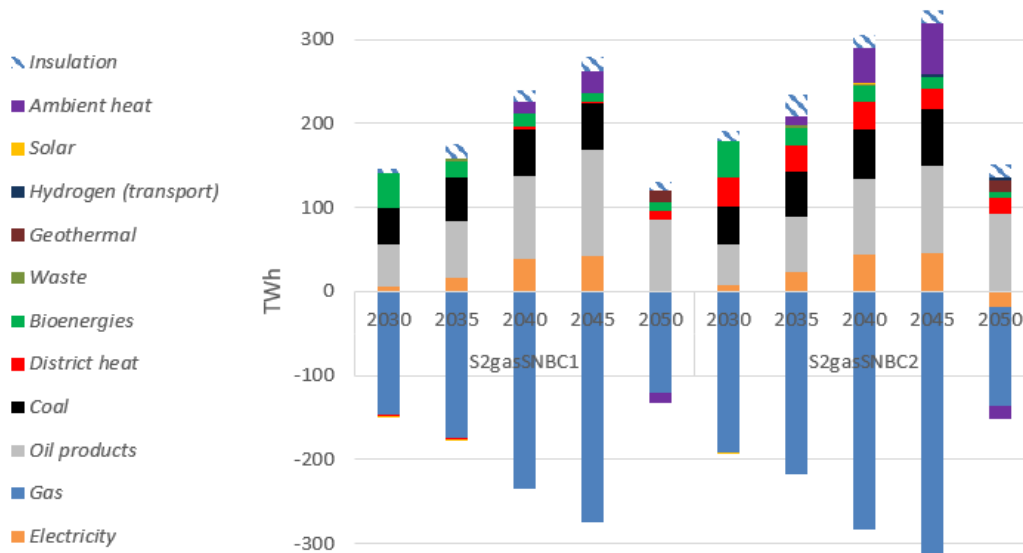


Figure 84 Difference of final energy consumption per time step between scenario S2_gasSNBC1, S2_gasSNBC2 and scenario S2

We first focus on scenario S2_gasSNBC1. Figure 85 compares S2_gasSNBC1 and S2 for end-use sectors. For the industry sector, a lower usage of gas induces a later withdraw of coal: for S2_gasSNBC1, we can observe a considerable volume of additional coal demand for the time steps between 2030 and 2045 compared to S2, and in 2045, the demand for coal is 55 TWh higher. Besides, before 2045, a significant part of gas demand is replaced by oil products, electricity, and bio-energies for industry. For the transport sector, oil products replace almost all gas consumption from 2030 to 2050, and in 2050, additional demand for oil products is higher than 50 TWh. For the building sector, the lower consumption of gas involves greater demand for insulation, solid biomass, and geothermal energy (by geothermal heat pumps). Another observation is that, in 2050 when the global consumption of gas is limited, the energy system chooses to maintain most gas for industry, while gas consumption in buildings and transport is reduced. This suggests that renewable gas may have an important role in decarbonizing the industry system.

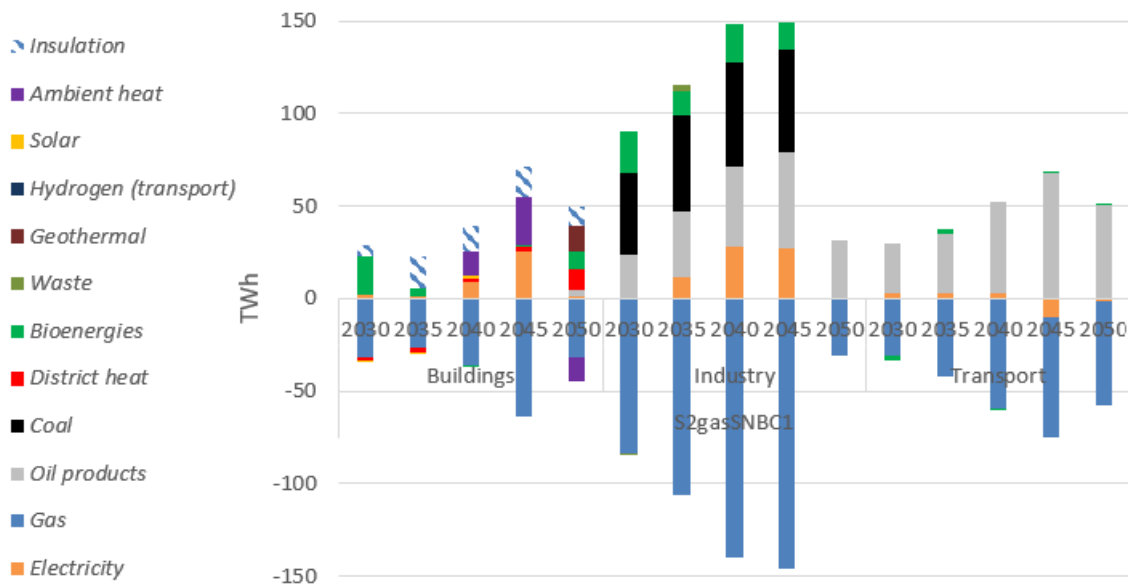


Figure 85 Difference of sectorial energy balance per time step between S2gasSNBC1 and S2

To replace gas, the energy system chooses to rely on more carbon-intensive oil products and coal. This implies additional efforts for the gas system by integrating more renewable gases. Figure 86 illustrates the evolution of the gas system after 2030. We see that for both scenarios, the consumption of natural gas decreases to a very low level after 2045, and renewable gases produced from methanization, pyro-gasification, and electrolysis dominate the gas balance.

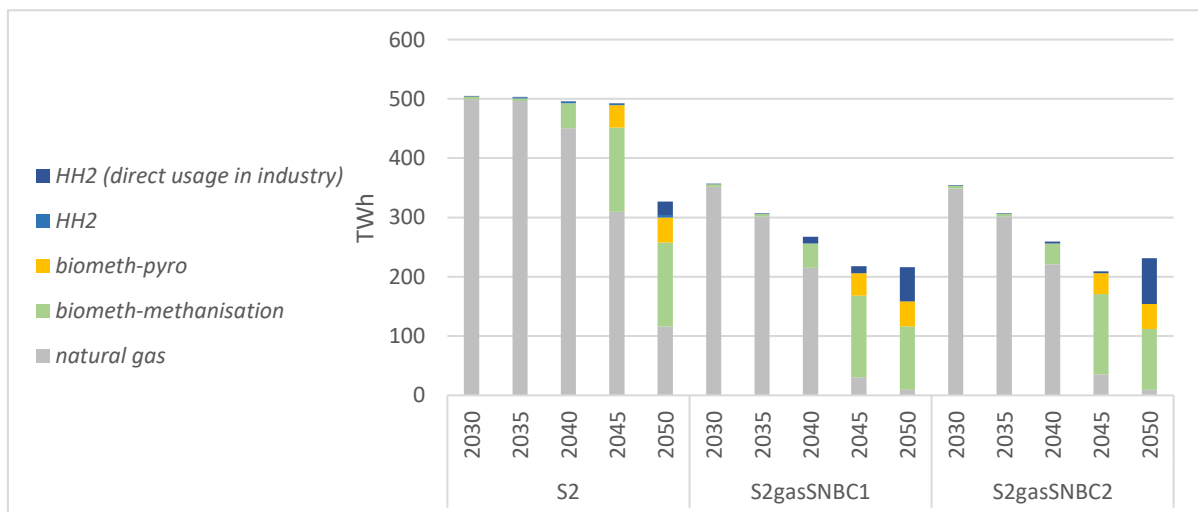


Figure 86 Evolution of gas production balance by scenario S2, S2gasSNBC1 and S2gasSNBC2

Figure 87 presents a comparison of the evolution of the sectorial energy balance between the S2_gasSNBC2 and S2 scenarios. In this scenario, we have additionally constrained the usage of gas, in particular for the industry and building sectors. Compared to industry and buildings, the constraint for transport is less strict. For industry, the stricter limit of gas leads to higher demand for coal (before 2045) and oil products. There is also more direct usage of hydrogen. Under S2_gasSNBC2, hydrogen produced by electrolysis reaches around 80 TWh, three times higher than in S2. Direct usage of hydrogen in this case represents around 75% of total industrial gas consumption. For the building sector, we note that the lower production by gas boilers before 2050 in particular leads to an earlier integration of electric heat pumps.

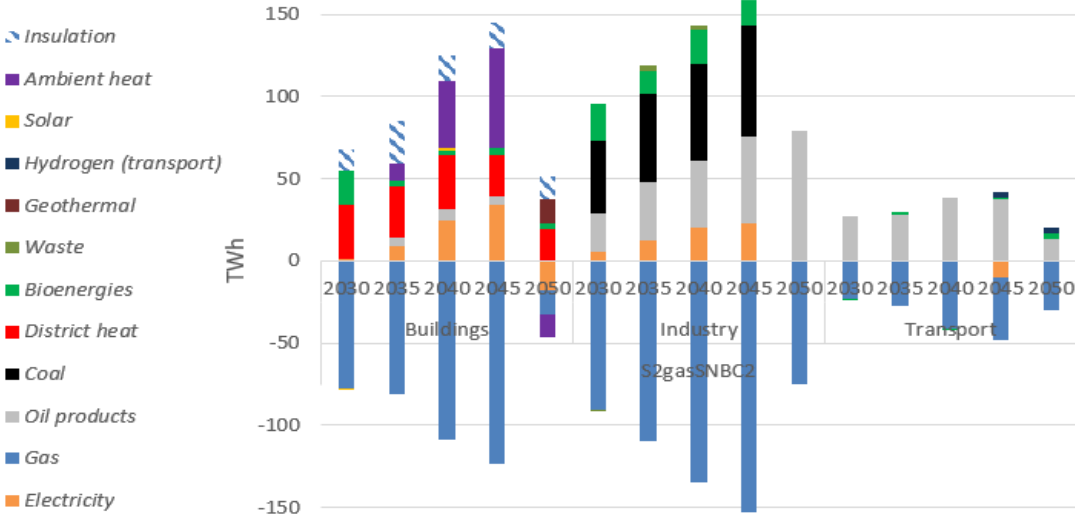


Figure 87 Difference of sectorial energy balance per time step between S2_gasSNBC2 and S2

3.3.5.2 Cases with hydrothermal gasification

Figure 88 presents the evolution of the gas mix under the three scenarios when the development of hydrothermal gasification is allowed. We note that for all three scenarios, the energy system chooses to integrate a high volume of biomethane produced from hydrothermal gasification after 2045, and that all these scenarios reach the maximum potential (63.8 TWh). We also observe that, in S2gasHighSNBC1 and S2gasHighSNBC2, under a strict constraint for the usage of gas, renewable gas produced from hydrothermal gasification replaces a significant part of biomethane by methanization. This suggests that hydrothermal gasification could be effectively competitive in terms of cost in the future.

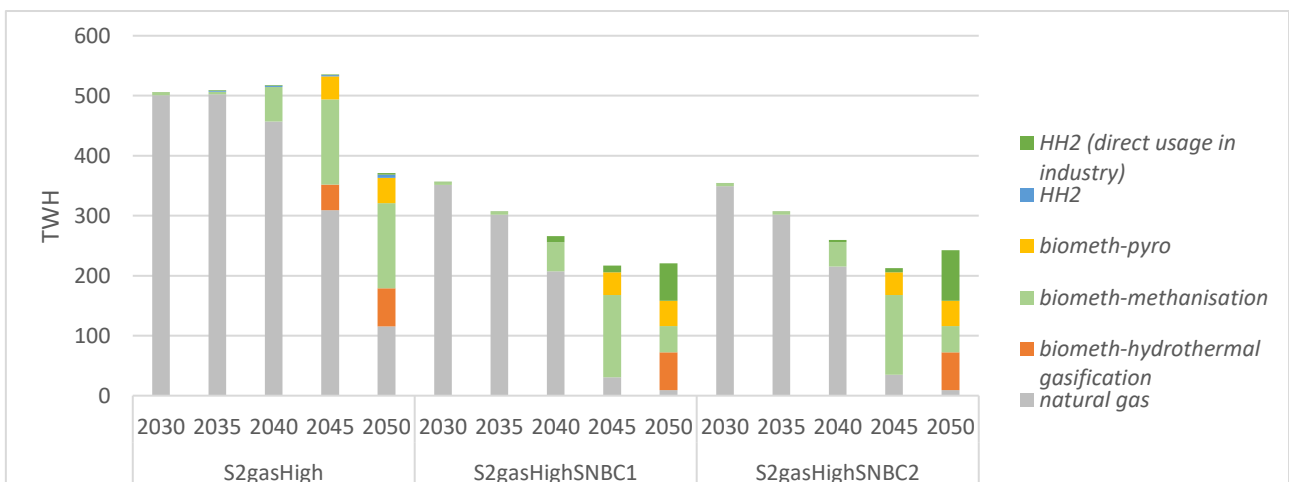


Figure 88 Evolution of gas production balance by scenario S2gasHigh, S2gasHighSNBC1, S2gasHighSNBC2

Figure 89 compares the evolution of the energy balance per sector between scenario S2 and S2gasHigh. A more abundant gas supply induces in particular a higher presence of gas in the building and industry sectors after 2045. Under the scenario with the presence of hydrothermal gasification, for buildings, gas consumption reaches 82 TWh in 2050, around 30 TWh higher than in S2. The additional consumption of gas in the building sector is mainly led by space heating: in 2050, gas consumption (including HHP) under S2highgas is 69 TWh, 57% higher than in S2. The additional gas supply replaces the share of thermal insulation (10 TWh) and electric heat pumps (12 TWh of electricity, around 20% lower than in S2). For the industry sector, gas consumption in 2050 is 15 TWh higher than in S2. Higher gas consumption in industrial processes induces a lower demand for solid biomass, which allows for more usage of solid biomass in building processes.

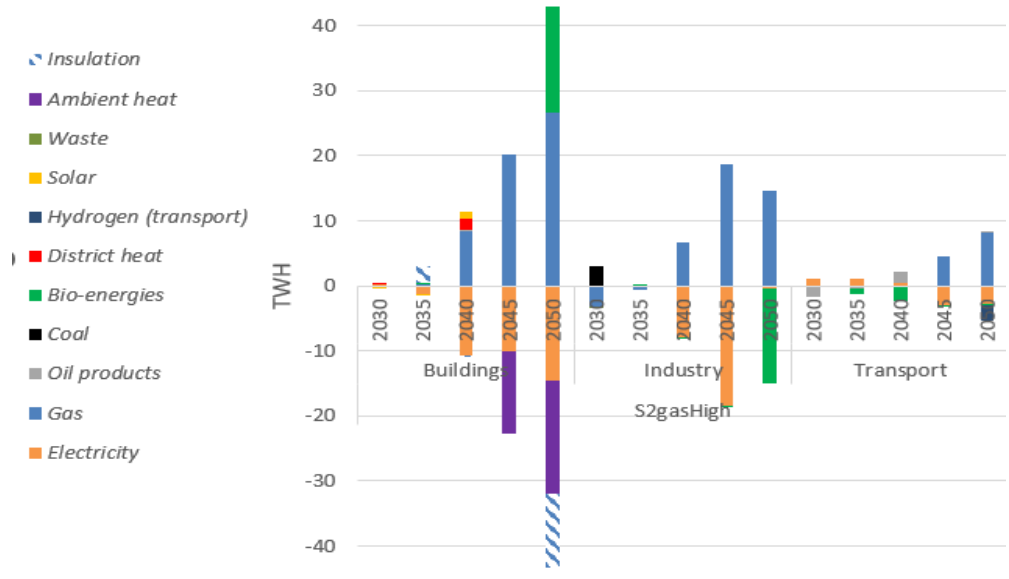


Figure 89 Difference of final energy balance per sector per time step between scenario S2gasHigh and S2

Figure 90 illustrates the difference in the energy balance between S2gasHighSNBC1, S2gasHighSNBC2 and S2gasHigh. We note that, when the usage of gas is limited in 2030 and 2050, cases that feature the presence of new gasification technology have higher demand for coal, oil products, and electricity to satisfy the energy demand. This is similar to the solutions proposed by the S2gasSNBC1 and S2gasSNBC2 scenarios without hydrothermal gasification. As the S2gasHigh scenario has a significantly higher gas demand for the building sector than S2, limiting the usage of gas in this case induces a higher demand for electric heat pumps.

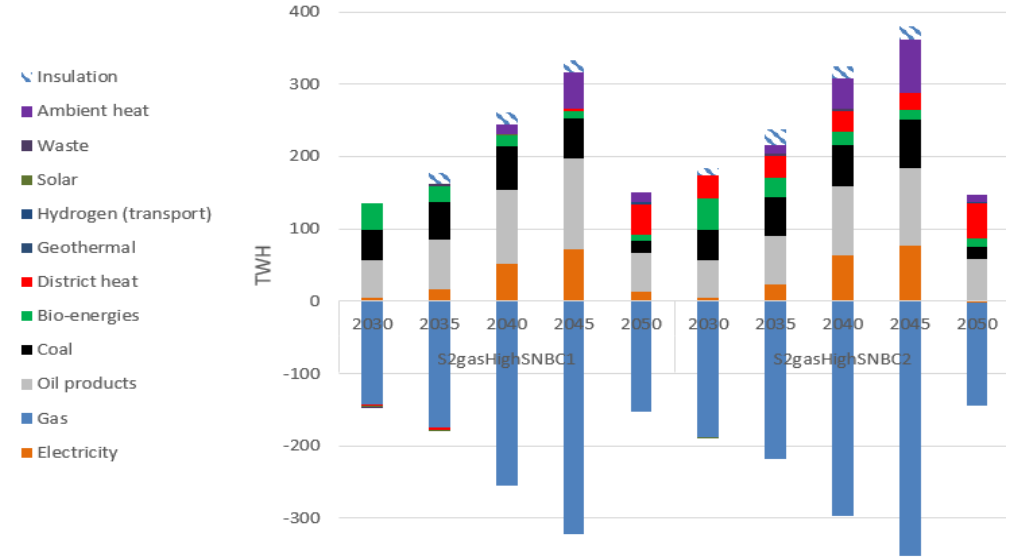


Figure 90 Difference of final energy balance per time step between S2gasHighSNBC1, S2gasHighSNBC2 and S2gasHigh

3.3.5.3 Economic analysis

The results of the S2gasSNBC1 and S2gasSNBC2 scenarios suggests that a more constrained usage of gas generates higher costs for the energy system (Figure 91). For both scenarios, the total annual cost is significantly higher than in S2 for all the time steps between 2030 and 2050. We also observe that under S2gasSNBC2, with a stricter limit on gas consumption for the industry and building sectors, the cost surplus is much higher. For both cases, the additional cost is explained by greater investment in electric heat pumps in buildings to replace gas (Figure 92) and more investments to produce renewable gas (Figure 93).

In case of a higher gas supply from hydrothermal gasification (S2gasHigh), the energy system involves lower annual costs, especially in 2050. Compared to S2, integration of renewable gas produced by hydrothermal gasification replaces a significant part of hydrogen with a high production cost. This contributes to reducing the cost of the gas supply. Besides, the more abundant gas supply for the building sector reduces investments in expensive electric heat pumps in 2050, thus lowering the annual cost for the building sector.

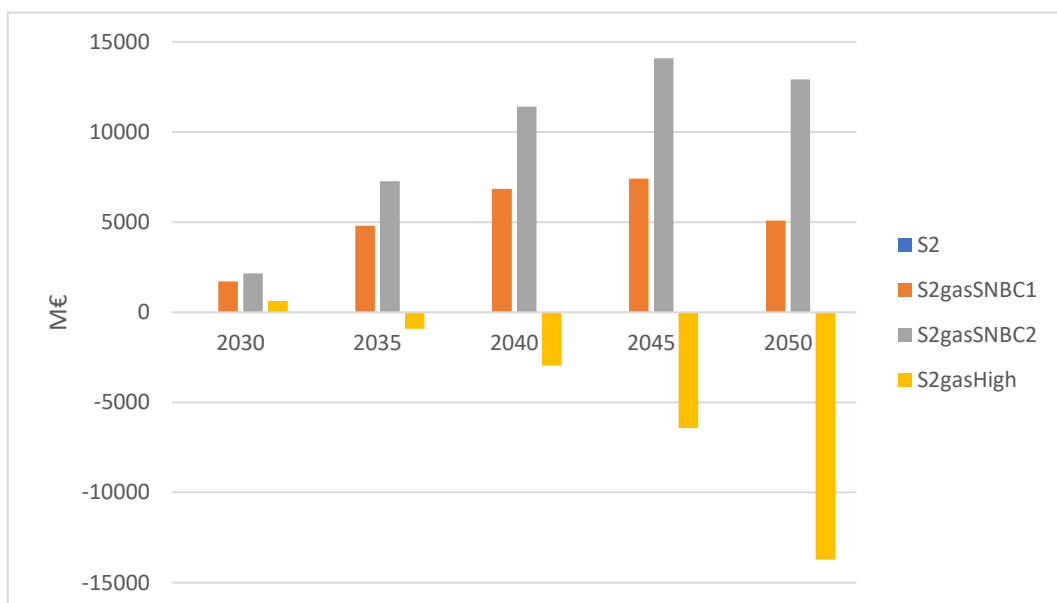


Figure 91 Difference of total annual cost per time step between scenario S2gasSNBC1, S2gasSNBC2, S2gasHigh and S2

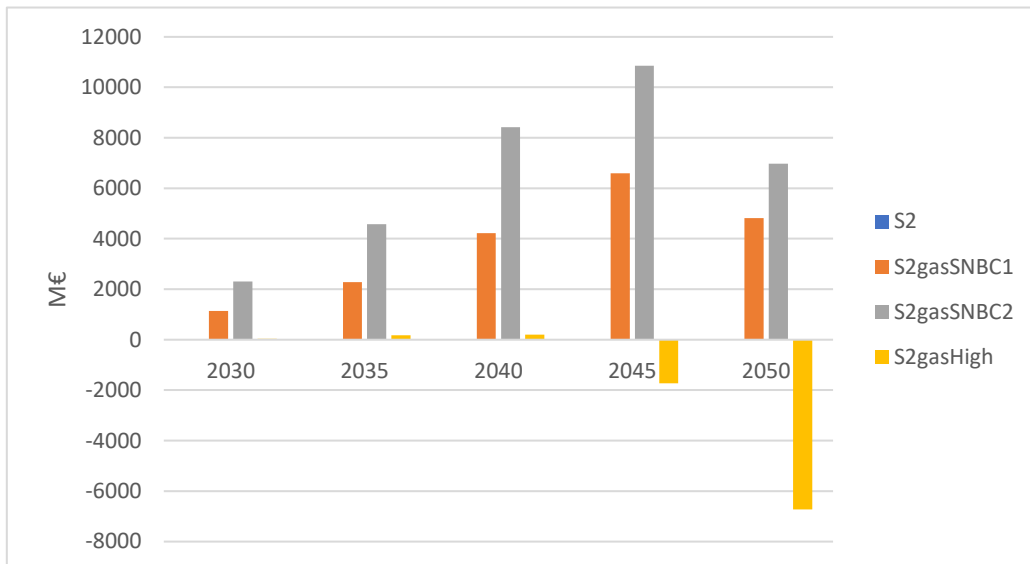


Figure 92 Difference of annual cost for buildings per time step between scenario S2gasSNBC1, S2gasSNBC2, S2gasHigh and S2

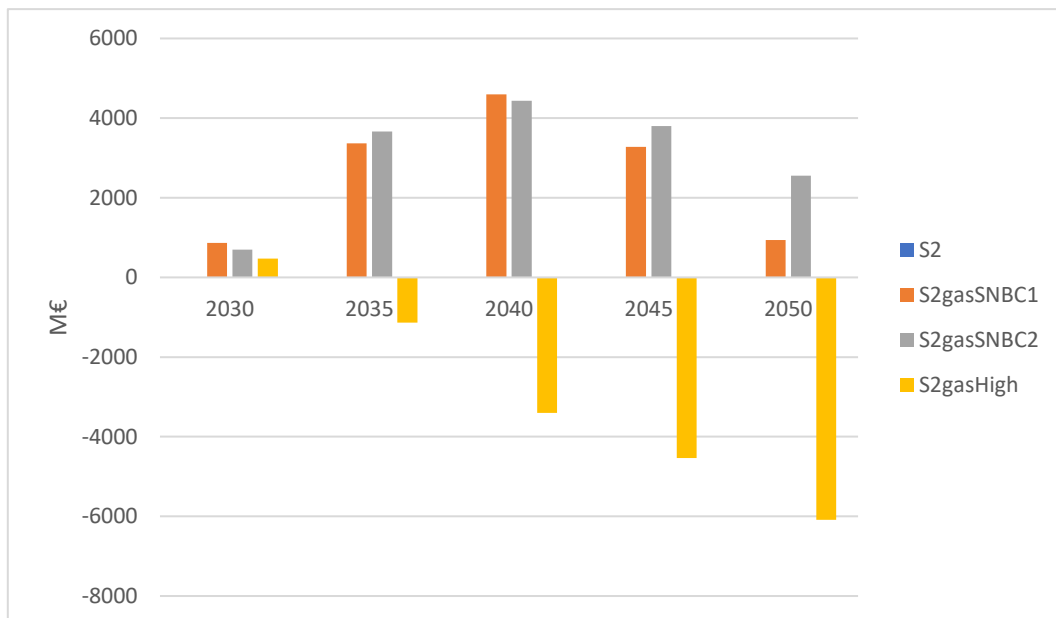


Figure 93 Difference of total annual cost for energy supply per time step between scenario S2gasSNBC1, S2gasSNBC2, S2gasHigh and S2

Conclusion

In Chapter Three, we have provided a complete analysis of the future transition of the heating system taking a systemic approach. Multiple scenarios elaborated from four key dimensions have been studied. From our analysis of the obtained results, we retain several key messages:

By observing the simulated results of the various scenarios based on different external conditions, we may retain a general tendency of energy transition and distribution of mitigation efforts over end-use sectors:

The trajectories of the global energy transition suggest that, in all cases (except variants of gas), to achieve carbon neutrality would require reducing the share of gas in the final energy balance by around 22.5%-26.5%, making electricity the first energy source, representing 30-35% of total consumption in 2050.

For the gas balance, the integration of renewable gases accelerates from 2040. In 2050, for all study scenarios, the gas system is dominated by renewable gases with more than 60% of gas produced by methanization, pyro-gasification, and power to gas.

In optimal conditions, under the global mitigation target, decarbonization efforts will initially focus on the transport sector by replacing carbon-intensive oil products with gas and electricity. For the building sector, the carbon mitigation pace significantly accelerates after 2040.

For space heating, electric heat pumps and insulation are two major investment choices for the building energy system, and the share of gas significantly decreases. For all of the simulated results, in 2050, gas consumption drops by at least two thirds compared to 2020.

When considering the presence of extreme cold events for heating, the building system still invests in a large quantity of electric heat pumps; however, their contribution to heat production decreases due to lower performance. The energy system chooses to invest in more gas boilers and thermal insulation. If investment conditions allow, hybrid heat pumps may play an important role after 2045. HHPs are effective to improve electric efficiency during extreme cold periods and to reduce electricity demand. In case of integration of HHP, the cost for the building energy system is significantly higher.

In case of a lower contribution from thermal insulation, the building system chooses to invest in replacement gas boilers. This involves lower costs for the building system, although a large cost surplus

is generated by more investments in renewable gas capacity and more electric vehicles for the transport sector.

The trajectory of gas and electricity between 2030 and 2045 is highly dependent on the mitigation pathway. Advanced decarbonization efforts require earlier replacement of gas by electricity, and vice versa for a late mitigation scenario. If earlier achievement of carbon mitigation is required, additional efforts are needed for all end-use sectors, including the building, transport and industry sectors. In terms of cost, compared to a linear pace, an anticipated mitigation pace can generate a high cost surplus for buildings and the energy supply. Besides, the cost surplus may not be proportional to the level of additional efforts required for intermediary time steps. A late achievement has a lower cost. However, the risk involved in achieving the neutrality goal is high, as massive efforts need to be carried out in the last five years before 2050.

In conclusion, by studying scenarios involving a limited usage of gas, we understand that achieving carbon neutrality with a very low participation of gas is feasible. The lower presence of gas has effects on all end-use sectors, including a later withdraw of coal from industry, more usage of oil products in industry and transport, and more usage of electric heat pumps in buildings.

Chapter Four French energy transition under carbon neutrality – analysis of core dimensions

Introduction

To draft future transition pathways, it is important to recognize that the transition of the energy system is dependent on factors from multiple dimensions, such as energy service demand, energy import strategies, and assumptions on the availability of various low-carbon energy solutions.

In this chapter, we propose an in-depth analysis of future trajectories for an energy transition that attains carbon neutrality for France. We more specifically explore the variability in optimal choices that may come from alternative assumptions regarding a broad range of factors. This is an important step to better map the complexity of the transition. This chapter thus extends our analysis in chapter three. In order to achieve this, we construct and integrate different hypotheses for seven core dimensions: the deployment potential of low-carbon electricity technologies, carbon sinks, mitigation of international transport, thermal insulation, biomass potential, energy service demand and discount rates. The adopted hypotheses for each dimension of study are based on a careful review of the existing literature, including technical reports and scenarios published by different stakeholders. The combination of assumptions according to these core dimensions produces a large number of variants, allowing us to investigate a broad range of possibilities for the future energy transition towards carbon neutrality.

The chapter focuses on two questions:

- What are the roles of different energy sources in the transition towards a carbon-free energy system, and what are the uncertainties suggested by the large number of scenarios?
- What is the explanation for these uncertainties, in particular for future gas consumption?

The rest of the chapter is organized into two sections. The first section presents the seven dimensions of our analysis and the motivations or rationale behind the alternative assumptions. Our hypotheses for biomass potential, thermal insulation, and the future demand trajectory have already been discussed. In Section One, we detail our hypotheses for the other four dimensions.

By crossing all the hypotheses of the seven key dimensions, we elaborate 576 variants of future energy transition trajectories for France. Section Two presents our analysis of these modeling results. We first present the consumption of various energy sources in 2050 in 576 scenarios. We are able to identify the major energy solutions to achieve carbon neutrality and the uncertainties. We then introduce the emission trajectories of the building, industry and transport sectors. This allows us to identify which

sector presents the highest uncertainty in the mitigation burden share for different time slices in the future. Next, we focus on understanding the uncertainties facing the gas sector in the future. We will firstly focus on representative trajectories of gaseous fuel demand for 2020-2050. This illustrates more clearly how the consumption of gaseous fuel will evolve in the future and the major tendencies. We will then carry out a sensitivity analysis to understand the favorable or unfavorable conditions for gas consumption in a carbon-neutral energy system. Finally, we will focus on how gas is produced in 2050 according to the 576 scenarios. This helps to better understand the uncertainties about the development of various types of gaseous fuels in the future. Next, we will present scenarios based on different hypotheses of the four key dimensions: carbon sinks, international transport, demand scenarios, and discount rates. As a result, we gain an in-depth understanding of possibilities of the energy transition to reach carbon neutrality.

Résumé

Pour élaborer des trajectoires de transition futures, il est essentiel de reconnaître que la transition du système énergétique dépend de facteurs provenant de plusieurs dimensions, tels que la demande de services énergétiques, les stratégies d'importation d'énergie et les hypothèses sur la disponibilité des différentes solutions énergétiques bas-carbone.

Dans ce chapitre, nous proposons une analyse approfondie des trajectoires futures pour une transition énergétique atteignant la neutralité carbone en France. Nous explorons plus particulièrement la variabilité des choix optimaux pouvant découler d'hypothèses alternatives concernant un large éventail de facteurs. Cela constitue une étape importante pour mieux cartographier la complexité de la transition. Ce chapitre prolonge ainsi notre analyse du chapitre trois. Pour ce faire, nous construisons et intégrons différentes hypothèses pour sept dimensions principales : le potentiel de déploiement des technologies électriques bas-carbone, les puits de carbone, la réduction des émissions liées au transport international, l'isolation thermique, le potentiel de la biomasse, la demande de services énergétiques et les taux d'actualisation. Les hypothèses adoptées pour chaque dimension d'étude reposent sur un examen minutieux de la littérature existante, y compris les rapports techniques et les scénarios publiés par différents acteurs. La combinaison d'hypothèses selon ces dimensions principales produit un grand nombre de variantes, nous permettant d'explorer un large éventail de possibilités pour la transition énergétique future vers la neutralité carbone.

Le chapitre se concentre sur deux questions :

Quels sont les rôles des différentes sources d'énergie dans la transition vers un système énergétique sans carbone, et quelles sont les incertitudes suggérées par le grand nombre de scénarios ?

Quelle est l'explication de ces incertitudes, notamment en ce qui concerne la consommation future de gaz ?

Le reste du chapitre est organisé en deux sections. La première section présente les sept dimensions de notre analyse ainsi que les motivations ou la logique derrière les hypothèses alternatives. Nos hypothèses sur le potentiel de la biomasse, l'isolation thermique et la trajectoire de la demande future ont déjà été discutées. Dans la première section, nous détaillons nos hypothèses pour les quatre autres dimensions.

En croisant toutes les hypothèses des sept dimensions clés, nous élaborons 576 variantes de trajectoires de transition énergétique future pour la France. La deuxième section présente notre analyse des résultats de modélisation. Nous commençons par présenter la consommation des différentes sources d'énergie en 2050 dans les 576 scénarios. Nous identifions les principales solutions énergétiques pour atteindre la neutralité carbone ainsi que les incertitudes. Ensuite, nous introduisons les trajectoires d'émission des secteurs du bâtiment, de l'industrie et des transports. Cela nous permet d'identifier quel secteur présente la plus grande incertitude en matière de répartition de l'effort de réduction des émissions à différents moments dans le futur. Nous nous concentrons ensuite sur la compréhension des incertitudes concernant le secteur du gaz dans le futur. Nous analyserons d'abord les trajectoires représentatives de la demande en combustibles gazeux de 2020 à 2050. Cela permet d'illustrer plus clairement comment la consommation de combustibles gazeux évoluera à l'avenir et les principales tendances. Nous réaliserons ensuite une analyse de sensibilité pour comprendre les conditions favorables ou défavorables à la consommation de gaz dans un système énergétique neutre en carbone. Enfin, nous examinerons comment le gaz est produit en 2050 selon les 576 scénarios. Cela permet de mieux comprendre les incertitudes quant au développement des différents types de combustibles gazeux dans le futur. Ensuite, nous présenterons des scénarios basés sur différentes hypothèses concernant les quatre dimensions clés : les puits de carbone, le transport international, les scénarios de demande et les taux d'actualisation. Cela nous permet de mieux comprendre les possibilités de la transition énergétique vers la neutralité carbone.

4.1 Key study dimensions: our hypotheses

Chapter Four explores seven core dimensions: the deployment potential of low-carbon electricity technologies, carbon sinks, mitigation of international transport, thermal insulation, biomass potential, energy service demand, and discount rates. In this section, we introduce why it is important to consider these elements as well as the scenarios that we retain for our exercise. In the previous chapters, we introduced our considerations for the dimensions of biomass potential (Chapter Two), thermal insulation (Chapter Three), and demand scenarios (Chapter Two). Here, we only mention the hypotheses for these three dimensions, and instead focus our efforts on the four dimensions that have not been introduced yet.

4.1.1 Key hypotheses for insulation effectiveness, biomass supply potential, and demand scenario

Regarding the potential of bio-energies, we study three cases including a high, a medium and a low scenario. In addition to the two scenarios focusing on the potential of solid biomass introduced in Chapter Two, the bioenergy dimension considers different cases for future availability of renewable gases. The high bioenergy scenario (b3) simulates a case of rapid development of the forestry and biogas industry in the future that allows for an abundant supply of solid and gaseous biomass for energy use. Currently, the supply of solid biomass is estimated at around 105 TWh, and biomethane injected to the gas network is estimated at 4.3 TWh (2021). Under the high bioenergy scenario, the supply potential of solid biomass reaches 260 TWh in 2050, including 60 TWh of wood waste, non-forestry solid biomass, and agriculture residue available for pyro gasification. The methanization industry allows for 152 TWh of biogas production in 2050. These values follow the hypotheses of (ADEME et al., 2018). Besides, we suppose that hydrothermal gasification processes for biomethane production will be available from 2030, following rapid technology progress. In 2050, biomethane production from hydrothermal gasification could reach 63.8 TWh. The medium bioenergy scenario (b1) is based on the same hypotheses for the supply potential of solid biomass and biogas from methanization as the high scenario. However, under b1, hydrothermal gasification technology will not be available in the future, allowing for a lower supply of renewable gas. Compared to the high and medium bioenergy scenarios, the low bioenergy scenario (b2) describes a very pessimistic future where the availability of both solid biomass and renewable gases remains low. The supply potential for solid biomass is around 80 TWh lower in 2050, and only half (76 TWh) of the biogas produced from methanization is available.

To test the impact of the effectiveness of thermal insulation, we study two contrasted cases: a high and a low scenario for the future pace of investment. The hypotheses are the same as those we introduced in Chapter Three. Under the high scenario of thermal insulation, the maximum potential of energy saving of around 140 TWh for residential buildings and 40 TWh for tertiary buildings can be achieved by 2035. The low insulation scenario allows for only half of the identified potential, and the technical potential can only be achieved 15 years later (2050).

Four demand scenarios will be studied here, as introduced in Chapter Two. The four demand trajectories simulate different levels of future demand for energy services and commodities demand from buildings, industry, transport and agriculture. From D1 to D4, the demand level follows a decreasing order.

Scenario	Dimension	Description	Variant	Details	Reference
I1	Thermal insulation	Maximum annual investment in thermal insulation for residential and tertiary buildings	High	Optimistic vision for future renovation pace in residential and tertiary buildings, rapid increase of renovation is authorized. The estimated insulation potential for both residential and tertiary building can be achieved no sooner than 2035.	
I2			Low	Pessimistic vision for future renovation pace. The estimated insulation potential for both residential and tertiary buildings can only be achieved after 2050. Half the potential of I1.	
B1	Potential of bio-energies	Maximum yearly potential of solid biomass for direct usage, pyro-gasification, and biomethane supply from methanization and hydrothermal gasification	Medium	Increase of forest exploitation leads to a higher availability of solid biomass for energy use: total potential will reach to around 200 TWh in 2050 (compared to 110 TWh in 2020), including an additional share of 60 TWh of wood waste, non-forestry solid biomass, agriculture residue available for pyro gasification. Potential of biogas provision for direct use or biomethane purification is 152 TWh.	(ADEME et al., 2018)
B2			Low	Lower growth rate of available solid biomass and there will be no available additional potential for pyro-gasification. Only half of biogas potential is available (76 TWh).	
B3			High	Potential of solid biomass and biogas provision follows the medium biomass scenario. Besides, rapid development of hydrothermal gasification in the future allows for 63.8 TWh of additional biomethane supply in 2050.	(Groupe de Travail Gazeification Hydrothermale, 2023)
D1	Demand for energy services		High	AME 2021	
D2			Intermediary 1	AMS 2018 (SNBC)	
D3			Intermediary 2	average of AMS 2018 and ADEME S1	
D4			Low	ADEME S1	

Table 39 Overview of retained hypotheses for insulation effectiveness, biomass supply potential, and future energy service and commodity demand

4.1.2 Deployment pace of low-carbon electricity technologies

In 2021, 2.7 GW of solar PV, 1.2 GW of onshore wind, and 1 GW of offshore wind power plants were newly connected to the French electricity grid. An EPR of 1.65 GW (Flamanville) is also under construction and planned to be in operation in 2024. For the future, France has expressed a strong ambition to commission new renewable electricity capacities as well as new nuclear power plants. The official vision for the short term (PPE 2021-2028) plans to accelerate the expansion of solar PV and onshore wind parks to 2.9 and 2.2 GW/year by 2028 (Ministère de la Transition écologique et de la Cohésion des territoires, 2019). For nuclear power, after a long public debate, the governmental report published in 2022 proposed a plan to construct six EPRs from 2035 to 2045 (with a total installed capacity of around 10 GW) (Ministère de la Transition Énergétique, 2023). The project for new nuclear installations foresees the network connection of a first pair of EPR2s⁷⁰ in 2035, with the remainder scheduled to be deployed at a rate of two EPRs every five years. This solution adopts the proposal made by the New Nuclear France (NNF) program defined by nuclear industry stakeholders in France. The same program also indicates the possibility to accelerate the deployment of new EPRs after 2045 with the potential to reach a total capacity of 23 GW by around 2050 (7 pairs of EPR2s).

Scenarios published by various stakeholders present different visions for the deployment pace of low-carbon electricity technologies in the future energy system. Under the Energy-Climate Scenarios by ADEME, renewable power plants develop rapidly in the future and replace the role of nuclear power. The three electricity perspective variants foresee a share of 50%, 80% and 90% of renewable energies (RE) in electricity production. For the nuclear industry, Energy-Climate scenarios have a pessimistic vision: no new nuclear power plants will be connected (ADEME, 2017a). This vision is close to the trajectories of the “M” family (M0, M1, M23) by RTE (French electricity transmission system operator) and négaWatt 2022, which also estimate fast integration of renewable electricity (see Chapter One). On the contrary, the “N” family scenario by RTE recognizes a key role for nuclear power in the future: in 2050, the capacity of new EPRs increases from 13 GW in N1 to 24 GW in N3.

Electricity has a vital role in the energy system. For our energy prospective study, it is important to consider different cases of the deployment potential of power plants, in particular for low-carbon electricity technologies that may be important solutions to decarbonize the electricity system. We elaborate three scenarios representing different potentials for developing solar, wind, and nuclear

⁷⁰ EPR2: Evolutionary Power Reactor 2

power in the future. These scenarios are inspired from the existing energy policy of France and published scenarios for future electricity system introduced above.

We first study a reference scenario that simulates a deployment based on the pace observed in 2021 for solar PV, onshore wind plants, and the construction of 6 EPRs as indicated in the governmental report. In 2021, the observed rates of solar PV and onshore wind plants are respectively 2.7 GW and 1.2 GW per year (SDES, 2022b). In the reference scenario, future capacity expansion cannot surpass this level. During the last five years before 2022, the average pace of solar PV and onshore wind plant installation was around 1.65 and 1.35 GW per year. The pace adopted for solar PV is based on an optimistic hypothesis. For offshore wind plants, the reference scenario supposes that the future pace cannot surpass 1 GW per year, which is twice the value observed in 2021. This is based on the ambition of the PPE to reach an installed capacity of 6 GW by 2028 (Ministère de la Transition écologique et de la Cohésion des territoires, 2019).

On the basis of this reference scenario, we study an optimistic vision of deployment potential (high scenario of low-carbon electricity deployment potential). This scenario allows for a rapid expansion of all types of renewable power plants, including solar PV, onshore, and offshore wind parks, and ambitious projects for implementing new-generation nuclear power plants after 2035. For the deployment potential of renewable power plants, the pace adopted by the high scenario follows the hypotheses of the RTE M23 scenario, characterized by the rapid development of all renewable energy sources (RTE, 2022).

The potential of solar PV, onshore, and offshore wind power plants can be as high as 4 GW, 1.9 GW and 2 GW of new capacity per year between 2020 and 2050. By 2050, the maximum installed capacity for solar PV, offshore, and onshore wind plants is respectively 150, 76 and 84 GW. For nuclear energy potential, the proposed pace according to the high scenario of low-carbon electricity deployment potential corresponds to the maximum level communicated by the NNF program (New Nuclear France): Starting from today, new nuclear installation projects allow for the network connection of a first pair of EPR2s in 2035. The next two pairs of EPR2s will be constructed in 2040 and 2045. And after 2045, the pace of new reactor installation accelerates to two pairs every three years. By 2050, the total capacity of new EPRs can reaches 23 GW in France.

In addition to the reference and relaxed scenarios of electricity potential, we propose to further explore a constrained future for new nuclear power plants according to the low electricity scenario. Under the low scenario, only the integration of EPR Flamanville is scheduled, and there are no new EPR2s after 2035. The aim is to investigate alternative solutions to nuclear power.

For all the three scenarios, a 20-year life extension of existing nuclear plants is allowed. If the maximum life extension potential is achieved, there will be around 12 GW of the current stock available in 2050. Besides, the potential of thermal power plants and power-to-gas remain the same for both scenarios. The table below presents the maximum yearly installation pace by type of power plant defined in the three scenarios.

	Reference electricity potential (GW/year)	High electricity potential (GW/year)	Low electricity potential (GW/year)
Onshore wind	Maximum 1.2 GW/year	Maximum 1.8 GW/year before 2030, maximum 2.2 GW/year after 2030	Maximum 1.2 GW/year
Offshore wind	Maximum 1 GW/year	Maximum 1 GW/year before 2030, maximum 2 GW/year after 2030	Maximum 1 GW/year
PV solar (ground + on roof)	Maximum 2.7 GW/year	Maximum 2.9 GW/year before 2030, maximum 5 GW/year after 2030	Maximum 2.7 GW/year
Nuclear	Installation of EPR Flamanville + 2 EPRs of 1.65 GW allowed every five years after 2035	Installation of EPR Flamanville + 2 EPRs of 1.65 GW allowed every five years after 2035, 2 EPRs every three years after 2045	Only grid connection of EPR Flamanville is scheduled, no installation of other new EPRs in the future
Thermal power plant	Maximum 2 GW/year	Maximum 2 GW/year	Maximum 2 GW/year
Thermal power plant with CO2 capture	Maximum 1 GW/year	Maximum 1 GW/year	Maximum 1 GW/year
Power to gas	Maximum 2 GW/year	Maximum 2 GW/year	Maximum 2 GW/year

Table 40 Hypotheses of deployment pace of low-carbon electricity technologies

4.1.3 Carbon sinks and emissions from international transport

Carbon sinks can be mobilized to capture and store CO₂ emitted by human activities. In the carbon inventory, carbon sinks are represented as negative emissions that contribute to neutralize the general carbon balance. We distinguish carbon sink options in the natural environment and artificial carbon sinks produced by the carbon storage or utilization industry. Natural carbon reservoirs are natural landscapes capable of absorbing CO₂, including vegetation, soil, and the ocean. The current carbon inventory of EU countries integrates carbon effects associated with five main land usages: forests, agricultural fields, grasslands, wetlands and settlements. In addition, the harvest of wood products⁷¹ is considered to be a source of negative carbon emissions. The figure below describes the evolution of carbon emissions linked with land use, land-use change and forestry (LULUCF) for France since 1990 by Eurostat (Eurostat, 2023). In 2020, forest land was estimated to have neutralized around 31.5 MtCO₂e, representing the great majority of the natural carbon reservoir. The negative effect linked with land use changes of cropland and settlements (land artificialization) on carbon sink capacity was around 11 MtCO₂e. Considering all elements of land usages, the net capacity was estimated at around 22 MtCO₂e.

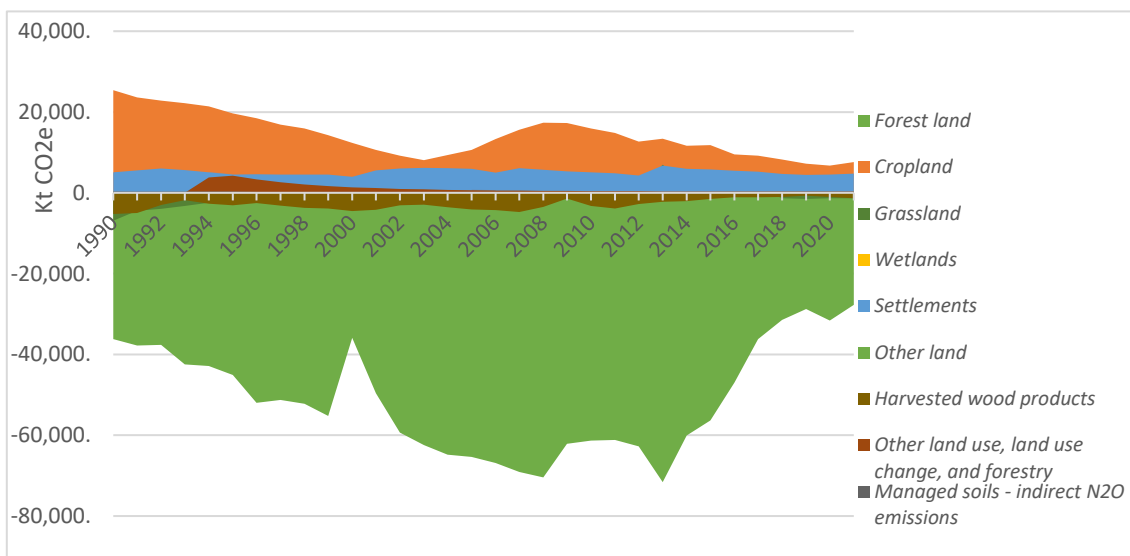


Figure 94 Emissions from LULUCF since 1990, source: (Eurostat, 2023)

Artificial carbon sinks consist of Carbon Capture and Storage (CCS) technologies. They can be used to neutralize emissions from carbon-intensive industrial sources such as cement production, steelmaking,

⁷¹ According to IPCC guidelines, wood products (e.g., wooden houses and furniture) extend the lifespan of CO₂ stored in biomass and are thus considered as carbon reservoirs (Académie d'Agriculture de France, 2017).

natural gas processing, and fossil energy power plants. CCS is distinguished from the Carbon Capture and Utilization (CCU) industry, which aims to reuse the captured CO₂ instead of permanently storing it (for example, methanation of hydrogen with CO₂ to produce synthetic methane). CCS comprises three steps: CO₂ capture, transport, and storage. The main CO₂ capture technologies are carbon scrubbing with amines (absorption), chemical looping combustion, membrane, and adsorption. Post-combustion capture by absorption is the dominant technology and the only one that has been used industrially (ADEME, 2020). Feasible solutions for storage include onshore and offshore oil fields, gas fields, saline formations, coal seams, and saline-filled basalt formations.

Concerning the development status of CCS technologies, 22 large-scale projects have been put into operation since the 1990s in the world. In France, there are currently no operational CCS installations, only projects under development. An analysis by ADEME estimates that the total amount of emissions that can be captured from 120 carbon-intensive industry sites is around 50 Mt CO₂e per year (ADEME, 2020). Among the 120 sites, 87 have easy accessibility to geological storage, representing 43 Mt CO₂e of emissions, and around 24 MtCO₂e of storable potential are identified as having favorable conditions to install CCS.

The development of carbon sink capacity in the future is faced with strong uncertainties, especially for the CCS industry. One of the major impediments is social acceptance associated with concern for the environmental and health risks in case of leakage from geological formations. In our exercise, we study a high scenario and a low scenario for the availability of natural and artificial carbon sinks. Under the high-carbon sink scenario, the capacity of natural carbon reservoirs to neutralize carbon emissions from energy systems follows a linear growth in the future and reaches 30 MtCO₂e in 2050. This is in line with the SNBC vision. The main hypotheses of scenario SNBC are: firstly, smarter and more sustainable forest management in the future leads to continuous afforestation and an increase in wood production; secondly, concerning land usage, the target of “zero net artificialization” will be achieved in 2050; thirdly, more ecological practices in the agricultural sector will bring a high increase in carbon sink capacity (Ministère de la Transition écologique et de la Cohésion des territoires, 2020a). For the potential of artificial carbon sinks, the high scenario allows for a linear increase of CCS potential in the future, and the availability will reach 50 MtCO₂e in 2050. We also assume that the CCS technology will not be available before 2025 and that only deep saline aquifers can be used to store CO₂. The value of 50 MtCO₂e in 2050 corresponds to the maximum storable industrial emissions estimated by ADEME (ADEME, 2020). Considering the current status and difficulties identified for future development, such as social acceptance, high storage cost, and technical complexity, the hypothesis of 50 MtCO₂e CCS capacity remains voluntary.

The low scenario represents a pessimistic view on the future of both natural and artificial carbon sinks. For the whole period till 2050, the scale of natural carbon reservoirs is limited to their level in 2021 (17 MtCO₂e from the LULUCF sector, and we suppose that around 7.6 MtCO₂e is attributed to the energy system). The lack of natural carbon sinks cannot be compensated by CCS: investment in artificial carbon sinks is not feasible in the low scenario.

Dimension	Scenario	Details
Carbon sink	High	Future capacity of natural carbon reservoirs will reach 67 MtCO ₂ e, of which 30MtCO ₂ is attributed to neutralize emissions from energy consumption. Possible to develop CCS industry from 2025 and potential will reach 50 MtCO ₂ e in 2050.
	Low	Capacity of natural carbon sinks will remain the same as 2021 level. 7.5 MtCO ₂ e is attributed to energy consumption. Artificial carbon sinks are not available in the future.

Table 41 Retained hypotheses of the high and the low carbon sink scenario

4.1.4 Decarbonization target for international transport

Currently, the target of carbon neutrality in France does not consider emissions from international transportation, including flights and bunkers, as according to international conventions (UNFCCC, United Nations Framework Convention on Climate Change), this part of emissions is not incorporated into the national GES inventory.

International transport is a major carbon emitter. It is estimated that emissions from international transport amounted to around 24 MtCO₂e in 2021 for France, representing around 19.3% of total emissions from the transport sector (domestic transport) in the national carbon inventory (Eurostat, 2023). Here we propose to introduce a scenario that considers emissions from international transport in the national neutrality target. The energy system in this case needs to achieve a higher level of decarbonization in order to meet the goal of “zero net emissions” in 2050.

Dimension	Scenario	Details
Obligation to mitigate international transport carbon emission	With	International transport sector, including international aviation and bunkers, is incorporated in carbon neutrality goal
	Without	International transport sector is not concerned

Table 42 Retained hypotheses of two variants of mitigating international transport carbon emission

4.1.5 Discount rate

In project investments, a discount rate is the rate of return used to discount future cash flows back to their present value. It reflects how the values of future gains or payments are perceived in the present. We typically distinguish between the discount rate for private sectors (financial discount rate) and a social discount rate that reflects a society's relative valuation on today's well-being versus well-being in the future (García-Gusano et al., 2016). The calculation of the financial discount rate can be mainly based on the opportunity cost of capital, which is the return on investments forgone elsewhere by committing capital to the investment under consideration (Khatib, n.d.).

The choice of social discount rate is usually made by governments. It is used for the socio-economic evaluation of public projects with a long-term impact. The decision regarding the social discount rate has been a focus of debate among economists since the beginning of the 21st century. Several factors are recognized as important in determining the value of social discount rates: a common expectation of increased wealth in the future (capital worth more at the present); risk of project failure in the future; and social trade-off between present and future welfare (Harrison, 2010). The evaluation of a social discount rate is always more complicated than for the private sector, and its value is in general lower than for the private sector, as it needs to consider social concerns such as sustainability, social welfare, and climate change.

The social discount rate in France has been fixed at 4.5% by the Quinet Commission since 2013, including 2.5% of risk-free discount rate and a risk premium of 2% (depending on the project) (France Stratégie, 2017).

The discount rate is an important variable in TIMES' optimization, which minimizes the total discounted cost of the modeled system. In the technology-explicit TIMES model, a higher discount rate can be used to represent a higher level of barriers or investment risks (García-Gusano et al., 2016).

We propose to explore two levels of discount rate in our study. The first scenario follows the current social discount rate of 4.5% in France. The discount rate of 4.5% represents a rather favorable and ideal case for investments in carbon mitigation. However, the adopted discount rate (WACC) could be higher due to the existence of multiple barriers, such as imperfect information, hidden costs (and benefits), risk and uncertainty, split incentives, access to capital, and bounded rationality (García-Gusano et al., 2016). Taking the example of the renewable electricity industry, according to a proposed business model of IEA for solar PV (IEA, 2021), the nominal capital cost in a future of supported revenues (feed-in tariff, contract for difference, long-term PPA, bilateral agreement) ranges between 2.9-4.3% in Europe, while this ratio rises to 9.6% if based on market risk. Moreover, as suggested by (Steffen, 2020),

the discount rate for onshore and offshore wind parks with higher risks is estimated to be considerably higher than for solar PV. Based on this, we introduce a scenario with a higher discount rate of 10%. This allows us to explore a future with higher investment barriers.

4.2 Result analysis

4.2.1 Overview of the roles of various energy sources in the transition to carbon neutrality

By crossing all the cases of the seven key dimensions, we construct 576 variants or prospective analysis cases. These cases cover a wide range of possible energy transition trajectories to achieve carbon neutrality. We will firstly give an overview of the roles of various energy sources proposed by these carbon neutrality scenarios.

Figure 95 presents the average trajectory from all the simulations and depicts the final energy consumption in France from 2020 to 2050. We note that, in this average vision, the consumption of electricity follows an increasing trend in the future with an accelerated rate after 2035. By 2050, average electricity demand reaches 453 TWh, around 30% higher than electricity consumption in 2020. The share of renewable energy sources, including liquid biomass (biofuel and black liquor) and renewable heat (geothermal energy for heating, ambient heat for heat pumps and solar thermal), also shows significant growth. In 2050, the average consumption of liquid biomass reaches 115 TWh, around 2.64 times the level in 2020. Demand for renewable heat increases rapidly after 2035. In 2050, the average consumption of renewable heat is 130 TWh, around 6 times its 2020 level. For gaseous fuels (gas from the network, use of hydrogen for industry and transport), consumption initially follows an increasing trend then decreases after 2035. In 2050, average gas demand reduces to 234 TWh, around 40% lower than in 2020. However, and as it will be detailed later, the gas mix for final consumption evolves over time with more renewable sources. The share of carbon-intensive energies including oil products and coal decreases sharply in the future: in 2050, the total average demand for oil products and coal reduces to 75 TWh, only around 15% of the 2020 level. This is in line with the increasing need to decarbonize the energy system following the strict emission constraint.

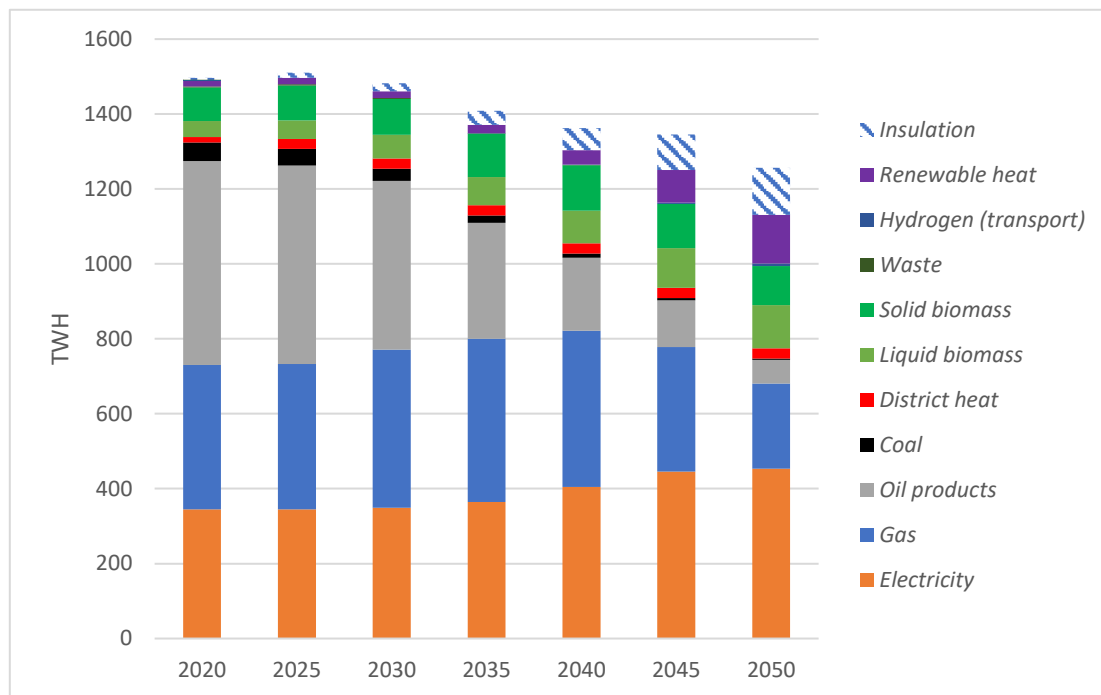


Figure 95 Evolution of final energy consumption in the average scenario (from calculation)

By observing the average values over different time periods, we are able to outline the average tendency for the energy system to reach carbon neutrality in 2050 based on a large number of trajectories. In addition, we need to pay attention to uncertainties regarding the future role of given energy sources. Next, we will try to identify these uncertainties. This is an important element to better understand our options for the future and make our prospective analysis more solid.

Figure 96 presents the distribution of final demand for various energy sources following all simulation results in 2030, 2040 and 2050. We note that the variability of the consumption of different energy sources increases with time, except for coal, district heat, and waste. In 2050, consumption of electricity, gaseous fuels, and liquid biomass presents high uncertainty. We see that the full set of runs gives a broad range of electricity consumption in 2050, from 320 to 600 TWh. Demand for gaseous fuels ranges from 56 TWh to 386 TWh, representing from 4.8% to 24.4% of total final energy consumption. We note that, in 2050, no scenario has a higher consumption of gaseous fuels than in 2020 (389 TWh). For the majority of the scenarios, consumption of biomass (liquid and solid biomass) ranges from 175-330 TWh in 2050, while around 10% of the scenarios feature a much higher biomass demand of above 400 TWh.

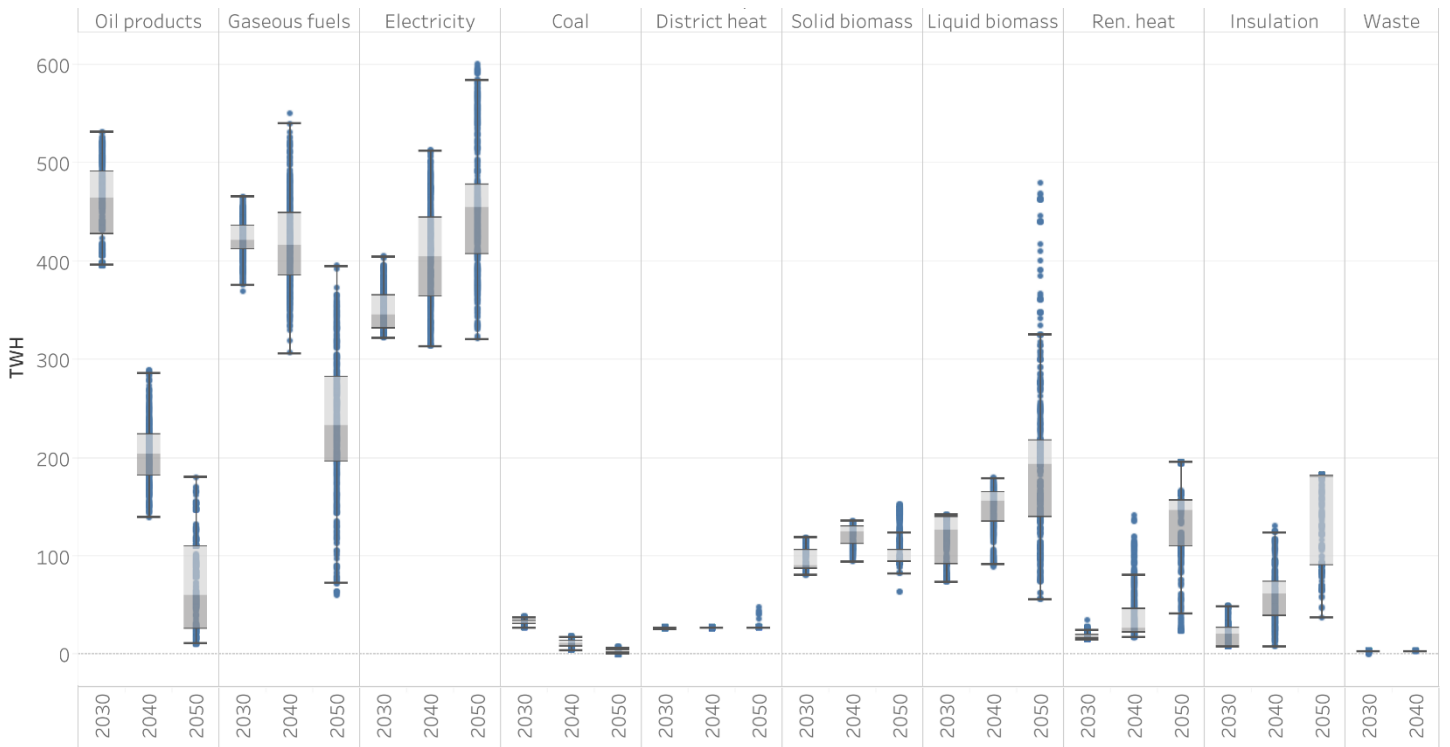


Figure 96 Distribution of final demand for various energy sources in 2030, 2040 and 2050

4.2.2 Share of mitigation burden over end-use sectors

We have presented the role of different energy sources to attain a carbon-free energy system. Next, we will focus on how different end-use sectors contribute to achieving the mitigation target and uncertainties in the future. This helps to better understand the uncertainties of global energy consumption previously presented. [Table 43](#) presents the average, maximum, and minimum values of carbon emissions in all of the simulations by end-use sector and time step, and their standard deviations (SD). [Figure 97](#) presents the distribution of final energy consumption by end-use sector, and energy type in 2030, 2040 and 2050. We will firstly focus on the suggested tendency from the average values. We note that the mitigation pace of global carbon emissions significantly accelerates after 2030. For time steps before 2040, carbon mitigation efforts are mainly achieved in the transport and building sectors. In 2040, the average emissions from the transport sector decrease to 32.3 Mt CO₂e, around 70% lower than in 2020. This is explained by the increasing the usage of biofuel (liquid biomass), electricity, and gas to replace carbon-intensive oil products. In 2030, the average consumption of oil products in transport is 380 TWh, and in 2040, demand for oil products decreases to less than a half. For buildings, in 2030, the average emissions of the building sector amount to 53.6 MtCO₂e (15% lower than in 2020). This value drops to 26.9 Mt CO₂e in 2040, around 57% lower than 2020. The efforts in the building sector mainly consist in increasing the usage of heat pumps (electricity, renewable heat) and investment in insulation retrofits. After 2040, the transport and building sectors maintain a fast pace of carbon mitigation. In 2050, the average carbon emissions from buildings reduce to around 2.1 MtCO₂e, the lowest among all four end-use sectors. We can observe a significant contribution from the industry sector in the last ten years before 2050. In 2040, the average industrial carbon emission value is 41.5 MtCO₂e, equivalent to around 80% of emissions in 2020. In 2050, the average emissions from industry drop to 11.4 MtCO₂e. Industrial emissions decrease by 73% between 2040 and 2050. In addition, we observe that for the average trajectory, emissions from the industry sector significantly surpass the other three end-use sectors. This part of carbon emissions is estimated to be neutralized by carbon sinks.

The global emissions trajectory shows significantly lower variability than the emissions trajectories of end-use sectors. For these end-use sectors, we can observe different levels of uncertainty in different time steps. Emissions from the building sector present very high variability in 2035, 2040, and 2045. This is because the simulated scenarios have different levels of consumption of carbon-based gaseous fuels. In 2040, for gas consumption, the highest scenario (250 TWh) is around twice the level of the lowest scenario (80 TWh). In 2050, simulation results present a significantly lower level of variability for the building sector. We can see that for two-thirds of scenarios (384 cases), the building sector

achieves zero emissions. For the industry sector, its uncertainty increases with time. In 2050, emissions from industry show a very high level of variability. The standard deviation reaches 9 MtCO_{2e}, the highest among all end-use sectors. In 2050, demand for gaseous fuel by industry ranges from 0 to 220 TWh. This explains the broad range of carbon emission options resulting from our simulation results.

	Global				Industry				Buildings				Transport				Agriculture			
	<i>Average</i>	<i>Min</i>	<i>Max</i>	<i>SD</i>	<i>Average</i>	<i>Min</i>	<i>Max</i>	<i>SD</i>	<i>Average</i>	<i>Min</i>	<i>Max</i>	<i>SD</i>	<i>Average</i>	<i>Min</i>	<i>Max</i>	<i>SD</i>	<i>Average</i>	<i>Min</i>	<i>Max</i>	<i>SD</i>
2020	260980				54267				62599				107506				11249			
2025	242327	225681	261583	9486	54977	51173	58150	2295	55112	50376	59629	1945	98469	88575	109570	6761	10857	10764	10912	61
2030	219819	203891	231754	7422	50243	44228	56405	2663	53679	44147	60507	3700	86025	74342	99650	7781	10397	10081	10587	210
2035	171501	156063	181989	8131	45848	36687	52915	3949	44394	23529	59713	7626	56708	47116	71774	4923	9518	7259	10277	592
2040	117362	96112	131101	10768	41518	28806	51400	5639	26877	521	49546	11762	32380	20041	48804	5003	8484	5110	9961	892
2045	63610	35202	80327	12363	32615	12837	50354	7810	8309	0	33188	8303	15196	7782	27499	4964	6055	3809	8449	982
2050	15463	3736	30000	10547	11404	917	27849	9347	2157	0	10803	2320	5230	102	14660	4350	3680	1672	5884	1517

Table 43 Maximum, minimum, average, and standard deviation of carbon emissions in 576 scenarios by time step and by end-use sector (in ktCO₂e)

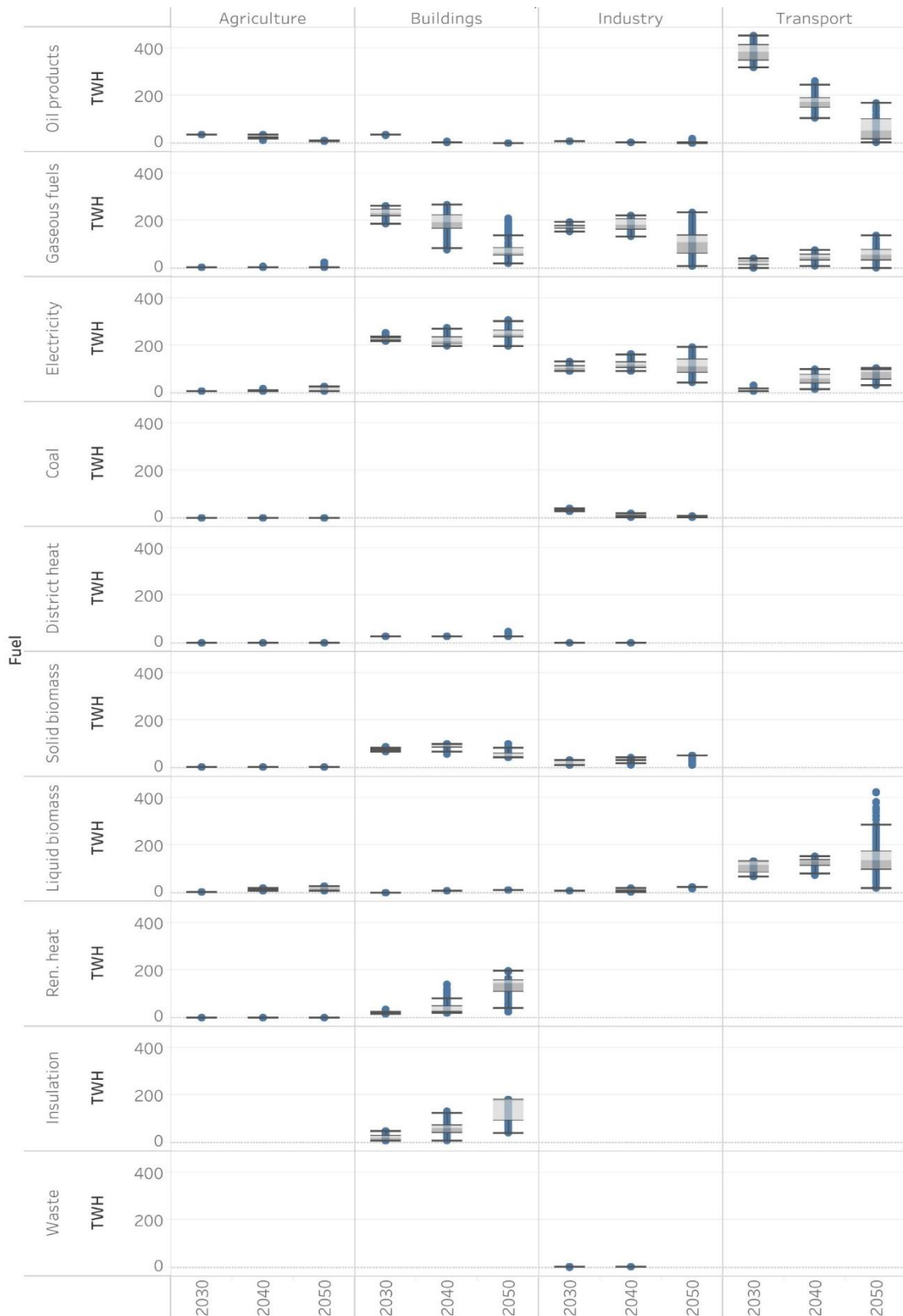


Figure 97 Distribution of final energy consumption over 576 simulations by energy group, end use sector, time step

4.2.3 Uncertainties for the future role of gas

By observing the distribution of gaseous fuel consumption in future time steps, we observe that a high variability exists for the role of gaseous fuels in the future. Here we propose to make an analysis to explain this uncertainty and help us better understand the role of gas networks in the energy transition under different conditions. We will firstly focus on identifying the decisive factors for gas consumption in the future, and then look at how the gas production system evolves.

4.2.3.1 Sensitivity analysis of future gas consumption: demand driven by carbon sinks and biomass potential

Figure 98 presents the trajectories of gas consumption from 2020 to 2050 produced by all the simulated scenarios. We outline ten trajectories representative of ten levels of gas consumption (Q1-Q10). These are scenarios with the smallest Root Mean Square Error (RMSE) from the average of ten quantiles of gas consumption for all the time steps from 2020 to 2050. Illustrating these trajectories can provide a clearer understanding of suggested tendencies by simulated scenarios for gas consumption in the future.

We note that nearly all of the scenarios in our study present an increasing trend for gas consumption before 2035. In 2035, gas consumptions in trajectory Q1-Q10 are within the range of 420-450 TWh per year, compared to 390 TWh in 2020. After 2035, the simulation results present highly divergent tendencies. We observe that scenarios close to the average (Q5, Q6), the highest (Q10) and the lowest (Q1) levels of gas consumption in the future show very varied pathways. Under scenario Q5 (scenario of the fifth quantile), which is close to the average level of gas consumption, gas demand reduces slightly between 2035 and 2040, and after 2040 the pace of the decrease significantly accelerates. In 2050, gas demand under scenario Q5 reduces to around 250 TWh, 36% lower than 2020. Compared to Q5, the decrease rate of gas consumption under scenario Q10 after 2040 is much slower, and in 2050, the share of gas remains very high. In 2050, the gas demand in scenario Q10 is 370 TWh, only 5% lower than in 2020. For the low scenario (Q1), we observe a sharp decrease in gas consumption from 2035 to 2050. In 2050, the gas consumption in scenario Q1 reduces to around 110 TWh, less than one-third of the level in 2020.

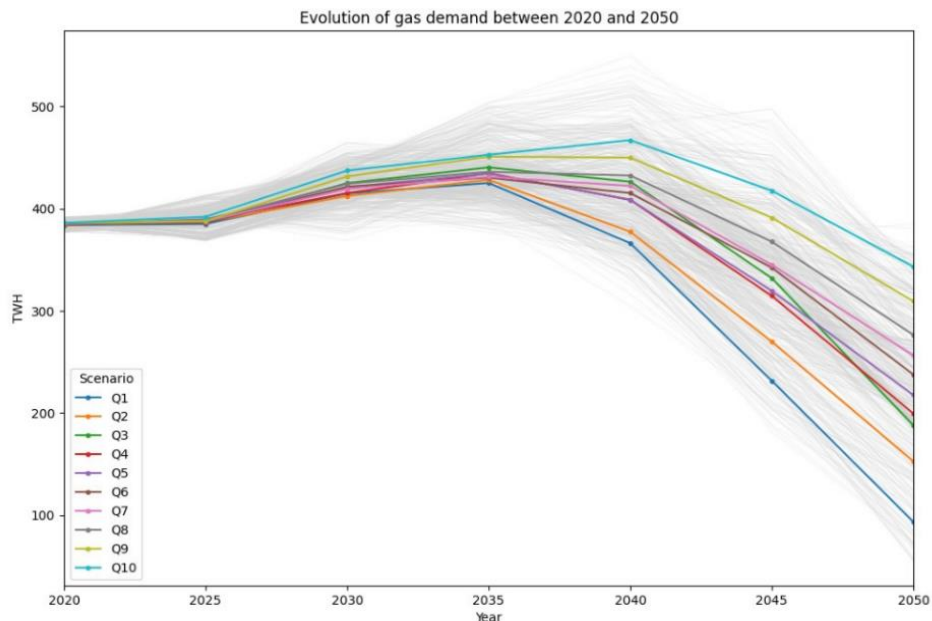


Figure 98 576 simulated trajectories of gas consumption between 2020 and 2050

The ten trajectories present a wide gap for gas demand in 2050. Next, we will try to explain this difference and identify the decisive factors of gas consumption. The heat map below (Figure 99) represents the number of scenarios based on each choice of the seven key dimensions of study. We focus on the scenarios featuring the highest (Q9, Q10) and lowest gas consumption (Q1, Q2). The red/orange color may suggest that this dimension is decisive to gas demand.

We note that the role of gas is closely linked with the development potential of carbon sinks. Nearly all the scenarios located in the last two quantiles of gas consumption have a high potential for carbon sinks, while all of the scenarios in the first quantile of the lowest gas demand are based on a low-carbon sink potential in the future. This is explained by variations in carbon-based natural gas consumption due to the level of emission constraint. A higher availability of carbon sinks allows for more usage of natural gas in the industry sector. We see that among the 270 scenarios with a relatively high natural gas supply (above 47 TWh), more than 90% are based on a high carbon sink potential (c1).

Apart from carbon sinks, the potential of biomass is another decisive factor for gas in 2050. The three scenarios of future biomass supply predict completely different futures for gas consumption. For the scenarios with the lowest gas consumption (1st and 2nd deciles), 113 out of 116 are based on the lowest biomass potential (b2), and for those with the highest consumption (9,10 deciles), all of them involve a higher biomass scenario (b1, b3). The greater availability of biomass supply enables more gas supply

from renewable gas branches including methanization and pyro-gasification. This is especially the case for the pyro-gasification industry, since it is highly dependent on the potential of solid biomass supply related to the development of forestry. We note that nearly all b3 scenarios (192 scenarios) without available wood waste for biogas production feature a very low level of biomethane produced from pyro-gasification (less than 10 TWh) in 2050. Another observation is that, nearly all of the scenarios with a possibility to develop hydrothermal gasification have gas consumption above the median level. This outlines the role of hydrothermal gasification in the future gas industry.

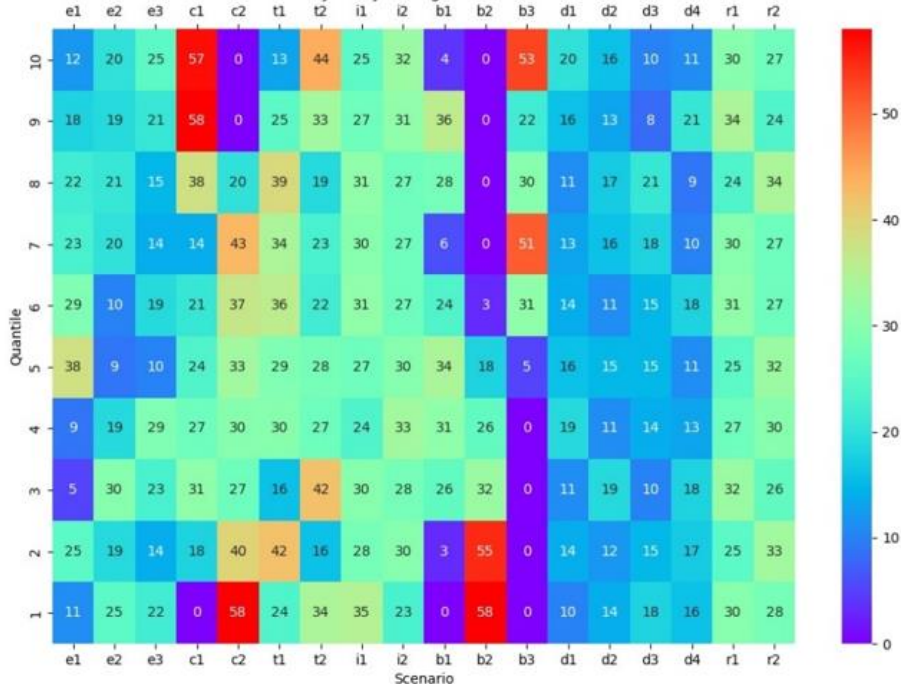


Figure 99 Sensitivity of gas consumption in 2050 to the seven key dimensions

4.2.3.2 Gas supply in 2050: future transition led by renewable gases

The previous discussions illustrate how demand for gas from the energy system evolves under different conditions. Here we focus on the gas production system in the future and the role of various gas supply solutions. We propose to compare scenarios of the highest gas consumption in 2050 (the last two deciles) and scenarios of the lowest gas consumption (the first two deciles) (Figure 100, Figure 101). This allows us to identify the development tendency and uncertainties about various sources and types of gaseous fuels in the future energy transition.

We note that, for all the scenarios with the highest and the lowest gas demand, imports of natural gas reduce significantly compared with the current gas mix. Even among those with the highest gas consumption, no scenario presents a natural gas import level higher than 156 TWh, compared with around 380 TWh in 2020 (decrease of more than 60%). This is in line with the need to reduce fossil energy consumption to reach the target of carbon neutrality. Biomethane will play an important role in the gas mix of 2050, and this is the case for both the highest and lowest gas demand scenarios. In 2050, biomethane production for most scenarios of the last two deciles reaches 138 TWh, and around 70 TWh for scenarios of the first two deciles. The lower production cost compared with other renewable gas branches may be one of the main reasons for the energy system to invest in methanization. We can also observe that, for the power-to-gas sector, valorization of renewable hydrogen by direct injection or by methanation is not a significant solution in the future for the scenarios at the two gas demand extremities. This can be explained on the one hand by the high cost of injecting renewable gas produced by power-to-gas, and on the other hand by the competition of electricity usage from other sectors.

For pyro-gasification, its development in the future is highly uncertain. For the high gas demand scenarios, renewable gas production from pyro-gasification constitutes a large share with 42-67 TWh of annual production in 2050, while its production is close to zero for most low gas demand scenarios. This may be linked with future conditions of biomass supply, which is vital for the development of the pyro-gasification industry. For the highest gas consumption scenarios (D9 and D10), most are based on a high potential with wide availability of solid biomass supply, and in particular an additional supply of wood waste exclusively recovered by pyro-gasification.

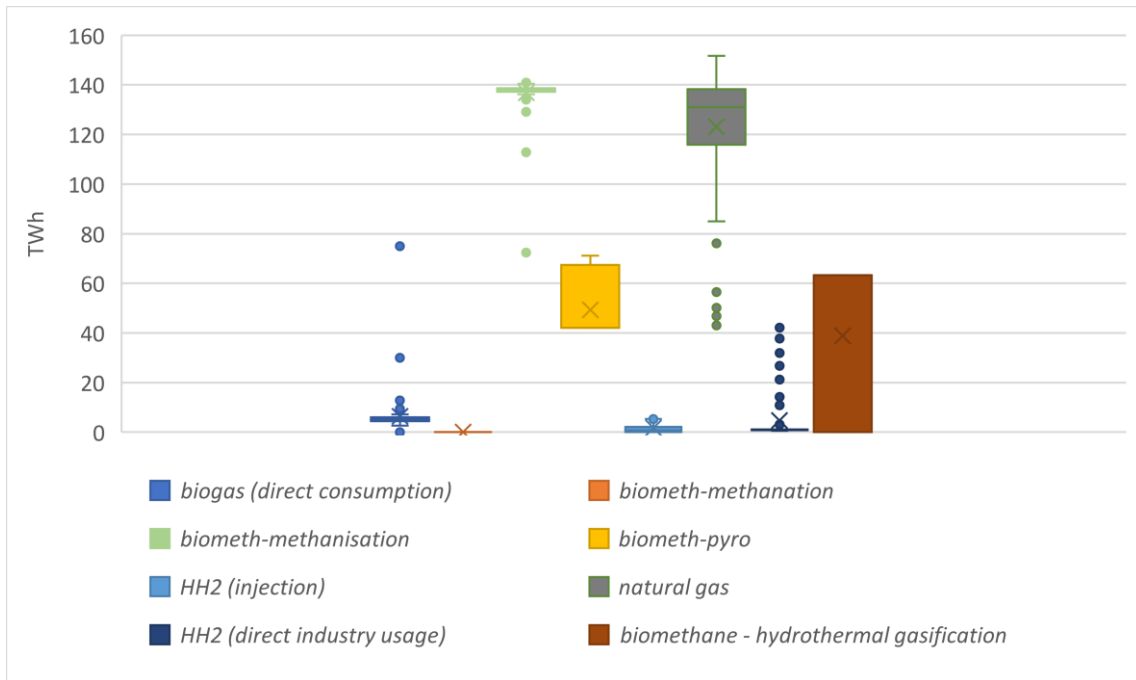


Figure 100 Distribution of gas production from different sources over scenarios of the last two deciles of gas consumption in 2050

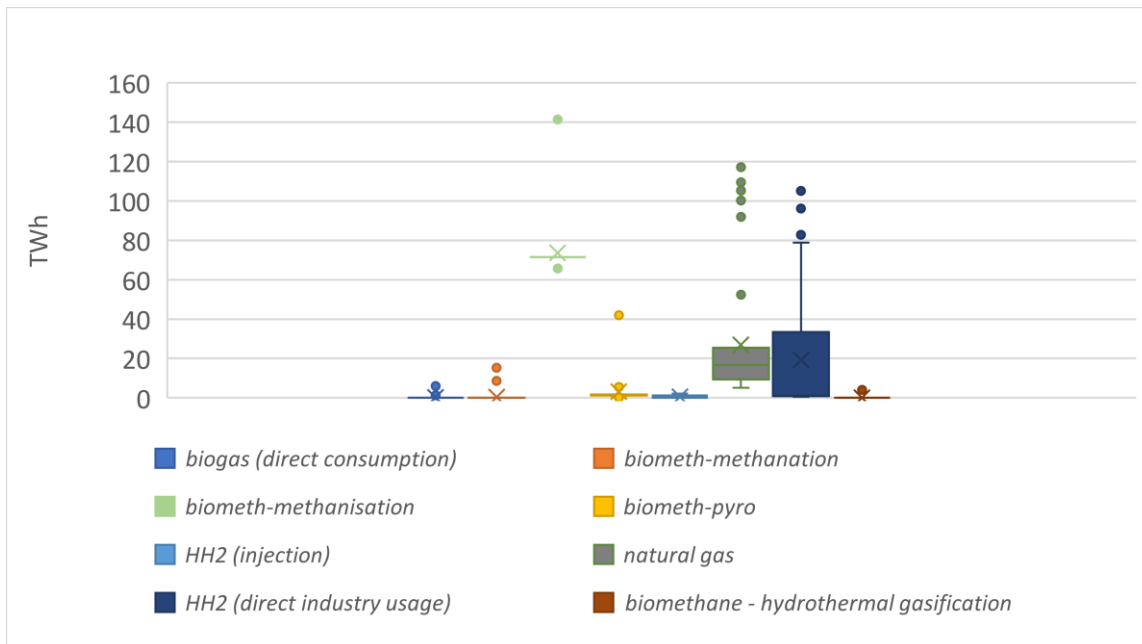


Figure 101 Distribution of gas production from different sources over scenarios of the first two deciles of gas consumption in 2050

4.2.4 Role of key dimension: analysis of specific scenarios

In this section, we will present multiple scenarios based on different hypotheses of four dimensions of study: carbon sinks, international transport, demand scenario, and discount rate. By studying in detail how the solutions to reach carbon neutrality adapt when changing these conditions, we can better apprehend future uncertainties for the energy system. Table 44 presents selected scenarios for our analysis. For each dimension, we focus on comparing several scenarios based on different cases of this dimension while controlling the conditions of other dimensions.

<i>Dimension of study</i>	<i>Scenarios for illustration</i>	<i>Description</i>
<i>Mitigation burden</i>	e1c1t1i1b1d1r1	High carbon sink potential, international transport not considered by mitigation target
	e1c1t2i1b1d1r1	High carbon sink potential, international transport considered by mitigation target
	e1c2t2i1b1d1r1	Low carbon sink potential, international transport not considered by mitigation target
<i>Demand scenario</i>	e1c1t2i1b1d1r1	Demand scenario D1 (highest trajectory)
	e1c1t2i1b1d2r1	Demand scenario D2
	e1c1t2i1b1d3r1	Demand scenario D3
	e1c1t2i1b1d4r1	Demand scenario D4 (lowest trajectory)
<i>Discount rate</i>	e1c1t2i1b1d1r1	Low discount rate (4.5%)
	e1c1t2i1b1d1r2	High discount rate (10%)

Table 44 Selected scenarios for analysis

4.2.4.1 Different mitigation burden perspectives for the energy system, effects of carbon sinks, and carbon mitigation of international transport

Although the national emissions target is to achieve zero net emissions for the entire French territory, the distribution of the decarbonization burden could vary greatly for a given energy system. The dimensions of carbon sink potential and international transport emissions are decisive to map the decarbonization efforts required. Here we propose to study three cases reflecting different perspectives of the decarbonization burden share for the energy system: high carbon sinks with decarbonization of international transport (C1T1), high carbon sinks without decarbonization of international transport (C1T2), and low carbon sinks without decarbonization of international transport (C2T2). The table below (Table 45) illustrates the emission constraint trajectories in TIMES-FR under these three scenarios.

	<i>Trajectory high natural CCS international transport included (C1T1)</i>	<i>Trajectory high natural CCS international transport not included (C1T2)</i>	<i>Trajectory low natural CCS international transport not included (C2T2)</i>
1990	397898	364071	364071
2020	295730	272808	272808
2025	298933	268045	258667
2030	252050	231754	221480
2035	196649	181427	168019
2040	141249	131101	114558
2045	85401	80327	61097
2050	30000	30000	7637

Table 45 Proposed emission trajectory of variant C1T1, C1T2, C2T2

We will firstly focus on how the energy system reacts under different carbon sink potential scenarios.

[Figure 102](#) and

[Figure 103](#) compare the mitigation paces of different end-use sectors between scenario e1c2t2i1b1r1d1 (low carbon sink) and scenario e1c1t2i1b1r1d1 (high carbon sink). We observe that a lower carbon sink availability adds a much higher mitigation burden to the industry and transport sectors in order to reach carbon neutrality. Under the high carbon sink scenario, in 2050, around 44 MtCO_{2e} and 22 MtCO_{2e} of positive emissions remain for the transport (international transport included) and industry sectors, compared with 34 MtCO_{2e} and 2 MtCO_{2e} under the low carbon sink scenario. Compared to transport and industry, a lower carbon sink potential makes no significant difference to mitigation efforts for residential and tertiary buildings.

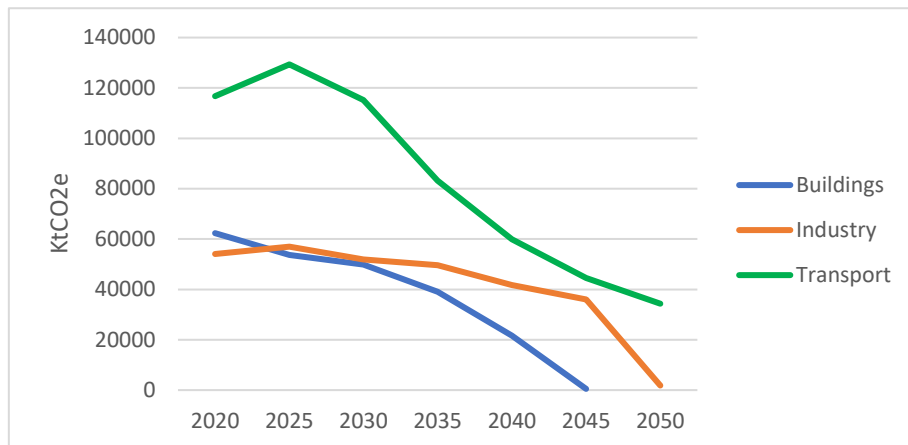


Figure 102 Mitigation burden share in low carbon sink scenario e1c2t2i1b1r1d1 (low carbon sink) (with emission from international transport)

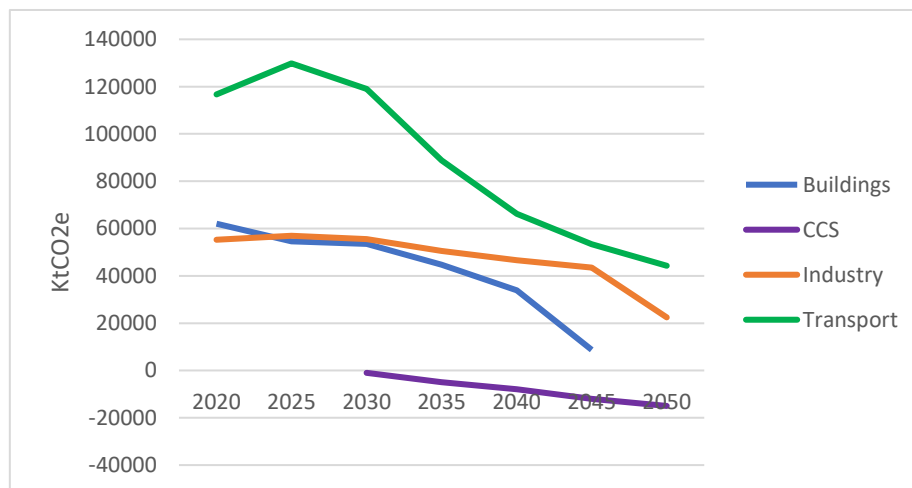


Figure 103 Mitigation burden share among end-use sectors of e1c1t2i1b1r1d1 (high carbon sink) (with emission from international transport)⁷²

Figure 104 and Figure 105 present the evolution of the sectorial energy balance of these two scenarios. The tighter emission constraint results in less use of natural gas and oil products in the energy system, inducing an increased level of competition between end-use sectors for a given energy resource. This significantly compounds the difficulties of achieving carbon neutrality in 2050. For the industry sector, under the low carbon sink scenario, as the development of CCS faces strong limitations, a much lower consumption of fossil natural gas is allowed in a system aiming for carbon neutrality in 2050. Moreover, in a situation of strong usage competition, as many industrial processes are highly dependent on gas, the industrial energy system has difficulties finding an alternative solution to natural gas, and has to

⁷² Emission from buildings in 2050 reduces to zero

import high volumes of materials to satisfy industrial demand. This means that implementation of CCS could play a vital role in the carbon mitigation of industry. In a case where nearly complete decarbonization is required, the results of the industry sector may suggest that the risks facing the energy system make it incapable of satisfying all domestic demand, thus posing a question of supply security. For the transport sector, the share of biofuel is significantly lower in 2050 under the low carbon sink scenario. This may be linked with the increased competition of carbon neutral biomass resource usage induced by a stricter emission constraint: more solid biomass is used for renewable gas production instead of second-generation biofuel. Around half (38 TWh) of biofuel supply for transport has to rely on imports.

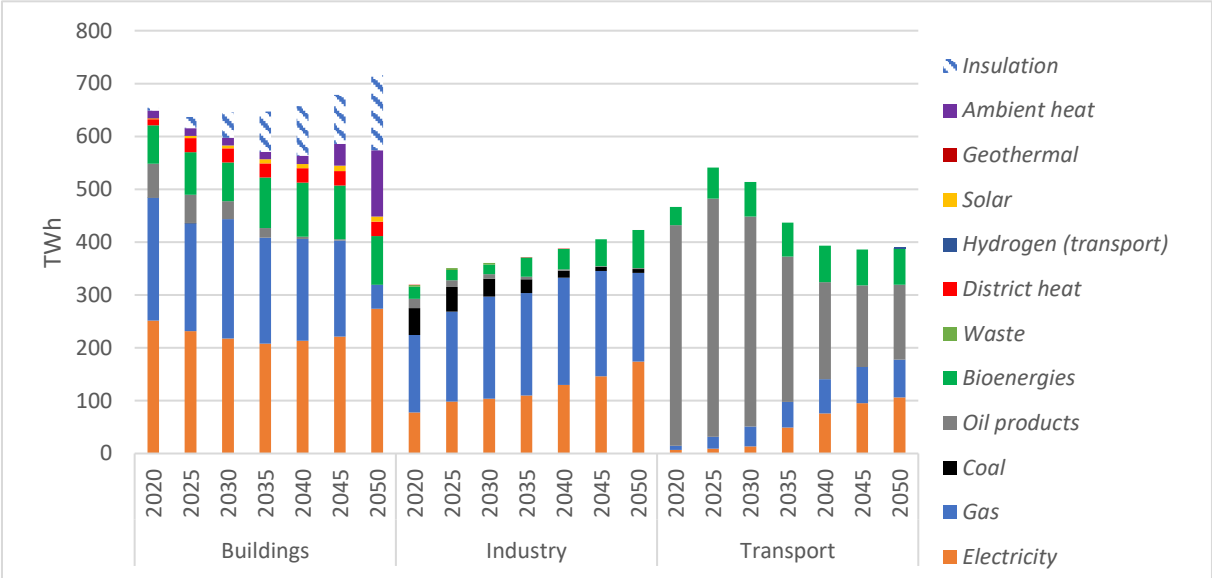


Figure 104 Sectorial energy balance of scenario e1c1t2i1b1r1d1 (high carbon sink) (with energy consumption of international transport)

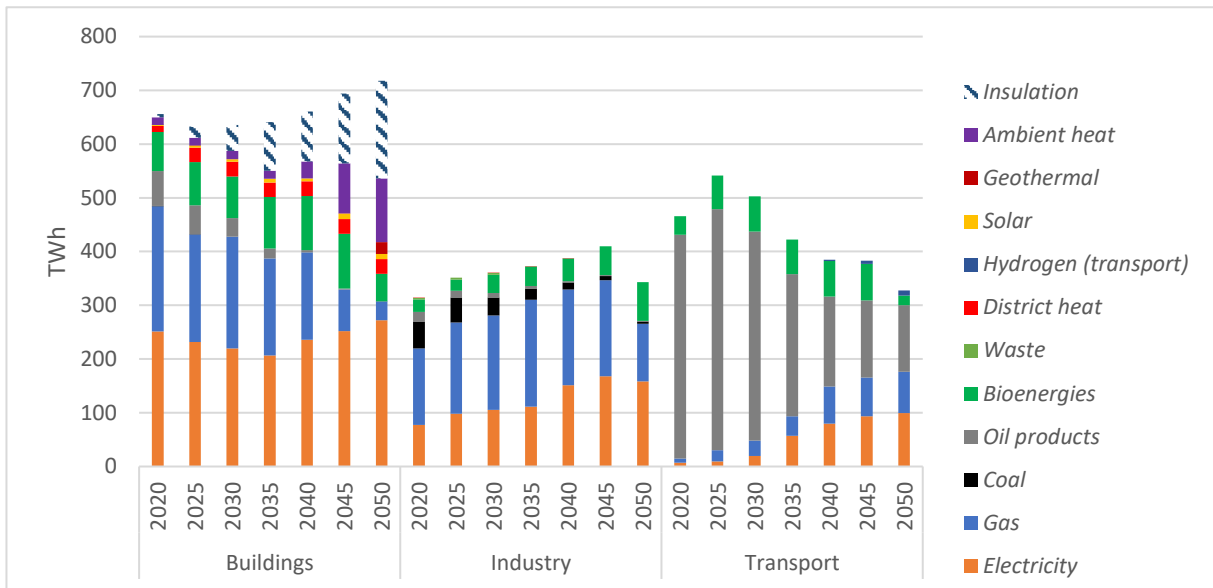


Figure 105 Sectorial energy balance of scenario e1c2t2i1b1r1d1 (low carbon sink) (with international transport)

Next, we will focus on the choice for the energy system when there is an additional burden to decarbonize the international transport sector. Figure 106 and Figure 107 present the evolution of the sectorial energy balance and emissions trajectory of scenario e1c1t1i1b1r1d1 that includes decarbonization of international transport (with high carbon sinks). Under the scenario that integrates international transport into the mitigation target, the transport sector makes additional efforts to replace around 20% of oil product consumption (22 TWh) by international transport with biofuel (biodiesel), and integrates more biofuel for domestic transport.

In 2050, the consumption of biofuel by transport reaches 98 TWh, compared to 69 TWh under the scenario without considering emissions from international transport. Apart from efforts in the transport sector, the energy system has to make considerable efforts in industry in order to achieve the global mitigation target. In 2050, emissions from industry drop to nearly zero, following a sharp decrease in gas consumption. This may be related to the existence of a less decarbonized solution for long-distance transport, except biofuel with limited supply potential. A greater mitigation burden from the transport sector leads to stronger competition for the usage of energy resources. In 2050, it is expected that a significant portion of industrial materials, such as cement, iron, and steel, will need to be imported.

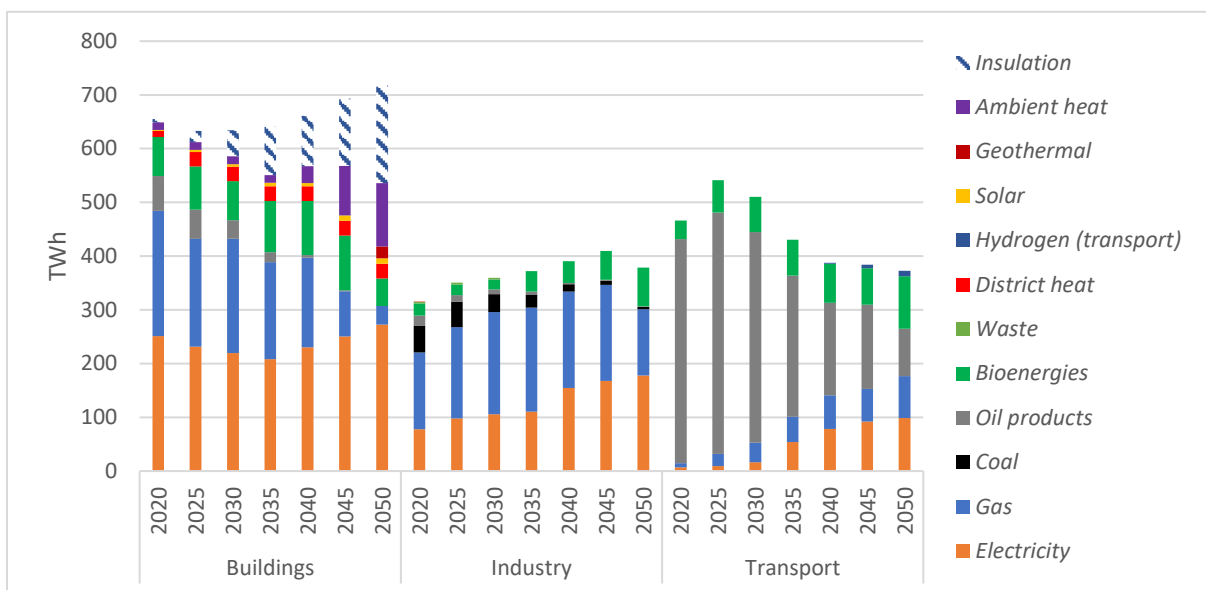


Figure 106 Proposed sectorial trajectory of energy transition by scenario e1c1t1i1b1r1d1 (with international transport, high carbon sink)

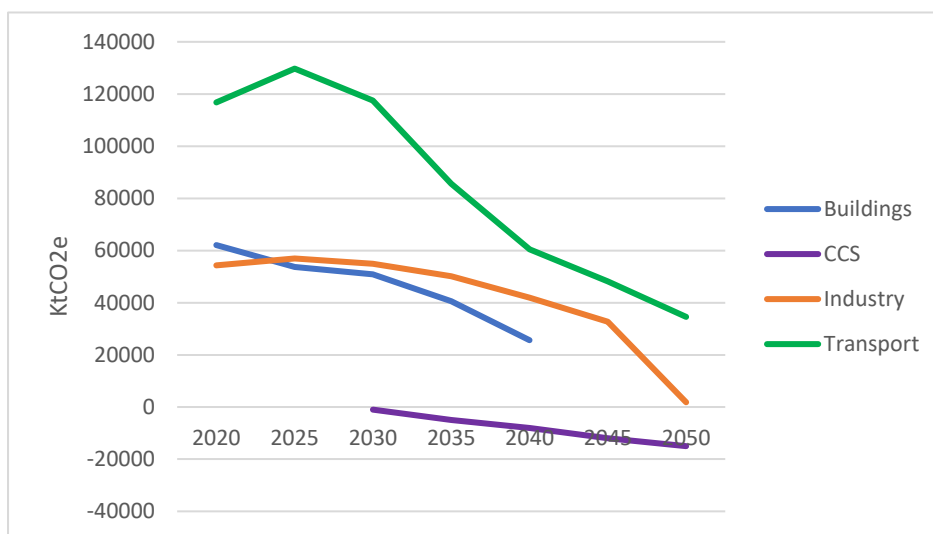


Figure 107 Proposed sectorial emission trajectory by scenario e1c1t1i1b1r1d1 (with international transport, high carbon sink)⁷³

⁷³ Emissions from buildings reduce to zero by 2045

4.2.4.2 Future demand from energy services as a key element shaping the energy transition

Here we focus on four scenarios with four levels of useful energy demand calibrated from different visions (D1-D4). Figure 108 presents the evolution of the final energy balance in these four scenarios.

Figure 109 compares the evolutions of building, industry, and transport energy balances in e1c1t2i1b1d1r1 (highest demand scenario) and e1c1t2i1b1d1r1 (lowest demand scenario). We observe that the level of final energy demand significantly varies across the four cases with different demand scenarios. Under D1, the total final energy demand surpasses 1450 TWh in 2050, around 44% higher than D4. Transport and industry final demand under D1 reaches 267 and 422 TWh, compared to 121 and 295 TWh under D4. Electricity consumption reduces significantly in a future with low demand: electricity demand drops from 563 TWh under D1 to 366 TWh under D4, driven by lower electricity demand from all end use sectors (industry, transport, buildings). For the building energy system, the share of insulation and ambient heat for space heating is significantly lower in low energy demand scenarios. As there is less competition for the use of energy sources, the building system chooses to use gas to replace thermal insulation and heat pumps, which require much higher upfront expenditure. Besides, a lower mobility demand allows for a much lower carbon mitigation burden for the energy system by shaving high oil product consumption from transport. Compared with electricity, gas demand remains stable across all scenarios with different levels of demand, as a result of a high demand from the building and industry sectors.

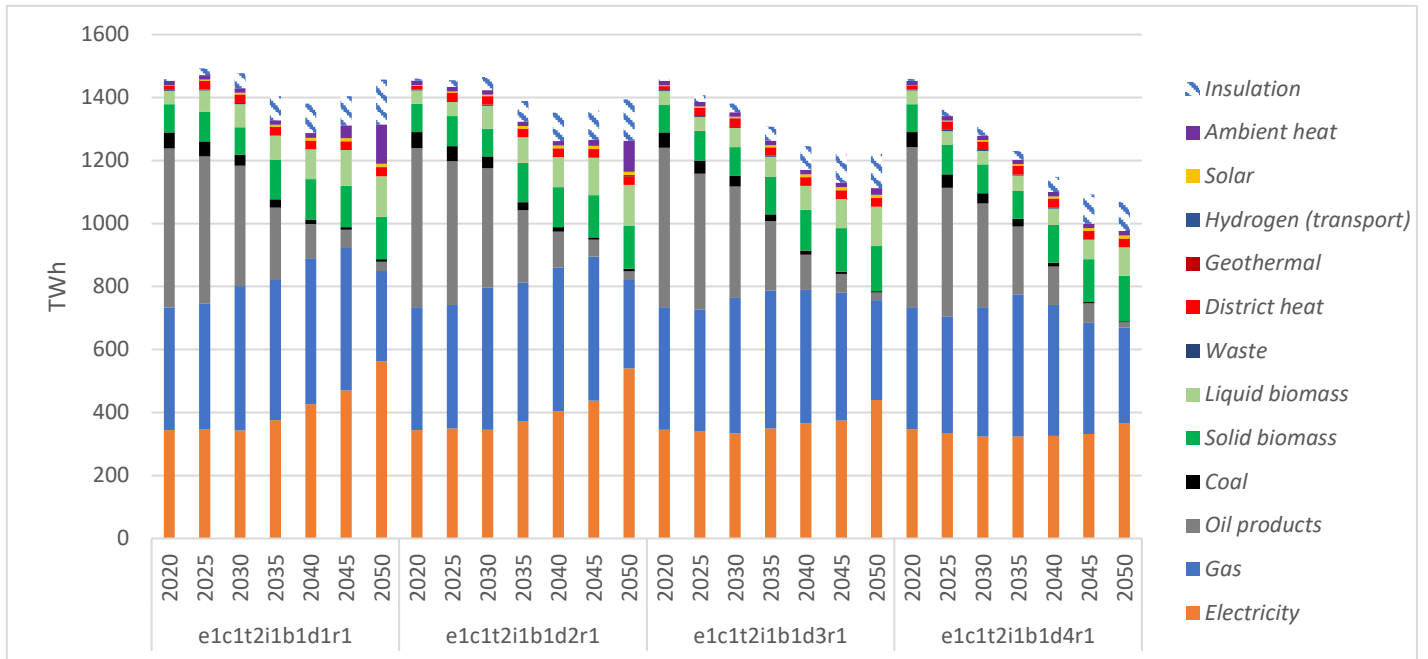


Figure 108 Evolution of final energy balance by four scenarios with different levels of energy demand (without international transport)

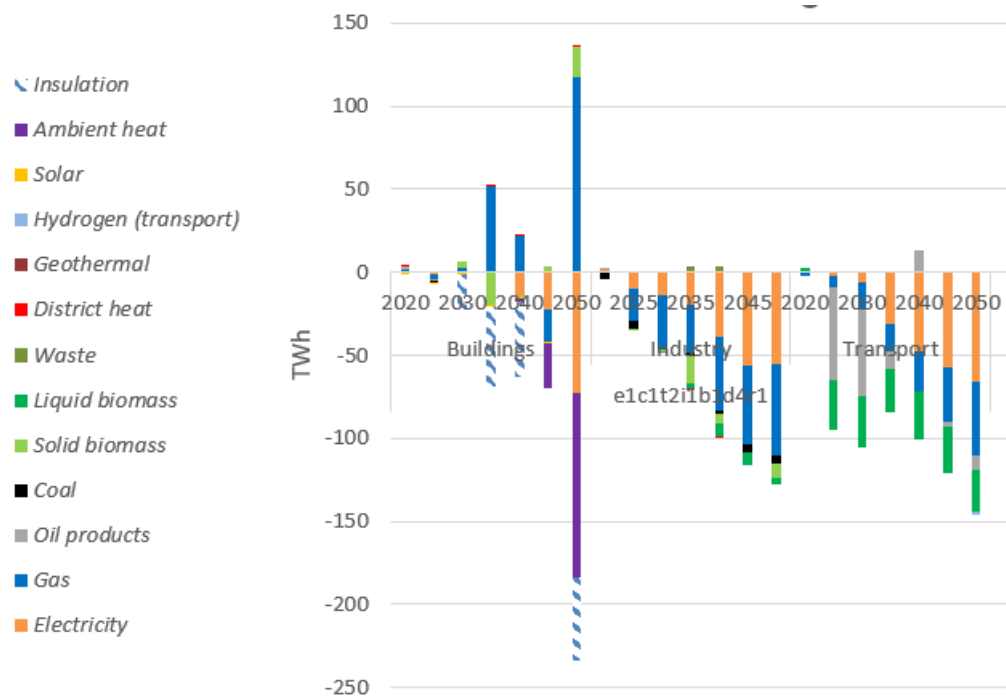


Figure 109 Final energy demand per sector for scenario e1c1t2i1b1d4r1 (compared with e1c1t2i1b1d1r1)

4.2.4.3 Role of discount rate

In order to investigate the effect of the discount rate on energy system investment choices, we compare scenario e1c1t2i1b1d1r1 with a low discount rate (4.5%) with e1c1t2i1b1d1r1 with a high discount rate (10%). Figure 110 and Figure 111 illustrate differences in the transport and building energy balance between the high and the low discount rate scenarios. We note that a higher discount rate has a major impact on the investment choices of end-use sectors, especially for time steps between 2030 and 2040. For the transport sector, a high discount rate induces lower investments in electric and gas vehicles that require higher investment costs from 2030 to 2045. As a result, the energy system chooses to use oil products as replacements. Besides, as conventional fuel vehicles generally have lower fuel efficiency than electric vehicles, a higher volume of oil products is required. In 2035, the high discount rate scenario has 19 TWh lower electricity demand and around 7 TWh lower gas demand for transport, and the additional consumption of oil products reaches 54 TWh. For the building sector, we observe a lower investment in thermal insulation in the midterm (50 TWh in 2035 and 61 TWh in 2040). In this case, the additional need for space heating is satisfied by gas boilers.

The decision to rely more on oil products in the transport sector significantly reduces its share in carbon mitigation efforts in the midterm. In 2035, for transport, carbon emissions in the high discount rate scenario are estimated to be around 13% higher than the low discount rate case. In order to meet the mitigation target, the energy system chooses to integrate more biomethane from methanization to replace carbon-based natural gas (Figure 112). In 2035, biomethane produced by methanization reaches 114 TWh under the high discount rate scenario, nearly twice as high as in the other case.

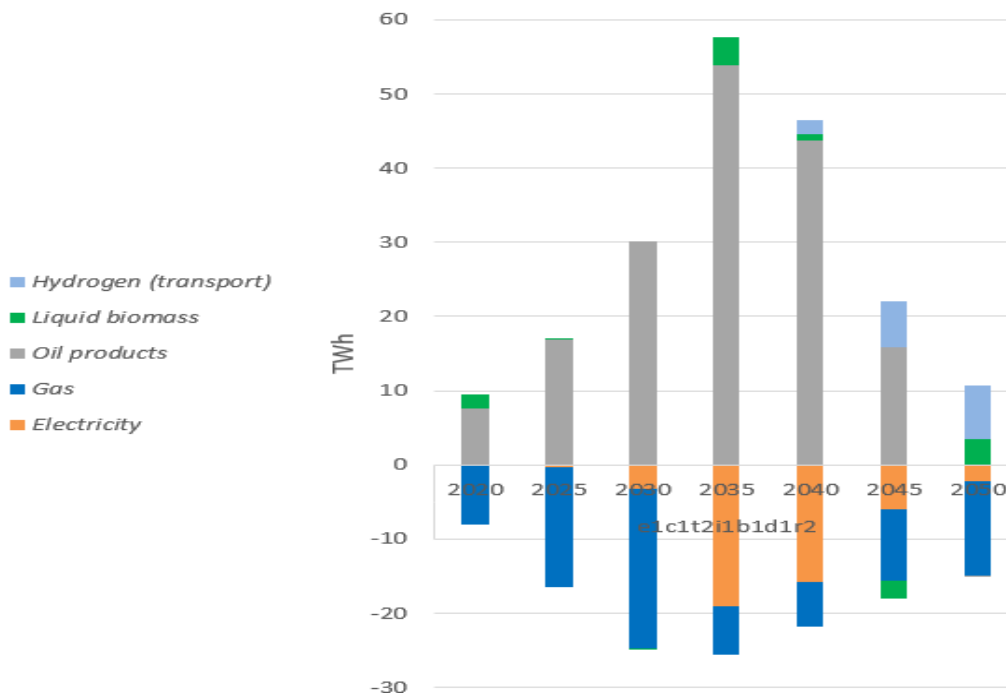


Figure 110 Difference of transport energy balance per time step by scenario e1c1t2i1b1d1r2 (high discount rate) compared to e1c1t2i1b1d1r1 (low discount rate)

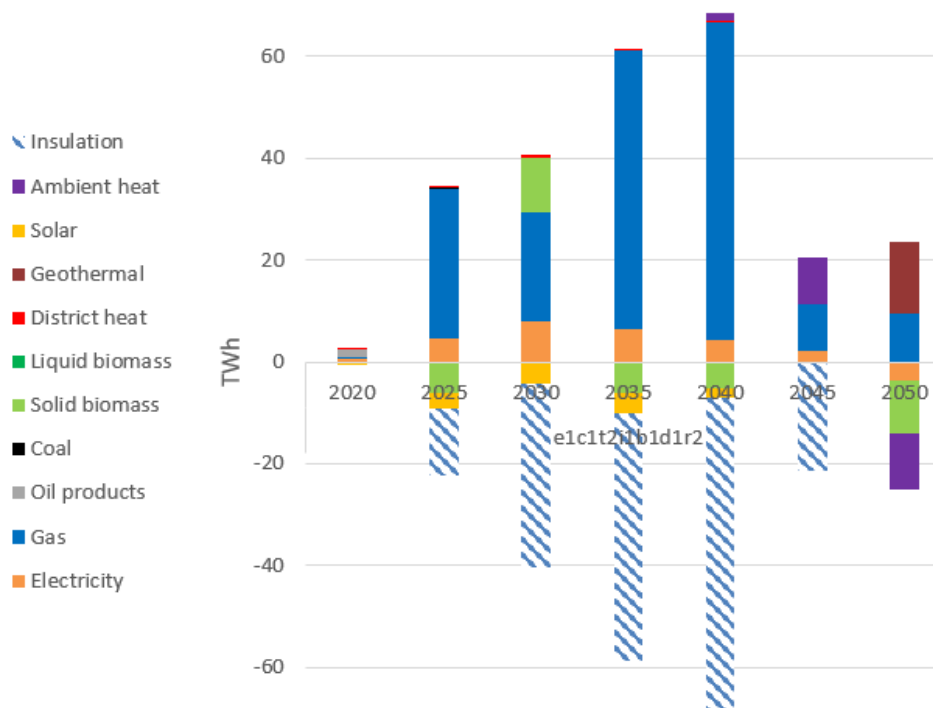


Figure 111 Difference of building energy balance per time step by scenario e1c1t2i1b1d1r2 (high discount rate) compared to e1c1t2i1b1d1r1 (low discount rate)

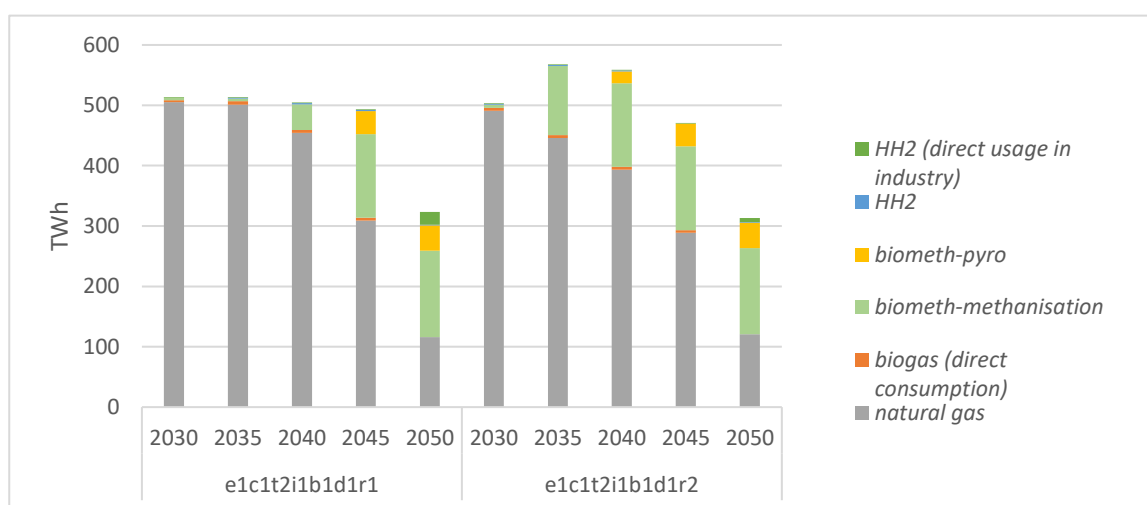


Figure 112 Evolution of gas supply balance by scenario e1c1t2i1b1d1r1 and e1c1t2i1b1d1r2 for 2030-2050

Figure 113 compares the evolution of annualized costs of the energy supply, buildings, industry, and transport sectors between the two cases. We observe that the scenario with a higher discount rate has a considerable cost surplus. In 2035, the total additional annual cost of the high discount rate scenario reaches 50 billion euros, around 14% higher than the low discount rate scenario. In 2050, the annualized fixed cost of the high discount rate scenario amounts to 375,000 million euros, and the gap between the two scenarios grows to 93,000 million euros, around 33% higher than in the scenario with a low discount rate. Among the end-use sectors, the transport sector represents the highest share of cost surplus for all time steps. This is explained by the higher investment cost of all types of vehicles induced by a higher discount rate. There is a significant increase in additional cost for energy supply from 2035 linked with more investments in renewable gas production. For the building sector, although the discount rate is higher, the cost surplus can only be observed after 2045. This is because the building system chooses to reduce the level of thermal insulation with high investment costs for time steps before 2045.

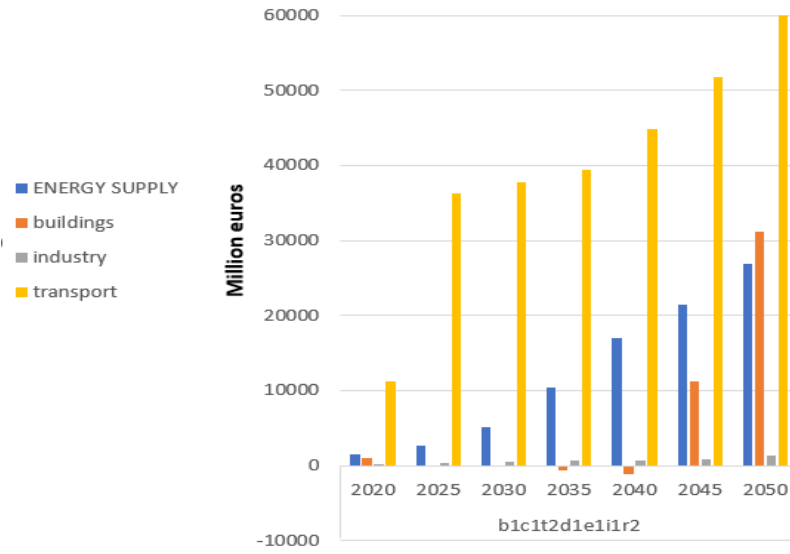


Figure 113 Annual cost per sector per time step by scenario e1b1c1t2i1r2d1 (high discount rate) compared to scenario e1b1c1t2i1r1d1 (low discount rate)

Conclusions

In this chapter, a large number of neutrality scenarios elaborated by varying hypotheses of seven key energy transition dimensions are studied. We have made an in-depth analysis from the broad range of possible energy system trajectories. Our analysis of the results outlines the long-term role and uncertainties of gas, electricity, and other important energy sources in a carbon free system. To further explain the uncertainties for gas, which is of high interest for the gas grid, we have elaborated a sensitivity analysis for gaseous fuel demands in 2050, and the corresponding evolution of the production system. We have also illustrated multiple scenarios based on different hypotheses concerning the potential of carbon sinks, decarbonization of international transport, demand scenarios, and discount rates. This allows us to better understand different possibilities for the energy transition to reach carbon neutrality.

From the analysis of modeling results, we retain several key points:

The suggested tendency of the average scenarios shows a significant increase in electricity, liquid biomass, and renewable heat in the energy transition to reach a carbon-free system. Compared to 2020, the consumption of electricity in 2050 is 30% higher. Demand for gaseous fuel firstly shows an increasing trend, then decreases after 2035. The share of oil products and coal is replaced. By 2050, the consumption of oil products is 15% of the 2020 level.

In 2050, the consumption of electricity, gaseous fuels, and liquid biomass presents high uncertainty. The simulated scenarios present a range of electricity consumption from 320 to 600 TWh, gaseous fuel consumption from 56 TWh to 386 TWh, and liquid biomass consumption from 50 to 470 TWh.

The average emission trajectories of end-use sectors suggest that considerable efforts are carried out in the transport and building sectors from 2030. The pace of carbon mitigation for industry accelerates after 2040. Emissions from the building sector present very high variability in 2035, 2040, and 2045, as the simulated scenarios feature very different levels of gaseous fuel consumption.

The simulated scenarios present high variability for the consumption of gas after 2035. In 2050, the gas consumption in the high gas trajectory scenario (Q10), the scenario close to average (Q5), and the low gas trajectory scenario (Q1) exhibit great differences.

The variability of gas consumption in the future can be explained by the development potential of carbon sinks and the potential of biomass supply. Nearly all the scenarios with relatively high gas demand in 2050 (the last two deciles) have a high carbon sink potential. This is linked with the variation

of carbon-based natural gas consumption towards the emission constraint. For gas supply in the future, the suggested tendency shows a significant increase in biomethane produced from methanization, while direct injection or methanation of hydrogen produced by power-to-gas does not play a significant role. For the development of pyro-gasification, high uncertainty exists.

In a low-carbon sink scenario, the energy system faces greater difficulties to reach carbon neutrality, in particular to decarbonize industrial emissions. Without the possibility to develop CCS, the share of natural gas in industry reduces significantly. For many gas-dependent branches, the question of supply security is put forward. If emissions from international transport are integrated to the neutrality target, additional efforts are required to reduce the consumption of fossil gas from both the transport sector, by increasing the share of biofuel to replace fossil oil products, and the industry sector.

By comparing the four cases with different demand scenarios, we note that electricity consumption decreases with the level of demand for all end-use sectors. Gas demand remains high, even in the lowest demand scenario, as a result of high demand from the building and industry sectors.

A higher discount rate has a major impact on the investment choices of the transport and building sectors. For the transport sector, a high discount rate induces lower investment in electric and gas vehicles before 2050. For the building sector, investment in insulation retrofit is reduced, replaced by gas boilers. Comparing the two selected study cases, the total annualized cost in 2050 is around 33% higher under the high discount rate scenario.

General conclusion

Key findings

In this Ph.D. thesis, we have studied the optimal technology choices for the French residential system to achieve carbon neutrality by 2050, with a focus on long-term technical choices. A systematic approach is adopted to understand the interaction of different sectors in the energy system in response to key questions regarding the residential energy transition. The research is based on a prospective modeling method with a linear optimization model, TIMES-FR, that represents the entire energy system of France from a technology rich, bottom-up structure.

We started by undertaking a bibliographical review to identify elements that enable us to understand the ramifications of our research question. We reviewed existing environmental and energy policies, and statistics on carbon emissions and energy consumption in France. The results outlined the important role of residential buildings in global decarbonization efforts. Energy prospective scenarios elaborated by multiple stakeholders, including the French government, a public institute (ADEME), an association (négaWatt), and gas and electricity network operators in France, were also studied and provided essential visions to consider. We reviewed the technical-economic features of the eligible technologies that may contribute to the future transition of the residential energy system, including insulation retrofit, condensing boilers, electric heat pumps, solar thermal systems, district heating, and fuel cells. Through this review, we gained an understanding of the technology side of the residential energy transition and attained the necessary elements to represent these technologies in the TIMES-FR model.

We identified multiple elements that may have important effects on investment choices. Based on this, we achieved multiple improvements on both the supply and demand sides of the building energy system in TIMES-FR to better account for these elements. On the supply side, we completed the structure of renewable gas industries by reviewing their production costs and supply potentials, and modeling the emerging hydrothermal gasification technology. We elaborated an improved modeling structure for biomass and district heating supply by disaggregating various supply processes. This helps to better account for the disparity of availability and cost existing over different supply modes. On the demand side, we recalibrated the technical-economic parameters of the entire energy process modeled in the building energy system. In addition, we introduced a detailed modeling of operation modes and energy efficiency over different temperature ranges for electric heat pumps. These efforts improve the representation of the building sector in TIMES-FR. Besides, we calibrated four scenarios

for all demands for energy services and commodities modeled in TIMES-FR. This allows our analysis to cover more possibilities of future demand, an essential element to consider.

We elaborated two studies that help us to answer questions about the future transition of the residential energy system. The first study proposed a complete analysis of the future transition of space heating to carbon neutrality. Our analysis considered multiple key elements, including the presence of extreme cold situations, the efficiency of thermal insulation, the pace of carbon mitigation from 2030-2045, and the opportunity cost of gas. Multiple scenarios were elaborated in order to investigate solutions for the energy system based on different hypotheses of these key factors.

The trajectories obtained for the global energy balance suggest that, to reach a carbon-neutral system will involve a significant increase in consumption of electricity (from 57% to 63% compared to 2020 in all scenarios) and renewable energies (biomass, renewable heat, waste). The share of gas drops significantly by 22.5-26.5% depending on the scenario. The results also illustrate that considerable decarbonization efforts are carried out in buildings after 2040 by investing in electric heat pumps and insulation retrofits to replace gas boilers.

In most scenarios, energy saving by thermal insulation reaches over 140 TWh in 2050, more than 28% of total heating demand. This will require achieving a high number of insulation retrofits per year till 2050. To maintain this pace may require providing support to households in terms of both finance and technical expertise to increase the quality of renovation work. We also observe that the space heating system will rely more on gas in a future with less effective insulation.

From scenarios with the presence of extreme cold events, we learned that, after 2045, hybrid heat pumps (HHP) play an important role in a carbon-neutral space-heating system in some scenarios and prove effective in reducing electricity demand during extreme cold periods. In 2050, the simulation results reach more than 3 million installations of hybrid heat pumps. Currently, HHP is still an emerging technology. Achieving this number of installations in the future requires policy support, for example, financial incentives for households, etc. Besides, a scale effect to reduce the production cost of equipment is required. In 2040, the total annual cost of the scenario with the most advanced mitigation pace is around 27% higher than the linear mitigation pace scenario.

From scenarios with varied emission trajectories covering 2030-2045, we learned that an anticipated mitigation pace leads to an earlier replacement of gas by electricity than in the linear emissions trajectory, and vice versa for a late mitigation pace. To achieve an advanced mitigation target, high investments in low-carbon technologies, such as electric heat pumps, biofuel, and electric vehicles, and renewable gas will be needed by around 2035 and 2040. This may require the stakeholders of

these sectors to take immediate action. Besides, reaching an advanced mitigation target can generate significantly higher costs for the energy system.

By studying scenarios with a limited consumption of gas following the SNBC hypotheses, we learned that achieving carbon neutrality with a low participation of gas is feasible although not optimal. The opportunity cost consists of greater usage of oil products in industry and transport, and more usage of electric heat pumps in buildings.

The second study extends the scope of analysis by specifically exploring the variability in optimal choices that may come from alternative assumptions regarding a broad range of factors, including the deployment potential of low-carbon electricity technologies, carbon sinks, mitigation of international transport, thermal insulation, biomass potential, energy service demand, and discount rates. 576 scenarios were elaborated by combining assumptions according to these core dimensions, covering a broad range of possibilities for the future energy transition towards carbon neutrality.

From our analysis of the simulation results, we learned that high variability exists for the future role of gas, electricity, and liquid biomass. Uncertainties also exist concerning the decarbonization efforts achieved by end-use sectors over different time steps. Emissions from the building sector present very high variability in 2035, 2040 and 2045, and similarly for the industry sector in 2050. This can be explained by the variability in the usage of gas in these time steps.

We carried out a detailed analysis to explain the uncertainties of the role of gas in the energy transition. We observed that most scenarios with high gas consumption are based on a high carbon sink potential. This is because, in a carbon neutral system, the development of artificial carbon sinks (CCS) allows for more usage of natural gas in industry and plays an important role in decarbonizing multiple gas-dependent industrial processes. We also learned that, for the gas supply, biomethane produced by methanization plays a key role in the future energy system, while high uncertainty exists for the pyro-gasification and power-to-gas industry. In around half of scenarios, injection of biomethane produced from methanization reaches 140 TWh per year in 2050, about 7 times the 2020 level. To achieve the rapid development of the methanization industry in the future will require considerable cost abatement thanks to technology progress and the scale effect, which makes methanization a cost-competitive technology to recover organic waste and produce renewable gas.

Main limits of study and perspectives

Throughout this work, we have presented possible solutions for the building energy system, mostly by addressing technical-economic dimensions such as the performance of energy equipment, resource potential, and the cost of investment options. Our analysis of the simulation results outlines the important role of these technical factors in future investment choices. However, one important aspect that has not been integrated in our analysis is human-centered factors, which are decisive to household strategy. For example, we can see that most carbon neutrality scenarios feature the large-scale integration of electric heat pumps and insulation retrofits. As these solutions require high upfront costs, it is important to consider that households may not have the same access to capital to invest. Apart from budget constraints, various socio-economic features such as education level, professional status, and family size may have a significant impact on the investment choices made by a household.

One proposal to integrate these socio-economic constraints in the technology-explicit TIMES-FR model is to represent different household groups (socio-economic groups) by various modules disaggregated from the residential energy system. Each household group has its own demand scenario and makes investment choices independently. The impact of socio-economic factors can be represented by applying group-specific discount rates. The choice of discount rates can be based on the Implicit Discount Rate (IDR) acquired from the values observed for different types of household (Train, 1985). Throughout the Ph.D. thesis, we have tried to integrate the effects of household income by separating the residential sector in TIMES-FR into a low-income group and a normal-high income group depending on yearly per capita revenue. We applied a 20% IDR to the low-income group and 4.5% to the rest of the households. However, this remains a preliminary work.

In our study, apart from the building sector, we have presented energy balance and carbon emission trajectories for the industry, transport and agriculture sectors. This served to better understand how the efforts of carbon mitigation are distributed, and the implications of residential technology choices for the energy system. The results illustrated for the industry, transport, and agriculture sectors require further examination, as these sectors are not the main focus of our modeling exercise in TIMES-FR.

In addition, in the hydrogen energy sector, for example hydrogen vehicles, our exercise did not investigate in detail the usage of hydrogen in industry. However, hydrogen might offer important solutions to decarbonize the energy system in the future.

We have tried to integrate short-term space-heating phenomena, including the evolution of heating demand and equipment performance in the long-term TIMES model. In our study, we have used statistical data to estimate heating demand over different temperature ranges, and theoretical values

to present the efficiency variation of electric heat pumps. This remains a first estimation. A more solid method would involve using thermal simulation models that represent in detail the dynamics of heating in buildings. Thermal simulation models can provide a more accurate estimation of the demand profile and variation of equipment yield by considering temperature chronicles, variations in consumption patterns, and variations in insulation levels, see Figure 114.

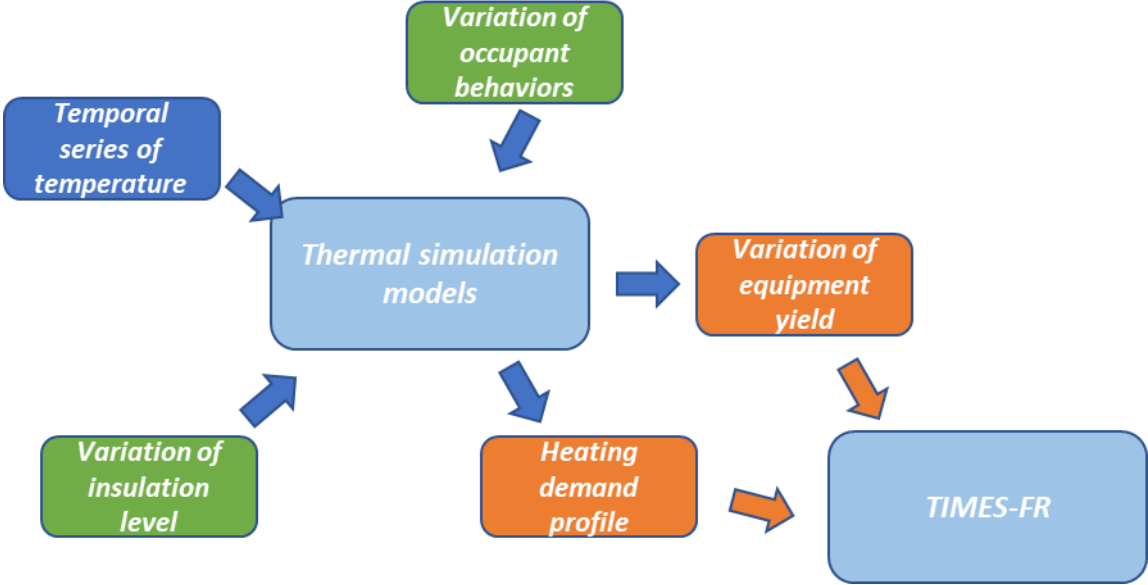


Figure 114 Proposition of an improved method to integrate short-term effects in TIMES-FR

List of figures

Figure 1 Energy balance of France in normal climate conditions (SDES, 2022a)	21
Figure 2 Final energy consumption by 5 sectors in normal climate conditions (SDES, 2022a).....	21
Figure 3 Final energy balance of residential sector in normal climate conditions (SDES, 2022a)	22
Figure 4 Final energy consumption by 4 residential energy usages in 2020, (Principal residences of Metropolitan France, normal climate) (CEREN, 2022)	23
Figure 5 Final energy balance of space heating of residential buildings in 2020 (principal residences, normal climate) (CEREN, 2022)	23
Figure 6 Balance of GHG emission linked with fuel combustion, international transport not included (Eurostat, 2023).....	24
Figure 7 Final energy balance of residential sector from 1990 to 2021 in normal climate conditions (metropolitan France + DROM) (SDES, 2022a).....	26
Figure 8 Trajectory of GHG emissions from direct fuel combustion by residential buildings and climatic rigor index from 1990 to 2021 (Eurostat, 2023; SDES, 2023)	26
Figure 9 History and projection of GHG emissions from the building sector from 1990 to 2050 in MtCO ₂ e (Ministère de la Transition écologique et de la Cohésion des territoires, 2020a).....	27
Figure 10 Trajectory of final energy balance, AME 2021, range: Metropolitan France and DROM (DGEC, 2021a).....	30
Figure 11 Trajectory of GHG emissions by AME 2021 (DGEC, 2021a)	30
Figure 12 Trajectory of residential energy balance by AME 2021, range: Metropolitan France and DROM (DGEC, 2021a)	31
Figure 13 Trajectory of final energy balance, AMS 2018, range: Metropolitan France and DROM (DGEC, 2021a).....	31
Figure 14 Trajectory of carbon emissions balance, AMS 2018, range: Metropolitan France and DROM (DGEC, 2020b)	32
Figure 15 Trajectory of residential final energy balance by AMS 2018, range: Metropolitan France and DROM (DGEC, 2020b).....	32
Figure 16 Trajectory of national final energy consumption (including non-energy usage), ADEME S1-S4 (ADEME, 2021b).....	35
Figure 17 Trajectory of residential final energy consumption by ADEME scenarios (ADEME, 2021b) .	35
Figure 18 Gas balance (production) by ADEME scenarios (ADEME, 2021b).....	36
Figure 19 Balance of carbon emissions and sinks by ADEME scenarios (ADEME, 2021b)	36
Figure 20 Final energy consumption of 2050 by scenario NégaWatt 2022 (négaWatt, 2022)	38
Figure 21 Production and consumption balance of gas projected by TERRITOIRE scenario of Gas Perspective (GRDF et al., 2022).....	40
Figure 22 2050 Capacity of power plants in 2050 by RTE scenarios (RTE, 2022).....	41
Figure 23 Balance of electricity production by RTE scenarios (RTE, 2022)	41
Figure 24 Flexibility of power system in 2050 by RTE scenarios (RTE, 2022).....	42
Figure 25 The three climate zones of Metropolitan France (PACTE, 2017a)	45
Figure 26 Housing stock by three climate zones, range: residencies in Metropolitan France (Ministère de la Transition écologique et de la Cohésion des territoires, 2018).....	45
Figure 27 Age structure of housing stock of Metropolitan France (CEREN, 2022)	47
Figure 28 Energy performance of current dwelling stock from EPC statistics, range: Metropolitan France (ONRE, 2022b)	50
Figure 29 Marginal cost of energy retrofits (in kWh of energy saving) by cumulative energy gain for individual house stock (Millot, 2019)	56

Figure 30 Operating principle of a condensing boiler (MEPAcademy, 2022)	59
Figure 31 Operation principle of an electric compressor heat pump (IEA, 2022)	61
Figure 32 Operating principle of a solar thermal system with forced circulation (ADEME, 2019a)	64
Figure 33 Energy balance (input energy) and temperature level (in number of networks) of French DH systems (FEDENE SNCU, 2022)	70
Figure 34 Schema of a process with one input and one output in TIMES	80
Figure 35 Schema of an energy system with multiple processes and commodities in TIMES	80
Figure 36 Simplified structure of TIMES-FR	84
Figure 37 Schema of time slices in TIMES-FR	85
Figure 38 Evolution of injected volume of biomethane to gas network in France since 2012 (SDES, 2022b)	91
Figure 39 Evolution of new biomethane injection capacity since 2011 in GWh/year (SDES, 2022b)....	91
Figure 40 Biomethane production from the pyro-gasification process	92
Figure 41 Biomethane production from the hydrothermal gasification process (ADEME et al., 2018)	93
Figure 42 Technologies of power-to-H2 and power to CH4 (ADEME et al., 2018)	97
Figure 43 Structure of the renewable gas sector and its interaction with the electricity system in TIMES-FR.....	101
Figure 44 Example of the national heat map produced by Cerema (Cerema, 2020)	104
Figure 45 heating demand by level of demand density, estimated by the national heat map	105
Figure 46 Disaggregated structure of residential district heating supply in TIMES-FR	107
Figure 47 Estimated technical economic availability of energy and industry wood in 2035 per region, under constant forest management scenario of ADEME and IGN (Source: IGN, ADEME, 2016)	110
Figure 48 improved modeling structure for biomass energy supply in TIMES-FR	112
Figure 49 Hypotheses for calibrating current stock and future supply potential of solid biomass energy	113
Figure 50 Illustration of residential energy system in TIMES-FR	117
Figure 51 Adopted hypotheses to calibrate availability factors for modeled building energy equipment	123
Figure 52 Improved modeling structure for HHP in TIMES	126
Figure 53 Schema of study	153
Figure 54 Potential of energy saving by residential buildings under the high and low insulation scenario (yearly rhythm)	156
Figure 55 Evolution of average minimal and maximal daily temperature in February, 2018 for France (Météo France, 2018)	158
Figure 56 Proposed carbon emission trajectories of the five variants of mitigation pace between 2030 and 2050.....	162
Figure 57 Evolution of final energy consumption by all end-use sectors for the contrafactual scenario (S1).....	167
Figure 58 Evolution of energy balance of gas production for the contrafactual scenario	168
Figure 59 Overall trajectory of carbon emissions	169
Figure 60 Mitigation trajectory of the industry, transport, and building sectors	171
Figure 61 Evolution of final energy balance per sector, the contrafactual scenario	171
Figure 62 Evolution of final energy balance for space heating under S1	174
Figure 63 Evolution of installed capacity of heating equipment, S1	174
Figure 64 Final energy balance for residential and tertiary space heating under S2 and S3	176
Figure 65 Installed capacity of heating equipment under S2 and S3	176
Figure 66 Details of energy consumption of HPs and HHPs under S2 for 2050	177
Figure 67 Electricity consumption by end-use sector in 2050, comparison between S2 and S3.....	178

<i>Figure 68 Electricity production mix under S2 and S3 in 2050</i>	178
<i>Figure 69 Evolution of annual costs for the building sector for S2 and S3 (difference compared with S1)</i>	179
<i>Figure 70 Evolution of energy balance of space heating under S2 and S4</i>	181
<i>Figure 71 Evolution of building equipment stock under S2 and S4</i>	181
<i>Figure 72 Difference in annual cost per energy sector between S4 and S2</i>	182
<i>Figure 73 Trajectory of final energy demand between 2030 and 2050 under 3 variants of advanced mitigation target</i>	184
<i>Figure 74 Evolution of balance of gas system (HH2 included) for three variants of anticipated mitigation pace</i>	185
<i>Figure 75 Trajectory of final energy consumption by end-use sector for S2_anticipated3</i>	185
<i>Figure 76 Trajectory of final energy consumption by end-use sector for S2</i>	186
<i>Figure 77 Final energy balance of space heating for 3 variants of anticipated mitigation</i>	187
<i>Figure 78 Trajectory of final energy demand between 2030 and 2050 under 2 variants of late achievement of mitigation target</i>	188
<i>Figure 79 Trajectory of final energy consumption by end-use sector for S2_late2</i>	188
<i>Figure 80 Final energy balance of space heating for S2 and 2 variants of late mitigation</i>	189
<i>Figure 81 Difference of total annual cost between five variants of mitigation pace and scenario S2 per time step</i>	191
<i>Figure 82 Difference of annual cost of building energy system between five variants of mitigation pace and scenario S2 per time step</i>	191
<i>Figure 83 Difference of annual cost of energy supply between five variants of mitigation pace and scenario S2 per time step</i>	191
<i>Figure 84 Difference of final energy consumption per time step between scenario S2_gasSNBC1, S2_gasSNBC2 and scenario S2</i>	193
<i>Figure 85 Difference of sectorial energy balance per time step between S2gasSNBC1 and S2</i>	194
<i>Figure 86 Evolution of gas production balance by scenario S2, S2gasSNBC1 and S2gasSNBC2</i>	194
<i>Figure 87 Difference of sectorial energy balance per time step between S2gasSNBC2 and S2</i>	195
<i>Figure 88 Evolution of gas production balance by scenario S2gasHigh, S2gasHighSNBC1, S2gasHighSNBC2</i>	196
<i>Figure 89 Difference of final energy balance per sector per time step between scenario S2gasHigh and S2</i>	197
<i>Figure 90 Difference of final energy balance per time step between S2gasHighSNBC1, S2gasHighSNBC2 and S2gasHigh</i>	197
<i>Figure 91 Difference of total annual cost per time step between scenario S2gasSNBC1, S2gasSNBC2, S2gasHigh and S2</i>	198
<i>Figure 92 Difference of annual cost for buildings per time step between scenario S2gasSNBC1, S2gasSNBC2, S2gasHigh and S2</i>	199
<i>Figure 93 Difference of total annual cost for energy supply per time step between scenario S2gasSNBC1, S2gasSNBC2, S2gasHigh and S2</i>	199
<i>Figure 94 Emissions from LULUCF since 1990, source: (Eurostat, 2023)</i>	212
<i>Figure 95 Evolution of final energy consumption in the average scenario (from calculation)</i>	219
<i>Figure 96 Distribution of final demand for various energy sources in 2030, 2040 and 2050</i>	220
<i>Figure 97 Distribution of final energy consumption over 576 simulations by energy group, end use sector, time step</i>	224
<i>Figure 98 576 simulated trajectories of gas consumption between 2020 and 2050</i>	226
<i>Figure 99 Sensitivity of gas consumption in 2050 to the seven key dimensions</i>	227

<i>Figure 100 Distribution of gas production from different sources over scenarios of the last two deciles of gas consumption in 2050</i>	229
<i>Figure 101 Distribution of gas production from different sources over scenarios of the first two deciles of gas consumption in 2050</i>	229
<i>Figure 102 Mitigation burden share in low carbon sink scenario e1c2t2i1b1r1d1 (low carbon sink) (with emission from international transport)</i>	232
<i>Figure 103 Mitigation burden share among end-use sectors of e1c1t2i1b1r1d1 (high carbon sink) (with emission from international transport)</i>	232
<i>Figure 104 Sectorial energy balance of scenario e1c1t2i1b1r1d1 (high carbon sink) (with energy consumption of international transport)</i>	233
<i>Figure 105 Sectorial energy balance of scenario e1c2t2i1b1r1d1 (low carbon sink) (with international transport)</i>	234
<i>Figure 106 Proposed sectorial trajectory of energy transition by scenario e1c1t1i1b1r1d1 (with international transport, high carbon sink)</i>	235
<i>Figure 107 Proposed sectorial emission trajectory by scenario e1c1t1i1b1r1d1 (with international transport, high carbon sink)</i>	235
<i>Figure 108 Evolution of final energy balance by four scenarios with different levels of energy demand (without international transport)</i>	237
<i>Figure 109 Final energy demand per sector for scenario e1c1t2i1b1d4r1 (compared with e1c1t2i1b1d1r1)</i>	237
<i>Figure 110 Difference of transport energy balance per time step by scenario e1c1t2i1b1d1r2 (high discount rate) compared to e1c1t2i1b1d1r1 (low discount rate)</i>	239
<i>Figure 111 Difference of building energy balance per time step by scenario e1c1t2i1b1d1r2 (high discount rate) compared to e1c1t2i1b1d1r1 (low discount rate)</i>	239
<i>Figure 112 Evolution of gas supply balance by scenario e1c1t2i1b1d1r1 and e1c1t2i1b1d1r1 for 2030-2050</i>	240
<i>Figure 113 Annual cost per sector per time step by scenario e1b1c1t2i1r2d1 (high discount rate) compared to scenario e1b1c1t2i1r1d1 (low discount rate)</i>	241
<i>Figure 114 Proposition of an improved method to integrate short-term effects in TIMES-FR</i>	248

List of tables

Table 1 Stock of heating equipment by energy source in 2020 estimated by CEREN, field: principal residences of Metropolitan France (CEREN, 2022)	48
Table 2 Distribution dwelling stock by EPC class and construction period (ADEME, 2021a).....	50
Table 3 Number of dwellings receiving energy retrofits and estimated final energy savings in 2019 (ONRE, 2022a)	54
Table 4 Standard of primary energy consumption from RT 1974 to RT 2020.....	57
Table 5 New parameters of RE 2020 (Ministère de la Transition écologique et de la Cohésion des territoires, n.d.-b)	57
Table 6 Market share of residential heating equipment in 2021 (Observ'ER, 2022).....	58
Table 7 Comparison of thermal and electrical efficiency between SOFC and PEMFC (ene.field, 2017)	66
Table 8 Characteristics of four generations of DH networks (ADEME, 2019c; Lund, 2014)	68
Table 9 Overview of existing projects of pyro-gasification and hydrothermal gasification (Bioenergy International, 2024; Doudard, 2018; GRDF, 2021; Groupe de Travail Gazeification Hydrothermale, 2023; IEA, 2019)	95
Table 10 Estimated biogas potential from multiple resources in 2050 (in TWh) (Groupe de Travail Gazeification Hydrothermale, 2023)	96
Table 11 Overview of existing power-to-gas and power-to-methane projects (Engie, n.d.; Jupiter 1000, n.d.; Power Technology, 2021; Techniques de l'ingénieur, 2022a)	99
Table 12 Estimated annual investment cost and operation cost DH networks of different thermal density (for the primary distribution circuit)	107
Table 13 Estimated supply potential of low, middle and high thermal density DH network covering areas of different demand density	107
Table 14 Production cost of wood logs and pellets	112
Table 15 Estimated supply availability of wood logs and wood chip supply and hypotheses for the high and low supply potential scenario (in TWh)	115
Table 16 Availability of wood by-products (second transformation) and wood waste.....	115
Table 17 Adopted hypotheses of tertiary insulation potential	118
Table 18 Adopted technical economic parameters for building technologies in TIMES-FR	120
Table 19 Adopted hypotheses for residential and tertiary useful demand profiles	121
Table 20 Projection of the impact of weather conditions on building energy demand in the long-term	122
Table 21 Retained availability factors of residential and tertiary technologies	123
Table 22 Retained hypotheses of technical economic parameters of modeled heat pumps	126
Table 23 Main macro-economic hypotheses by reviewed scenarios (ADEME, 2021b; DGEC, 2020b, 2021a; négaWatt, 2022).....	129
Table 24 Hypotheses of housing stock by reviewed scenarios, comparison between 2015 and 2050	131
Table 25 Hypotheses of tertiary demand by reviewed scenarios, in Mm ² of construction (ADEME, 2021b; Association négaWatt, 2022; DGEC, 2021b; Ministère de la Transition Ecologique et de la Cohésion des Territoires, 2023)	132
Table 26 Hypotheses of transport demand according to AME, AMS and négaWatt 2022 scenarios, comparison between 2015 and 2050 (DGEC, 2020b, 2021a; négaWatt, 2022).....	135
Table 27 Hypotheses of transport demand according to ADEME scenarios, comparison between 2015 and 2050 (ADEME, 2021b)	135

<i>Table 28 Hypotheses of industrial demand by reviewed scenarios (ADEME, 2021b; DGEC, 2020b, 2021a; négaWatt, 2022)</i>	137
<i>Table 29 variation of total surface area used by agricultural activities by AME 2021 and ADEME S1 source: (ADEME, 2021b; DGEC, 2021a)</i>	140
<i>Table 30 Retained hypotheses per sector for four scenarios of future energy service and commodity demand</i>	143
<i>Table 31 Final energy gain by number of renovated parts of a building, all individual houses renovated in 2019 (ONRE, 2022a)</i>	155
<i>Table 32 Hypotheses for future investment rhythm of thermal insulation under the high and low insulation pace scenario</i>	157
<i>Table 33 Retained hypotheses on the distribution of heating demand over four seasons and three temperature ranges</i>	161
<i>Table 34 Trajectory of gas consumption according to the SNBC (DGEC, 2020b)</i>	163
<i>Table 35 Hypotheses of four central scenarios</i>	165
<i>Table 36 Hypotheses of five variants of mitigation pace between 2030 and 2050</i>	166
<i>Table 37 Hypotheses of five variants to study opportunity cost of gas</i>	166
<i>Table 38 Comparison between simulated pace of gas and SNBC</i>	192
<i>Table 39 Overview of retained hypotheses for insulation effectiveness, biomass supply potential, and future energy service and commodity demand</i>	208
<i>Table 40 Hypotheses of deployment pace of low-carbon electricity technologies</i>	211
<i>Table 41 Retained hypotheses of the high and the low carbon sink scenario</i>	214
<i>Table 42 Retained hypotheses of two variants of mitigating international transport carbon emission</i>	215
<i>Table 43 Maximum, minimum, average, and standard deviation of carbon emissions in 576 scenarios by time step and by end-use sector (in ktCO₂e)</i>	223
<i>Table 44 Selected scenarios for analysis</i>	230
<i>Table 45 Proposed emission trajectory of variant C1T1, C1T2, C2T2</i>	231

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RÉSUMÉ

L'objectif de neutralité carbone de la France, inscrit dans la loi Énergie-Climat, impose une attention particulière au secteur résidentiel, fortement émetteur. Cette thèse identifie les solutions technologiques optimales pour décarboner ce secteur d'ici 2050, en adoptant une approche systémique intégrant les interactions avec les autres secteurs.

L'analyse repose sur une modélisation prospective à l'aide du modèle TIMES-FR, qui représente le système énergétique français. Ce modèle linéaire permet une optimisation technico-économique des futurs investissements. Il a été enrichi pour mieux représenter les choix d'investissement résidentiels, en intégrant la biomasse, la chaleur de réseau, les gaz renouvelables, les pompes à chaleur et les scénarios de demande.

Deux études sont menées. La première évalue l'impact des vagues de froid, de la performance des rénovations et du rythme de décarbonation sur les choix de chauffage. La seconde explore les trajectoires optimales selon différentes hypothèses sur les ressources bas carbone, les biais d'investissement et la demande. Au total, 576 scénarios sont construits pour couvrir un large éventail de trajectoires vers la neutralité carbone.

MOTS CLÉS

Décarbonation, Bâtiments, Chaleur, Optimisation, Systèmes multi-énergies

ABSTRACT

France's carbon neutrality target, enshrined in the Energy-Climate Law, necessitates a particular focus on the residential sector, which is a significant emitter of greenhouse gases. This thesis explores the optimal technological solutions for decarbonizing this sector by 2050, employing a systemic approach that considers interactions with other sectors.

The analysis is based on prospective modeling using the TIMES-FR model, which represents the entire French energy system. This linear optimization model facilitates techno-economic assessments of future technological investments. It has been further refined to better capture investment decisions in the residential sector, incorporating biomass supply, district heating, renewable gases, electric heat pumps, and demand scenarios.

Two primary studies are conducted. The first assesses the impact of extreme cold spells, renovation efficiency, and the pace of decarbonization on optimal heating solutions. The second expands the analysis by exploring optimal pathways under various assumptions regarding low-carbon resources, investment biases, and energy demand. A total of 576 scenarios are developed, covering a broad spectrum of potential trajectories toward carbon neutrality.

KEYWORDS

Decarbonization, Buildings, Heat, Optimization, Multi-energy systems