École polytechnique de Louvain

Technical arguments in the service of climate litigation against Belgium

Authors: **Simon GEORGES, Julia JOVENEAU**
Supervisor: **Hervé JEANMART**
Readers: **Emmanuel DE JAEGER, Thomas PARDOEN, Paolo THIRAN**
Academic year 2022–2023
Masters [120] in Electro-mechanical Engineering & Mathematical Engineering

L'impact de l'activité humaine sur le réchauffement climatique est reconnu depuis des décennies. Cet impact se traduit déjà aujourd'hui en termes de sécheresses, inondations, vagues de chaleurs extrêmes, perte de la biodiversité, augmentation du niveau des eaux... Au vu de la trajectoire mondiale actuelle, ces évènements ne vont que s'intensifier et se multiplier davantage, engendrant ce que l'on appelle une double injustice. En effet, bien que toutes les régions du monde soient touchées, ce sont les populations contribuant le moins au réchauffement climatique qui sont le plus à risque d'en subir les conséquences. Depuis la Conférence de Stockholm en 1972, jusqu'aux dernières Conférences des Parties (COP), de nombreux accords ont été signés par une grande partie des pays du monde dans le but d'atténuer et de faire face aux conséquences de cet impact. Cependant, les mesures nécessaires trainent à être implémentées et un réchauffement de 1.5°C par rapport à l'ère pré-industrielle, fixé par le GIEC comme étant la limite d'un *réchauffement climatique dangereux*, est déjà projeté comme étant inévitable. Dans son dernier rapport, le GIEC insiste sur la vitesse à laquelle se ferme notre fenêtre d'opportunités pour agir et sur l'insuffisance des flux financiers dirigés vers ces mesures nécessaires, alors que la majorité des solutions existe déjà[a].

Face à d'une part l'inaction des instances de pouvoir et d'autre part les activités toujours plus émettrices en gaz à effet de serre (GES) des grandes multinationales, les citoyen.e.s et organisations se tournent de plus en plus vers la justice, menant à des affaires judiciaires regroupées sous le nom de *contentieux climatiques.* Bien que les premières affaires aient vu le jour dans les années 2000, le contentieux climatique a connu un tournant avec l'introduction de l'affaire *Urgenda*[b] aux Pays-Bas en 2013, et la décision de la Cour d'Appel en 2018, obligeant l'Etat des Pays-Bas à réduire ses émissions de GES d'au moins 25% par rapport aux niveaux de 1990[c]. Dans les nombreuses affaires qui ont suivi ou sont toujours en cours, on peut citer par exemple l'affaire *Shell*[d] aux Pays-Bas et *Klimaatzaak*[e] en Belgique. Que ce soient des affaires dirigées vers un Etat ou une firme, des arguments similaires sont souvent utilisés. La responsabilité civile, le droit à la vie privée et familiale et le droit des futures générations sont souvent invoqués. Des éléments du droit de l'environnement interviennent aussi fréquemment, comme les principes de précaution et de prévention.

Dans les questions climatiques, la science est au centre de l'argumentaire juridique, ce qui fait du contentieux climatique un sujet interdisciplinaire par

essence. Nous sommes trois étudiant.e.s en droit et quatre étudiant.e.s en ingénierie civile, associés autour de deux sujets de mémoire communs : la construction d'arguments au service de contentieux climatiques contre l'Etat belge d'une part, contre une grande multinationale d'autre part. L'objectif était de construire des arguments techniques par les étudiant.e.s ingénieur.e.s, pour fonder les arguments juridiques construits par les étudiant.e.s en droit. Des réunions régulières sous différentes formes (en plénière, avec tout le groupe de travail, mais aussi entre étudiant.e.s travaillant sur le même sujet ou d'une même discipline) ont été organisées tout au long de l'année. Chaque thèse aura bénéficié de retours réguliers afin d'assurer sa pertinence dans les deux disciplines concernées. Les réunions auront aussi permis de confronter les idées et les points de vue, et elles se sont avérées particulièrement riches et diversifiées dans un tel contexte.

Ce groupe de travail interdisciplinaire s'inscrivant dans le contexte du contentieux climatique est un projet innovant à l'UCLouvain. Les différentes questions de recherche investiguées auront suscité beaucoup d'intérêt, notamment lors d'un colloque sur la justice climatique ayant eu lieu au début de l'année, auquel chaque groupe a eu l'occasion de présenter son approche initiale. Cette expérience nous aura permis de récolter de nombreux avis externes sur le sujet. Outre les éléments de réponse qu'elles apportent aux questions de recherche initiales, ces thèses auront aussi débouché sur de nombreuses autres questions à approfondir qui, nous l'espérons, pourront être traitées dans un cadre semblable dans les prochaines années.

---

[a] *Synthesis Report of the IPCC Sixth Assessment Report (AR6): Summary for Policymakers*

[b] Site internet : `https://www.urgenda.nl/`

[c] *Urgenda Case: final judgement Supreme Court*, disponible à l'adresse `https://www.urgenda.nl/wp-content/uploads/ENG-Dutch-Supreme-Court-Urgenda-v-Netherlands-20-12-2019.pdf`

[d] *Milieudefensie et al. v. Royal Dutch Shell plc.*, disponible à l'adresse `http://climatecasechart.com/non-us-case/milieudefensie-et-al-v-royal-dutch-shell-plc/`

[e] Site internet : `https://www.klimaatzaak.eu/`

Abstract

The inaction and insufficiency of the measures planned by government in the fight against climate change has led citizens and organizations to turn to justice. Climate change litigation is getting more and more attention. In collaboration with the Faculty of Law at UCLouvain, this thesis focuses on the transition of the Belgian energy system and its planning as described in the Belgian national energy and climate plan. We highlight the inadequacy of the projections made therein, and thanks to the whole-energy system modelling tool *EnergyScope Pathway*, we show an alternative, technologically possible, transition pathway. The results allow to bring out main directions for the energy transition, that lead to the achievement of the greenhouse gas emissions reduction targets imposed by the 2021 European Climate law. Thanks to the interdisciplinary context of this thesis, it will serve as a basis for juridic arguments in the context of climate change litigation against Belgium.

Acknowledgements

First of all, we would like to thank our supervisor, Hervé Jeanmart, and our mentor, Paolo Thiran, as well as Xavier Rixhon and Gauthier Limpens, for their availability, the precious advice and the energy they gave us.

We express our gratitude to Tom Dedeurwaerdere for the coordination of this interdisciplinary thesis and to Céline Romainville for her trust. We also thank the other students who worked with us throughout this research: our fellow engineering students Noha Haddad and Ludovic Rappe, as well as Zoé Evrard and Thomas Coppieters, and a special thank to Max Cartuyvels for taking care of the continuation of our work.

We also thank our readers, Emmanuel De Jaeger and Thomas Pardoen.

Last but not least, we are grateful for our families and friends who gave us the support needed to complete this work, with special thanks to Sophie Dardenne, Nylan Ramnauth, Marc and Martine Georges-Vandervlies, Arthur, Antoine and everyone else at Orchestrakot.

Contents

List of Figures

List of Tables

List of Abbreviations

AC Apparent Consumption.

BEV Battery Electric Vehicle.

CC Carbon Capture.

CCGT Combined Cycle Gas Turbine.

CHP Combined Heat and Power.

CNG Compressed Natural Gas.

DHN District Heating Network.

ECHR European Convention on Human Rights.

ES EnergyScope.

ETS Emission Trading System.

EU European Union.

EUD End Use Demand.

EUT End Use Type.

FEC Final Energy Consumption.

FNEC Final Non-Energy Consumption.

GHG Greenhouse Gas.

GIC Gross Inland Consumption.

GWP Global Warming Potential.

HP Heat Pump.

HT High Temperature.

HVC High Value Chemicals.

IEA International Energy Agency.

IGCC Integrated Gasification Combined Cycle.

IPCC Intergovernmental Panel on Climate Change.

LFO Light Fuel Oil.

LP Linear Programming.

LSA Local Sensitivity Analysis.

LT Low Temperature.

MILP Mixed-Integer Linear Programming.

NED Non-Energy Demand.

NG Natural Gas.

O&M Operation and Maintenance.

PEC Primary Energy Consumption.

PHEV Plug-in Hybrid Electric Vehicle.

PHS Pumped Hydro Storage.

PNEC *Plan National Energie-Climat*.

PV Photovoltaic.

RE Renewable Energy.

RES Renewable Energy Sources.

UNFCCC United Nations Framework Convention on Climate Change.

USST Ultra-Supercritical Steam Turbines.

V2G	Vehicle-To-Grid.
WAM	With Additional Measures.
WEM	With Existing Measures.

PRELIMINARY NOTE: *the files of the optimisation model, as well as all the outputs and the code used to process them are available at* ***`https://github.com/sigeorges/EnergyScope_pathway_climate_litigation.git`***

Chapter 1

Context

1.1 Greenhouse gas emissions and climate change

Since the start of the Industrial Revolution in the 19th century, global Greenhouse Gas (GHG) emissions have considerably increased, leading to a rapid increase in the CO_2 atmospheric concentration, as illustrated in Figure 1.1 (data from the National Oceanic and Atmospheric Administration (NOAA) [1]). This concentration had never exceeded 300 ppm in more than 800000 years before the Industrial Revolution, and is currently of more than 419 ppm.

When sun rays are reflected by the Earth surface, some of the heat is trapped by greenhouse gases present in the atmosphere. This is called the greenhouse effect, and it is a natural process allowing the Earth to keep an average temperature of $15°C$ [2]. However, emissions from human activities expand this phenomena to a damaging point, leading to global warming. Today, the rise in temperature compared to the pre-industrial era is already of more than $1°C$ [2]. It is also important to acknowledge the latency between GHG emissions and their global warming effects. The lag is around a decade and the full warming effects could occur several decades later, depending on the scale of the emissions [3].

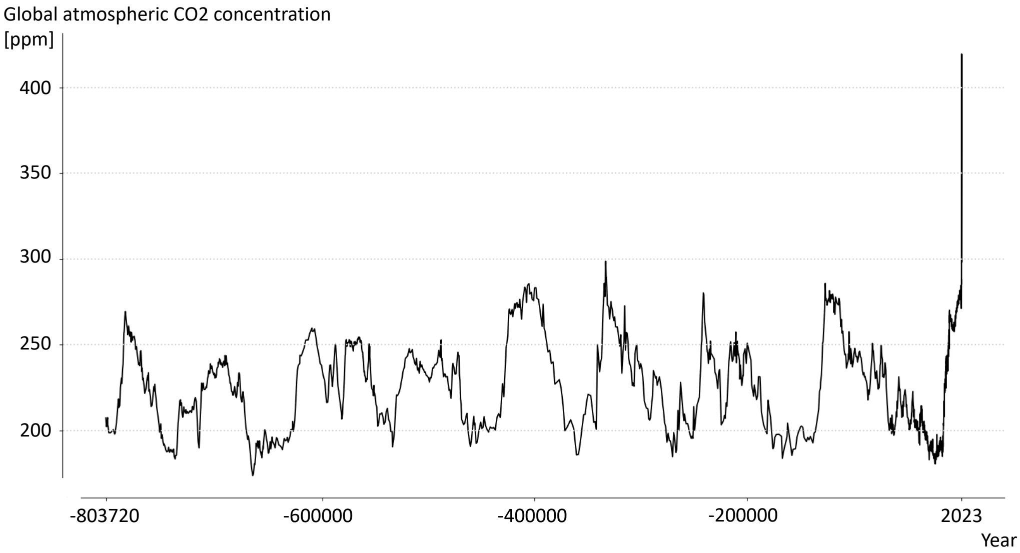


Figure 1.1: Historic global atmospheric CO_2 concentration [ppm].

The concept of anthropogenic global warming was consolidated by the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and by the signature of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. Since then, several international treaties and agreements have been signed, such as the Kyoto Protocol in 1997 and the Paris Agreement in 2016. These commitments respectively targeted a reduction in GHG emissions of 5% compared to 1990 levels over the period 2008-2012 [4] and to keep the average temperature well below $2°C$ above pre-industrial levels, trying to limit it below $1.5°C$ [5].

The IPCC highlights the differences in risks a warming of $1.5°C$ and a warming of $2°C$ would induce [6]. Impacts on human health, biodiversity and ecosystems, food availability and risks from droughts, precipitation deficits, heavy precipitation events, sea level rise, water stress, are just some examples of increased effects when projections go from a $1.5°C$ to a $2°C$ global warming. Tipping points (points of no return), such as the melting of the permafrost, are also more likely to occur in the $2°C$ scenario.

1.2 Arising of climate change litigation

1.2.1 Definition and objectives

Despite these international conventions and scientific warnings, it is clear that the efforts made in practice are not sufficient. Indeed, it is estimated that the implementation of the measures taken in line with the Paris Agreement will lead to a global warming of more than $3°C$ by the end of the century [7]. Moreover, signatories of the Agreement are even failing to meet their commitments. As a reaction to this inaction and insufficient measures, and to the climate emergency, climate change litigation has arisen as a way for citizens and associations to bring governments and companies to court.

In Europe, two rights of the European Convention on Human Rights (ECHR) are often invoked in these cases: the right to life (Article 2) and the right to respect for private and family life (Article 8). Citizens and associations try to hold governments or companies accountable for threatening their life and future by not addressing the climate crisis with the urge the scientific consensus appeals them to.

The Synthesis Report of the IPCC Sixth Assessment Report [8], released in March 2023, reinforces the credibility of these legal actions, by emphasizing the importance of political commitment, governance and policies, and the "*rapidly closing window of opportunity*". They argue that feasible, effective, and low-cost mitigation and adaptation options are already available, while the allocated financial flux is not sufficient. These options will become constrained and less effective with increasing global warming. Therefore, there is an urgent need to take effective actions now, and that is why citizens seek the support of justice.

1.2.2 Klimaatzaak in Belgium

In 2013 in the Netherlands, the Urgenda Foundation asked the Court to oblige the State of the Netherlands to cut their national GHG emissions by at least 25% compared to the year 1990, by the end of 2020 [9]. The District Court allowed Urgenda's claim in 2015 and the Court of Appeal confirmed it in 2018.

This case inspired a similar case in Belgium : Klimaatzaak [10]. In 2014, Klimaatzaak sent a formal notice to the four Belgian authorities (the federal state and the three regions: Wallonia, Flanders and Brussels-Capital), to ask them to reduce Belgian GHG emissions by 40% by 2020, compared to 1990. After some legal complications, the pleadings took place in March 2021. The judge claimed the four authorities guilty of violation of legal duty of care and human rights, but did not impose concrete targets, in regards to the principle of separation of powers. In November 2021, Klimaatzaak proceeded to appeal, asking for targets to be imposed, based on articles 2 and 8 of ECHR and articles 1382 and 1383 of the Civil Code:

- a reduction in GHG emissions of 30% by 2020 compared to 1990 was necessary and wasn't achieved;
- a reduction in GHG emissions of 48% by 2025 and of 65% by 2030, compared to 1990.

Articles 1382 and 1383 of the Civil Code respectively stipulate that *every fact of someone, which causes damage to other, imposes whose fault it is, to repair it*, and that *everyone is liable for the damage one has caused not only by their fact, but also by their negligence and recklessness.* The case is pending and the trial will take place on October 2023. In the main conclusions of the appeal (September 2022, [11]), Klimaatzaak advances some juridic and technical arguments that are worth developing here.

When planning emissions reduction trajectories, an important concept is the remaining carbon budget. The remaining carbon budget is the quantity of carbon allowed to be emitted from anthropogenic emissions from a starting year and to hold global warming to a given limit. Indeed, for the same reduction target for a given year, the carbon budget spent to achieve this target will depend on the trajectory. This can be observed in Figure 1.2, where the areas under the different curves are the total carbon budget spent from 2020 to 2050. The necessity of a linear emissions reduction trajectory is supported by the Urgenda case as well as by the Neubauer ruling, in which the German Federal Constitutional Court claimed that a convex emissions reduction trajectory was violating human rights.

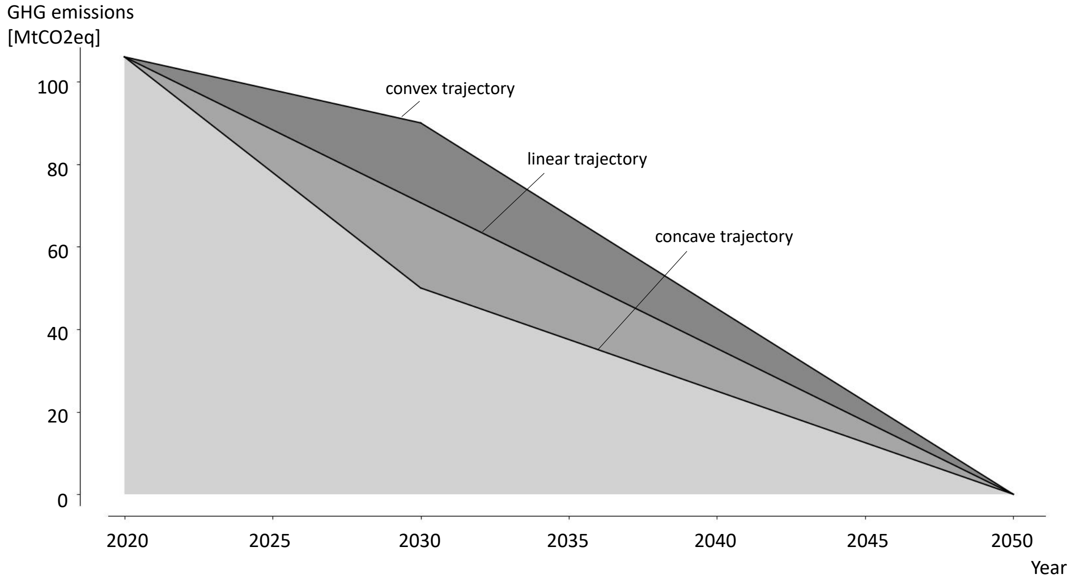


Figure 1.2: Different GHG emissions reduction trajectories for Belgium, and the associated carbon budgets.

In the *Summary for policymakers* of the contribution of Working Group III to the last IPCC report [12], the IPCC sets a global remaining carbon budget from 2021 of 500 $[GtCO_2]$ and of 400 $[GtCO_2]$ for respectively a 50% chance and a 67% chance of keeping global warming under $1.5°C$ (today, there are around 40 $[GtCO_2]$ emitted per year). Based on these figures, Klimaatzaak presents Belgium remaining carbon budgets, computed by J. Rogelj, depending on different approaches. These budgets are listed in Table 1.1. The different approaches are the following:

- Grandfathering: based on the 2020 GHG emissions, this approach supposes that the historic major polluters have the right to continue emitting more, because reducing their emissions to the same levels as the smallest polluters would be too much of an effort compared to the smallest polluters' efforts. Note that this criterion goes against the international environmental law principles, such as the Polluter Pays principle, the principle of common but differentiated principle or the principle of sustainable development.

- Equal per capita emissions: based on the 2020 population, the global remaining budget is shared equally amongst countries.

- Equal cumulative per capita emissions: the global remaining budget is divided such that the per capita emissions from 2015 to 2050 are equal between countries. Note that if the considered period starts in 1990, Belgium's budget is already exceeded.

	50% chance	67% chance
Grandfathering	1018	797
Equal per capita emissions	687	538
Equal cumulative per capita emissions	376	239

Table 1.1: Belgian remaining carbon budgets depending on different approaches (listed in Klimaatzaak main conclusions of the appeal [11]), in [$MtCO_2$].

According to Klimaatzaak, the equal per capita emissions approach is the most commonly admitted approach. Taking into account a global remaining carbon budget of 400 [$GtCO_2$] and a linear reduction trajectory, this implies a reduction of Belgian GHG emissions of 87% by 2030, compared to 1990 levels. The grandfathering approach, under the same conditions, implies a reduction of Belgian GHG emissions of 72% by 2030, compared to 1990 levels. Recalling that this latter approach violates the principles of climate governance, Klimaatzaak yet only demands a reduction of 65% by 2030.

1.3 Belgium's National Energy and Climate Plan (the PNEC)

In line with this pending case, this master thesis will try to bring additional technical arguments which could be used in the case or in a future similar one. The starting point of the argumentation is the Belgian National Energy and Climate Plan [13] (called the *PNEC* (*Plan National Energie-Climat*) throughout this work). The submission of an integrated national energy and climate plan for each ten-year period, starting with the period 2021-2030, is a requirement from a regulation on the *Governance of the Energy Union and Climate Action* (Regulation (EU) 2018/1999 [14]) adopted by the European Union (EU) following the Paris Agreement and its subsequent commitments. These national plans should be a guideline for transitioning to a sustainable energy system and is built following the five dimensions of the European energy union:

- decarbonization;
- energy efficiency;
- energy security;

- the internal energy market;
- research, innovation and competitiveness.

In Belgium, the decision-making power is shared between the Federal State, the three Regions (Wallonia, Flanders, Brussels Capital) and the three Communities (the Flemish Community, the Wallonia-Brussels Federation, the German-Speaking Community). The PNEC was built as an aggregate of distinct plans from the Federal State and the Regions. The first part of the plan describes the contexts, the objectives and the measures. The second part presents projections until 2030 with regards to two different scenarios: the With Existing Measures (WEM) and the With Additional Measures (WAM) scenarios. The main projections of the latter are presented hereafter, and they will shed light on the insufficiency of the projected measures and on Belgium's lack of ambitions regarding the achievement of its emissions reduction targets.

1.3.1 Projections of the PNEC

The PNEC focuses on the sectors not included in the EU Emission Trading System (ETS) (see Section 2.1.3). The focus is then made on the household and transport sectors. Measures include the development of Renewable Energy Sources (RES), the digitalization of the energy system, greening of the car fleet, building insulation, inclusion of efficient storage technologies, phasing out oil boilers,... Some specific measures will be discussed in Chapter 4.

Preliminary definitions

The following definitions will be important in the course of this work. They are taken from [15], the Eurostat energy balance guide.

- *Gross Inland Consumption* (GIC): overall supply of energy for all activities on the territory of the country
- *Primary Energy Consumption* (PEC): total energy demand of a country
  = + GIC – Final non-energy consumption (FNEC)
- *Final Energy Consumption* (FEC): the energy that reaches the consumer's door (excluding final non-energy consumption)
  = + Industry sector + Transport sector + Other sectors

Energy consumption

The evolution of the PEC and the FEC is predicted by the PNEC in the WAM scenario, as shown in Table 1.2. Values from 2005 to 2015 are data from Eurostat. Note that the accounting method changed from the time these data were used compared to today [15], but the total values only differ by around an average 1%.

Year	2005	2010	2015	2020	2025	2030
PEC	611.1	627.3	532.9	556.1	530.4	496.7
FEC	439.7	442.4	417.3	418.8	421.1	409.4
Industry	150.4	145.0	138.6	152.7	167.9	174.5
Households	115.4	109.5	94.9	90.7	83.4	75.8
Services	58.1	67.6	62.3	58.3	55.7	52.6
Transport	115.7	120.3	121.4	117.0	114.2	106.5

Table 1.2: FEC projections in the WAM scenario, in $[TWh]$.

Primary energy mix

Table 1.3 presents the projections for the energy mix of the GIC, in percent. The data for years 2005 to 2015 are sourced by Eurostat and the data for years 2020 to 2030 are projections compiled by the WAM scenario. At the time the PNEC was written, Belgium planned on completely phasing out nuclear energy from its energy mix by 2030. In January 2023, however, Belgium decided on prolonging reactors Doel 4 and Tihange 3 for an additional ten years, i.e, until 2035.

The strategy seems to be the replacement of nuclear energy by natural gas, without decreasing the proportion of the other fossil fuels, and only slightly increasing the proportion of RES. This leads to a projected mix still consisting in more than 80% of fossil fuels in 2030, which makes it hard to believe any GHG emissions reduction target could be achieved.

Year	2005	2010	2015	2020	2025	2030
Solid Fossil Fuels	10.6	6.8	5.9	5.2	5.5	5.9
Oil	40.9	39.8	44.6	40.1	40.2	40.2
Natural Gas	24.5	27.3	25.7	24.4	32.4	38.9
Nuclear Heat	20.4	20.2	12.4	19.1	8.6	0.0
Electricity	0.9	0.1	3.3	1.0	1.6	1.1
Renewable Energy Sources	1.9	4.6	6.8	8.6	9.8	12.2
Waste	0.8	1.2	1.3	1.7	1.7	1.7

Table 1.3: Energy mix of the GIC, WAM scenario [%].

GHG emissions

The WAM projected emissions due to the energy sector (IPCC Guidelines sector 1) are listed in Table 1.4[1], as well as Belgium's total GHG emissions.

Year	2005	2010	2015	2020	2025	2030
Total GHG emissions, LULUCF included	142.3	131.4	115.9	112.6	118.7	126.3
Energy sector emissions	105.5	98.8	85.7	79.2	83.6	84.0

Table 1.4: Total emissions and energy sector emissions in the WAM scenario, in $[MtCO_2\text{-}eq]$

The total net GHG emissions in 1990 were 142.7 $[MtCO_2\text{-}eq]$. The total GHG emissions are thus projected to be reduced by only 11.5% in 2030, compared to 1990. The GHG emissions from the energy sector in 1990 were 103.7 $[MtCO_2\text{-}eq]$ and are thus projected to decrease by 19% in 2030. These reductions in emissions are clearly not enough for Belgium to do its part on achieving the global GHG emissions reduction goals. Following the Paris Agreement, the EU committed to a reduction of GHG emissions by 40% in 2030 compared to 1990 [16]. For Belgium, this would mean the total GHG emissions cannot exceed 85.6 $[MtCO_2\text{-}eq]$ in 2030. If a similar reduction percentage is applied to all sectors, this would mean the energy sector emissions cannot exceed 62.2 $[MtCO_2\text{-}eq]$ in 2030. These ambitions were increased with the 2021 European Climate Law [17], with the new intermediate objective of a reduction of 55% compared to 1990 towards carbon neutrality in 2050.

The different trajectories are presented in Figure 1.3. The dashed lines from 2020 to 2030 represent the trajectories implied by the intermediate targets, and the dotted lines from 2030 to 2050 represent the additional effort that will be needed to achieve carbon neutrality in 2050 following a linear decrease. The 2021 European Climate Law trajectory is the only concave one, whereas the PNEC trajectory is strongly convex and will reduce the probabilities to achieve carbon neutrality in 2050. The carbon budgets Belgium would consume from 2020 to 2050 following these trajectories are listed in Table 1.5. These values highlight the importance of the trajectory. Compared to the estimated remaining carbon budgets presented in Table 1.1, none of these trajectories allow Belgium to even respect the budget allocated by the unlawful grandfathering approach, and the PNEC trajectory is by

---

[1] This data comes from the WEM-WAM emissions template available on the PNEC website [13]. Table 13 of part 2 of the PNEC on page 19 is false since it is the same as Table 3 on page 5, which lists emissions in the WEM scenario.

far the worse. Even if the effort made after 2030 is more important than a linear decrease in emissions, Belgium would already have overshot its remaining budget by 2030, with 1176 $[MtCO_2\text{-}eq]$ emitted between 2020 and 2030.

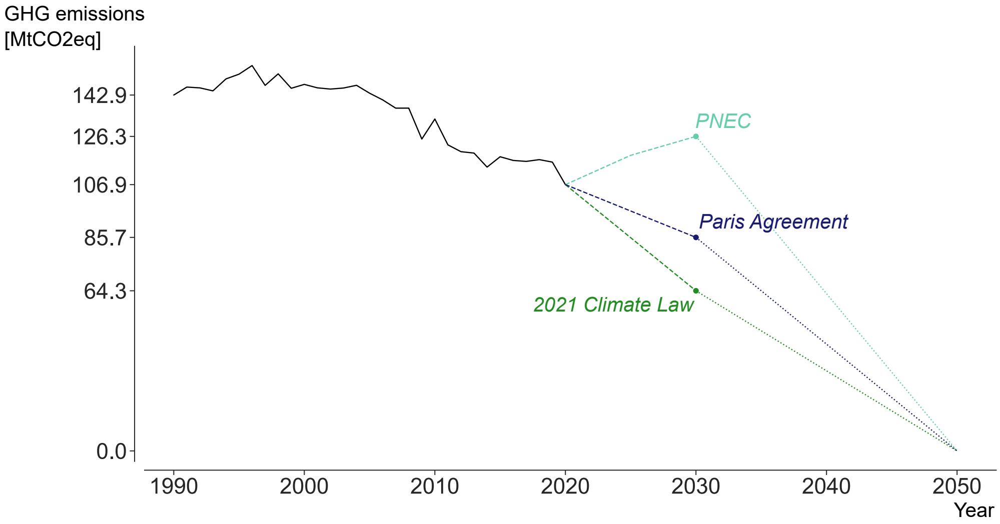


Figure 1.3: Historical national Belgian GHG emissions and pathways to carbon neutrality in 2050.

PNEC	Paris Agreement	2021 European Climate Law
2439	1821	1499

Table 1.5: Projected carbon budget consumed by Belgium from 2020 to 2050, according to the different trajectories drawn in Figure 1.3, in $[MtCO_2\text{-}eq]$.

1.4 Interdisciplinary framework and objectives

Given the projections detailed above, it is reasonable to claim that Belgium's climate policy is inadequate to face the urgency of the climate crisis. The PNEC should be a guideline to achieve GHG emissions reduction targets and therefore plan measures in line with these objectives. Since it is not the case, the Louvain School of Engineering and the Faculty of Law and Criminology at UCLouvain decided to gather around the construction of arguments supporting the ongoing climate litigation against the State of Belgium, with a focus on the PNEC. This thesis is done in association with Max Cartuyvels, law master student at UCLouvain. Focusing on the energy system implementation, our objective is to provide him with technical arguments supporting that the PNEC does not allow Belgium to respect its commitments regarding climate change, whereas other measures are feasible and lead to a more acceptable emissions reduction trajectory. For these technical arguments to be usable in the legal argumentation, the methodology adopted throughout the thesis was built and discussed with M. Cartuyvels.

After highlighting the PNEC's lack of ambitions, this thesis will go beyond these facts and suggest an alternative possible energy system implementation and evolution throughout the transition to net zero carbon for the specific case of Belgium. For this, an energy system optimization model co-developed at the Louvain School of Engineering and at the *Ecole Polytechnique Fédérale de Lausanne* (EPFL), called EnergyScope, is used [18]. The model takes into account Belgium's available resources and energy conversion technologies, energy demands and GHG emissions reduction goals. Its outputs will give indications on a feasible transition towards a sustainable energy system. This will demonstrate that other decisions can be taken by Belgium, that lead to achieving emissions reduction targets. Showing an alternative feasible pathway will have the juridic value of claiming that the projected results put forward by the PNEC are not a fatality.

Chapter 2 introduces the model and discusses the GHG accounting method. Chapter 3 presents the case study, the transition of the Belgian energy system from 2020 to a low carbon system in 2050, and studies the impact of a few important parameters on the outputs of the model with local sensitivity analyses. Chapter 4 details and discusses the solution found by the model, and compares it to the PNEC projections. A discussion about the limitations of the study and the interpretation of the results is made in Chapter 5 and finally, the thesis ends with a conclusion in Chapter 6.

Chapter 2

Materials and Methods

2.1 Accounting of the GHG emissions

Before introducing the model, this section presents an overview of the accounting methodologies internationally recognized and some related issues to be kept in mind. The validation of the accounting method used in the model will be discussed after the presentation of the model.

2.1.1 Different accounting techniques

According to the European Energy Agency (EEA) [19], there are three perspectives in the EU to account for the GHG emissions from a country. It is important to distinguish them because they result in different data.

The *territorial perspective* takes into account the gases emitted within the country's border or jurisdiction. The *production perspective* takes into account the emissions from the economic activities of a country's resident companies and households. The *consumption perspective* takes into account the emissions from the national consumption of goods and services.

The territorial emissions are the ones considered by international environmental law and thus estimated for and reported to the UNFCCC inventories, on which this study will be based.

2.1.2 2006 IPCC Guidelines for National Greenhouse Gas Inventories

For the inventories to be reliable and comparable across years and countries, the IPCC set up a methodology, the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* [20]. The territorial emissions have to be reported following five main sectors:

1. Energy;
2. Industrial Processes and Product Use (IPPU);
3. Agriculture, Forestry and Other Land Use (AFOLU);
4. Waste;
5. Other.

Each sector is divided into categories and subcategories, and they take into account the most important greenhouse gases. The total emissions are the sum of the emissions of each subcategory of each category of each sector, for each gas. The perspective is thus territorial, but there are some exceptions such as the emissions from international transport by ship or aircraft, which are not taken into account, or the emissions from road transport, which are estimated based on the amount of fuel sold within the country's border.

Since this work focuses on the energy system only, the GHG emissions considered will be the total of the first sector. Its main categories are the following:

1A. Fuel Combustion Activities;

1B. Fugitive emissions from fuels;

1C. Carbon dioxide Transport and Storage.

Stationary combustion accounts for about 70% of the GHG emissions from the energy sector and mobile combustion for about 25%. The energy sector represents about 75% of the total GHG emissions in developed countries. The emissions from combustion can be estimated via three different methodologies - *Tiers*, depending on the level of detail of the available data. Tier 1 method is the simplest and consists in multiplying the activity data (the amount of fuel combusted, Q_f) by its default emission factor EF_f (as given in the IPCC database [21]):

$$CO_2 = \sum_f Q_f \times EF_f \tag{2.1}$$

Tiers 2 and 3, which require fuel and conversion technology specific data, are generally considered more accurate. However, given the level of detail they need and since the Guidelines provide more detailed information on how to apply Tier 1, the latter method is considered throughout this work. The errors caused by this approximation are assessed and quantified in Section 2.3.

2.1.3 The EU Emission Trading System

Launched in 2005, the EU Emission Trading System (EU ETS) was the world's first international emissions trading system [22]. By granting allowances, which constitute the currency of the carbon market, it sets a global cap limiting the total GHG operators can emit. At the end of the year, operators must report their emissions and give back the corresponding number of allowances or face fees. If they don't have enough allowances to cover their emissions, they can buy allowances other operators didn't use.

The system covers about 40% of the EU's GHG emissions and includes the following sectors:

- electricity and heat generation;
- energy-intensive industry sectors;
- aviation within the European Economic Area;
- other producers emitting nitrous oxide and perfluorocarbons.

This trade incites operators to reduce their emissions or pay others to reduce theirs. This way, the emissions are cut where it costs the least to do so. As a limitation of our work and due to the single cell point of view of our model described in Section 2.2, the trading system is not included in this thesis. Further work could implement it in the model and assess its impact on the optimal Belgian transition policies.

2.1.4 Focus on the non-energy demand (NED)

The non-energy use is defined as the "*fuels that are used as raw materials and are not consumed as fuel or transformed into another fuel*" [23]. This sector is not well integrated in the accountability methods and requires some insight in the context of this work. Indeed, the interactions between the energy sector and non-energy production are worth being taken into account, the non-energy sector representing around 10% of the fossil energy supply worldwide [24].

However, for this thesis, we seek to assess the national emissions in a way that is consistent with the national inventories. In Chapter 6 of Volume 1 of the 2006 IPCC Guidelines, [20], the notion of *excluded carbon* is defined as the carbon not leading to fuel combustion emissions (category 1A.). This carbon can be emitted in another sector or stored in the product. Thus, the carbon stored in the products is excluded from these inventories. Though, there will be some point in time where it will be emitted somehow, and not taking it into account may be subject to transparency concerns. That is why we decided to include a short review of Belgium's non-energy sector situation hereinafter, based on the work from X. Rixhon et. al [25].

In Belgium, the Non-Energy Demand (NED) represents 20% of the final energy consumption (more than 87 $[TWh]$ in 2021). This demand can be divided into four categories:

- High Value Chemicals (HVC): light olefins and aromatics, produced mainly from naphtha and liquefied petroleum gas;
- Ammonia, from hydrogen from Natural Gas (NG);
- Methanol, not produced in Belgium but traded and used by the country;
- Other products: bitumen, lubricants,... from coal tar, and other oil products.

In 2021, the final non-energy consumption consisted in the following resources:

Resources	Final non-energy consumption $[TWh]$
Oil and petroleum products	73.2
Natural gas	11.9
Solid fossil fuels	2.5

Table 2.1: Resources breakdown of 2021 Belgium's final non-energy consumption (source: Eurostat).

Table 2.1 shows that all the resources are non renewable. X. Rixhon et al. [25] analyzed a transition to renewable resources, considering only end-products HVC, ammonia and methanol, and their implication in the whole energy system. They find out that the HVC production can be ensured by methanol, and that this latter, as well as ammonia, will have to be imported. This kind of study is very important to get a systemic view of the whole energy system and its transition towards a sustainable one.

As explained in Section 2.2, the modeling tool used for this thesis originally takes into account the NED, with the purpose of adopting an integrated point of view of the energy system. As further mentioned in Section 2.2.3, in the context of this work, the NED is excluded from the equations.

2.2 EnergyScope, a whole-energy system model

In this section, the EnergyScope model is introduced. After a short description of the overall features of the base model, EnergyScope TD, the structure of the program will be presented. A deeper dive will then be made into the successive steps necessary for its good functioning. Finally, the additional steps required for pathway modelling - the approach used in this thesis - will be explained.
NOTE: This section is directly based on the phD thesis of G. Limpens [26], the master's thesis of A. Hernandez and P. Thiran [27], as well as the documentation on EnergyScope, available online [18]. For any complementary information on the model, please refer to those references first[1].

2.2.1 Model introduction and structure

EnergyScope is a whole-energy system modelling tool designed for large-scale regional energy systems (thus well suited for small European countries with overall homogeneous demands and renewable energy potentials) with an hourly resolution. The model was first created and developed at EPFL, in Lausanne, under the name EnergyScope Monthly. It was then further developed as a joint effort of EPFL and UCLouvain, which lead to the creation of EnergyScope TD[2], the base upon which several variations were subsequently built. The variation of the program used for this thesis is called EnergyScope Pathway. This version allows to optimize the system with respect to its total cost every 5 years, on a time interval spanning 30 years (from 2020 to 2050). The GHG emissions of the system can be constrained. Overall, these features make EnergyScope Pathway convenient for planning the emissions reduction in the Belgian energy system, with the objective of reaching a net carbon neutral system in 2050.

Several modelling choices were made, as there are a lot of different ways of modelling large-scale energy systems. The model is based on energy balances, as opposed to market equilibria. This choice was made as it is very hard to forecast market prices over such long time horizons.

---

[1] Should the information be missing from these documents, feel free to contact the authors at: juliajoveneau@gmail.com, simongeorges.19@gmail.com

[2] "TD" stands for Typical Days.

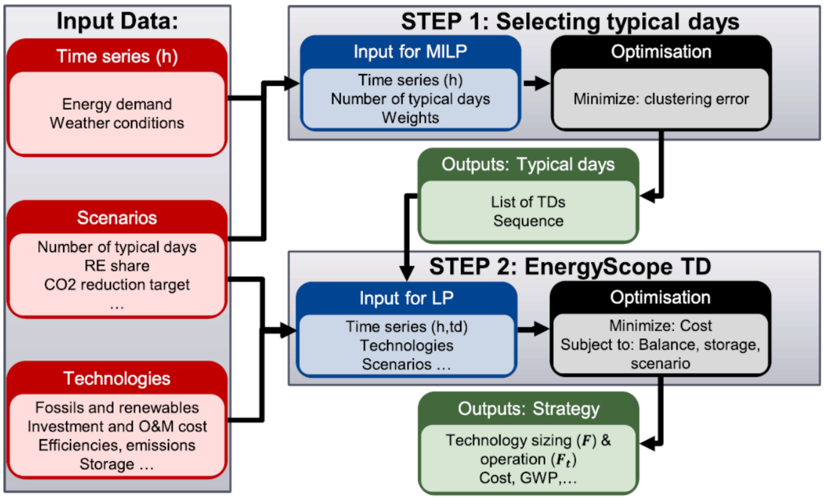


Figure 2.1: Structure of EnergyScope TD [28]. Abbreviations: renewable energy (RE), operation and maintenance (O&M), mixed-integer linear programming (MILP), linear programming (LP), global warming potential (GWP).

When working on such programs, an inevitable trade-off always appears between the granularity of the model and its computational time. Several techniques were used to keep the latter low, while retaining an acute level of detail (an hourly resolution, in our case). First, a linear programming approach was used to solve the optimization problem. Then, the use of typical days was introduced, to considerably reduce the computational time. This method corresponds to one step amongst others in the execution of the program. Figure 2.1 presents the whole execution thread, each main step composing it will now be further explained.

Input data

The input data regroups three main kinds of information:

1. Time series are hourly data for a whole year, representing the demands (electricity, mobility and heating) of the energy system and the energy potentials (wind, photovoltaic, hydro...) for the region considered. As mentioned previously, these demands and potentials are assumed homogeneous (i.e. constant in space) over the whole region studied.

2. Scenarios data give information about how the user wants to run the model. This data is only used in the context of the optimization of the model and it does not contain any information that represents physical laws. The number of typical days is specified there, as well as the GHG emissions constraints and other information which are unrelated to the energy system directly.

3. Energy conversion technologies information comprise information about the efficiency, the cost and the emissions of each conversion technology, etc.

A part of this data (time series and scenarios) will be directly used for the selection of typical days (step I), while the data about technologies will only be used in the energy model (step II).

Step I: Selection of typical days

Typical days are determined based on the time series described previously. They are computed by clustering all the days of the year according to similarities.

Step II: Energy model

The energy system is modelled using three main components: resources, energy conversion technologies and demands. The model determines the cost-optimal combination of energy conversion technologies that allows to satisfy the demands by transforming the primary energy contained in the resources, with the possibility of constraining the GHG emissions from the system.

There are several ways of defining the demands in the system. In the case of EnergyScope, the End-Use Demand (EUD) is used. It is defined as the final energy used by the consumer, independently of the technology used (e.g.: the amount of heat required to maintain the temperature in a room at x $[C°]$, in the case of space heating demand). The EUD is represented as the sum of four sectors in EnergyScope: electricity, heating, mobility and non-energy demand; some of these sectors are further subdivided according to the End Use Type (EUT) of the demand: mobility comprises passenger mobility and freight, electricity has a component that varies in time (corresponding to lighting) and a component that stays constant, and heating is distributed between space heating, water heating and high temperature industrial heating.

Additionally, *layers* are defined for each element in the system that has to be balanced at each time step (i.e.: production and storage must equal consumption and losses). All EUTs and resources thus have corresponding layers. The transition of energy from one layer to another is done through technologies (a gas turbine can be used to go from the NG layer to the electricity layer, for example). The example of the electricity layer from EnergyScope is presented in Figure 2.2.

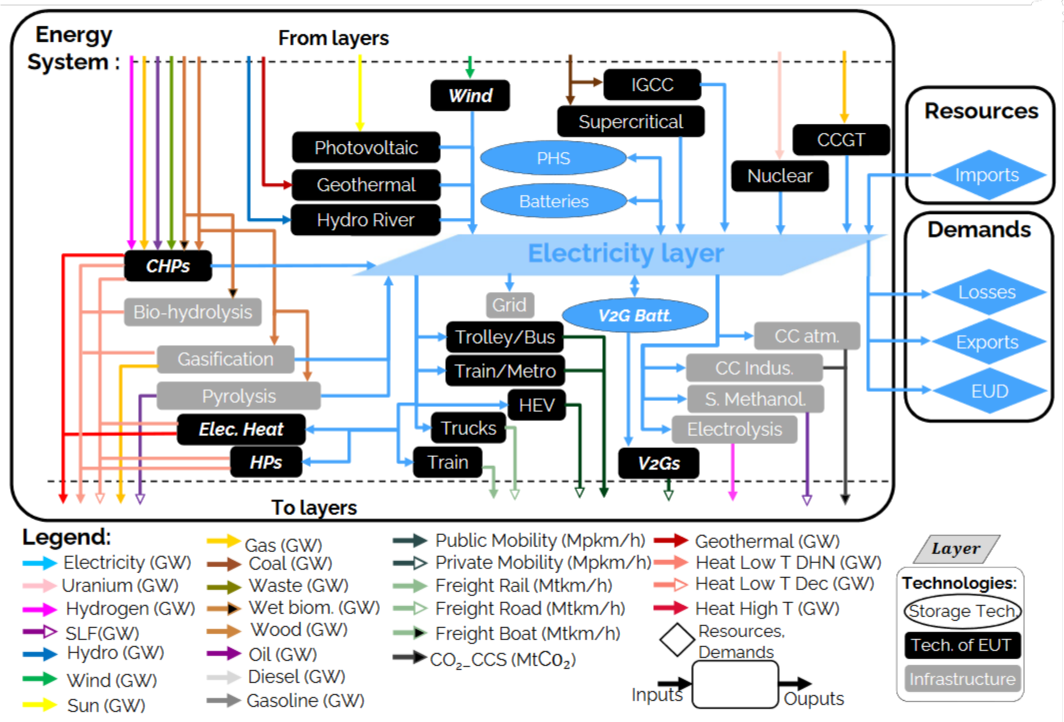


Figure 2.2: Representation of the electricity layer implemented in EnergyScope TD [26]. Abbreviations: atmospheric (atm.), carbon capture (CC), combined cycle gas turbine (CCGT), cogeneration of heat and power (CHP), electricity (elec.), heat pump (HP), industrial (ind.) integrated gasification combined cycle (IGCC), pumped hydro storage (PHS), synthetic methanolation (S. Methanol.), vehicle-to-grid (V2G), end-use demand (EUD).

Resources correspond to any primary energy input in the system. They comprise fossil fuels (coal, gas, NG...) and renewable energies (wind, sun, hydro...), as well as imported energy vectors (electricity, renewable methanol, (synthetic) NG...).

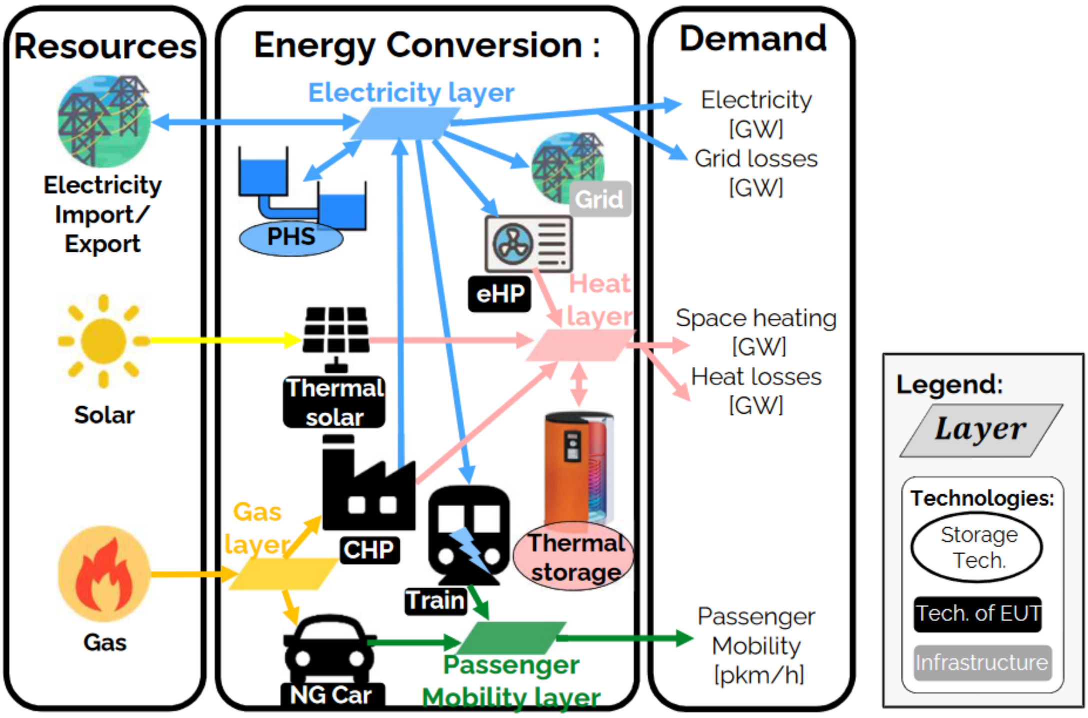


Figure 2.3: Conceptual example of an energy system with 3 resources, 8 technologies (of which 2 storages (in colored oval) and 1 infrastructure (grey rectangle)) and 3 end use demands [26]. Abbreviations: pumped hydro storage (PHS), electrical heat pump (eHP), combined generation of heat and power (CHP), compressed natural gas (CNG).

The conversion technologies are classified in three categories: technologies of end-use type, storage technologies and infrastructure technologies. First, technologies of EUT correspond to technologies converting energy from one layer to an EUT layer (i.e.: a boiler converting the chemical energy contained in wood to heat used for space/water heating). Storage technologies, as the name suggests, correspond to converting energy from one layer to the same layer (with batteries for electricity, for example). Lastly, infrastructure technologies gather the remaining technologies, including networks (such as the grid), but also technologies linking non-EUT layers (such as methane to hydrogen, through methane reforming). Figure 2.3 presents a schematized example of the modelling of a system with 3 resources, 8 technologies (of which 2 storage and 1 infrastructure) and 3 EUDs.

2.2.2 LP problem formulation

The whole linear programming problem will now be more formally introduced. A preliminary explanation of the concept of *sets*, necessary for the implementation of the model, will be given. The inputs and outputs will then be defined, as well as the objective cost function and the main constraints (mainly the constraints related to emissions since they were modified to match the emissions accounting of the PNEC).

As defined by G. Limpens, "*SETS are collections of distinct items*" [26]. RESOURCES and TECHNOLOGIES are examples of sets that are frequently used (especially in the equations below). They exhaustively comprise all items related to them that are present in the model (i.e. RESOURCES includes Uranium, wind, coal and every other energy resource used in the model). The model also has sets for each hour of the day, each hour of the year and each typical day (HOURS, PERIODS, TYPICAL_DAY), as well as a set linking the 3 latter together (T_H_TD)[3].

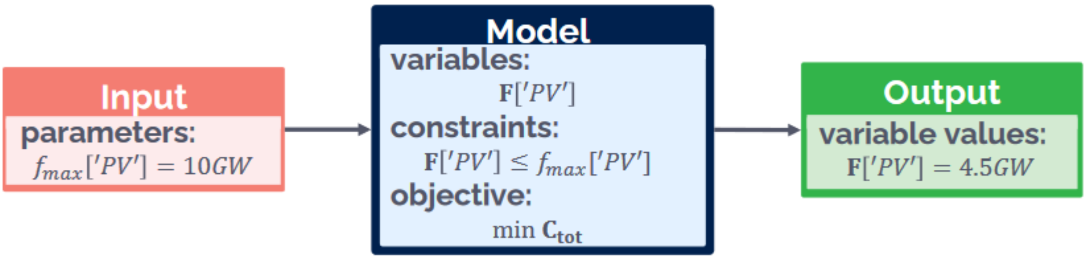


Figure 2.4: Conceptual illustration of a linear programming problem and the nomenclature used [26]. Symbol description: maximum installed size of a technology (f_{max}), installed capacity of a technology ($\mathbf{F}$) and total system cost ($\mathbf{C_{tot}}$).

The inputs of the energy model consist in the time series for both the EUDs and the energy potentials, as well as all data about conversion technologies (construction and maintenance costs, efficiency...). All this information corresponds to parameters of the optimization problem.

The mathematical model itself comprises 3 main components: the objective function, constraints and (in)dependent variables. Figure 2.4 illustrates how the mathematical model works (with examples of each element composing it).

---

[3] These examples are **not** exhaustive, numerous other sets are defined and used in the model.

The objective function chosen here expresses the total cost of the energy system. The point of the optimization problem is thus to minimize that cost. It is mathematically expressed as:

$$C_{tot} = \sum_{j \in \text{TECH}} \Big(\tau(j) C_{inv}(j) + C_{maint}(j)\Big) + \sum_{i \in \text{RES}} C_{op}(i); \tag{2.2}$$

$$\text{with } \tau(j) = \frac{i_{rate}(i_{rate}+1)^{lifetime(j)}}{(i_{rate}+1)^{lifetime(j)} - 1}. \tag{2.3}$$

The yearly cost of the system (C_{tot}) is thus expressed as the sum of the investment and the maintenance costs of the technologies installed and the operational costs of the energy resources used as input to the conversion technologies (respectively C_{inv}, C_{maint} and C_{op}). Note that the investment cost is annualised over the lifetime of the technologies through the factor τ, which is based on the interest rate and the technology lifetime (i_{rate} and $lifetime$).

The constraints used in EnergyScope serve several different purposes: some ensure that the physical model stays consistent (constraints ensuring the energy balance of the system or imposing the limits in the availability of each resource) while others are used to constrain the system to simulate political decisions (most notably the constraints on GHG emissions but also other measures, such as the phasing out of nuclear plants). During the development of EnergyScope TD, it was decided to work in terms of Global Warming Potential (GWP) of greenhouse gases. The constraints on GHG emissions (through the global warming potential) are thus defined as:

$$GWP_{tot} \leq GWP_{lim} \tag{2.4}$$

$$GWP_{tot} = \sum_{j \in \text{TECH}} \frac{GWP_{constr}(j)}{lifetime(j)} + \sum_{i \in \text{RES}} GWP_{op}(i) \tag{2.5}$$

Similarly to the cost, the yearly global warming potential of the system (GWP_{tot}) is expressed as the sum of the emissions related to the construction of the conversion technologies (cushioned over the lifetime of the technology) and the emissions related to the use of the energy resources (GWP_{constr} and GWP_{op}, respectively). This methodology is close to the production perspective described in Section 2.1. It is important to note that the emission factors used in these equations correspond to a life-cycle assessment accounting approach (i.e., emissions related to the whole life of technologies and resources are taken into account, from cradle to grave).

Finally, variables are values that vary between an upper and a lower boundary. Some variables, called *dependent* variables (such as losses in the system, total costs and emissions, etc.), vary according to *independent* variables (installed capacity of conversion technologies, hourly storage energy input and output, etc.), through the constraints of the model. The point of the optimization problem is thus to find the combination of independent variable values that minimises the overall cost of the system.
NOTE: Tables comprising every parameters and variables used in the pathway model (which was used for this thesis) are available in the EnergyScope documentation [18].

The outputs of the model thus consist in the values of all variables. This includes all conversion technologies' installed capacities and hourly operation for the whole system, but also estimated GWP and the costs of the system.

2.2.3 Adaptations for this thesis and pathway modelling

Now that the base model is properly defined for a year, the next step is to use several representative years and fill the gap between them to model a transition pathway from 2020 to 2050 as accurately as possible. Several additions to the model must be made for it to work coherently on such a large time horizon, notably with PHASES (another set) which are used to ensure a consistent transition between each representative year (which are 5 years apart each). The emphasis will be placed on the main equations ruling the system (i.e. the cost objective function and the equations for emissions accounting), whose definitions, presented above, were adapted for the pathway model. Independently, the accounting of GHG emissions must also be adapted to be comparable with official international regulations and, more specifically, the PNEC.

A preliminary change[4] was made to initialize the model in 2020 instead of 2015. This was mainly done to use more recent information at the input of the model (when the Pathway version was first developed, historical data from 2020 was not available yet) but also to reduce the computational cost of the model (by leaving out 5 years which have become irrelevant).

First, the objective function has to be changed from a yearly cost function to a total cost over the whole transition. It is thus expressed as follows:

$$C_{trans,tot} = C_{capex,tot} + C_{opex,tot} \tag{2.6}$$

---

[4] Made by X. Rixhon.

The capital expenditure cost ($C_{capex,tot}$) corresponds to the money invested in the different technologies at the initialisation and during each phase (C_{inv} and $C_{inv,phase}$) minus the return on investment retrievable from all installed technologies at the end of the transition in 2050 ($C_{inv,return}$):

$$C_{capex,tot} = \sum_{j \in \text{TECH}} C_{inv}(2020, j) + \sum_{p \in \text{PHASE}} C_{inv,phase}(p) - \sum_{j \in \text{TECH}} C_{inv,return}(j) \quad (2.7)$$

The other component of the total transition cost, $C_{trans,tot}$, is the operational expenditure, $C_{opex,tot}$:

$$\begin{aligned} C_{opex,tot} = {} & C_{opex}(2020) + \\ & \sum_{\substack{p \in \text{PHASE}| \\ y_{start} \in \text{PHASE\_START}(p), \\ y_{stop} \in \text{PHASE\_STOP}(p)}} \Big(\tau(p) \frac{C_{opex}(y_{start}) + C_{opex}(y_{stop})}{2} \Big) * t_{phase} \end{aligned} \quad (2.8)$$

The total operational expenditure is thus computed by adding the yearly cost of all years. The yearly cost during a phase is estimated by taking the cost at the representative year starting the phase with the cost resulting from the year ending it (this yearly cost is then multiplied by the duration of each phase, t_{phase}).

$$C_{opex}(y) = \sum_{j \in \text{TECH}} C_{maint}(y, j) + \sum_{i \in \text{RES}} C_{op}(y, i) \qquad \forall y \in \text{YEARS} \quad (2.9)$$

Finally, the yearly operational expenditure, C_{opex}, is defined as the sum of all yearly maintenance costs for the conversion technologies with the yearly operational costs of resources, C_{maint} and C_{op}.

The adaptation of equations (2.4) and (2.5) for constraining the emissions over the whole transition is straight-forward:

$$GWP_{tot}(y) \leq GWP_{lim}(y) \quad (2.10)$$

$$GWP_{tot}(y) = \sum_{j \in \text{TECH}} \frac{GWP_{constr}(y, j)}{lifetime(y, j)} + \sum_{i \in \text{RES}} GWP_{op}(y, i), \forall y \in \text{YEARS} \quad (2.11)$$

The variable representing yearly emissions (GWP_{tot}) now has a value assigned for each representative year and so does its upper bound constraint (GWP_{lim}). GWP_{tot} is computed the same way as explained in the previous section, the only difference is that it is computed for every representative year.

As stated earlier, some adjustments must be made to the constraints on GHG emissions so that the accounting used in the model matches the one used in the PNEC. While equations (2.10) and (2.11) take the emissions due to the construction of conversion technologies into account (in addition to the emissions related to the use of resources), the accounting prescribed by the EU leaves those construction-related emissions out of the scope. The emission factors for the use of each resource also have to be changed to account only for the emissions occurring in Belgium (mostly corresponding to the combustion of fuels, leaving out the refining and freight of said fuel if it occurs outside the country). Table 2.2 presents all new emission factors used[5]. A new variable, $GHG_{net,tot}$, is thus defined to replace GWP_{tot}:

$$GHG_{net,tot}(y) \leq GHG_{net,lim}(y) \tag{2.12}$$

$$GHG_{net,tot}(y) = \sum_{i \in \text{RES}} GHG_{net}(i,y), \forall y \in \text{YEARS} \tag{2.13}$$

$$GHG_{net}(i,y) = ghg_{net}(i) \sum_{\substack{t \in \text{T}| \\ \{h,td\} \in \text{T\_H\_TD}(t)}} \Big(F_t(i,h,td) * t_{op}(h,td)\Big). \tag{2.14}$$

While the constraint imposing an upper bound on the emissions stays practically the same, the computation of $GHG_{net,tot}$ is even simpler, as construction-related emissions are left out. $GHG_{net}(i,y)$, defined in equation (2.14), corresponds to the yearly territorial emissions of each resource, with $F_t(y,i,h,td)$, an independent variable corresponding to the hourly production of resource i, at the hour h of typical day td, during year y and $t_{op}(h,td)$ corresponding to the time period duration (which is set at 1 hour by default).

Resource	ghg_{net} $[ktCO_2\text{-}eq/GWh]$
GASOLINE	0.25
DIESEL	0.27
LFO	0.28
GAS	0.2
COAL	0.36
WASTE	0.26
METHANOL	0.246

Table 2.2: Emission factors of non-renewable primary resources.

Table 2.2 displays the emission factors used for the territorial accounting method followed in this thesis.

---

[5] These values were taken from preliminary work done by P. Thiran [29]

2.3 Validation of our GHG accounting method

After an overview of the international regulations and good practices for GHG emissions accounting and how these emissions are handled in EnergyScope Pathway, it is key for the relevance of this work to validate the accounting method implemented in the model by a comparison with historical values from official agencies.

The method used in EnergyScope is the Tier 1 method from the IPCC Guidelines, as stated by equation (2.1). To evaluate the quantity of fuel combusted, Q_f, we will interpret it as the *activity data* of fuel f, defined in the Reference Approach of Chapter 2 of the Guidelines as the Apparent Consumption (AC) of fuel f, of which is excluded the amount of excluded carbon defined as in Section 2.1.4. The Apparent Consumption is defined as:

$$\begin{aligned} AC_f &= \text{Production}_f + \text{Imports}_f - \text{Exports}_f \\ &\quad - \text{International Bunkers}_f - \text{Stock Changes}_f \end{aligned} \tag{2.15}$$

Note that *Stock Changes* has a different definition in the Eurostat document [15] and in the IPCC Guidelines. Indeed, in the latter, a positive stock change means withdrawing supply from consumption, whereas according to Eurostat, a positive stock change means using fuel previously put in stock. Hence, in terms of the total energy supply defined in equation (2.17) and recalling the definition of the GIC given in Section 1.3.1, AC can be rewritten as:

$$AC_f = TES_f - \text{Recovered \& Recycled products}_f \tag{2.16}$$

$$\begin{aligned} TES_f = &+\text{Primary production}_f + \text{Recovered \& Recycled products}_f + \text{Imports}_f \\ &- \text{Export}_f + \text{Stock changes}_f - \text{International maritime bunkers}_f \\ &- \text{International aviation}_f \\ = &\ \text{GIC}_f - \text{International aviation}_f \end{aligned} \tag{2.17}$$

Emission factors for equation (2.1) are those used in EnergyScope and defined in Section 2.2.3, but to comply to Eurostat available data, the emitting resources are aggregated in the categories listed in Table 2.3. The emission factor for *Oil and Petroleum Products* is averaged over the emission factors of EnergyScope resources falling into that category.

Fuel Category	Emission Factor $[ktCO_2\text{-}eq/GWh]$
Solid Fossil Fuels	0.36
Oil and Petroleum Products	0.267
Natural Gas	0.2
Waste	0.26

Table 2.3: Emission factors for Eurostat fuel categories.

To validate the GHG accounting method of this version of EnergyScope, we start from data taken from the Eurostat complete energy balances dataset [30]. These include the TES, final non-energy consumption (FNEC) and Recovered & Recycled Products. To get the activity data of each fuel category, the FNEC of each fuel is subtracted from its apparent consumption, which is computed from Eurostat data. Then, the activity data is multiplied by the respective emission factor, and the resulting emissions are summed. We get estimations of the total GHG emissions from fuel combustion which are listed in Table 2.4. This table also shows Eurostat energy sector historical data and the error, between both values, computed using equation (2.18):

$$\text{error} = \frac{ghg_{Eurostat} - ghg}{ghg_{Eurostat}} \tag{2.18}$$

Year	2005	2010	2015
Computed fuel combustion emissions $[MtCO_2\text{-}eq]$	107.6	107.5	93.7
Eurostat energy sector GHG emission $[MtCO_2\text{-}eq]$	105.7	99.5	87
Error [%]	-1.8	-8.0	-7.7

Table 2.4: GHG emissions from fuel combustion estimated from Eurostat data, and the error with Eurostat values.

The order of magnitude of the error seems relatively high. This could be due to the Tier used (developed countries like Belgium are supposed to be able to use higher tier), the emission factors that we averaged for each category of fuels, or a difference in the scope considered. However, the obtained values can also be compared with the *Greenhouse Gas Emissions from Energy* from the International Energy Agency (IEA) [31], given in Table 2.5.

Year	2005	2010	2015
GHG emissions from Energy [$MtCO_2$-eq]	109	105.6	93.9
Error [%]	+1.3	-1.8	+0.21

Table 2.5: GHG Emissions from Energy computed by the IEA, and the error of emissions computed from Eurostat data.

These results are much better than when the comparison is made with Eurostat values. The IEA uses Tier 1 method from the IPCC Guidelines. Their methodology is described in the *Greenhouse Gas Emissions from Energy 2022 Edition* database documentation [32]. For Annex II countries (including Belgium), they state that the error between their values and official national submission values can be of $5 - 10\%$, which corresponds to the range of the errors between our values and the Eurostat ones. Even though the IEA specify that they do not represent an official source of data, they remain a highly competent body in the field, and this observation confirms the idea that our methodology is valid, while giving us a range of error to consider. Note that from now on, the term *primary energy* will be abusively used to denote *activity data*.

Chapter 3

Case study and local sensitivity analyses

This chapter presents the detailed implementation of the pathway towards a carbon neutral Belgium in 2050. A Local Sensitivity Analysis (LSA) on some parameters of interest is also proposed in order to get an idea of the impact of these parameters on the solution found by the model and to determine the values chosen in the case study.

3.1 Initialization of year 2020

As explained in Section 2.2, the pathway model starts in 2020. In practice, the year 2020 is known and therefore must be highly constrained by using historical data in order to represent the real system at best. To initialize the model, preliminary work from X. Rixhon was incorporated, and slightly modified. The initialization is based on data from *SPF Economie* and the EU, completed by hypotheses made by G. Limpens in his thesis [26]. Due to lack of available data, the High Temperature (HT) heat end-use category was initialized based on data from 2015, which led to a gap of around 51 $[TWh]$ of NG in the primary energy mix output by EnergyScope, compared to historical data. However, along with the energy balance database [30], Eurostat provides the data as a Sankey diagram [33]. Based on this document, we computed the shares of the technologies in the supply of the HT heat end-use demand. The computations are available in Appendix B, and the results are presented in Table 3.1.

Boiler Waste	1.68
Boiler Coal	13.21
Boiler Oil	21.39
Boiler Gas	57.30
Cogeneration Gas	5.50
Cogeneration Waste	0.92

Table 3.1: Shares of the technologies for the production of HT heat, implemented in the initialization of year 2020 in EnergyScope, in [%].

Figure 3.1 shows the activity data in 2020 in EnergyScope compared to the one computed from historical Eurostat values. We see that, with these modifications to the file of X. Rixhon, EnergyScope still generates a total gap in the primary energy of 43.6 $[TWh]$ compared to the historical data (gap of 8.7%). However, this gap is more distributed amongst the energy sources. Table 3.2 presents the relative differences between Eurostat and EnergyScope and the differences in the shares of the resources in the mix. These two values are computed following equations 3.1 and 3.2, respectively.

From these indicators, we see that the errors in the consumption of each resource are less important when we look at the differences in terms of shares in the mix. During our research on the energy balance Eurostat database, we found out that the efficiencies implemented in EnergyScope are a bit too optimistic, and without changing them, it is impossible for EnergyScope to simultaneously match historical data for the end-use demands and for the primary energy mix. Further work could then focus on these efficiencies. In the meantime, these differences compared to historical data will have to be kept in mind when analyzing the results.

$$\Delta AD_{res} = \frac{AD_{ES,res} - AD_{EU,res}}{AD_{EU,res}} \tag{3.1}$$

$$\Delta\%_{res} = \frac{AD_{ES,res}}{AD_{ES,tot}} - \frac{AD_{EU,res}}{AD_{EU,tot}} \tag{3.2}$$

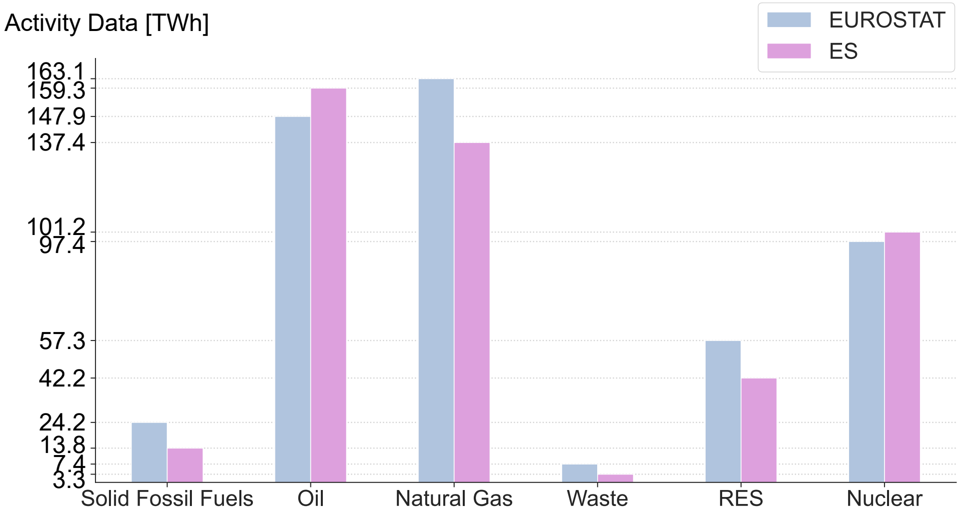


Figure 3.1: Comparison between the consumption of resources in 2020 according to Eurostat (blue) and EnergyScope (violet).

Resource	ΔAD_{res}	$\Delta\%_{res}$
Solid Fossil Fuels	-42.9	-1.8
Oil	7.7	5.3
NG	-15.8	-2.5
Waste	-55.5	-0.76
RES	-26.4	-2.2
Nuclear	3.9	2.7

Table 3.2: Errors made by EnergyScope compared to historical data from Eurostat, following indicators defined in equations 3.1 and 3.2, in [%].

3.2 GHG emissions reduction trajectory

The emissions reduction trajectory is based on the 2021 European Climate Law, mentioned in Section 1.3. The objective is to achieve a GHG emissions reduction of 55% in 2030, compared to 1990. In 2020, the emissions of the energy sector reported by the IEA were 83.9 [$MtCO_2$-eq] [31]. Since our GHG accounting method is consistent with the IEA, we start from this value to implement the reduction trajectory. But since the year 2020 is highly constraint without perfectly representing the reality, as seen in the previous section, we allow a margin and set the limit at 90 [$MtCO_2$-eq] for that first representative year. For the end of the transition, we allow annual emissions of 5 $[MtCO_2\text{-}eq]$. This value accounts for the emissions due to the total waste available, that we force the system to use. Then, linear interpolations are computed between the 2020 limit, the reduction targeted by the Climate Law and the 2050 limit. This gives limits on the system emissions for each representative year, listed in Table 3.3. Figure 3.2 shows the historical values of the GHG emissions from the energy sector (reported by the IEA), and the projected limits implemented in the case study.

Year	**Emission limits** $[MtCO_2\text{-}eq]$
2020	90
2025	69.2
2030	48.4
2035	37.6
2040	26.7
2045	15.9
2050	5.0

Table 3.3: Emissions reduction trajectory implemented for the case study.

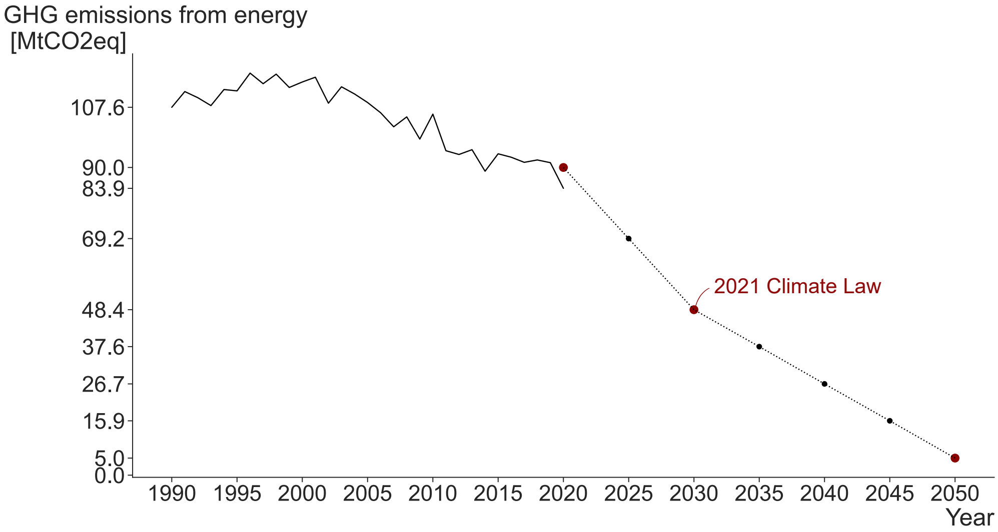


Figure 3.2: GHG emissions from the energy sector, historical values from 1990 to 2020 (from [34], plain line) and projected limits implemented in EnergyScope (dotted line).

3.3 Final Energy Consumption

The data for the evolution of the final energy consumption over the years are taken from the *EU Reference Scenario 2020* [35] which projects the evolution of the energy and transport sectors and the related GHG emissions to 2050. Values for 2020 to 2050 are presented in Table 3.4.

	2020	2025	2030	2035	2040	2045	2050
Residential [TWh]	93.7	90.0	82.5	76.1	73.9	72.5	71.1
Tertiary [TWh]	54.0	59.2	57.0	60.9	61.9	62.7	62.0
Industry [TWh]	115.1	133.2	147.4	141.9	140.1	141.9	143.5
Passenger Transport [$Gpkm$]	110	142	148	151	154	157	159
Freight Transport [$Gtkm$]	69	79	82	85	87	90	93

Table 3.4: Final Energy Consumption by sector projected by the *EU Reference Scenario 2022* and implemented in EnergyScope.

In EnergyScope, the values have to be entered into the following end-uses:

- Electricity
- Lighting
- Low Temperature (LT) Heat
- High Temperature (HT) Heat
- Passenger Mobility
- Freight Mobility

X. Rixhon had previously computed the data to enter in EnergyScope from the data on Table 3.4.

Figure 3.3 shows the differences in projections of the PNEC and the Reference Scenario for the residential, tertiary and industry sectors. These differences are minor for the residential and tertiary sectors, but more important for the industry sector, even though it qualitatively follows the same evolution. These differences will have to be kept in mind when comparing the optimal solution from EnergyScope to the PNEC projections.

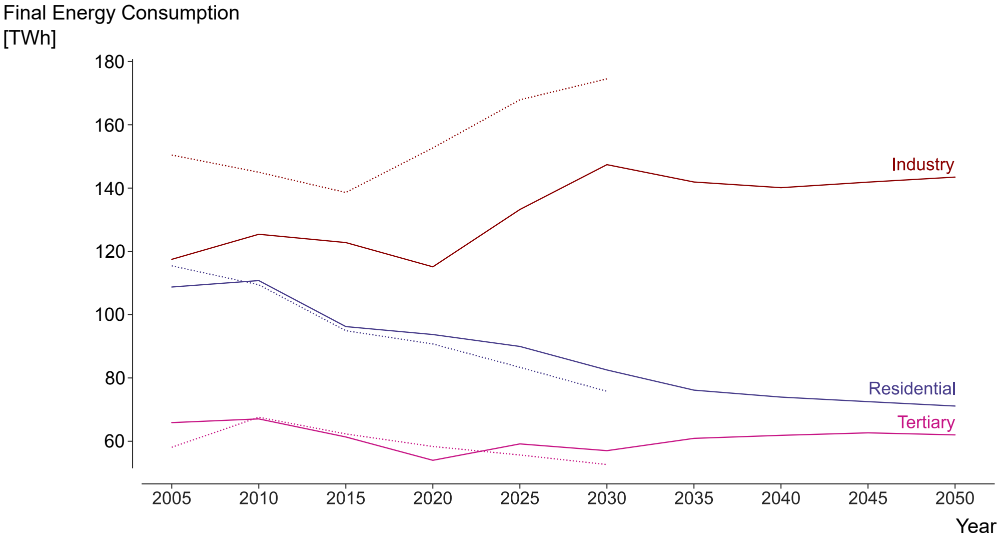


Figure 3.3: Comparison between the PNEC (dotted lines) and the Reference Scenario (plain lines) FEC projections.

3.4 Local sensitivity analyses

As foreseen in Chapter 2, the model includes a large amount of parameters that have to be determined beforehand. Given the large time range concerned by this study, and the hypotheses that must sometimes be done, the impact of the uncertainties on the parameters can be high and must be assessed to ensure that the projections are relevant.

Such sensitivity analyses on EnergyScope parameters have already been carried out before and we refer the reader to G. Limpens' thesis [26]. In this chapter, we focus on four parameters :

- `limit_LT_renovation` [%]: limits the change in technology of the low temperature heat sector per phase.
- `limit_pass_mob_changes` [%]: limits the change in technology of the passenger mobility sector per phase.
- `limit_freight_changes` [%]: limits the change in technology of the freight transport sector per phase.
- $\texttt{share\_mobility\_public\_max}_{year}$ [%]: for each year, limits the share of public mobility in the total passenger mobility.

These parameters have been chosen because they reflect the inertia of the system. On previous runs of the model, it was observed that the transition implementation found by EnergyScope tends to include very sharp changes that are not realistic given the current trend and slowness of the evolution of the system. This inertia accounts for political decisions, population resistance to changes as well as technical barriers. The latter parameter implies that the sum of the parts of the passenger mobility supplied by public transport technologies cannot exceed the limit set by the parameter. The model integrates the three other parameters through the following equations:

$$\begin{aligned}\sum_{\substack{euc \in EUT\_OF\_CAT(''HeatLowT'')\\ j \in TECH\_OF\_EUT(euc)}} \Delta_{change}(p,j) \leq \texttt{limit\_LT\_renovation}\\ \times[eui(y_{start}, ''HotWater'')\\ + eui(y_{start}, ''SpaceHeat'')];\end{aligned} \tag{3.3}$$

$$\begin{aligned}\sum_{\substack{euc \in EUT\_OF\_CAT(''MobPass'')\\ j \in TECH\_OF\_EUT(euc)}} \Delta_{change}(p,j) \leq \texttt{limit\_pass\_mob\_changes}\\ \times eui(y_{start}, ''MobPass'');\end{aligned} \tag{3.4}$$

$$\begin{aligned}\sum_{\substack{euc \in EUT\_OF\_CAT(''MobFreight'')\\ j \in TECH\_OF\_EUT(euc)}} \Delta_{change}(p,j) \leq \texttt{limit\_freight\_changes}\\ \times eui(y_{start}, ''MobFreight''),\end{aligned} \tag{3.5}$$

with $\Delta_{change}(p,j)$, defined as the difference between the total production of a technology j at the beginning and at the end of phase p:

$$\begin{aligned}\Delta_{change}(p,j) \geq \sum_{\substack{t \in T\\ |\{h,td\} \in T\_H\_TD}} F_t(y_{start}, j, h, td) - \sum_{\substack{t \in T\\ |\{h,td\} \in T\_H\_TD}} F_t(y_{stop}, j, h, td),\\ \forall j \in TECH,\\ p \in PHASE,\\ y_{start} \in Y\_START(p),\\ y_{stop} \in Y\_STOP(p),\end{aligned} \tag{3.6}$$

where $F_t(y, j, h, td)$ corresponds to the hourly production of technology j (as defined in Section 2.2.3), and $eui(y, EUC)$ is the end-use demand input for the end-use category EUC in year y.

These parameters thus help model the inertia of these sectors. The high temperature heat and electricity sectors are assumed to not be constrained by this kind of inertia. To conduct local sensitivity analyses (LSA), we consider minimal, nominal and maximal values for the first three parameters. The nominal values were set on the basis of some hypotheses:

- There are currently around 6 million cars in the Belgian private fleet, and approximatedly 500 thousands new cars enter the fleet each year [36]. 12 years (rounded to 15 years, corresponding to 3 phases) would then be needed to replace the whole fleet. The nominal value for parameter `limit_pass_mob_changes` would then be 1/3.
- The freight transport sector is assumed to have the same inertia as the passenger mobility sector.
- It is more difficult to estimate how fast the system used for the production of LT heat can change, as it comprises various, very different technologies at different scales. In light of the values chosen for the previous parameters and, as a first approximation (which will be verified through the LSA), the nominal value chosen is 1/3. Running the model at lower and higher values around that number will allow to confirm whether or not the evolution of the system is reasonable for this range of values.

Parameter $\texttt{share\_mobility\_public\_max}_{year}$ is a bit different from the others as it has a different value for each year. It thus corresponds to a trajectory with a fixed value in 2020 (the historical value of 18.8%), a maximum value to determine, and the year at which that maximum is reached. It is a reasonable assumption (which was previously made by G. Limpens in his thesis [26]) to set that value to 50%. The value around which this LSA is done is the year at which the maximum value is reached. The years considered are 2040, 2045 and 2050 (nominal value). In each case, a linear interpolation is made between the 2020 historical value, i.e., 18.8% and the upper limit. The values of the trajectories for the different cases are available in Table 3.5.

	2020	2025	2030	2035	2040	2045	2050
Limit reached in 2040	18.8	26.6	34.4	42.2	50	50	50
Limit reached in 2045	18.8	25.04	31.28	37.52	43.76	50	50
Limit reached in 2050	18.8	24.0	29.2	34.4	39.6	44.8	50

Table 3.5: Values of parameter $\texttt{share\_mobility\_public\_max}_{year}$ during the transition, depending on the first year the limit of 50% can be reached, in [%].

All the values for the different parameters studied are thus determined. Table 3.6 presents a summary of all cases along with the values of each parameter of interest.

Case	LT heat	Passenger mob	Freight	Public mob max share
(*base*)	0.33	0.33	0.33	0.5 (in 2050)
(a_{min})	0.2	0.33	0.33	0.5 (in 2050)
(a_{max})	0.46	0.33	0.33	0.5 (in 2050)
(b_{min})	0.33	0.2	0.33	0.5 (in 2050)
(b_{max})	0.33	0.46	0.33	0.5 (in 2050)
(c_{min})	0.33	0.33	0.2	0.5 (in 2050)
(c_{max})	0.33	0.33	0.46	0.5 (in 2050)
(d_{2040})	0.33	0.33	0.33	0.5 (in 2040)
(d_{2045})	0.33	0.33	0.33	0.5 (in 2045)

Table 3.6: Cases considered in the local sensitivity analyses and values of the parameters studied: `limit_LT_renovation` (*LT heat*), `limit_pass_mob_changes` (*Passenger mob*) and `limit_freight_changes` (*Freight*) and `share_mobility_public_max` (*Public mob max share*).

Three axes of analysis are considered to assess the sensitivity of the outputs to changes in these parameters. The first is the variation of the costs in the system. The second is the variation in the primary energy mix. The third is the variation in the technology mix of each end-use category. Indeed, each parameter is related to a certain end-use category but the constraints on one category are expected to have an impact on other categories, given the fact that some constraints link all categories together (the most obvious example being that if a category emits less, other categories will be allowed to emit more).

3.4.1 Base case

First, an overview of the nominal case is presented so that the comparisons made for each case can be put in perspective.

Primary energy mix

Figure 3.4 shows the evolution of the primary energy mix in the nominal case.

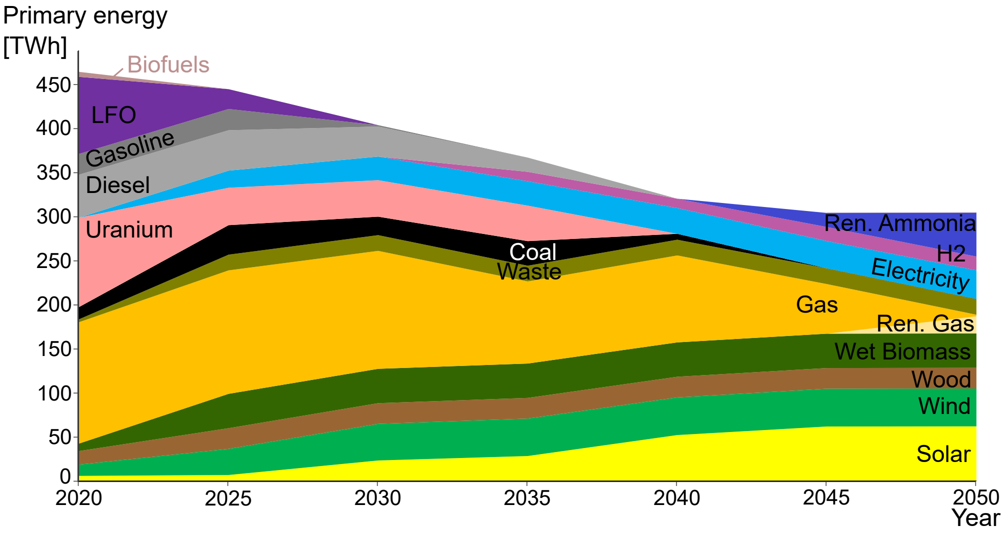


Figure 3.4: Evolution of the primary energy mix in the nominal case.

Technology mix

In order to have an overview of the technologies used, and of their relative importance in the whole system, we can observe their energy production normalized to the most important production amongst all technologies and amongst all representative years. This indicator $I_{j,y}$ in year y is computed as in equation (3.7) for all technologies j, except those of end-use categories *Mobility Passenger* and *Freight* (since their end-use demands are expressed in different units). For the latter technologies, the same indicator can be computed restricting the set of technologies to that of the corresponding end-use category.

$$I_{j,y} = \frac{P_{j,y}}{\max_{\substack{k \in TECH \\ y \in YEARS}} P_{k,y}} \; \forall j \in TECH, y \in YEARS \tag{3.7}$$

where $TECH$ is in fact restricted as explained above.

These indicators are shown in Figures 3.5 (only technologies whose indicator is greater than 0.5 for at least one representative year are represented for the sake of readability[1]) and 3.6 (only technologies whose indicator is greater than 0.05 for at least one representative year are represented for the sake of readability[2]). We observe that the gas and oil boilers quickly decrease in importance, while

---

[1] And this will be the case throughout the local sensitivity analyses.

[2] Same as above.

heat pumps technologies, with negligible importance at the start of the transition, become the most important ones. Thermal heat pumps are implemented to ease the transition but are removed at the end of the transition when GHG emissions have to be cut off. The increasing part of the district heating network in the production is also visible, based on heat pumps as well. Finally, in the electricity end-use category, photovoltaic (PV) technologies become gradually prominent. In the passenger mobility end-use category, electric cars get more weight than any other technology ever had, while trains and CNG buses are the ones chosen to support the increasing share of public mobility. For the freight, diesel trucks, prominent at the start of the transition, are quickly decommissioned to make room for cleaner technologies, mainly fuel cell trucks, NG boats and trains.

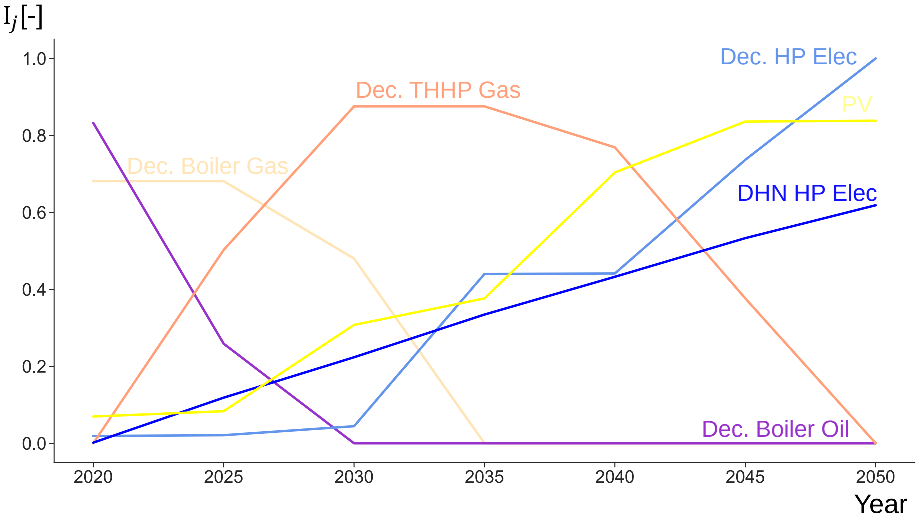
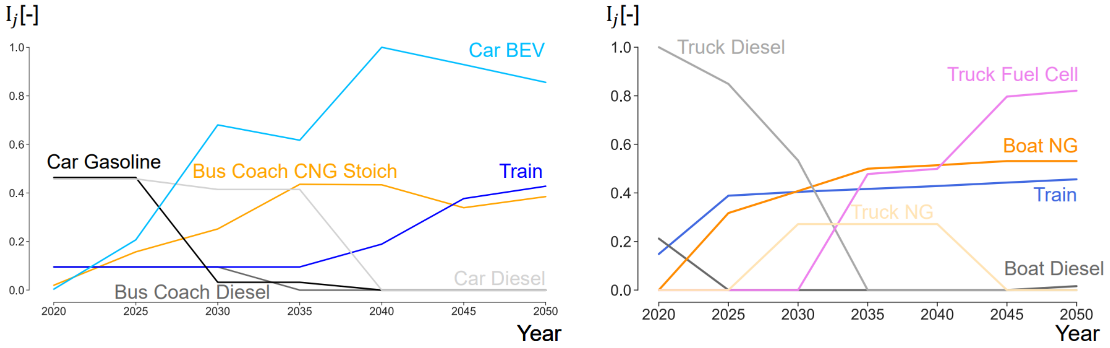


Figure 3.5: Normalized productions of technologies of electricity, HT heat and LT heat end-use categories, following indicator defined in equation (3.7) in the nominal case.



(a) (b)

Figure 3.6: Normalized part of (a) passenger mobility (b) freight demands supplied by the different technologies, following indicator defined in equation (3.7) in the nominal case.

3.4.2 Cases ($a_{min/max}$): `limit_LT_renovation`

Cost

Figure 3.7 presents the annualised costs of the system for the two different cases corresponding to the minimal and the maximal value of the parameter analysed, as well as the base case. It directly appears that the fastest transition, case (a_{max}) (with the highest upper limit on technological change of the sector), is the cheapest. The reason for this might be that the system and the infrastructures used in the low temperature heating sector are able to change faster which leads to more efficient and cheaper technologies being installed earlier in the transition (and thus being used for a longer part of the transition). District heating systems (on a large scale) and electric heat pumps (on a smaller scale) are two good examples of technologies that have better performances than the system that is currently in use. These two technologies also take a considerable time to install and to set up.

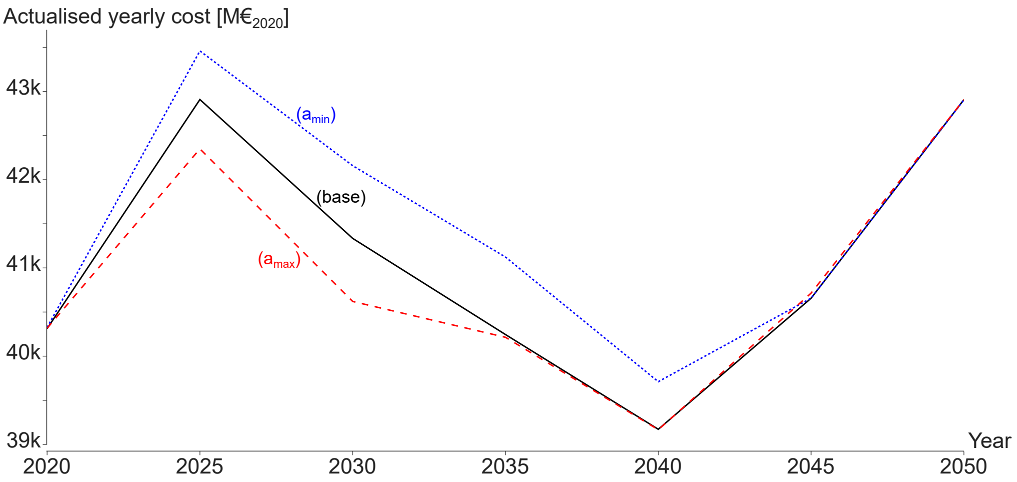


Figure 3.7: Actualised yearly costs of the system: cases ($base$), (a_{min}) and (a_{max}).

Upon seeing the higher cost of the slower transition, case (a_{min}), one might think that making the transition as fast as possible is the best way to go. Unfortunately, it is not as simple as it seems (as will be explained in the following sections) and it is important to remain cautious when interpreting the different results from EnergyScope. First because of the interdisciplinary aspect of the transition. While EnergyScope is able to give a clear solution on how to achieve it, putting this transition in practice is far from easy and many other aspects are as important as the technical one treated with the model. Thus, even if a fast transition is technically possible, the habits of people also have to change along, which might be a slow process. Secondly, it is clear that, on the scale of the system costs, these cost differences are not very significant. These differences, however, are quite significant compared to the system cost differences in the other cases yet to be studied, which highlights the important place of the LT heating sector in the whole energy system.

Primary energy mix

The absolute change in the total amount of primary energy compared to the base case is reported in Table 3.7 and computed following equation (3.8) (where $\text{res}_{tot,y,c}$ is the total amount of primary energy used in representative year y, in case c). These changes are minimal, the bigger ones occurring in the middle of the transition with a difference of around 3%.

$$\Delta\text{res}_{tot,y,c} = \frac{\text{res}_{tot,y,nom} - \text{res}_{tot,y,c}}{\text{res}_{tot,y,nom}} \; \forall c \in \{\text{min,max}\}, y \in YEARS \tag{3.8}$$

Case	2020	2025	2030	2035	2040	2045	2050
Min	0.020	0.44	-0.93	-2.98	-1.01	0.20	-0.0064
Max	-0.0032	0.69	2.90	-0.54	-0.49	-0.71	0.052

Table 3.7: Change in total amount of resources used for each representative year, in [%].

The change in the part of the total primary energy mix supplied by each resource, for each representative year, is reported following equation (3.9). For the sake of readability, only the resources whose changes are greater or equal to 1% for at least one representative year are reported in Figure 3.8[3]. For both cases, the most important variations are in the shares of natural gas, with a peak of around -6% in 2025. The two other most important variations occur for LFO (in case (a_{max}), only in 2025) and coal (especially in case (a_{min})). However, at the end of the transition in 2050, the mix does not present any significant variation. These variations are to be looked at keeping in mind their relative importance in the mix (see Figure 3.4).

$$\begin{aligned} &\Delta\text{share}_{i,y,c} = \text{share}_{i,y,nom} - \text{share}_{i,y,c} \\ &\forall i \in RESOURCES, y \in YEARS, c \in \{\text{min,max}\} \end{aligned} \tag{3.9}$$

---

[3] And this will be the case throughout the analyses

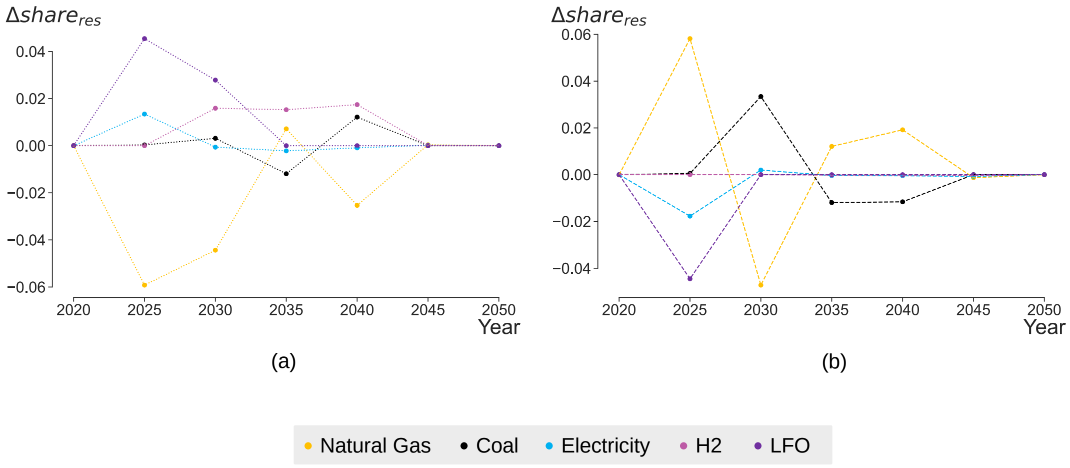
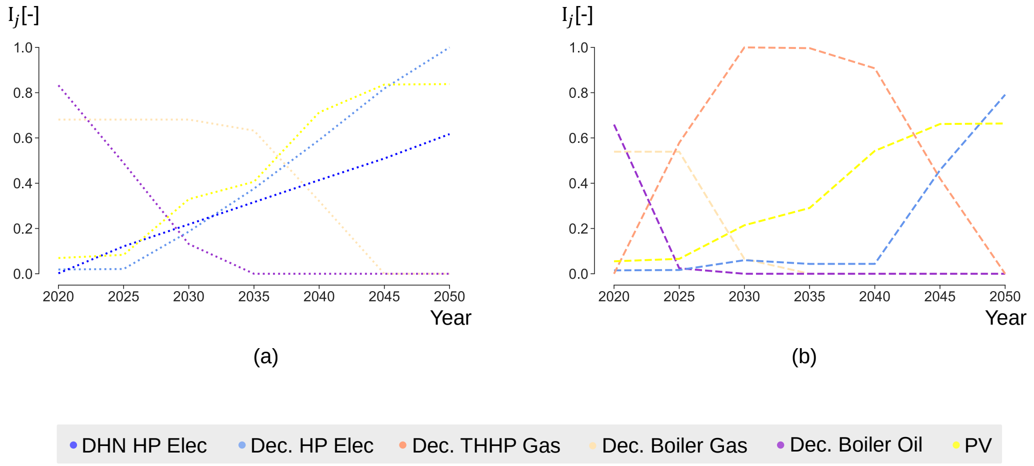


Figure 3.8: Changes in the shares of the primary energy mix, following equation (3.9). (a): parameter `limit_LT_renovation` at minimal value; (b): parameter `limit_LT_renovation` at maximal value.

Technology mix

An overview of the importance of the technologies can be provided by the normalized production indicator defined in equation (3.7), shown in Figure 3.9. The case (a_{min}), i.e., when the inertia is bigger, is quite similar to the nominal case, except that thermal HPs do not impose themselves as a principal technology during the transition. In comparison, in case (a_{max}) the latter seem to have the same role as in the nominal case, but taking even more place, while the prominence of electric HPs arises later. A smaller inertia then seems to allow a rapid and significant installation of thermal HPs, delaying the installation of electric ones.



(a)

(b)

Figure 3.9: Normalized production indicator of technologies of electricity, HT heat and LT heat end-use categories, following indicator defined in equation (3.7) for parameter `limit_LT_renovation` at minimal (a) and maximal (b) values.

The variations in the technology mix, for each end-use category, are computed following equation (3.10). Again, these variations must be considered while keeping in mind the relative importance of the end-use category in the total demand. Figure 3.10 shows the variations for cases (a_{min}) and (a_{max}). Not surprisingly, the most significant changes occur in the LT heat category, especially in the decentralized end-use category. Changes in the HT heat and freight categories are also notable.

$$\begin{aligned}&\Delta \text{share}_{euc,y,c} = \sum_{j \in TECH} |\text{share}_{euc,j,y,c} - \text{share}_{euc,j,y,nom}| \\ &\forall euc \in EUC, y \in YEARS, c \in \{\text{min}, \text{max}\}\end{aligned} \tag{3.10}$$

where

$$\begin{aligned}EUC = \{&\text{Electricity, High Temperature Heat, Low Temperature Heat Decentralized,} \\ &\text{Low Temperature Heat DHN, Passenger Mobility, Freight}\}\end{aligned}$$

.

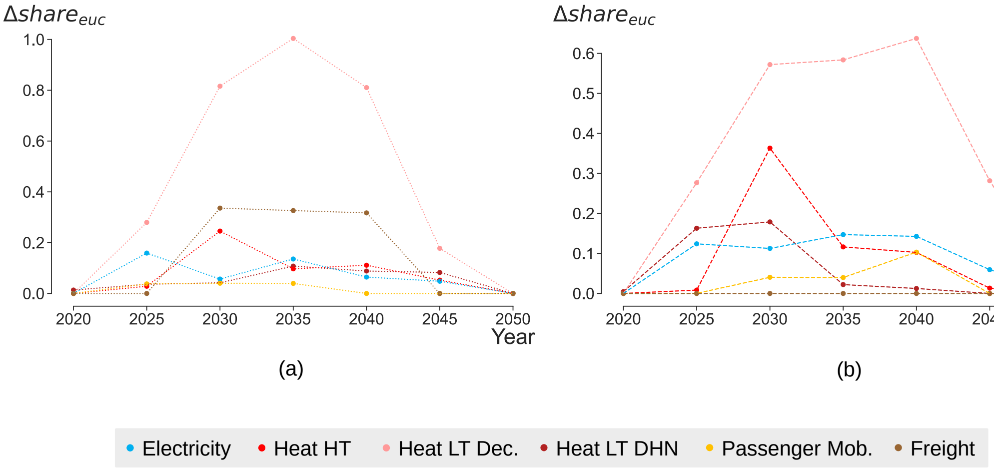


Figure 3.10: Change in the technology mix for each end-use category, following equation (3.10). (a): parameter `limit_LT_renovation` at minimal value; (b): parameter `limit_LT_renovation` at maximal value.

3.4.3 Case ($b_{min/max}$): `limit_pass_mob_changes`

Cost

As displayed in Figure 3.11, case b_{min}, corresponding to a more constrained and slower transition is cheaper than the base case, which might seem surprising at first: how is it that our optimization algorithm does not find the same cheaper solution in the base case as in case (b_{min}) when the only difference is an upper bound on a parameter ? The model could use the same rate of change as the bounded one from the slower case (the system is not constrained by any lower bound). An explanation could be that the optimization algorithm used, *CPLEX*, does not necessarily find the optimal solution for the system and, for economy reasons, it may sometimes stop at the best solution it has found so far, before finding the global optimum. While this phenomenon has an influence on the solutions found, it does not seem to invalidate the observations made here, as each system studied has a consistent direction and yields coherent results.

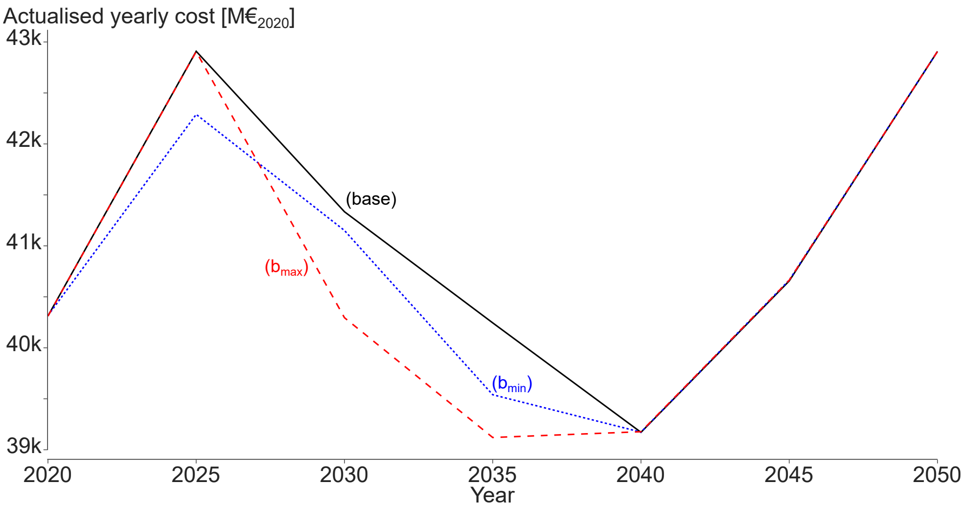


Figure 3.11: Actualised yearly costs of the system: cases ($base$), (b_{min}) and (b_{max}).

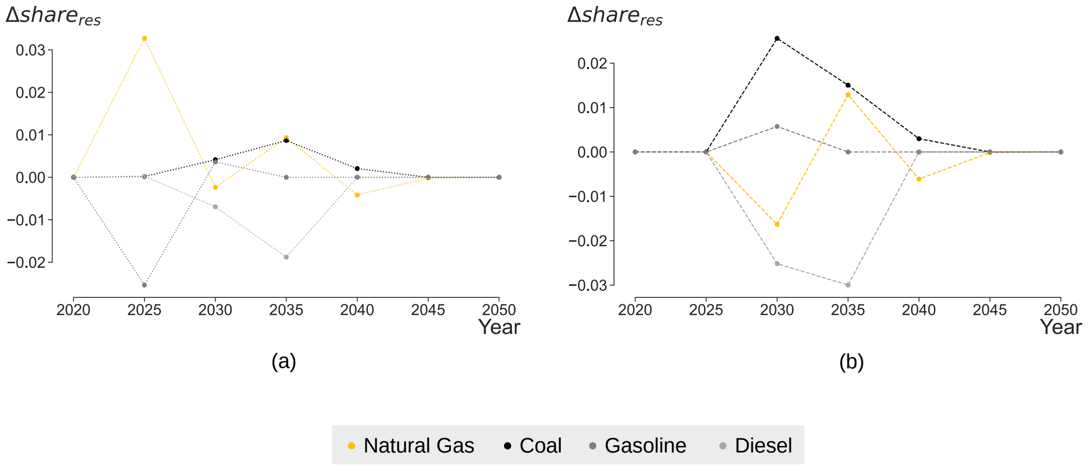
Again, the cost differences are negligible compared to the total costs and the three cases even converge as early as 2040, showing the robustness of the system to considerable changes contained to one sector.

Primary energy mix

Changes in the total amount of primary energy are again very small, the only significant ones being in 2025 for the case (b_{min}). Figure 3.12 shows the variations in the share of the mix for resources which present a variation from at least 1% compared to the nominal case. Gas and coal are again among these resources, along with gasoline and diesel, two important resources of the passenger mobility sector.

Case	2020	2025	2030	2035	2040	2045	2050
Min	-0.0096	0.26	0.047	-0.093	-0.14	-0.097	-0.00027
Max	-0.0025	0.0029	0.54	-0.11	-0.21	-0.083	-0.0021

Table 3.8: Change in total amount of resources used for each representative year, in [%].



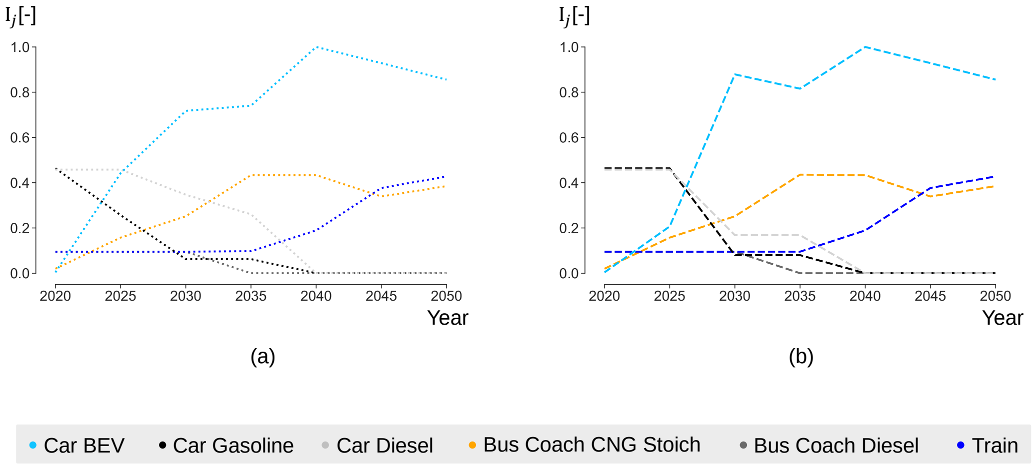
(a)

(b)

Figure 3.12: Change in the share of the primary energy mix, following equation (3.9). (a): parameter `limit_pass_mob_changes` at minimal value; (b): parameter `limit_pass_mob_changes` at maximal value.

Technology mix

The normalized production indicator for the passenger mobility is displayed in Figure 3.13. We observe that for a larger inertia of the end-use category (case b_{min}), phasing out gasoline cars must begin sooner for the system to be able to achieve the upcoming GHG emissions reduction target. A smaller inertia (case b_{max}) implies the ability to impose sharper changes and thus allows to keep the prominence of the technology a little longer. The importance of diesel cars is also decreasing more smoothly when the system is more inert and electric cars are introduced more significantly from the start. These observations can be matched with the change in the share of the resources, in Figure 3.12. Indeed, in both cases (b_{min}) and (b_{max}), diesel is less important in the mix compared to the nominal case. Gasoline cars are more or less phased out in a similar way in the nominal case and in case (b_{max}), so its share does not change much in the latter case whereas in case (b_{min}), the phasing out of gasoline cars starts sooner.



(a)

(b)

Figure 3.13: Normalized part of passenger mobility demand supplied by the different technologies following indicator defined in equation (3.7). (a): parameter `limit_pass_mob_changes` at minimal value; (b): parameter `limit_pass_mob_changes` at maximal value.

Figure 3.14 shows the total absolute change in each end-use category, computed following equation (3.10). The category directly concerned by the varying parameter is the one that has the bigger changes, but they cancel in 2040, for both cases. In 2025, the peak in the electricity end-use category for case (b_{min}) can be matched with the preliminary increase in electric cars. The HT heat category is also significantly affected by the change in the inertia of the passenger mobility, especially in the (b_{max}) case.

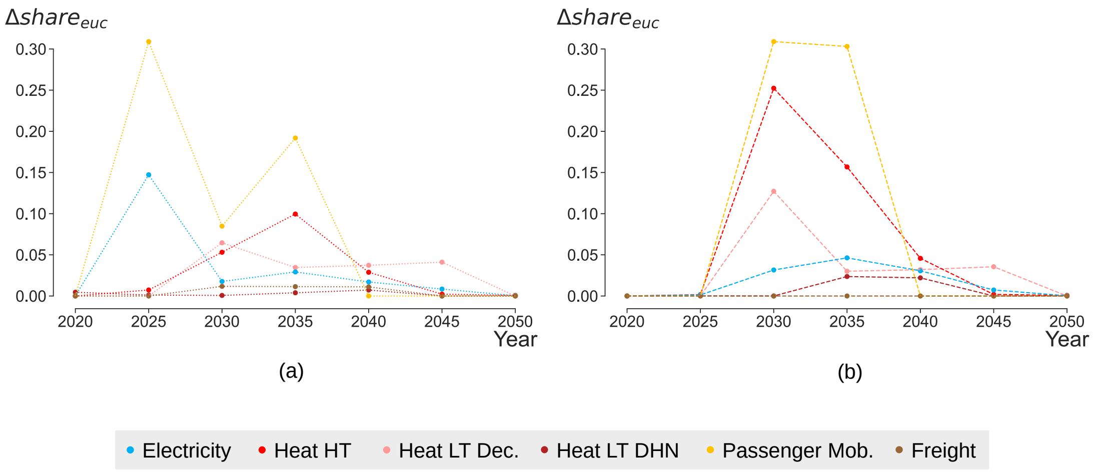


Figure 3.14: Change in the technology mix for each end-use category, following equation (3.10). (a): parameter `limit_pass_mob_changes` at minimal value; (b): parameter `limit_pass_mob_changes` at maximal value.

3.4.4 Case ($c_{min/max}$): `limit_freight_changes`

Cost

The yearly costs of the three cases of interest are displayed in Figure 3.15. The fact that the three curves are very close shows that the system is not very sensitive to changes in the freight sector. This is because of the small part of the demand it takes up, as well as the fewer technologies that are available in this sector (compared to the two sectors that were previously studied) which naturally does not lead to big technological changes.

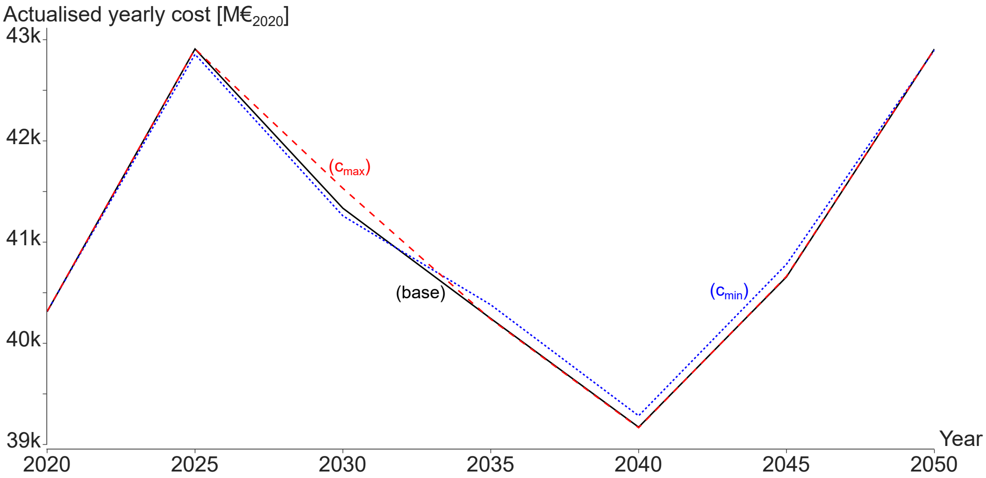


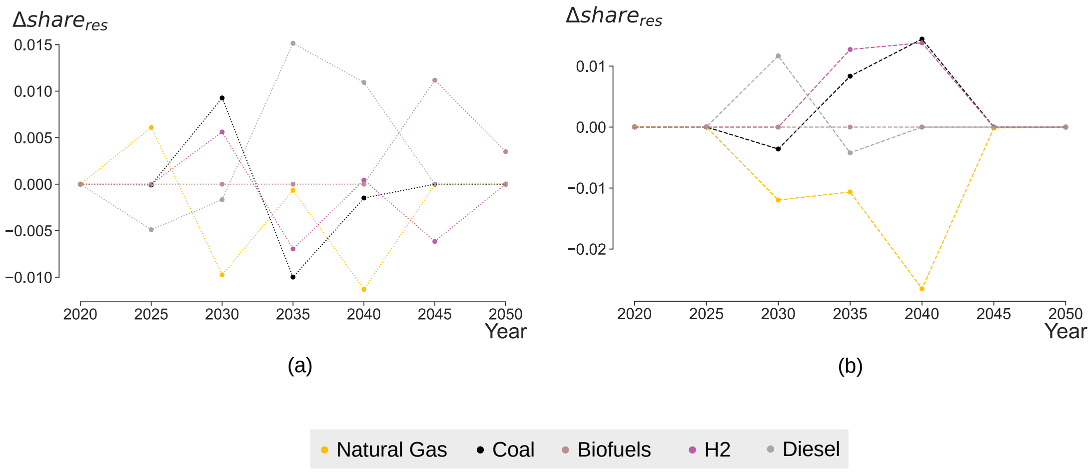
Figure 3.15: Actualised yearly costs of the system: cases (*base*), (c_{min}) and (c_{max}).

Primary energy mix

Changes in the total amount of primary energy (Table 3.9) are even more insignificant than in the previous cases, never reaching more than half a percent. The changes in the share of each resource (Figure 3.16) are also smaller, and the most important ones now include biofuels.

Case	2020	2025	2030	2035	2040	2045	2050
Min	0.0019	-0.11	0.036	0.40	0.23	0.0035	0.047
Max	0.017	0.016	0.18	-0.29	-0.15	-0.076	-0.0015

Table 3.9: Change in total amount of resources used for each representative year, in [%].


(a)

(b)

Figure 3.16: Change in the share of the primary energy mix, following equation (3.9). (a): parameter `limit_freight_changes` at minimal value; (b): parameter `limit_freight_changes` at maximal value.

Technology mix

Figure 3.17 presents the normalized production indicator for freight. By comparing to the nominal case (Figure 3.6), we first observe that the train does not seem to be affected. In case (c_{min}), diesel boats keep the same importance throughout the transition, whereas they quickly disappear in case (c_{max}), as in the nominal case. As a consequence, NG boats are not as developed as in the latter cases. Fuel cells trucks are smoothly introduced a bit sooner in case (c_{min}) compared to the two other cases where diesel trucks stay prominent for a bit longer, before being sharply replaced by fuel cells ones, even more sharply in case (c_{max}). Thanks to this ability to quickly give so much importance to this technology, the case with a smaller inertia needs to introduce less NG trucks than the other cases.

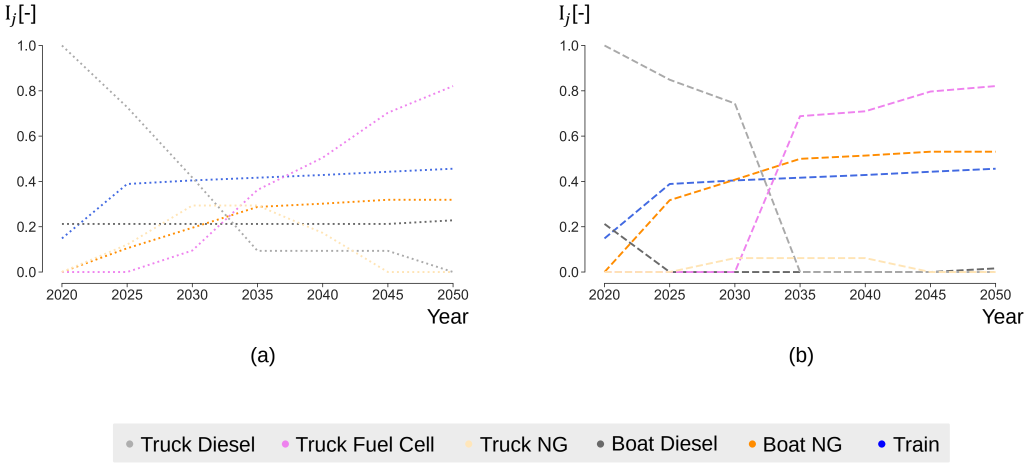
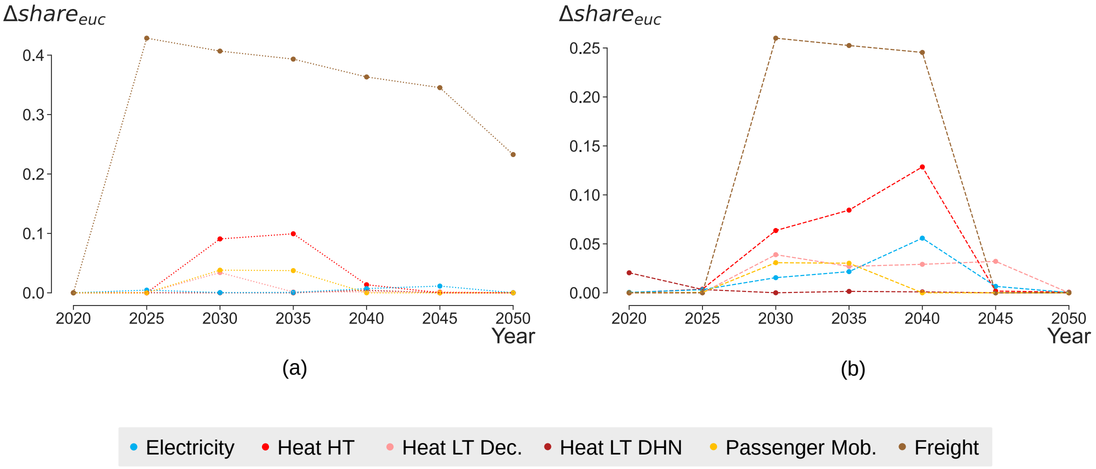


Figure 3.17: Normalized part of freight demand supplied by the different technologies following indicator defined in equation (3.7). (a): parameter `limit_pass_mob_changes` at minimal value; (b): parameter `limit_pass_mob_changes` at maximal value.

Figure 3.18 shows the total absolute change in each end-use category, for both cases. As seen just above, the freight category is significantly impacted, and for the first time so far, in case (c_{min}) we observe that the difference does not subside at the end of the transition (due to the persistence of diesel boats as seen in Figure 3.17).



(a)

(b)

Figure 3.18: Change in the technology mix for each end-use category, following equation (3.10). (a): parameter `limit_freight_changes` at minimal value; (b): parameter `limit_freight_changes` at maximal value.

3.4.5 Case ($d_{min/max}$): `share_mobility_public_max`

Cost

This last case is a bit different from the other ones, especially as the parameter studied has a different meaning in the model. The reaction of the system to changes of that parameter is therefore different from the ones seen before and, one might find, easier to understand. The evolution of the cost in each case (in Figure 3.19) is very similar, with only a downward stretch between the set points of 2020 and 2050. The earlier the year at which the maximum public share (equal to 50% of the sector) is reached, the lower the cost of the system. As public mobility is much cheaper than private mobility, it seems obvious that the cheaper system will be the one with the highest share of public mobility, as early as possible.

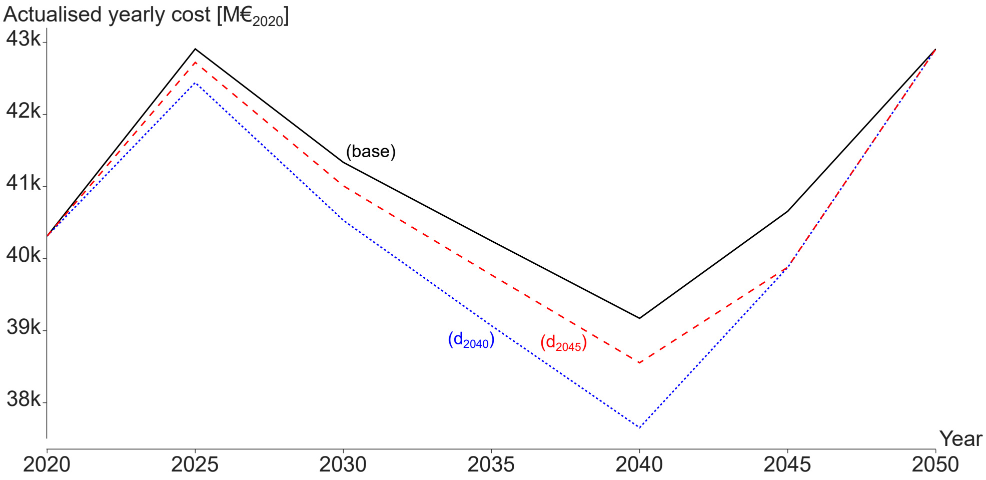


Figure 3.19: Actualised yearly costs of the system: cases (*base*), (d_{2040}) and (d_{2045}).

Primary energy mix

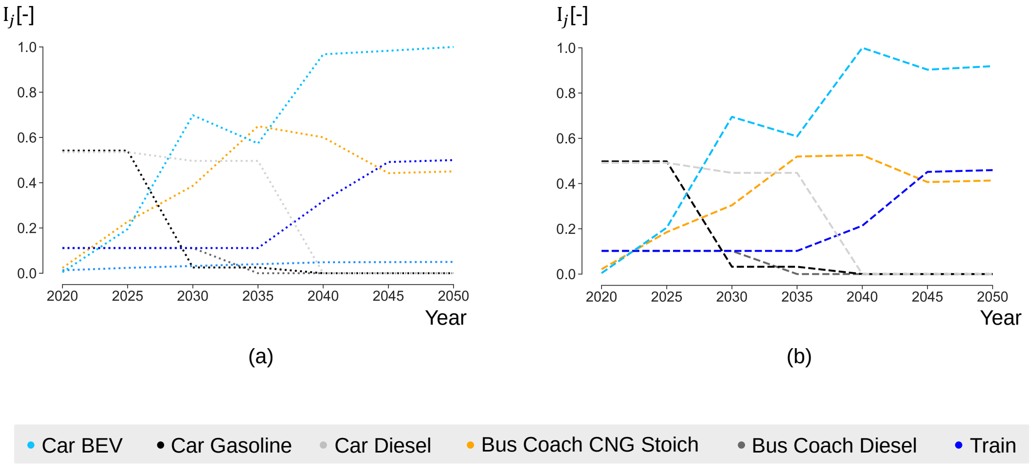
The variation in the total amount of primary energy stays insignificant as in the previous cases. No variation in the resources is greater or equal to 1% so none is shown.

Case	2020	2025	2030	2035	2040	2045	2050
$\lim_{2040}$	0.00066	0.025	0.067	0.19	0.42	0.36	0.026
$\lim_{2045}$	-0.00022	0.013	0.061	0.078	0.098	0.34	0.028

Table 3.10: Change in total amount of resources used for each representative year, in [%].

Technology mix

The normalized production indicator for the passenger mobility is drawn in Figure 3.17. Changes are less notable. We can still observe a more important peak in the share of *bus coach CNG stoich* for both cases compared to the nominal case. The later the limit can be reached, the smoother is the increase for the train. Finally, when the limit can be reached in 2040, electric cars do not decrease in the end of the transition as in the two other cases.



(a)

(b)

Figure 3.20: Normalized part of passenger mobility demand supplied by the different technologies following indicator defined in equation (3.7) (a): limit of 50% for parameter $\texttt{share\_mobility\_max}_{year}$ reachable in (a) 2040, (b) 2045.

Figure 3.21 shows the total absolute changes in each end-use category, following equation (3.10). We observe the same trend in both cases (d_{2040}) and (d_{2045}), with the peak occurring at the year the limit can be reached. This peak is half as important in case (d_{2045}).

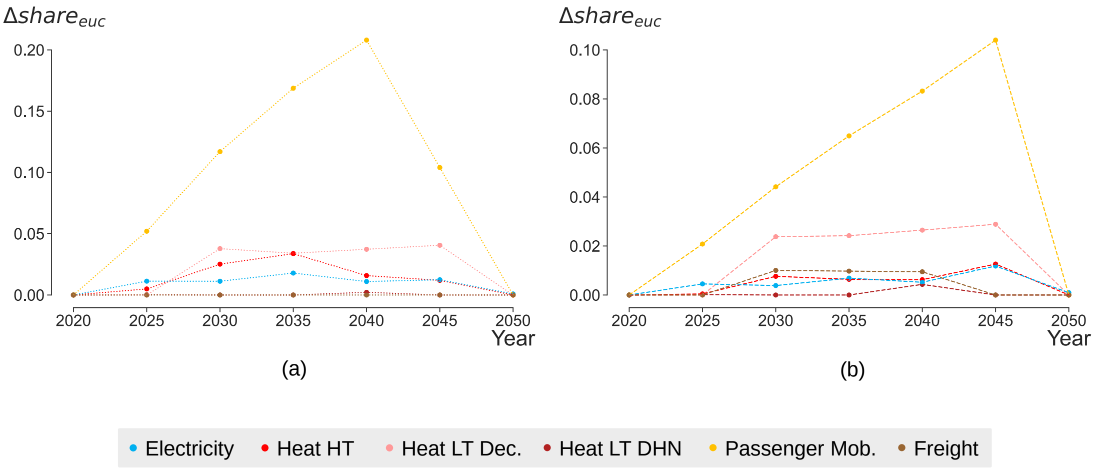


Figure 3.21: Change in the technology mix for each end-use category, following equation (3.10). (a): limit of 50% of public mobility reachable in 2040; (b): limit of 50% of public mobility reachable in 2045.

3.4.6 Transition costs sensitivity

The total transition costs of the system represent a good indicator of how the system reacts to the variations introduced in each aforementioned parameter, especially since the model optimizes the cost of the system. Some perspective on the sensitivity of the system to the parameters studied can be gained by comparing the total transition costs of each case. This is what was done in Figure 3.22, which displays the total transition costs of the base case, as well as the difference between the transition costs of each case with the base case:

$$\Delta C_{trans,i} = C_{trans,i} - C_{trans,base} \ \forall i \in \text{cases studied.} \tag{3.11}$$

At first glance, it is directly clear that the sensitivity of the objective function to the parameters studied is quite low (the mean relative difference being less than 1%).

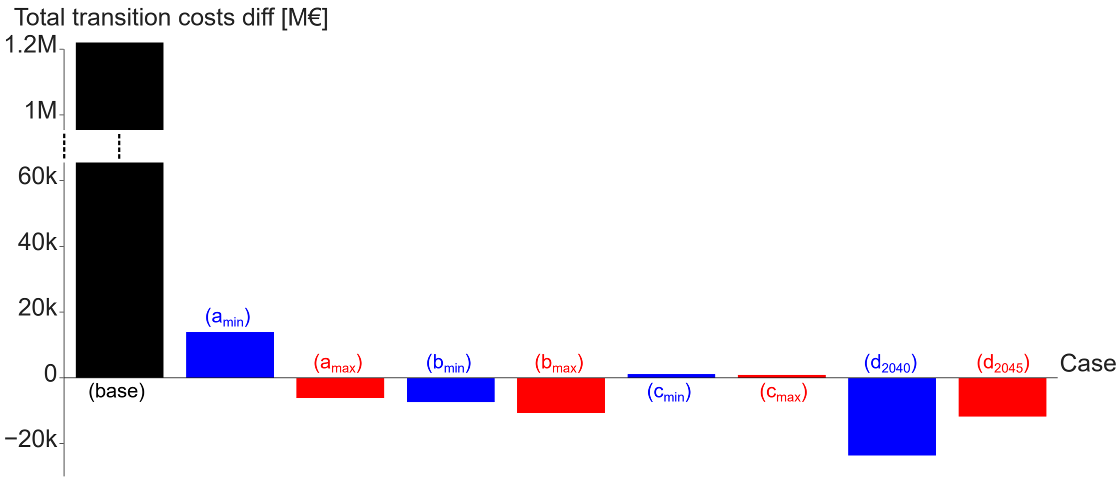


Figure 3.22: Total transition costs of case (*base*) and difference between each case and case (*base*).

3.4.7 Conclusion of the LSA

As observed in this Chapter, the system is quite robust to significant uncertainties (±40%) around the parameters studied (for single parameter variations only). Despite that, some significant variations were observed in the technology mix of some sectors, in some cases. Figure 3.22 shows how the value of the objective function used for optimization does not vary much in every case. It is thus important, when making conclusions about these analyses, to keep in mind that the relative variations at stake remain low, which allows a certain margin of error when selecting the values that will be used for the study case. In addition to that, it was previously observed that almost every case's transition pathway ended up converging in 2050 (except for case (c_{min})). This can be explained by the fact that the parameters studied only concern the rate at which the distribution of technologies in a sector changes (for the first 3 parameters) or the year at which a sector reaches its final distribution of technologies (for the last one). It seems thus plausible that each pathway converges towards the same final year, as the parameters only affect how fast the system changes and the model optimises the system over the whole transition.

With the results of the LSA in mind, an informed choice on the values of the parameters studied can be made. It seems that the values that induce the most inertia in the different sectors (corresponding to the (x_{min}) cases) are preferable. Observations of systems with higher rates of technological change (both the (*base*) and the (x_{max}) cases) showed replacement of one important technology by another in 10/15 years (as seen in the LT heat sector with thermal, then electric HPs), which can be considered as unrealistically fast. Furthermore, slower and, incidentally, longer transitions must be planned earlier. It is thus safer to plan a slow transition (and, if it turns out to happen faster than expected, it's for the best) than to plan a fast transition, which can be undertaken later but will have negative consequences, should it happen slower than expected.

Parameter	Value
`limit_LT_renovation`	0.2
`limit_pass_mob_changes`	0.2
`limit_freight_changes`	0.2
$\texttt{share\_mobility\_public\_max}_{year}$	2050

Table 3.11: Summary of the parameter values used in the case study.

These considerations concerned the three parameters limiting technological change in a sector more directly than the one limiting the share of public mobility in the passenger mobility production mix. For this parameter, the choice of the year at which it reaches its maximum value seems more arbitrary and closer to a sociological choice than a technical one. To remain in the same direction as the choice made for the values of the other parameters, it was chosen to allow the public mobility share to reach its maximum value as late as possible. This reinforces the idea of the slow transition and allows to plan a longer (but safer) transition. Table 3.11 presents the values used for this transition which will be investigated in detail in Chapter 4.

Chapter 4

Results

This chapter presents the main results of the case study defined in Chapter 3. After an overview of the transition, the evolution of the system is analyzed under different perspectives: the primary energy mix, the distribution of technologies in each sector, the costs and the GHG emissions. Some comparisons with the PNEC are also made when relevant.

4.1 Transition overview

To get a good qualitative first glance at the state of the system at different representative years, Sankey diagrams are used. These diagrams display all yearly energy flows, from the primary resources input to the end-use demands. In this section, the evolution of the system will be analysed through Sankey diagrams corresponding to years 2020, 2030 and 2050 (displayed in Figures 4.1, 4.2 and 4.3 respectively).

4.1.1 Year 2020

This year was initialized in the model by constraining it to represent the actual energy system of 2020 as accurately as possible. The interest here being to analyse the output of EnergyScope, this analysis will only focus on the optimized energy system as it is the base for the rest of the transition pathway. No comparison will thus be made with the actual system (see Section 3.1 for a comparison and details about the initialization of year 2020).

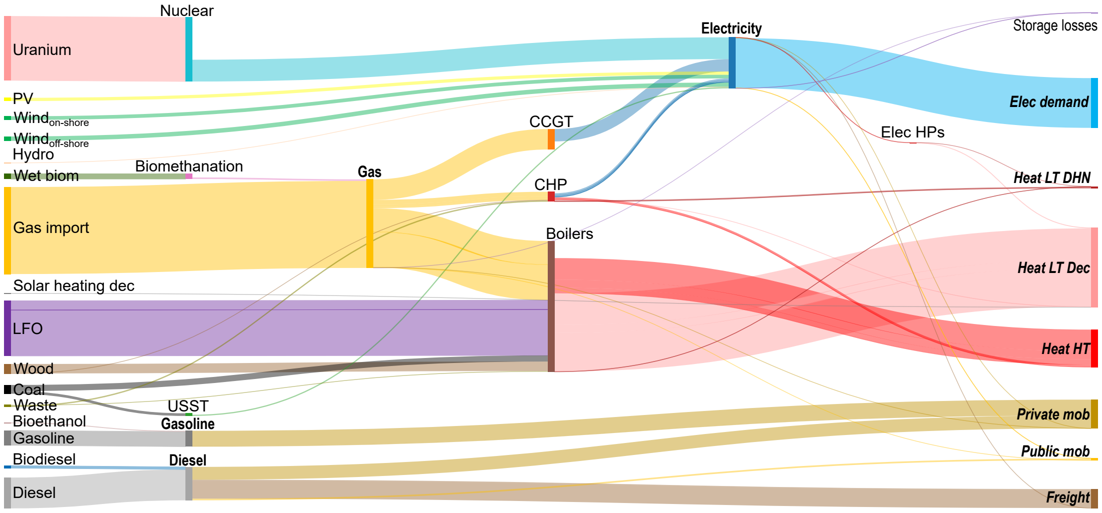


Figure 4.1: Sankey diagram representing the 2020 energy system. **Bold** is used for the main layers and ***bold italic*** is used for layers of EUD. Abbreviations: photovoltaic panels (PV), hydroelectric power (Hydro), Wet biomass (Wet biom), decentralised (dec), light fuel oil (LFO), ultra-supercritical steam turbine (USST), combined-cycle gas turbine (CCGT), combined production of heat and power (CHP), electric heat-pumps (Elec HPs), electricity (Elec), low temperature (LT), district heating network (DHN), decentralised (Dec), high temperature (HT), mobility (mob).

Each end-use demand corresponding to different practical energy needs, the primary resources used to meet each one vary accordingly.

- Electricity is primarily supplied by non-renewable resources, mainly imported natural gas, through combined-cycle gas turbines (CCGT) and combined heat and power production (CHP), and uranium, using nuclear power plants. The share of renewable energy remains marginal.

- The heating sector mainly uses boilers (although a small part of the high temperature demand is met by CHP). The principal resources used are imported NG and light fuel oils (LFO) which are, again, two fossil fuels. Some coal is also used, mainly in boilers to produce heat but also in ultra-supercritical steam turbines (USST), to produce electricity. Only a small part of the low temperature sector is supplied by electric heat pumps.

- Both mobility sectors (passenger mobility, which comprises private mobility and public mobility, and freight) almost exclusively use fossil fuels (gasoline and diesel), with the exception of small bio-fuels inputs. A small part of each sector is also supplied by electricity and gas (both layers' primary energy inputs being mostly emitting fuels).

The system is thus very rooted in non renewable resources. To respect the constraints on GHG emissions imposed on the system in the years ahead, the technologies used will have to change, especially to make more of the renewable potential that is available in Belgium, notably with storage technologies, which are only used for electricity and NG at the moment.

4.1.2 Year 2030

As the constraints on GHG emissions get lower and with nuclear energy being phased-out, the system has to turn more and more to renewable energy sources. The renewable primary resources which were already in use in 2020 are all more important in the mix. Some fossil fuels (such as diesel, coal and LFO) are being partially phased-out, while gasoline is no longer used at all.

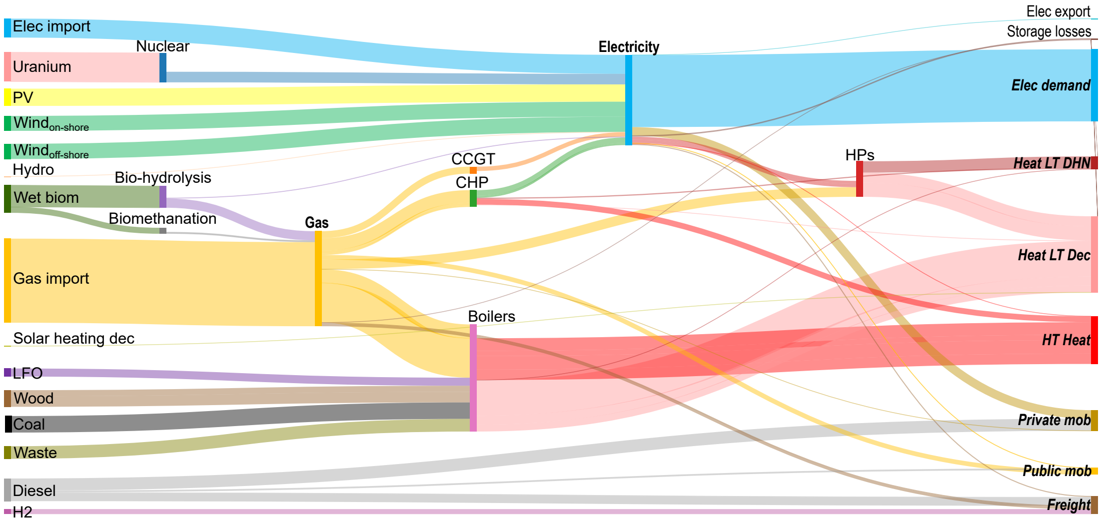


Figure 4.2: Sankey diagram representing the 2030 energy system. **Bold** is used for the main layers and ***bold italic*** is used for layers of EUD. Abbreviations: electricity (Elec), photovoltaic panels (PV), hydroelectric power (Hydro), Wet biomass (Wet biom), decentralised (dec), light fuel oil (LFO), combined-cycle gas turbine (CCGT), combined production of heat and power (CHP), heat-pumps (HPs), low temperature (LT), district heating network (DHN), decentralised (Dec), high temperature (HT), mobility (mob).

Some electricity is imported to cope with the decrease in nuclear production, as well as with the increasing demand in electricity both as an end-use and as an energy vector for the other sectors (most notably the electrification of the private mobility sector and the increase in electric heat pumps for low temperature heating). In addition to the contribution of electricity, the share of wood and waste in the heating sectors has increased, allowing to reduce the consumption of fossil fuels. Wet biomass is also used to produce renewable gas more significantly than in 2020, which allows to import less NG, the consumption of NG remaining important as it is one of the fossil fuels with the lowest emissions factor (NG is notably used in thermal heat pumps, which make up more than half of the production from heat pumps in 2030). With diesel import decreasing, a significant part of the freight demand is now met by hydrogen.

4.1.3 Year 2050

This is the final year of the transition and it corresponds to a quasi net carbon neutral system (the only remaining emissions corresponding to the recovery of waste through combustion). Compared to 2030, most fossil fuels have been phased-out (the only remaining fossil fuel is imported NG, which remains marginal in the mix) in favour of renewable energy sources, which evolution differed from resource and technology to another:

- Some technologies (such as wind turbines, wood and waste) had almost all already reached their maximum capacity by 2030, meaning the production from these technologies hasn't changed much since then.
- Other technologies (such as PV and imported H_2) have seen their installed capacity increase since 2030, leading to their share being more important in the mix.
- Finally, some new technologies and resources (such as imported renewable ammonia (NH_3), used in CCGT) were introduced in the system to fill the gaps in the production.

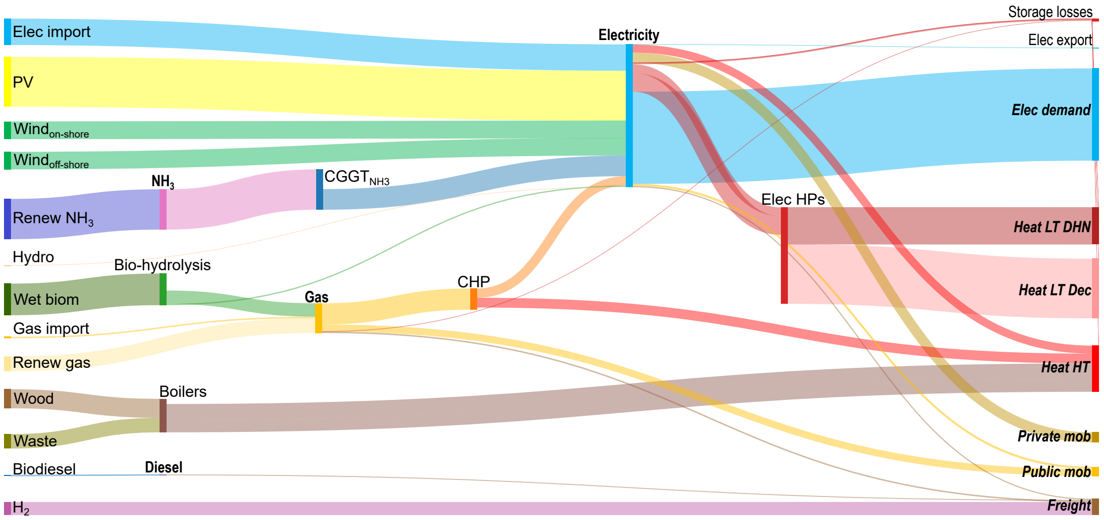


Figure 4.3: Sankey diagram representing the 2050 energy system. **Bold** is used for the main layers and ***bold italic*** is used for layers of EUD. Abbreviations: electricity (Elec), photovoltaic panels (PV), renewable (Renew), hydroelectric power (Hydro), Wet biomass (Wet biom), combined-cycle gas turbine (CCGT), combined production of heat and power (CHP), electric heat-pumps (Elec HPs), low temperature (LT), district heating network (DHN), decentralised (Dec), high temperature (HT), mobility (mob).

Overall, the technologies and resources used in the system have diversified a lot, going from 4-5 primary resources that were mainly used to 8-9 resources that are much more evenly distributed. One can also notice how inefficient technologies (such as gas CCGT and boilers) were (partially) decommissioned in favour of much more efficient technologies (such as CHP, heat pumps and, more generally, centralised systems) to make the most of the available primary resources. Because it is a very convenient energy vector, electricity also took an increasingly important place in the system. Since most renewable resources are not dispatchable, storage technologies were slowly introduced, leading to increasing (but relatively small) losses. Again, some electricity is imported to ensure that the important electricity demand is met.

4.2 Energy mix

After an overview of the main developments throughout the transition, the first focus concerns the evolution of the primary energy mix, shown in Figure 4.4. The amount of total primary energy is decreasing, which shows that the system becomes more efficient with time (taking into account that the total FEC of the industry, residential and tertiary sectors stay overall constant, as observed in Figure 3.3, while the transport demand increases). Gasoline is the first emitting resource to leave the mix, in 2030, followed by LFO in 2035 while diesel stays until 2040 and coal until 2045. Gas is kept throughout the transition and only disappears in 2050, replaced by its renewable equivalent. The classic renewable energy sources (biomass, wind and solar) take a gradually more important place in the mix. H_2 is quickly introduced in the mix at the same time gasoline is phased out. The system also relies on the import of electricity from the beginning of the transition, and of ammonia, only introduced in the end.

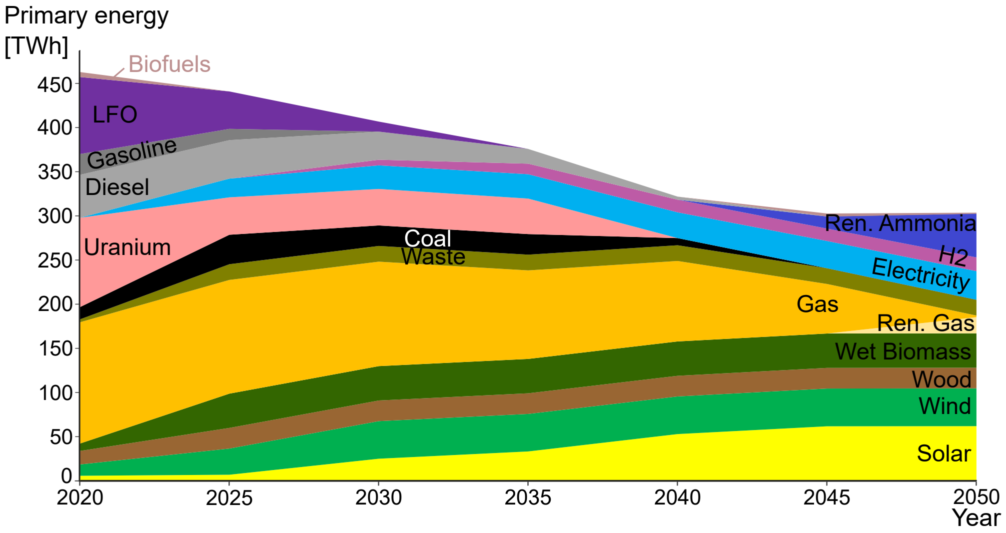


Figure 4.4: Evolution of the energy system's resources consumption during the transition.

In particular, for years 2025 and 2030, the optimal primary mix found by EnergyScope can be compared with the projections of the PNEC (Figure 4.5), presented in Table 1.3. Since these values are expressed in percentage of the GIC, some hypotheses and computations have to be made for the comparison to be possible. These hypotheses and computations are developed in Appendix A.

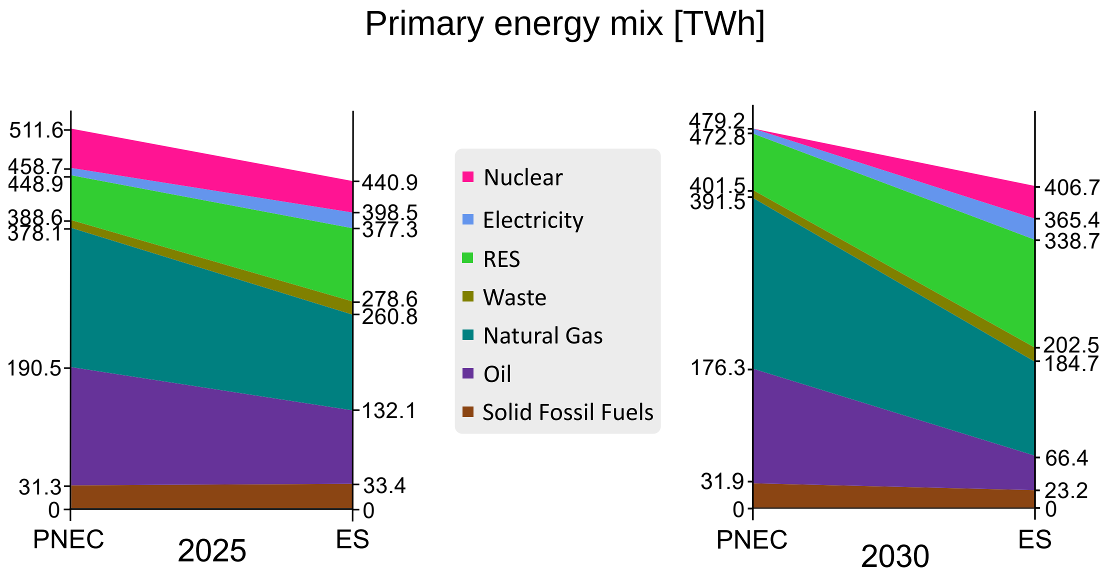


Figure 4.5: Comparison of the primary energy mix between projections from the PNEC and EnergyScope.

The first observation is that the system implemented by EnergyScope (ES) uses less resources, but this must be observed keeping in mind the difference in FEC implemented in both cases, and the optimistic efficiencies implemented in EnergyScope, as mentioned in Section 3.1. The most relevant observations are thus the proportion of resources in the mix, shown in Figure 4.6. Because of the inertia of the system, the mix in a representative year strongly depends on the mix in the previous representative years. This discussion must thus include the observations made in Section 3.1, where the differences between the primary energy mix in year 2020 in EnergyScope and the actual one are highlighted. Since the PNEC was written in 2019, the values presented for 2020 are also projections and the differences with the actual mix are also to be discussed. Following the same methodology as explained in Appendix A, and the same indicator as defined in equation (3.2), Table 4.1 presents the differences in the shares of the resources in the mix, compared to the same Eurostat values as used in Section 3.1. The shares in the mix of 2020 in EnergyScope and in the PNEC are also presented in Table 4.2, and we see that the order of magnitude is similar, except for waste and solid fossil fuels. Since the transition starts from a similar mix in 2020, thh ambitions of both pathways can be compared.

Resource	$\Delta\%_{res}$ [%]
Solid Fossil Fuel	1.1
Oil	4.1
NG	-4.8
Waste	0.64
RES	-0.72
Electricity	1.2
Nuclear	4.4

Table 4.1: Differences in the shares of the resources between the projections of the PNEC and the actual mix computed from actual data reported by Eurostat.

	PNEC	ES
Solid Fossil Fuel	5.9	3.0
Oil	33.6	34.9
NG	27.7	30.0
Waste	2.1	0.72
RES	10.7	9.2
Electricity	1.2	0
Nuclear	23.8	22.1

Table 4.2: Shares of the resources in the mix of 2020 according to the projections of the PNEC and the solution found by EnergyScope, in [%].

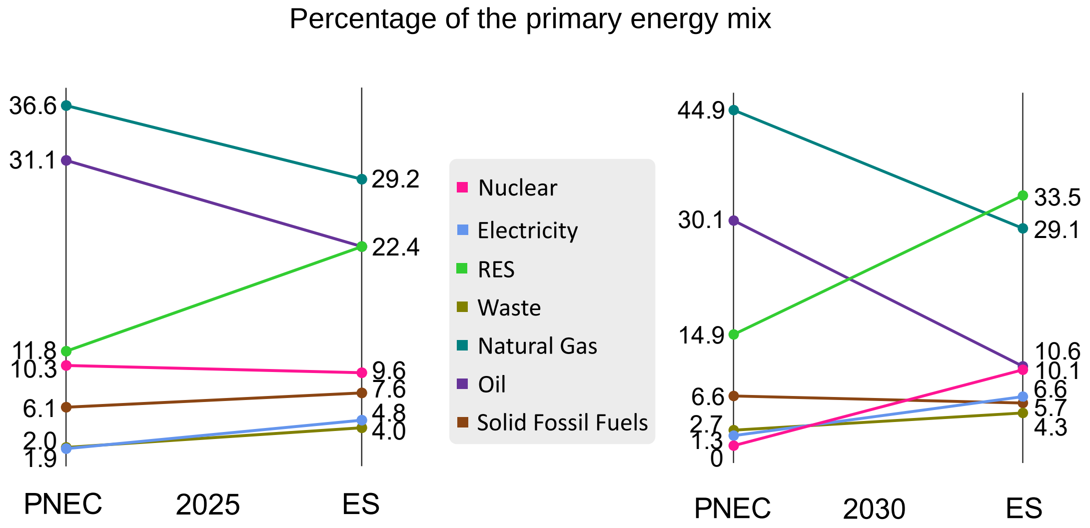


Figure 4.6: Comparison of the shares of the resources in the primary energy mix following the projections of the PNEC and the pathway optimal solution from EnergyScope.

We can clearly see that the approaches to the transition differ a lot. In EnergyScope, the part of RES largely increases as of 2025 and keeps increasing, making them twice as important as in the projections of the PNEC in 2030, although the mix in 2020 in EnergyScope underestimated their importance compared to the PNEC. In EnergyScope, this increase in the share of RES is accompanied by an important decrease in the share of oil products, whereas NG keeps a constant share until 2030. In the PNEC, we see that the strategy to tackle the nuclear phase-out is to replace it by NG. From the results of EnergyScope, we indeed see that NG can be a strong asset to lead the transition. However, the PNEC does not decrease the share in oil product, resulting in a mix heavily dependent on fossil fuels.

4.3 Technologies per end-use category

This section will help visualize how these resources are used in practice thanks to the reporting of the evolution of the technology mix of each end-use category.

4.3.1 High temperature heat

The evolution of the sector is drawn in Figure 4.7. The oil boilers are phased out as of 2025, whereas at the same time, waste and wood boilers already grow in importance. An unexpected observation is the sharp decrease in gas boilers in favor of an increase of coal boilers, which are more polluting. This increase in the use of coal must be contrasted in light of the difference in the amount of coal initialized in 2020 compared to the actual one. As seen in Figure 4.4, the total amount of gas used in the first part of the transition is more or less constant and we will see that other gas technologies develop in other sectors, as well as the gas co-generation here. Recall that in 2050, natural gas is completely replaced by renewable gas, even if this conversion is not seen here. At the end of the transition, the HT heat is supplied by only 4 technologies: waste and wood boilers, gas co-generation and direct electricity. For the record, a constraint imposes the system to use all the available waste, which explains the sharp increase in 2025 and its maintaining until the end of the transition though it has an important emission factor.

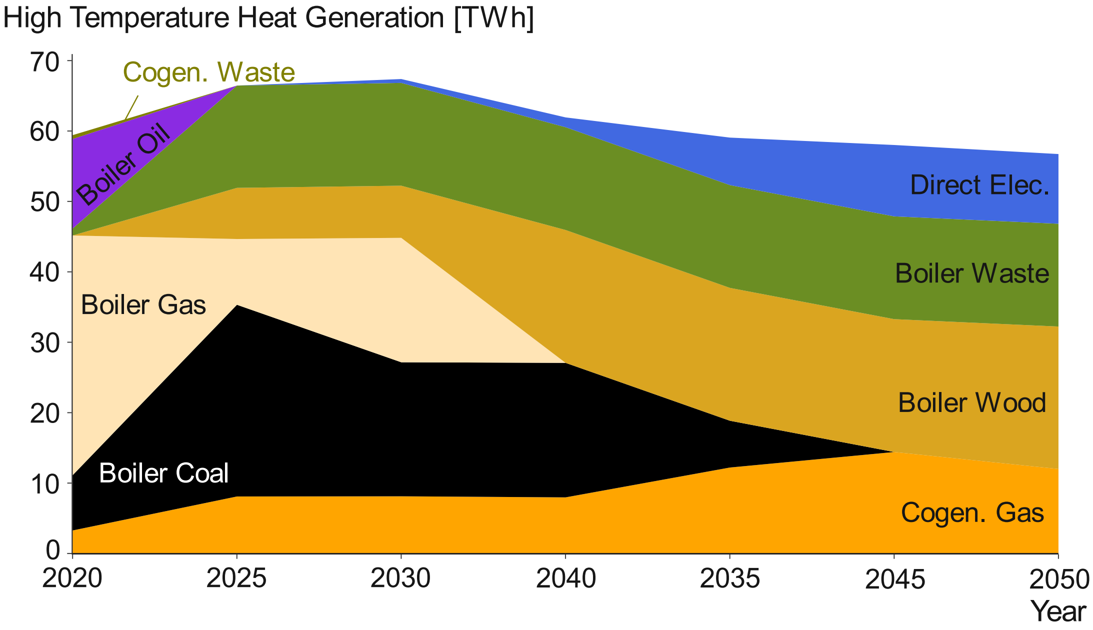


Figure 4.7: Evolution of the HT heat end-use category.

4.3.2 Low temperature heat

LT heat can be supplied by either a decentralized system (Figure 4.8) or a District Heating Network (DHN) system (Figure 4.9). To avoid unrealistic changes, the limit of the share of DHN in the total LT heat generation was set to 0.37 in

2050, based on projections of the heat roadmap study [37]. This limit for the other representative years was computed by a linear interpolation between the actual share of DHN in 2020 (around 2%) and the limit in 2050. Figure 4.9 shows that this limit is attained throughout the transition, clearly showing that DHN is seen as optimal compared to decentralized systems. It relies mostly on electric heat pumps and slightly on gas cogeneration. For the decentralized generation, we see that heat pumps also play a big part. Thermal heat pumps are introduced at the start of the transition and disappear in 2050 when the electric heat pumps are the only remaining technology. Gas boiler production stays more or less constant until 2035 before it becomes zero in 2045. Oil boilers, which currently supply a little less than half of the LT heat, are quickly decommissioned, which implies a lot of change from the population.

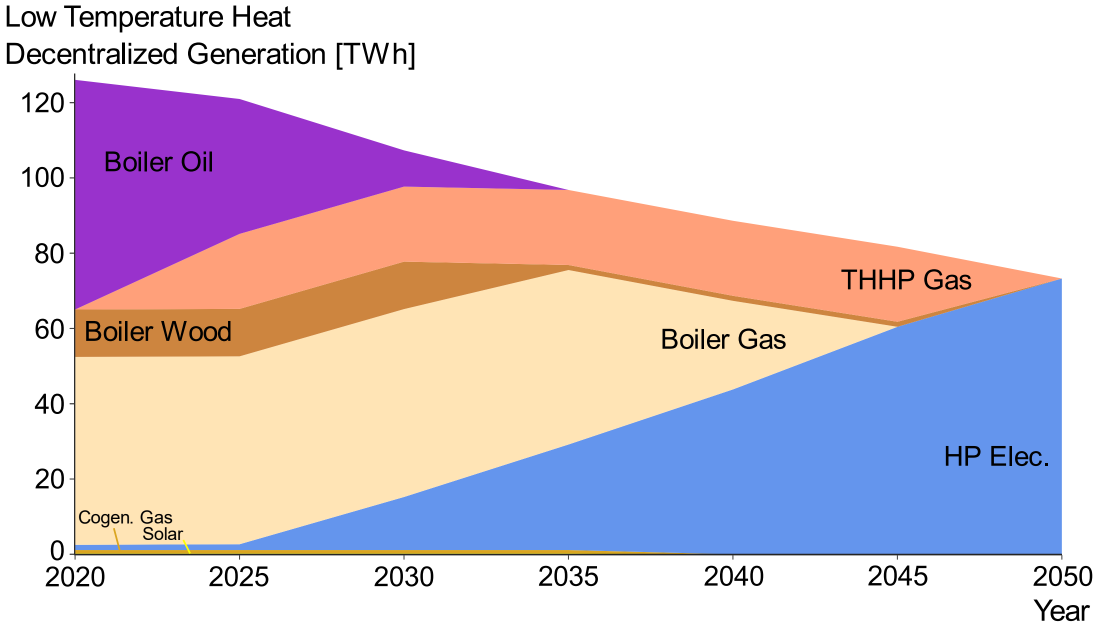


Figure 4.8: Evolution of the decentralized LT heat end-use category.

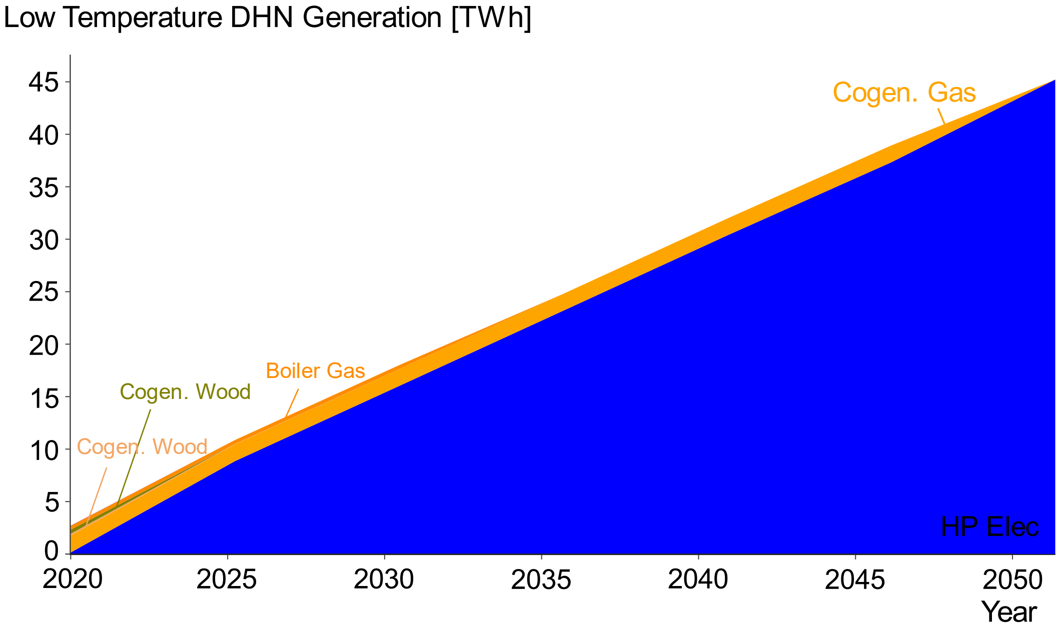


Figure 4.9: Evolution of the DHN LT heat end-use category.

4.3.3 Passenger mobility

The evolution of the sector is drawn in Figure 4.10. For the record, the share of public mobility is constraint to a linear interpolation between the historical value in 2020 and 50% in 2050. We see that the trend is to maximize the share of public mobility, as it is more efficient. The tramway share is constraint to their historical value of 2020 throughout the transition, since it is assumed that no big deployment of this means of transportation will occur. Trains do not increase until 2035, the development of public transportation is mainly done thanks to CNG buses, which considerably increase as of 2025. As a result, diesel buses disappear in 2035.

The evolution of the private mobility is driven by the important deployment of electric cars, yet almost nonexistent in 2020. Gasoline cars disappear from the fleet in 2030 while diesel cars stay until 2040, when electric cars become the only technology in the fleet. Note that the EU has voted to ban the sale of thermal vehicle as of 2035 [38]. The transition presented in Figure 4.10 is thus faster but the end point in 2050 is not unrealistic.

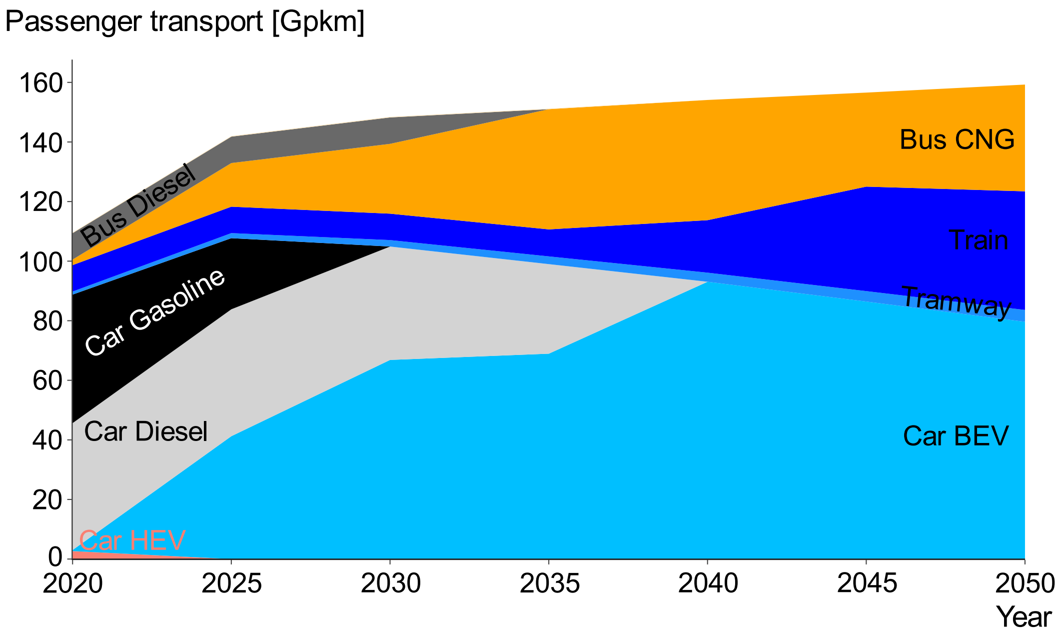


Figure 4.10: Evolution of the passenger mobility end-use category.

4.3.4 Freight

The evolution of the sector is drawn in Figure 4.11. Note that the shares of each category of means of transportation (boats, trains, trucks) are limited (to 30%, 25% and 100%, respectively), and as observed, they tend to reach their limit. NG boats are introduced to increase the share of boats in the sector. Trains develop quickly as well. Concerning the trucks, diesel ones, which were supplying the whole part of the demand supplied by road, linearly decrease to be replaced by fuel cell trucks. The transition is eased by NG trucks but they disappear in 2040.

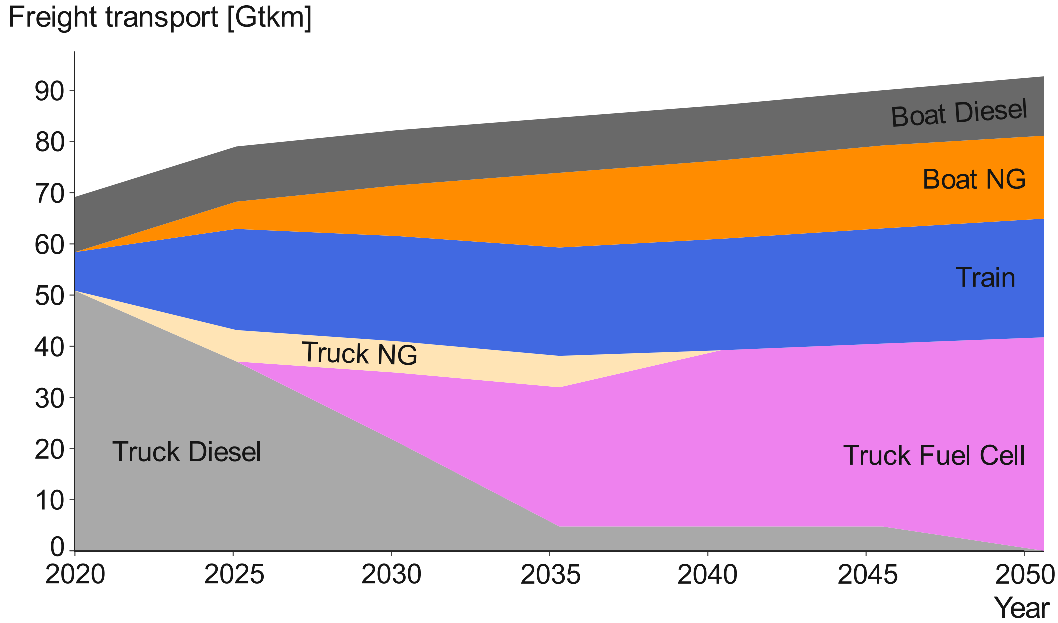


Figure 4.11: Evolution of the freight end-use category.

4.3.5 Electricity

The other sectors strongly depend on electricity to achieve the transition. Indeed, we saw a large deployment of electric heat pumps, trains and electric cars. Figure 4.12 shows how the generation of electricity increases during the transition. For the record, the nuclear phase-out was implemented as planned by the actual policies. The share of RES strongly increases. Wind technologies reaching their maximal capacity in 2030, PV keeps on increasing until the end of the transition. CCGT and gas cogeneration continue to supply a less important part of the demand during the transition. CCGT is phased out in 2050, after ammonia CCGT was introduced in 2040, taking a significant importance in 2050.

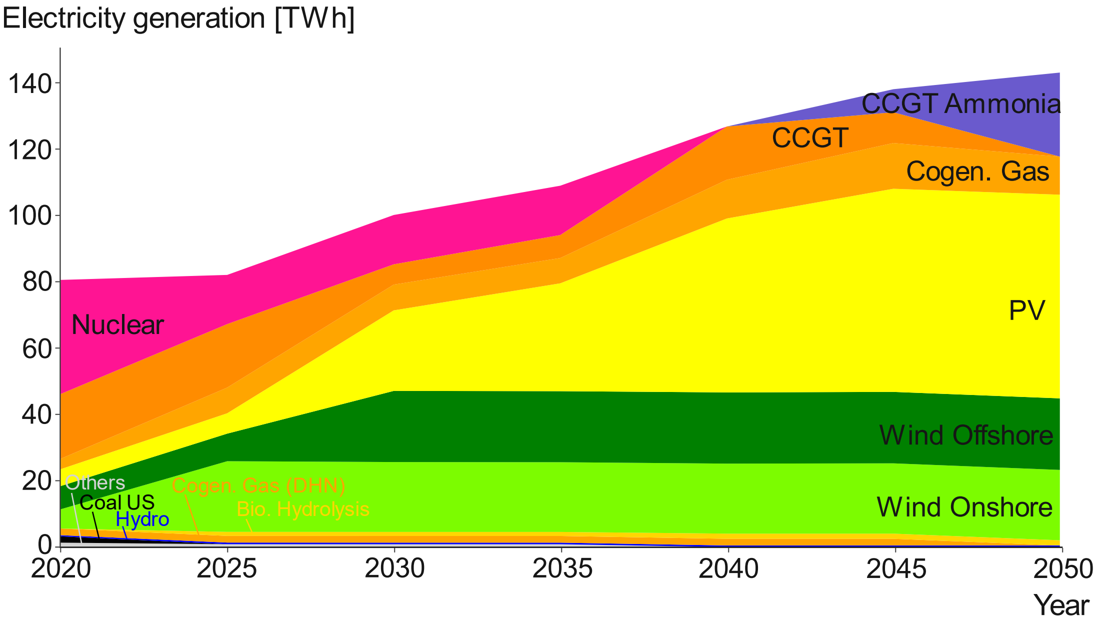


Figure 4.12: Evolution of the electricity end-use category.

4.4 Costs analysis

Estimating accurately the costs of such a large scale energy system is very hard, especially if one wants to compare these costs with other estimations (such as the one from the PNEC, for instance). The following analysis will thus only consist in comparisons of cost shares in the system. As explained in Section 2.2.2, the yearly costs of the system can be decomposed into the investment costs and the maintenance costs (respectively C_{inv} and C_{maint}) and the operational costs (C_{op}, which correspond to the costs of primary resources). A first angle of analysis, based on the total yearly cost of the system, C_{tot}, is presented, followed by a discussion based on the operational costs, C_{op}.

4.4.1 Main yearly total costs shares

Figure 4.13 presents the sectors with the biggest cost shares in the system. These shares were computed in the following way (note that the sectors taken into account here comprise all EUD sectors, as well as renewable and non-renewable resources, infrastructure, storage and synthetic fuel technologies):

$$
\begin{aligned}
\text{share}(\text{RES\_TYPE}, y) = &\sum_{i \in \text{RES\_TYPE}} \frac{C_{op}(i,y)}{C_{tot}(y)}, \\
&\forall y \in \text{YEARS}, \\
&\text{RES\_TYPE} \in \{\text{renew\_res}, \text{non\_renew\_res}\};
\end{aligned}
\tag{4.1}
$$

$$
\begin{aligned}
\text{share}(\text{SECTOR}, y) = &\sum_{j \in \text{SECTOR}} \frac{C_{inv}(j,y) + C_{maint}(j,y)}{C_{tot}(y)}, \\
&\forall y \in \text{YEARS}, \\
&\text{SECTOR} \in \text{EUD} \cup \{\text{infra}, \text{storage}, \text{synth\_fuels}\}.
\end{aligned}
\tag{4.2}
$$

As seen in the figure, the most costly sector for the most of the transition is the private mobility sector. Given that this sector has one of the smallest shares in the energy mix, it is important to highlight how expensive this sector is compared to others (especially the public mobility sector, which is much cheaper).

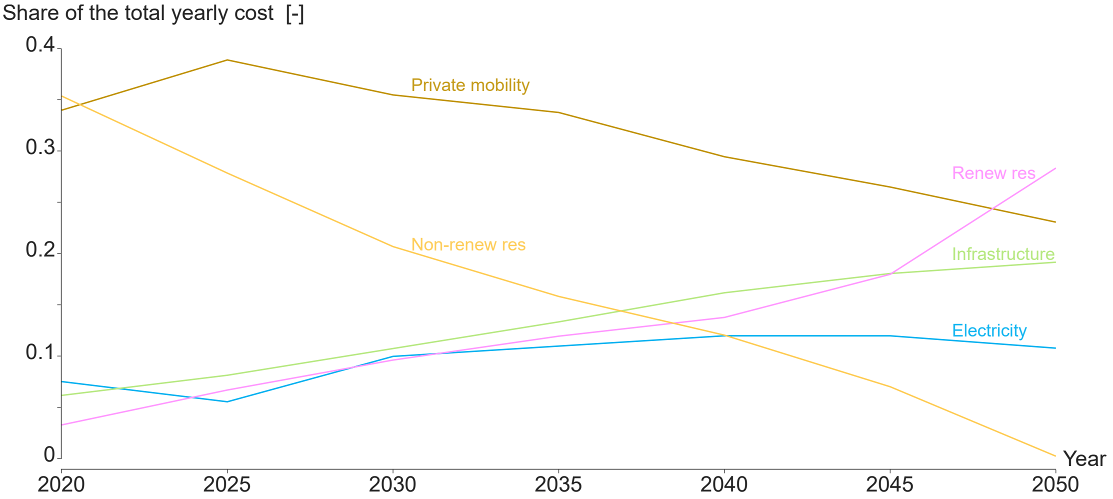


Figure 4.13: Main shares of the total yearly cost of the system, per sector. Abbreviations: renewable resources (Renew res), non-renewable resources (Non-renew res).

Another point of interest is the importance of the share of infrastructure technologies. Although these technologies do not directly supply the end-use demand, they are essential for the energy system. The share rises throughout the transition, as the system is electrified and has to transport more and more electricity and, more generally, energy. Interestingly, although renewable resources completely replace non-renewable ones by 2050, the share of the total cost of renewable resources in 2050 is smaller than the share of almost exclusively non-renewable resources in 2020. This might seem surprising at first but one must keep in mind that the total consumption of the system decreases through the transition, as the system's efficiencies improve with time, while its demands remain relatively stable.

4.4.2 Main yearly operational costs shares

As shown in Figure 4.13, resources constitute an important share of the total costs of the system. It is thus interesting to see more closely how their shares are distributed. The share of each resource is thus computed as a ratio of the annual cost of operation of the resource with the total operational cost of every resource:

$$\text{share}(i,y) = \frac{C_{op}(i,y)}{\sum\limits_{i \in \text{RES}} C_{op}(i,y)}, \qquad \forall i \in \text{RES}, \forall y \in \text{YEARS}. \tag{4.3}$$

The first observation made from Figure 4.14 is how the shares of non renewable resources, dominant in the beginning of the transition, decrease through it while on the contrary the shares of renewable resources increase. This first observation is quite trivial as it directly comes from the shift of the system towards renewable resources (as seen above).

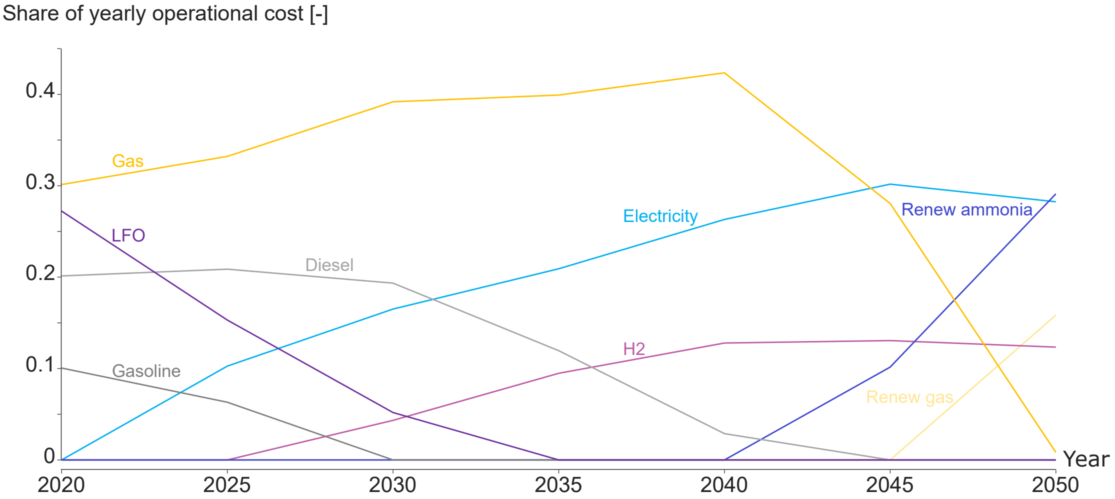


Figure 4.14: Main shares of the yearly operational cost of resources. Abbreviations: light oil fuel (LFO), renewable (Renew).

Secondly, electricity shares appear to rise through the transition, as expected with the electrification of the system. However, in 2050, the share decreases while the share of renewable ammonia increases rapidly. The explanation might be that, when short of primary energy, the system will always try to import the resource that will minimize its total cost. It thus imports electricity during most of the transition until, for some reason (which might be the costs of infrastructure and storage related to this electricity import, for example), it becomes cheaper to import renewable ammonia, at which point the system starts doing so. The same observation seems valid (in smaller proportions) for hydrogen and renewable gas, with imports of renewable gas starting in 2045.

4.5 GHG emissions

The limit on the GHG emissions is imposed according to Table 3.3 (based on the 2021 European Climate Law). Figure 4.15 shows the evolution of the emissions from the system, and the resources that generate them. This evolution was expected: all the other resources being phased-out as the transition goes on, the emissions in 2050 are almost exclusively due to waste (which we forced the system to use). We also observe that the limit on the emissions is always reached, except in 2020, where we overestimated the emissions compared to the historical ones. Indeed, since the amount of primary energy is less important and the efficiencies are higher in EnergyScope than in reality, the resulting emissions are consequently reduced. Note that this pathway results in 1193 $[MtCO_2\text{-}eq]$ emitted by the Belgian energy system throughout the transition. If we assume that the energy system account for around 75% of the country's total emissions [20], this results in 1591 $[MtCO_2\text{-}eq]$ emitted by Belgium from 2020 to 2050. As expected, this is the same order of magnitude as the estimated carbon budget resulting from the 2021 European Climate Law GHG emissions reduction trajectory (see Section 1.3).

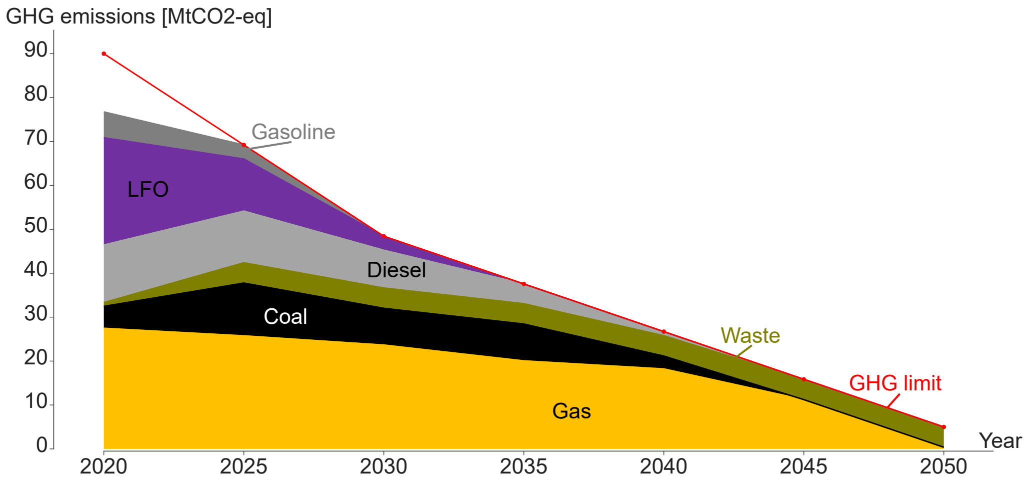


Figure 4.15: Yearly GHG emissions per resource.

4.6 Further comparisons with the PNEC

In this section, some comparisons are made between the transition projected in the PNEC and the one optimized by EnergyScope. These comparisons are not homogeneous because comparable data are not always supplied by the different entities.

4.6.1 Technology trajectories

Based on different tables available in the PNEC from page 74 to page 93 (Section 2.1.2 of the PNEC), Table 4.3 shows the evolution of four technologies that have a particular importance in the transition. The values are the increase in production in 2030 compared to 2020 (or 2015 in some specified cases), projected by the different entities and EnergyScope. In general, we see that the increase is significantly more important in EnergyScope. This would indicate an important delay in the achievement of the transition targets in Belgium. For the record, the solution found by EnergyScope is not supposed to be interpreted as the only way of transitioning towards 2050, but it represents a feasible path and therefore can be seen as giving general trajectories which, if followed, can help achieve the targets. In particular, the heat LT sector in the EnergyScope solution strongly relies on an important increase in production by heat pumps. We see that the different entities do not plan such a significant increase. For PV, only Wallonia is close to the order of magnitude of EnergyScope, but the increase is computed from 2015. The same observation is valid for wind technologies. Note that this comparison does not take into account the specific potential of expansion of the technologies on each entity. However, it gives an idea of the supplementary efforts that would be needed if the directions given by EnergyScope were to be followed.

As a conclusion, Wallonia seems to be the one entity planning more expansion efforts on these technologies qualified as necessary for the transition by EnergyScope. The overall planned effort does not allow to follow the directions advocated by EnergyScope.

	Flanders	Wallonia	Brussels-Capital	Belgium	ES
HP	+138%	+375%	+58%	+235%	+1867%
PV	+76%	+317^a%	+85%	+115%	+376%
Wind onshore	+65%	+220^a%	-	-	+263%
Wind total	-	-	-	+81%	+232%

Table 4.3: Increase in production from HP, PV and wind technologies in 2030 compared to 2020, according to the projections of the different entities.
^{a}: increase in 2030 compared to 2015 since no values were projected for 2020.

4.6.2 Projections of Wallonia for the mobility

The comparison of the composition of the mobility sector can only be done for Wallonia since these figures are not available for the other entities. For Wallonia, they are available from page 65 to page 68 in the PNEC. The comparison is made in Table 4.4. Note that Wallonia projects 10% of soft mobility (pedestrians and bikes) that is not taken into account in EnergyScope. Wallonia plans on decreasing the share of private cars in mobility faster than it is done in EnergyScope and on increasing the share of train by twice the share in EnergyScope by 2030. Buses are less developed. The other types of buses not listed in the table are Battery Electric Vehicle (BEV) (20%), Plug-in Hybrid Electric Vehicle (PHEV) (15%) and Hydrogen (5%). For the private mobility, the introduction of BEV cars is less important than in EnergyScope and the fleet still relies on fossil fuels for three quarters of the fleet.

If the measures that come along these projections are indeed implemented, the efforts made by Wallonia in the mobility sector are to be recognized. However, if the emissions reduction targets are to be achieved, the fleet of private cars should be de-carbonized faster.

	Wallonia	ES
Bus	**0.1**	**0.217**
incl. Diesel	0.5	0.27
incl. CNG	0.1	0.73
Car	**0.6**	**0.708**
incl. Diesel	0.17	0.36
incl. Gasoline	0.4	0
incl. CNG	0.18	0
incl. BEV	0.19	0.64
incl. PHEV	0.05	0
incl. Hydrogene	0.01	0
Train	**0.15**	**0.074**

Table 4.4: Shares of the different categories of technologies (bus, car, train) in the passenger mobility in 2030 (in **bold**) and shares of different technologies in each of these categories, according to Wallonia (concerning Wallonia only) and Energyscope (concerning the whole country).

Chapter 5

Discussion

In this chapter, we discuss some limitations of the model, as well as the interpretation of the results of this study in the context of climate litigation. We will see that if we are to build some legal arguments based on this work, a particular attention will be needed in regards to these limitations.

5.1 Model limitations

Uncertainties of the parameters projected until 2050

This limitation is involved in every aspects of the transition. Indeed, the evolution of the value of the majority of the many parameters included in the model has to be estimated throughout the transition, i.e., until 2050. If a parameter is estimated wrongly while having a significant importance in the outcomes of the model, this can lead to non-negligible misjudgements about the trajectories recommended by the model. Sensitivity analyses are therefore essential. In this thesis, only four local sensitivity analyses were presented and studied. To assess the importance of the parameters' uncertainties on the model outputs, further work should include a global sensitivity analysis. This would determine the parameters to which the system is most sensitive and allow to focus on reducing their uncertainties to make the system more robust.

Although some hypotheses are more approximate and can be discussed (for example, linear approximations between the start and the end of the transition or fixing the values of the inertia), the majority is justified and based on recognized projections and trends (for example, the EU Reference Scenario [35]). All the hypotheses could not be displayed in this work, that is why we refer to the thesis of G. Limpens for more insights [26].

Absence of spatial resolution

EnergyScope Pathway is a single cell model and the only exchanges implemented with the exterior are the imports[1]. However, Europe is strongly connected in many ways, while the entire world is highly heterogeneous in its geopolitical contexts and can difficultly be reduced to a single point called "the exterior". In the fight against climate change, the transition of the energy system concerns all countries around the world and implies a lot of international interactions. An obvious example is the EU Emission Trading System which allows GHG emissions allowances to be traded between countries, as introduced in Section 2.1.3. The *multicells* version of EnergyScope [27] allows to represent several regions at once, linking them with exchanges of energy carriers. This version could be used in the context of climate litigation against Belgium but could also be interesting to get a wider view of the transition of Europe.

Non-energy sector not accounted for

This limitation is developed in Section 2.1.4. The non-energy sector was left out of the model for the purpose of matching the IPCC GHG accounting method. However, given the strong link between the energy sector and the non-energy sector, and the necessary transition of both, the consideration of the latter would have been relevant. Further work could include it without accounting for the *excluded carbon* it implies so as to be coherent with the IPCC Guidelines.

Absence of market equilibrium

The market economy is not represented in EnergyScope. The demand is considered fixed and is not influenced by the cost of the system. However, we can imagine that if the price of energy is too high, consumers would certainly be willing to reduce their consumption.

Dominant economic model not questioned

By fixing the end-use demands, EnergyScope cannot implement strategies that would consider these end-use demands as variable. The end-use demand projections used in the case study do not consider a change of paradigm in our energy consumption. Though, energy sobriety is more and more emphasized as a prerequisite to the achievement of the transition. This aspect was left out of this study but deserves a particular attention. The solution suggested by EnergyScope is thus purely technical and does not consider very profound changes in habits (except

---

[1] As well as some electricity export which is minor and negligible.

maybe for the changes implied by the increase of the share of public mobility). However, as advocated by Prof. Contino in an interview for the RTBF [39], energy efficiency is not sufficient. As seen in Chapter 4, achieving the transition while keeping the same level of consumption is technologically possible. But as seen in the several comparisons with the PNEC also presented in Chapter 4, this is not where we are currently going. The transition suggested in this work does not question the currently dominant economic model. More than ever, we must keep in mind that the world is a finite place and infinite growth is thus an unachievable ideal of the latter model. And this should be seen as an opportunity rather than a constraint: the transition is technologically feasible with a high demand but implies rapid investments and switches to technologies which are not yet widely accessible; it should be easier if we redefine our relationship with energy.

5.2 Interpretation in the context of climate litigation

Case study not fully detailed

Given the consequent number of parameters and variables involved in the model, and since describing the whole model in its smallest details was not the point of this study, we could not include a description of the entire case study. As explained above, every value of a parameter constitutes an hypothesis and must then be available for the sake of transparency. This is even more the case if this work is used in a legal context. The majority of these hypotheses comes from the work of G. Limpens and is therefore available in his thesis [26]. For further details, the authors of this master thesis can be contacted[2].

Initialization partially captures reality

This limitation was detailed in Section 3.1. As explained, the model is initialized in 2020 with historical data from various sources, but the resulting primary energy mix does not perfectly matches the reality. Our hypothesis is that the efficiencies of the technologies defined in EnergyScope are too high compared to the reality. Further work should review these values, defined in G. Limpens' thesis [26]. As shown in Section 3.1, the errors in terms of share of resources in the mix are not as high as the absolute errors in terms of consumption. With a similar mix in terms of proportion, we can assume that the transition pathway is applicable to the reality of 2020.

---

[2] juliajoveneau@gmail.com, simongeorges.19@gmail.com

Timing of the study

The first issue related to the timing of this study is that it comes mid-2023 while the transition pathway starts in 2020 and the next representative year is 2025, i.e., only 1.5 years from now, which makes it very unlikely for the necessary measures to be taken in the meantime. The second issue is the lag between this study and the PNEC, the latter written in 2019. Four years later, some decisions would certainly not have been taken the same way. The most relevant example is the phase-out of nuclear power which was postponed after the PNEC was written. Moreover, a new version of the PNEC is supposed to be released soon but comes too late compared to the deadlines of this thesis. However, the analyses made in this thesis can then be done with the new projections in order to see if the ambitions are higher.

Interpretation of the results

The transition advocated by EnergyScope is the solution of an optimization problem based on a model built so as to reflect reality as closely as possible. However, a model implies, by essence, numerous limitations, the more important ones presented in last section. This solution, presented in Chapter 4, gives a technically and economically feasible pathway to achieve the climate change related obligations until 2050, without invalidating other possible pathways. Nonetheless, after showing that the projections of the PNEC are not a solution, in the sense that they do not allow Belgium to respect its commitments, the solution output from EnergyScope can be seen as the main directions that could be considered by policy-makers to wisely plan the transition. These main directions are summarized in the conclusion (Chapter 6). In this regard, the solution is not meant to be interpreted in a literal way. The outputs are to be discussed and questioned, and are precisely meant to enrich the debates and bring new considerations to the planning of the energy transition and to the related climate litigation.

Chapter 6

Conclusion

The urgency of global warming and its consequences has led to increasingly ambitious transition plans by European countries, notably with the Paris Agreement in 2016, committing signatories to try and keep the global average temperature increase below $1.5°C$, and the 2021 European Climate Law, setting the goal of reducing GHG emissions by 55% compared to 1990 levels by 2030. However, the efforts put in practice to reach these goals are often insufficient, which resulted in the emergence of climate litigation led by citizens and associations to legally constrain governments and companies to take sufficient action. Such a litigation was undertaken in Belgium under the name Klimaatzaak. The idea behind this thesis was to collaborate with law students at UCLouvain to produce technical arguments to be used in similar legal cases. For this, a whole-energy system model, EnergyScope Pathway, was used to model the Belgian energy system and its transition, and to compare the model's output with the national energy and climate plan (PNEC). More precisely, the two main goals were to assess whether the measures described in the PNEC were relevant and sufficient to reach the 2030 GHG emissions reduction target, as well as to provide an alternative transition pathway, showing that it is possible, technically and economically, to decarbonize the Belgian energy system. This interdisciplinary methodology was established with M. Cartuyvels, a law student whose thesis focuses on the legal side of the matter. His valuable inputs helped validate the legal legitimacy of the arguments developed. Using data from the PNEC, it was shown that the implementation of the measures it advocates would not be sufficient to reach the emissions reduction goals.

After adapting EnergyScope to the needs of this work, notably by adapting the accounting methodology that was previously implemented, so that it matches the one used in the PNEC, the case study was built to optimize the transition of the Belgian energy system from 2020 to a net carbon neutral system in 2050, with the GHG emissions reduction trajectory required by the 2021 European Climate Law. Preliminary local sensitivity analyses were performed to tune some important parameters in the model. This also allowed to acquire a better comprehension of the model, especially of the inertia of installed technologies in the system.

The analysis of the results allowed to bring out the principal directions undertaken in this transition pathway:

- Massive investment in renewable energy sources and technologies;
- Electrification of the system, especially in the mobility and heat sectors, with massive investments in electric cars and electric heat pumps;
- Centralisation of low temperature heat production systems into heat networks;
- Centralisation of passenger mobility systems, through investments in public mobility.

The results also offered several angles of comparison with the PNEC, which allowed to further show that the transition it offers is too slow and insufficient in terms of emissions reduction.

This study and the interdisciplinary discussions opened a new research question that would study a transition pathway specific to each entity (the Federal State, Wallonia, Flanders and Brussels-Capital). Indeed, the legal distribution of authority is complex in Belgium and makes it hard to impose concrete targets to each entity. Implementing a version of EnergyScope where the model would be split into the different entities would allow to define transition pathways specific to each of them, resulting in clear indications for the judge to impose separate objectives.

To conclude, the use of EnergyScope showed that transition pathways respecting the European emissions reduction goals are technically end economically possible, while the measures put forward in the PNEC are clearly insufficient to achieve these goals. Although the model inevitably has limitations, the results highlight important directions to be considered for the transition. This thesis also emphasizes the value of interdisciplinarity in the context of the fight against climate change, and more specifically the value of the collaboration between jurists and engineers in the context of climate litigation. Hopefully, it will constitute a basis on which further successful work can be elaborated.

Appendix A

From projected GIC percentage values to projected Activty Data

Amongst the WAM scenario projections, evolution of the relative composition of the *gross inland consumption* (GIC) and of the total *primary energy consumption* (PEC) can be found. For the definitions of these quantities, readers can refer to Section 1.3.1. These projections are given in Tables A.1 and A.2, this latter also reporting the projections for the total *final non-energy consumption* (FNEC). This appendix will only focus on years 2025 and 2030, since they are the only years comparable with projections from EnergyScope.

	2025	2030
Solid Fossil Fuels	5.5	5.9
Oil	40.2	40.2
Natural Gas	32.4	38.9
Waste	1.7	1.7
RES	9.8	12.2
Electricity	1.6	1.1
Nuclear	8.6	0

Table A.1: Projected percentage of the GIC per resources, in [%].

	2025	2030
PEC $[TWh]$	530.4	496.7
FNEC $[TWh]$	85.1	88.0

Table A.2: Total PEC and FNEC projections from the PNEC.

By summing the PEC with the FNEC, we get projections of the GIC, which are not directly given in the PNEC. But the values that we want to get are the *Apparent Consumption* values of each resource. For that, we will first compute the GIC values of each resource (see Table A.3), thanks to percentages of Table A.1. Then, the approximated FNEC values (see Table A.4) of each resource will be subtracted from the GIC, allowing us to get the PEC values of each resource (not detailed in the PNEC, see Table A.5). Finally and following the AC definition, values of *International Aviation* and *Recovered & Recycled Products*, approximated from Eurostat database [30] (see Table A.6) will be further subtracted (see Table A.7). This last table thus gives values comparable with the primary energy used in EnergyScope.

	2025	2030
GIC [TWh]	615.4	584.7
Solid Fossil Fuels [TWh]	33.8	34.5
Oil [TWh]	247.4	235.1
Natural Gas [TWh]	199.4	227.5
Waste [TWh]	10.5	9.9
RES [TWh]	60.3	71.3
Electricity [TWh]	9.8	6.4
Nuclear [TWh]	52.9	0

Table A.3: GIC breakdown values computed from tables A.1 and A.2.

	2025	2030
Solid Fossil Fuels [TWh]	2.55	2.64
Oil [TWh]	71.06	73.52
Natural Gas [TWh]	11.47	11.86

Table A.4: Approximated FNEC projections. Factors 0.02995, 0.8353 and 0.1348 were applied to the total projected values of the FNEC, to respectively compute the share of *Solid Fossil Fuels*, *Oil* and *Natural Gas*. These factors were found by computing a weighted moving average of the historical shares from 2005 to 2021, taken from the Eurostat database [30].

	2025	2030
Solid Fossil Fuels $[TWh]$	31.3	31.9
Oil $[TWh]$	176.3	161.5
Natural Gas $[TWh]$	187.9	215.6
Waste $[TWh]$	10.5	9.9
RES $[TWh]$	60.3	71.3
Electricity	9.8	6.4
Nuclear	52.9	0

Table A.5: PEC breakdown of the resources following the PNEC's projections.

	IA	RRP
Oil $[TWh]$	16.8	0.32
Natural Gas $[TWh]$	0	0.33

Table A.6: *International Aviation* (IA) and *Recovered & Recycled Products* (RRP) breakdowns approximated from Eurostat database [30]. Values are weighted moving averages from the historical values from 2005 to 2021, and assumed the same in 2025 and 2030.

	2025	2030
Solid Fossil Fuels $[TWh]$	31.3	31.9
Oil $[TWh]$	159.2	144.4
Natural Gas $[TWh]$	187.6	215.3
Waste $[TWh]$	10.5	9.9
RES $[TWh]$	60.3	71.3
Electricity $[TWh]$	9.8	6.4
Nuclear $[TWh]$	52.9	0
Total $[TWh]$	511.6	479.2

Table A.7: *Apparent Consumption* values computed by the methodology explained above.

Appendix B

High Temperature heat initialization in 2020

Based on [33], the HT heat end-use category initialization for year 2020 is approximated thanks to the methodology described hereunder.

Looking at the input of the final energy consumption for the industry, flows of *waste, solid fossil fuels, oil, gas* and *heat* are considered to be the input of the HT heat end-use demand. To compute the resulting end-use demand, these flows are multiplied by the efficiency of the corresponding technology implemented in EnergyScope. Before doing these computations, we notice that a non-negligible amount of coal is used in blast furnaces to produce gas. However, this technology is not implemented in EnergyScope. We thus decide to subtract the assumed amount of gas produced from coal (5874 $[GWh]$) from the total FEC gas flow directed to the industry (46651 $[GWh]$). Based on the efficiency of gas boilers in EnergyScope, these 5847 $[GWh]$ of gas would produce 5395 $[GWh]$ of HT heat. Based on the efficiency of coal boilers in EnergyScope, we consider that 6642 $[GWh]$ of coal would have been needed to produce the same amount of heat. We thus add this quantity of coal to the FEC coal flow directed to the industry. These modified flows and the corresponding values are summarized in Table B.1. The total end-use demand amounts to 65360 $[GWh]$, compared to 59414 $[GWh]$ implemented in EnergyScope.

Resource	FEC [GWh]	Technology	Efficiency	EUD [GWh]
Waste	1349	Boiler Waste	0.812	1096
Solid Fossil Fuels	10633	Boiler Coal	0.812	8637
Oil	16172	Boiler Oil	0.864	13977
Gas	40777	Boiler Gas	0.918	37452
Heat	4198	-	-	4198

Table B.1: HT heat resources flows towards industry, corresponding technology and efficiency implemented in EnergyScope and resulting end-use demand.

From these results, we compute the share of each technology in the EUD. For the heat, we assume it is produced by cogeneration. In the sankey, several flows enter the cogeneration technology, but to match EnergyScope implemented technologies, we assume only gas and waste flows. The relative shares of the latter (flow_gas/(flow_gas + flow_waste) and flow_waste/(flow_gas + flow_waste)) are 0.857 and 0.143, respectively. The heat flow accounting for 6.42% of the EUD, we allocate 5.50% to gas cogeneration and 0.92% to waste cogeneration. The shares of all technologies are summarized in Table B.2.

Boiler Waste	1.68
Boiler Coal	13.21
Boiler Oil	21.39
Boiler Gas	57.30
Cogeneration Gas	5.50
Cogeneration Waste	0.92

Table B.2: Shares of the technologies for the production of HT heat, implemented in the initialization of year 2020 in EnergyScope, in [%].

Bibliography

[1] Hannah Ritchie, Max Roser, and Pablo Rosado. "CO and Greenhouse Gas Emissions". In: *Our World in Data* (2020).

[2] IPCC. *IPCC Special Report Global Warming of 1.5°C - Summary for Teachers*. 2018.

[3] Kirsten Zickfeld and Tyler Herrington. "The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission". In: *Environ. Res. Lett* (2015).

[4] UNFCCC. *What is the Kyoto Protocol?* `https://unfccc.int/kyoto_protocol`.

[5] UNFCCC. *The Paris Agreement.* `https://unfccc.int/process-and-meetings/the-paris-agreement`.

[6] IPCC. "Summary for Policymakers". In: *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* Cambridge University Press, 2022, pp. 1–24. DOI: `10.1017/9781009157940.001`.

[7] UN News. *UN emissions report: World on course for more than 3 degree spike, even if climate commitments are met.* `https://news.un.org/en/story/2019/11/1052171`.

[8] IPCC. "Summary for Policymakers". In: *Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (2023). (in press).

[9] *Urgenda Case: final judgement Supreme Court.* `https://www.urgenda.nl/wp-content/uploads/ENG-Dutch-Supreme-Court-Urgenda-v-Netherlands-20-12-2019.pdf`.

[10] *Klimaatzaak website.* `https://affaire-climat.be/`.

[11] Klimaatzaak. *Main conclusion of the appeal.* `https://affaireclimat.cdn.prismic.io/affaireclimat/bdb1acfd-ed1c-45b5-9f36-081b649c224e_20220930_Klimaatzaak_Concl+Principales+d%27Appel_def_anoniem.pdf`. Sept. 2022.

[12] IPCC. “Summary for Policymakers”. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (2022).

[13] *Plan national énergie-climat website.* `https://www.plannationalenergieclimat.be`.

[14] *Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action.* `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.328.01.0001.01.ENG`.

[15] Eurostat. *Energy Balance Guide: Methodology guide for the construction of energy balances & Operational guide for the energy balance builder tool.* `https://ec.europa.eu/eurostat/documents/38154/4956218/ENERGY-BALANCE-GUIDE.pdf`.

[16] European Commission. *Paris Agreement.* `https://climate.ec.europa.eu/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en`.

[17] *Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’).*

[18] *EnergyScope Pathway documentation.* `https://energyscope-pathway.readthedocs.io/en/master/`.

[19] European Environment Agency. *European Union CO2 emissions: different accounting perspectives.* Publications Office, 2013. DOI: `10.2800/10691`. URL: `https://data.europa.eu/doi/10.2800/10691`.

[20] Simon Eggleston, Leandro Buendia, Kyoko Miwa, Todd Ngara, and Kiyoto Tanabe. *2006 IPCC guidelines for National Greenhouse Gas Inventories: Intergovernmental Panel on Climate Change.* The Institute for Global Environmental Strategies, 2006.

[21] IPCC. *Emission Factor Database.* `https://www.ipcc-nggip.iges.or.jp/EFDB/main.php`.

[22] European Commission. *EU Emissions Trading System (EU ETS).* `https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en`.

[23] Eurostat. *Energy statistics - an overview.* `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Non-energy_consumption`.

[24] Vassilis Daioglou, Andre P C Faaij, Deger Saygin, Martin K Patel, Birka Wicke, et al. "Energy demand and emissions of the non-energy sector". In: *Energy Environ. Sci.* 7.2 (2014), pp. 482–498.

[25] Xavier Rixhon, Martin Colla, Davide Tonelli, Kevin Verleysen, Gauthier Limpens, et al. "Comprehensive integration of the non-energy demand within a whole-energy system: Towards a defossilisation of the chemical industry in Belgium". In: *Proceedings of the 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.* 2021.

[26] G. Limpens. "Generating energy transition pathways: application to Belgium". Supervisor: H. Jeanmart. PhD thesis. UCLouvain, 2021.

[27] A. Hernandez, P. Thiran, H. Jeanmart, and G. Limpens. "EnergyScope Multi-Cell : A novel open-source model for multi-regional energy systems and application to a 3-cell, low-carbon energy". Supervisors: H. Jeanmart and G. Limpens. MA thesis. UCLouvain, 2020.

[28] Gauthier Limpens, Hervé Jeanmart, Stefano Moret, Giangranco Guidati, Xiang Li, et al. "The role of storage in the Swiss energy transition". In: *Proceedings of the 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.* 2019.

[29] *EnergyScope Multi-cells.* `https://github.com/energyscope/EnergyScope_multi_cells/blob/Multi_cell/Data/2035/00_INDEP/Resources_indep.csv`.

[30] Eurostat. *Complete Energy Balance database.* `https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_C__custom_6245536/default/table?lang=en`.

[31] IEA. *Greenhouse Gas Emissions from Energy Data Explorer.* `https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer`.

[32] International Energy Agency. *Greenhouse Gas Emissions from Energy 2022 Edition, Database documentation.* `https://iea.blob.core.windows.net/assets/f535fcce-abe8-49ff-9cc9-5c1d9d6eec07/WORLD_GHG_Documentation.pdf`.

[33] Eurostat. *Energy flow diagrams.* `https://ec.europa.eu/eurostat/cache/sankey/energy/sankey.html?geos=BE&year=2020&unit=KTOE&fuels=TOTAL&highlight=_&nodeDisagg=1111111111111&flowDisagg=false&translateX=33.45317289713432&translateY=6.5247510774576085&scale=0.9447054993435796&language=EN`.

[34] Eurostat. *Greenhouse gas emissions by source sector database.* `https://ec.europa.eu/eurostat/databrowser/view/ENV_AIR_GGE__custom_6080759/default/table?lang=en`.

[35] European Commission, Directorate-General for Climate Action, Directorate-General for Mobility Directorate-General for Energy, Transport, A. De Vita, et al. *EU reference scenario 2020 – Energy, transport and GHG emissions : trends to 2050.* 2021.

[36] Statbel. *Registration of motor vehicles.* `https://statbel.fgov.be/en/themes/mobility/traffic/registration-motor-vehicles#:~:text=The%20number%20of%20cars%20registered,third%20year%20in%20a%20row&text=In%202022%2C%20374%2C597%20passenger%20cars,one%20third%20in%20three%20years.`.

[37] Susana Paardekooper, Rasmus Søgaard Lund, Brian Vad Mathiesen, Miguel Chang, Uni Reinert Petersen, et al. *Heat Roadmap Belgium: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps.* English. Oct. 2018.

[38] Parlement Européen. *Tout savoir sur l'interdiction de l'UE concernant la vente de voitures neuves à essence et diesel à partir de 2035.* `https://www.europarl.europa.eu/news/fr/headlines/economy/20221019STO44572/interdiction-de-l-ue-sur-la-vente-de-voitures-neuves-a-partir-de-2035-expliquee`.

[39] Guillaume Woelfle. *Francesco Contino (UCLouvain) : 'Je milite pour la sobriété car l'efficacité énergétique ne suffit pas'.* `https://www.rtbf.be/article/francesco-contino-uclouvain-je-milite-pour-la-sobriete-car-lefficacite-energetique-ne-suffit-pas-11125783`. Dec. 2022.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**