

École polytechnique de Louvain

Formulating Energy Policies for Belgium under Uncertain Carbon Budgets

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Abstract

Facing the climate emergency and the European goal of carbon neutrality by 2050, energy planning is essential. This study uses the EnergyScope Pathway techno-economic optimization model to simulate transition pathways for the Belgian energy system over the period 2020–2050. The approach used is distinguished by two methodological choices. Firstly, a study of the impact of uncertain carbon budgets on transition pathways, with a view to identifying key decisions. These budgets are established on the basis of principles of distributive justice and Shared Socioeconomic Pathways (SSPs). Secondly, the integration of a sufficiency scenario (derived from the Clever project), an essential yet often overlooked dimension. The results show that, regardless of the carbon budget constraints, a massive electrification of the energy system represents a structural imperative. The optimization consistently points to a major expansion of electricity generation capacity: onshore wind, solar PV, geothermal, and nuclear. This dynamic is accompanied by widespread adoption of heat pumps in the building sector, a 100% electric vehicle fleet, and the use of hydrogen to decarbonize freight transport. However, achieving these trajectories goes beyond the model's mathematical feasibility and will require the implementation of ambitious policies. Although current measures are moving in the right direction, a significant acceleration in the deployment of these technologies remains essential to ensure that the set targets are met. Finally, the study confirms that sufficiency is not a substitute, but rather a complementary lever for the deployment of renewable technologies in order to achieve carbon neutrality.

Keywords: Energy transition; Techno-economic optimization; Carbon budgets; Shared Socioeconomic Pathways; Sufficiency.

1 Introduction

In response to the climate emergency, the European Union has set itself the target of achieving climate neutrality by 2050 [1]. Although this goal is clear, the pathways to achieving it remain a matter of debate. In Belgium, different visions of the energy transition coexist. A study conducted by Climact for the FPS Public Health in 2021 [2] highlights several possible pathways based respectively on behavioural changes, technological advances, a combination of these levers, or even an increase in energy demand. There is therefore no universal path to climate neutrality: it will have to emerge from a compromise between different visions.

In this context, energy planning plays an important role. Energy planning models are essential tools for guiding decision-making and informing policymakers about the feasibility and impact of different transition pathways. A review of energy planning models is presented in Samarasinghe et al.[3], a specific example is EnergyScope Pathway, a techno-economic model developed at UCLouvain, which enables the optimization of the energy system’s evolution over the long term [4].

To incorporate the climate dimension into this type of model and thereby comply with the Paris Agreement, which aims to limit the rise in temperature to below 1.5°C [5], many models impose annual emissions reductions along a predefined trajectory. Such an approach nevertheless has certain limitations, insofar as the climate impact depends primarily on cumulative CO₂ emissions rather than their temporal distribution. Indeed, there is a quasi-linear relationship between the increase in global average temperature and cumulative anthropogenic greenhouse gas emissions [6]. From this perspective, the use of a cumulative carbon budget appears to be a particularly relevant approach, as it allows for compliance with a global climate constraint while allowing flexibility regarding the path of the transition.

Furthermore, energy trajectories remain subject to numerous technological, economic and societal uncertainties. The aim of energy models is therefore not to identify a single, deterministic trajectory, but rather to explore a range of scenarios. Indeed, generating and comparing a large number of optimised scenarios enables an in-depth analysis of the trade-offs within the system [7]. Consequently, assessing a range of possible futures is essential, as it helps inform decision-makers about the structural implications of each choice, without arbitrarily imposing a single trajectory. This approach to scenario exploration is notably adopted by the IPCC [8] through the Shared Socioeconomic Pathways (SSPs) [9], which describe different possible futures for our society. The use of carbon budgets associated with different SSPs thus allows these uncertainties to be integrated into the models.

Finally, a limitation frequently highlighted in techno-economic models concerns the still inadequate representation of strategies that influence energy demand. Yet the integration of sufficiency is a fundamental pillar of climate neutrality, as demonstrated by Wiese et al. [10] in their analysis of the CLEVER (Collaborative Low Energy Vision for the European Region) scenario and by Gaur et al. [11] in a case study. By reducing energy needs, sufficiency strategies can facilitate the decarbonisation of the system, limit infrastructure requirements, increase energy sovereignty and reduce dependence on certain technologies that are still uncertain. The exploration of scenarios incorporating demand reduction assumptions therefore appears to be an important element in the assessment of robust pathways towards climate neutrality.

In this context, this study proposes using the EnergyScope Pathway model to optimize Belgium’s energy transition over the period 2020–2050 by examining the impact of uncertain carbon budgets on the resulting transition pathways. To establish carbon budgets, several societal future scenarios are examined, particularly SSP1 and SSP2, and are associated with different levels of radiative forcing. Additionally, an energy sufficiency scenario is evaluated and compared to a baseline scenario to analyze the impact of reduced demand on optimal transition pathways. The ultimate goal is to identify the key decisions for Belgium’s energy transition despite the uncertainty on the carbon budget.

The paper is structured as follows : In the methodology (Section 2), the EnergyScope Pathway model is briefly presented. This section then details the mathematical downscaling of global carbon budgets using three principles of distributive justice, the Egalitarian, Grandfathering, and Utilitarian approaches, as well as the methodology for incorporating national carbon budgets based on different Shared Socio-Economic Pathways (SSPs). It concludes by presenting the adaptation and mapping techniques required to integrate a demand-reduction scenario into the model’s baseline parameters. Then, the application of the methodology especially to the Belgian energy system is presented (Section 3). Next, the results section illustrates the simulated transition pathways under the different sharing principles and explores the detailed sector-by-sector dynamics of the energy transition (Section 4). This section examines also in detail the impact of various shared socio-economic scenarios to identify the technological choices common to all scenarios for 2050 and concludes by assessing how sufficiency affects the overall cost and technological configuration of the system. The discussion (Section 5) puts the findings into context in relation to the current situation and pace of deployment. This section ends by presenting sufficiency as a key complementary lever for action. Finally, the study concludes by identifying several areas for improvement for future work.

2 Methodology

This first section presents the methodological framework used in this study. The energy planning model employed is first presented. This model is used to translate climate objectives (carbon budget) into concrete technological choices. Two complementary approaches are outlined for defining the carbon budgets to be incorporated into the model. On the one hand, the use of allocation factors based on a fixed global budget, and on the other hand, the use of Shared Socioeconomic Pathways combined with RCP trajectories, allow carbon budgets to be derived from various global socioeconomic and climate assumptions. For both approaches, carbon budgets are downscaled to the national level using sharing principles. This section concludes by presenting a methodology for applying the Clever scenario to the model.

2.1 Energy Planning

This work is based on EnergyScope Pathway [4], an open-source, bottom-up model designed to optimize long-term investments and operations. This energy planning model was designed to plan transition pathways for the 2020–2050 period. Initially, its parent model, EnergyScope Typical Day (TD), developed by Gauthier Limpens at UCLouvain [12], optimized a single isolated target year. To address this limitation and account for transition dynamics, the model was extended into the Pathway version. Specifically, the model seeks to minimize the total cost of the energy system by integrating all energy carriers (heat, electricity, mobility) while respecting technical and environmental constraints. In this work, the model’s Perfect Foresight (PF) approach is used: the model performs a single optimization over the entire transition period (discretized into 7 representative years), assuming that the evolution of all future parameters (demand, costs, efficiencies) is perfectly known from the initial year. Furthermore, instead of the Typical Day (TD) formulation, this work employs a monthly (MO) temporal resolution. This approach consists of averaging the various time series (e.g., variations in electricity and heat demand) over the 8760 h of the year to obtain a single value per month. A detailed explanation of the model and the model’s source code are available in [13] and [14], respectively. The Appendix A briefly presents the extension of the TD model to Pathway.

In this work, the EnergyScope Pathway model is used to identify, based on a cumulative carbon budget and a maximum emissions limit for 2050, the optimal emission reduction pathways compatible with a profound transformation of the energy supply, including the deployment of new technologies and the shift to carbon-free resources, while minimizing the total system cost. Additional details

about the carbon constraint are available in Appendix B. The methodology for deriving a carbon budget and emission limits at the national level will be now outlined.

2.2 Allocation principles

Establishing a national carbon budget is a complex challenge that requires translating a global emissions budget into a local budget through a process known as downscaling. This downscaling can be achieved using allocation factors derived from Sharing Principle. For this study, three Sharing Principles were selected: the Egalitarian, Grandfathering, and Utilitarian approaches. These sharing rules enable the transformation of concepts of distributive justice into quantitative trajectories.

In a nutshell, they can be defined as follows:

- **Egalitarian:** It is based on the idea that every person has an equal right to emit. The emissions are distributed in proportion of the population [15].
- **Grandfathering:** Nations have an inherent right to emit greenhouse gases. It allocates emission allowances to countries equivalent to the emission levels of a reference year [15].
- **Utilitarian:** It aims to maximize overall welfare. Since directly quantifying welfare is particularly complex, economic indicators are often used to estimate it [16].

2.2.1 Calculation

To apply these principles of distributive justice, the first step is to define the global carbon budget corresponding to the targeted climate goal. To limit the temperature increase to 1.5 °C (with a 50% probability), the global carbon budget allocated for the period 2020–2050 is estimated at 550 Gt of CO₂ [17]. In this study, the choice was made to compare the system’s results against this strict budget (expressed in CO₂), rather than against a broader budget including all greenhouse gases (CO₂ equivalent). Although the EnergyScope Pathway model assesses the impact of resources using a life-cycle analysis approach (in CO₂ equivalent), this accounting remains incomplete. Indeed, it applies only to the resource value chain (extraction, transport, and combustion) and excludes indirect emissions associated with the construction and decommissioning of energy infrastructure. Therefore, relying on an overall budget covering all greenhouse gases would be inconsistent, as it would allow for too much leeway in the model.

Next, from this CO₂ budget, we focus on emissions related to the energy sector, which account for 74.8% in 2020 [18]. Finally, to downscale these emissions to the country level, the Equation 1 is used. This equation, as well as Equation 2, 3 and 4, are based on the work of Romain Cattoor [19] and the theory of Rose et al. [15].

$$aSOS_{\text{principle, country of interest}} = \alpha_{\text{principle, country}} \cdot SOS \quad (1)$$

$aSOS_{\text{principle, country}}$ refers to the the share of the SOS allocated to the country of interest for the considered sharing principle. SOS refers to Shared Obligation System. This is the total global volume of emissions reductions. α is the allocation factor.

1. **Egalitarian principle:** CO₂ are divided around population number.

$$\alpha_{\text{egal, country}} = \frac{\text{pop}_{\text{country}}}{\text{pop}_{\text{world}}} \quad (2)$$

2. **Grandfathering principle:** CO₂ are divided around actual and past emissions.

$$\alpha_{\text{gf, country}} = \frac{\text{CO}_{2\text{country}}}{\text{CO}_{2\text{world}}} \quad (3)$$

3. **Utilitarian principle:** CO₂ are divided around the GDP

$$\alpha_{\text{util, country}} = \frac{\text{GDP}_{\text{country}}}{\text{GDP}_{\text{world}}} \quad (4)$$

Using these various allocation factors, which are based on different sharing principles, the global carbon budget can be downscaled to the level of the desired country. In principle, no single allocation factor takes precedence over the others; the decision is left to the author.

2.3 Shared Socio-Economic Pathways

Beyond the allocation factors used to downscale emissions to the national level, it is worth asking whether starting with a fixed carbon budget derived from the IPCC's sixth assessment report is the most robust method for evaluating the emissions reduction trajectory through 2050. Another approach, which involves using different carbon budgets based on various possible futures for our society, is therefore employed here. To this end, the Shared Socio-Economic Pathways (SSPs) are used.

According to O’Neill et al. [9], SSPs describe a set of alternative futures for the development of global society during the 21st century. They reflect socio-economic assumptions such as: population, education, urbanization, GDP and technologies. Five SSPs are feasible and cover a sufficiently broad range of uncertainties regarding future societies. These five SSPs correspond to specific combinations of socio-economic challenges, making mitigation (reducing emissions) and adaptation (reducing vulnerability) easier or more difficult. In SSP 1, called Sustainability, the world is shifting toward a more sustainable way of life and prioritizes human well-being, education, and the reduction of inequalities. The world is aware of environmental limits, thereby promoting the use of renewable energy. SSP 2, called Middle of the Road, continues historical economic, social, and technological trends. The environment continues to deteriorate. In SSP 3, called Regional Rivalry, the world becomes divided, with priority given to national interests rather than global interests. Environmental issues are not the primary concern. SSP 4, named Inequality, shows very high levels of inequality both within and between countries. Finally, SSP 5, named Fossil-fueled development, presents a world that is turning heavily toward fossil fuels and the development of carbon capture technologies.

These socioeconomic trajectories (specifically SSP 1 and SSP2 in this study) are combined with climate projections known as Representative Concentration Pathways (RCPs) to form the reference scenarios used, among other places, in the IPCC’s sixth assessment report [8]. While the SSPs describe possible societal developments, the RCPs quantify the expected level of radiative forcing in 2100, expressed in $[\text{W}/\text{m}^2]$. For example, the SSP2-2.6 scenario refers to a trajectory in which the socio-economic assumptions of SSP2 are combined with a radiative forcing of $2.6 \text{ W}/\text{m}^2$ in 2100 [20].

2.3.1 Calculation

To be usable, these SSPs and climate targets (RCPs) must be converted into input data for the EnergyScope Pathway model. More specifically, this involves quantifying the cumulative carbon budget for the period 2025–2050 as well as the permitted residual emissions limit for the year 2050 for each SSP. The methodology followed consists of three steps (Figure 1):

1. **Selection of SSP scenarios and warming targets:** Of the five existing SSP trajectories, only SSP 1, 2, and 5 were initially considered. SSP 3 and 4 were excluded because they describe futures marked by high levels of inequalities. To ensure consistency with the Paris Agreement (which aims to limit the rise in global average temperature to less than 2°C compared to pre-industrial levels [5]), the radiative forcings used in this study are 1.9 and $2.6 \text{ W}/\text{m}^2$ ¹. This second constraint requires the removal of SSP 5, since the

¹There is no strict equivalence between a fixed value of radiative forcing and an exact

socio-economic assumptions of this SSP depict a world dominated by fossil fuels, making it impossible to keep the temperature increase below 2°C.

2. **Extraction of global emissions data:** For the selected SSP-RCP combinations, emission trajectories (2020–2100) are extracted from the AR6 scenarios database hosted by IIASA [21]. These trajectories are generated by integrated assessment models (IAMs). To ensure methodological consistency and avoid any bias between scenarios, the "IMAGE 3.2" IAM is used as the only model for all selected SSPs. Carbon budgets are then calculated for the period from 2025 to 2050 for all these SSP-RCP combinations.
3. **Downscaling :** Global budgets are translated to the national level using the Egalitarian and Grandfathering sharing principles described above (Equation 2 and 3).

In summary, following these three steps, the resulting scenarios depend on (i) the socioeconomic assumptions, (ii) the temperature limit, and (iii) the allocation factor.

Figure 1 illustrates the application of the first two steps. On the left are the four selected scenarios, all derived from the same IMAGE 3.2 model. Only emissions related to the energy sector are extracted from this model. This scope is essential since EnergyScope Pathway focuses on the energy system. However, the data from the AR6 database represent net emissions (CO_2 capture is already deducted). Since EnergyScope model is using raw data, CO_2 capture volumes (CCS) are added to the trajectories to obtain the sector's actual emissions. These raw trajectories then allow for the calculation of global carbon budgets (illustrated on the right side of Figure 1 for the SSP 1 - RCP 1.9 scenario, by simply calculating the area under the curve). Further details are provided in Appendix D.

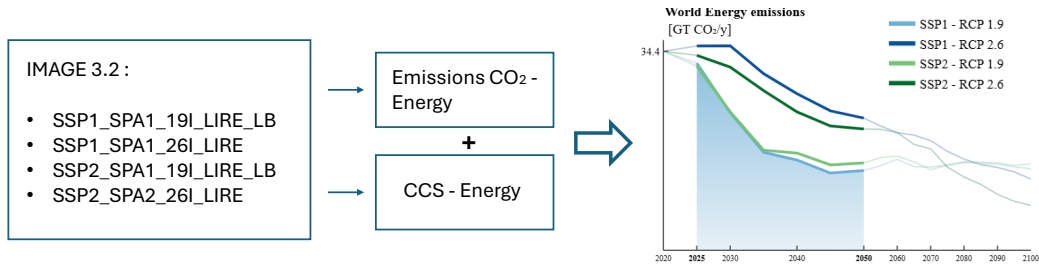


Figure 1: From IAM SSP scenarios to world carbon budget. Emissions associated to CCS are added to the energy sector's emissions to obtain sector's total emissions. CCS refers to Carbon Capture and Storage.

temperature rise; however, the IPCC's sixth Assessment Report (AR6) establishes an approximate correspondence, for SSP 1, between radiative forcing levels of 1.9 and 2.6 W/m^2 by 2100 and a limit on global warming of approximately 1.5°C and 2°C relative to the pre-industrial period [17].

2.4 Sufficiency approach

Until now, the focus has been on presenting methodologies for incorporating a carbon budget and an emissions limit into the model in order to derive optimal transition pathways, which rely on the use of renewable energy and equipment efficiency to meet these constraints. However, these levers can be complemented by a reduction in demand, an approach that is increasingly being emphasized. For example, the IEA incorporates the reduction of final demand into its mitigation pathways [22]. This approach is also shared by the IPCC, which notes that reducing emissions requires the adoption of behaviors and policies focused on sufficiency [23].

This section therefore presents the application of a sufficiency scenario to the EnergyScope model. It was decided to use the “Collaborative Low Energy Vision for the European Region” (CLEVER) scenario. The relevance of this choice stems from the bottom-up approach of the Clever project: although it describes overall reductions in final energy consumption at the European level, it is based on trajectories modeled at the national level [24]. This provides national data that can be integrated into the model.

To incorporate the sufficiency scenario into the energy model, data is extracted from Clever’s online visualization tool [25], specifically from the interactive graph showing the evolution of final energy consumption by sector between 2015 and 2050. Integrating this data requires special adaptation since Clever provides final consumption data (output) whereas EnergyScope requires baseline demand data (input). Furthermore, the two models group economic sectors differently. Specifically, Clever groups them as follows: Residential - Tertiary - Industry - Domestic transport - Non-energy - Maritime bunkers - Aviation bunkers - Agriculture - Energy. Only the first five are of interest to us here. Energyscope, on the other hand, groups them as shown in Table 1, using the year 2015 as an example. To align them, the following mappings are applied: Residential → Household, Tertiary → Services, Industry → Industry, Domestic transport → Mobility passenger, Non-energy → Non-energy. Freight transport, however, retains its initial demand due to a lack of precise data for this sector.

Unity	TWh					Gkm-pass	Gkm-tons	TWh
	Electricity	Lighting	Heat HT	Heat LT SH	Heat LT HW	Mobility passenger	Mobility freight	Non-Energy
2025								
Household	11.7	6.3	0.0	57.4	14.7	0.0	0.0	0.0
Services	12.2	9.5	0.0	30.6	6.8	0.0	0.0	0.0
Industry	33.9	11.2	66.5	17.3	4.5	0.0	0.0	52.0
Transportation	0.0	0.0	0.0	0.0	0.0	142.0	79.1	0.0

Table 1: Implementation of the demand in EnergyScope: demands are organised by economic and energy sectors.

Since one presents final consumption and the other presents initial demand, and since the sectors are not presented in exactly the same way, sometimes using different units (e.g., for the mobility sector: passenger-km or tonne-km instead of TWh), a relative reduction approach has been chosen. This involves applying the relative changes between the different years in the Clever data (in %) to the input data of EnergyScope. Further details are provided in Appendix E.

3 Application to the Belgian energy system

This methodology can be applied to any system, but this section applies it to the Belgian case because of its particularly challenging situation of high demand and low renewable potential.

3.1 Hypothesis and limitation of the model

Before applying the methodology described above to the case of Belgium, the key assumptions and main limitations are presented. Indeed, the relevance of results derived from modeling inevitably depends on the initial assumptions. For this study, several methodological choices were made, in addition to those already established by Gauthier Limpens in his thesis [13].

3.1.1 Main Hypothesis

- Use of CO₂ rather than CO₂ equivalent: This choice stems from the fact that the Life Cycle Assessment (LCA) used for the model data is partial. It focuses on the resource value chain (extraction, transport, combustion) but excludes indirect emissions related to the construction and decommissioning of energy infrastructure.
- Exclusion of Direct Air Capture (DAC): Although the model may include capture technologies, they are not accounted for in the carbon footprint of this study. This prevents the model from delaying the structural transition by relying on massive compensation through negative-emission technologies. Residual emissions in 2050 are adjusted to account for this assumption.
- Baseline: The baseline emissions for 2020 are set at 123 Mt of CO₂, reflecting the state of the Belgian energy system in 2020.
- Uranium neutrality: The global warming potential (GWP) associated with uranium is set to 0. This simplification is made so that nuclear power is a viable option in a model where CO₂ capture is not permitted.

- Perfect Foresight (PF) optimization: The model assumes that all future parameters are known from the beginning. This can lead to an underestimation of actual costs by allowing the model to perfectly anticipate technological price declines.
- Monthly (MO) temporal resolution: The various time series are averaged over the 8760 h in a year to obtain a single value per month. Consequently, this method excludes the modeling of short-term storage technologies.

3.1.2 Discrepancies in carbon accounting

To define carbon budgets in EnergyScope Pathway, data from the IPCC’s Sixth Assessment Report and the AR6 database are used. However, the IPCC and EnergyScope do not calculate CO₂ emissions in exactly the same way. This difference is a limitation of the study.

The IPCC’s approach

To establish the carbon budgets for the various SSPs, net emissions from the energy sector are taken into account. These correspond to sectors 1A and 1B of the IPCC [26]. Sector 1A (Combustion Activities) includes all emissions resulting from the intentional combustion of fuels in equipment designed to provide heat or mechanical work (heat generation, electricity generation, all types of transportation, and manufacturing). Sector 1B (fugitive emissions from fuels), on the other hand, accounts for fugitive emissions. That is, all gases that escape into the atmosphere unintentionally or without any combustion that is useful to society (not included in EnergyScope).

The EnergyScope approach

The model accounts for emissions differently. It does not break down emissions by sector at the output stage, but instead accounts for them at the point of entry into the system, at the level of primary resources.

The model includes only emissions from the maritime sector related to freight transport. Recreational activities and passenger transport are not included, unlike the approach adopted by the IPCC. However, it does account for non-energy demand (involving molecules such as ammonia, methanol, and HVCs). This demand has been maintained because it reflects competition among different sectors for access to resources. Removing it would result in an overestimation of the biomass available for the energy sector. Furthermore, it accounts for emissions using a Life Cycle Assessment (LCA) approach rather than solely on the basis of direct emissions.

Nevertheless, as explained above, this LCA is partial and is therefore not considered here to be a real LCA.

There is therefore a discrepancy between these two approaches, which should be kept in mind when analyzing the results obtained.

3.2 Belgian input data

The Belgian input data are drawn from the work of Gauthier Limpens [13] and Benjamin Goffaux [27]². Once the data has been entered into the model (demand, efficiency, cost, etc.), the technologies to be installed and their capacities are provided as output. These outputs are obtained mathematically by satisfying all constraints (availability, production, limited inertia, carbon budget, etc.) and the objective function: minimizing the total system cost.

3.3 Allocation factors

The various allocation factors (AF) for Belgium are obtained using the methodology described in the relevant section. The data are presented in Appendix F, and the results are shown in Table 2.

Carbon budgets are derived from the global budget of 550 Gt of CO₂ [17] and downscaled to the national level using various allocation factors. A factor of 0.75 is also applied to account only for emissions related to the energy sector. The remaining emissions in 2050 correspond to 95% reduction compared to 2020 emissions. This percentage is based on the CORE-95 scenario from the federal report “Climate Neutral Belgium by 2050” [28], but this study proposes an updated trajectory. In fact, the reduction is applied to the year 2020 rather than 1990.

Principle	AF [-]	CB [GT CO ₂]	Emissions in 2050 [MT CO ₂]
Egalitarian	0.0015	0.604	6.163
Grandfathering	0.0023	0.966	6.163
Utilitarian	0.0062	2.530	6.163

Table 2: Allocation factors, carbon budgets, and residual emissions for Belgium based on different principles of distributive justice.

The approach based on the principle that every person has an equal right to emit (c.f. Egalitarian) is the strictest, followed by the emissions-based approach (c.f. Grandfathering), and finally the approach based on financial means (c.f. Utilitarian).

²B. Goffaux updated certain model data in 2020. According to the work of G. Limpens, the optimization period began in 2015; it has been adapted and updated to begin in 2020.

3.4 Shared Socio Economic Pathways

Unlike the carbon budgets presented earlier, which are based on a fixed global carbon budget, this section adopts the approach based on the Shared Socioeconomic Pathways (SSPs) for Belgium. Following the methodology presented earlier, 8 carbon budgets were derived, along with corresponding emission limits for 2050. Table 3 presents these values and reveals clear trends:

- Regarding allocation factors, without any surprises, the carbon budget is consistently higher when the grandfathering principle is applied compared to the egalitarian principle.
- Regarding climate targets, the carbon budgets increase automatically with radiative forcing (the RCP 2.6 budget is larger than the RCP 1.9 budget).
- Regarding the SSP scenarios, a more surprising observation concerns the comparison between SSP 1 and SSP 2. For a forcing of 1.9 W/m^2 , the budget is higher in the SSP 2 scenario (707 Mt vs. 681 Mt in Egalitarian), which seems logical since SSP 2 corresponds to a continuation of our past emissions without any real change in our habits. Conversely, for a forcing of 2.6 W/m^2 , it is SSP 1 that offers a larger budget (1072 Mt vs. 969 Mt), which is more surprising. This reversal can be explained by the technological assumptions of SSP 1 (Green Road), which anticipates massive global deployment of carbon capture and storage (CCS), thereby altering the distribution.

CO2 related to energy [MT of CO ₂]			
/	CB 2025–2050	Target CO ₂ in 2050	Scenario
Egalitarian	681.06	20.24	SSP 1 - RCP 1.9
Grandfathering	1088.64	32.36	
Egalitarian	1072.87	33.55	SSP 1 - RCP 2.6
Grandfathering	1714.92	53.63	
Egalitarian	707.01	22.19	SSP 2 - RCP 1.9
Grandfathering	1130.12	35.46	
Egalitarian	969.18	30.79	SSP 2 - RCP 2.6
Grandfathering	1549.17	49.21	

Table 3: Carbon Budgets (CB) and CO₂ emissions under different SSP-RCP scenarios. The carbon budget is higher when the grandfathering principle is applied compared to the egalitarian one. Furthermore, the budgets increase automatically with radiative forcing.

3.5 Sufficiency scenario

By following the methodology explained earlier and applying it to the data for Belgium [29], demand curves can be obtained. These are presented in Figure 2. Here, they are shown by demand type rather than by economic sector (Household, Industry, etc.). The sector by sector reduction is presented in Appendix G.

Demand in the passenger mobility sector has declined significantly. Indeed, Clever’s data reflect final energy consumption, which also includes a reduction in consumption resulting from increased efficiency. To align this with the model, the assumption is made here that the downward trend in final consumption is the same as that followed by the demand integrated into the model. Nevertheless, in Appendix M, the balance between private and public mobility shows that the sum of final energy consumption in 2050 is 35.2 TWh, whereas in the Clever data it is 24.7 TWh, indicating that consumption remains higher than in the baseline scenario and that this reduction in demand is therefore not inconsistent with the Clever data.

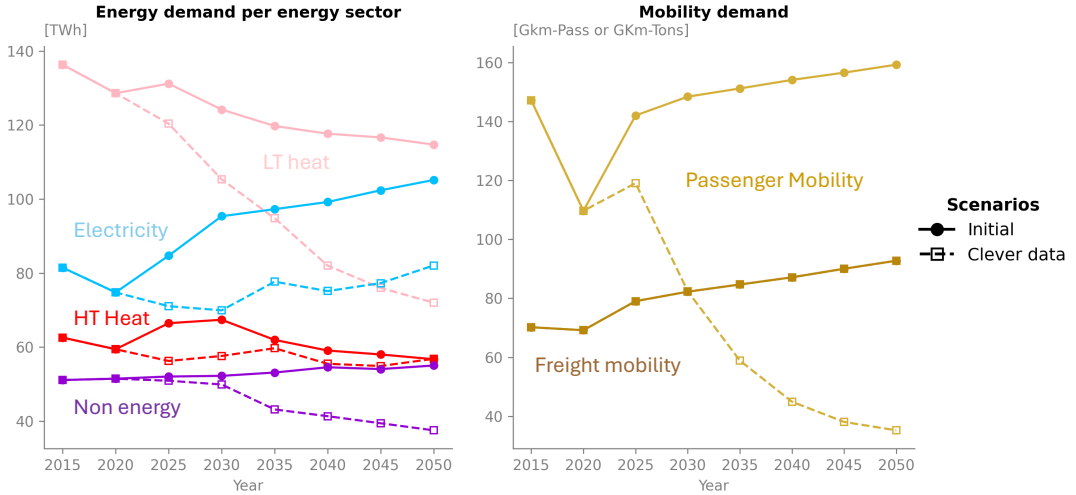


Figure 2: Comparison of initial demand and Clever demand. LT for low Temperature and HT for high Temperature.

4 Results

This section presents the results of simulations conducted using EnergyScope Pathway for the Belgian energy system. It is divided into three parts:

- First, the different emission trajectories resulting from the three principles of distributive justice applied to the fixed budget outlined in the IPCC’s Sixth Assessment Report are presented. Next, focusing on the Grandfathering

scenario, the transition path is presented sector by sector (heating, transportation, electricity). This helps clarify how the model works and enables the reader to understand the practical “how” of the transition.

- The second part involves outlining desirable policies for a future characterized by diverse and uncertain socioeconomic scenarios. Once the various emissions trajectories have been presented, the next step will be to develop an investment roadmap with a focus on installed capacity.
- The third part presents the results of applying the Clever scenario to the model. This scenario is first applied to the Egalitarian case and then to the Grandfathering case, for which an analysis is conducted both with and without a reduction in demand.

4.1 Allocation factors

4.1.1 Emissions trajectories from the three sharing principles

The values from Table 2 are incorporated into EnergyScope, and the resulting emission curves are shown in Figure 3. These emission curves, for the Egalitarian and Grandfathering budgets, are consistent with the results presented in the NewClimate Institute report [30].

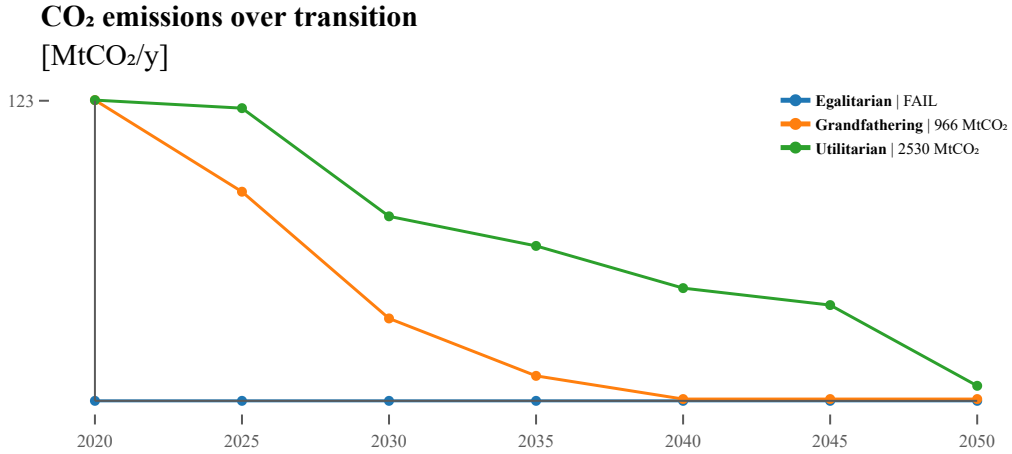


Figure 3: Failure of the carbon budget based on egalitarian allocation. The two others exhibit very different transition dynamics: rapid and immediate versus gradual and delayed.

Figure 3 shows several insights into possible decarbonization pathways for Belgium. The most immediate insight is the failure of the carbon budget based on the egalitarian principle, a finding also reported in the NewClimate Institute’s report [30]. With a budget of approximately 600 Mt of CO₂, Belgium cannot meet

this trajectory given its starting point in 2020. Compared to the Grandfathering curve, meeting this budget (600 MtCO₂) would require near-immediate carbon neutrality shortly after 2025, which is materially impossible since Belgium remains heavily dependent on fossil fuels in 2020 and the transition to new energy sources takes time. More specifically, the model imposes maximum rates of technological changes for the residential heating, passenger transport, and freight transport sectors, which prevents the model from adopting new technologies too quickly compared to reality.

The second concerns the dynamics of transition. The two budgets reveal diametrically opposed approaches for transition:

- Grandfathering (966 MtCO₂): This pathway requires a sharp and early reduction in emissions. The decline is extremely steep starting in 2020, reflecting a strategy in which the effort is concentrated at the beginning of the transition.
- Utilitarian (2530 MtCO₂): This scenario calls for a gradual reduction at the outset, followed by a massive effort as the target approaches (a “final run” between 2045 and 2050).

Figure 4 shows the cost of the two systems at each stage of the transition. The Grandfathering budget generates a peak in annual spending starting in 2025 (approx. 45 b€/y), reflecting the immediate need for decarbonized infrastructure. Conversely, the Utilitarian curve shows a lower total cost (890 b€ vs. 980 b€), as it maintains the use of existing assets for longer and delays investments enabling the transition to low-carbon technologies. It does not catch up to the investment level of the Grandfathering scenario until 2050, during its accelerated decarbonization phase.

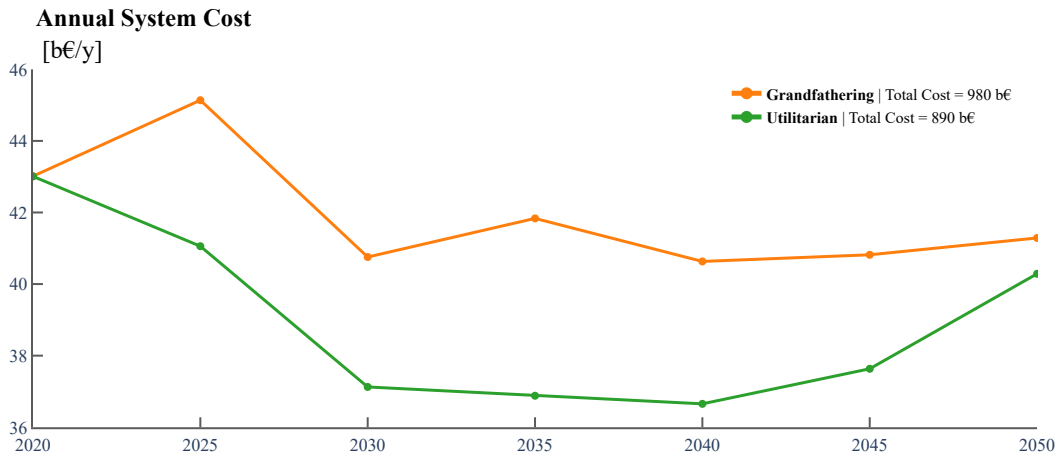


Figure 4: The Grandfathering budget generates a peak in 2025 (approx. 45 b€), reflecting the immediate need for low-carbon infrastructure. The Utilitarian case catches up to the Grandfathering investment level in 2050 when it accelerates the transition.

Figure 4 also highlights the non-correlation between climate constraints and the overall cost of the system: although the available carbon budget more than doubles between the two trajectories, rising from 966 to 2530 MtCO₂, the total system cost decreases by only about 10%, falling from 980 to 890 b€. This demonstrates that a restrictive carbon budget does not lead to a linearly proportional increase in transition costs, even in the case of an optimization where the future is perfectly known.

4.2 Dynamic of transition for Grandfathering case

It has just been established that the egalitarian budget is unfeasible for Belgium and that the other two scenarios presents different transition costs. Although the total cost of the system is higher for the Grandfathering scenario (980 b€ versus 890 b€ for Utilitarian), its severity makes it an excellent case study for observing technological substitution mechanisms. This section therefore describes the transition process envisaged under the Grandfathering (GF) scenario.

On Figure 5, emissions are expressed by final demand sector, i.e., the final service provided (heating, transportation, etc.). It is clear that sectors are not transitioning away from fossil fuels at the same rate, although this is more evident when the carbon budget is large. Sectors will be transitioned away from fossil fuels in order of increasing cost.

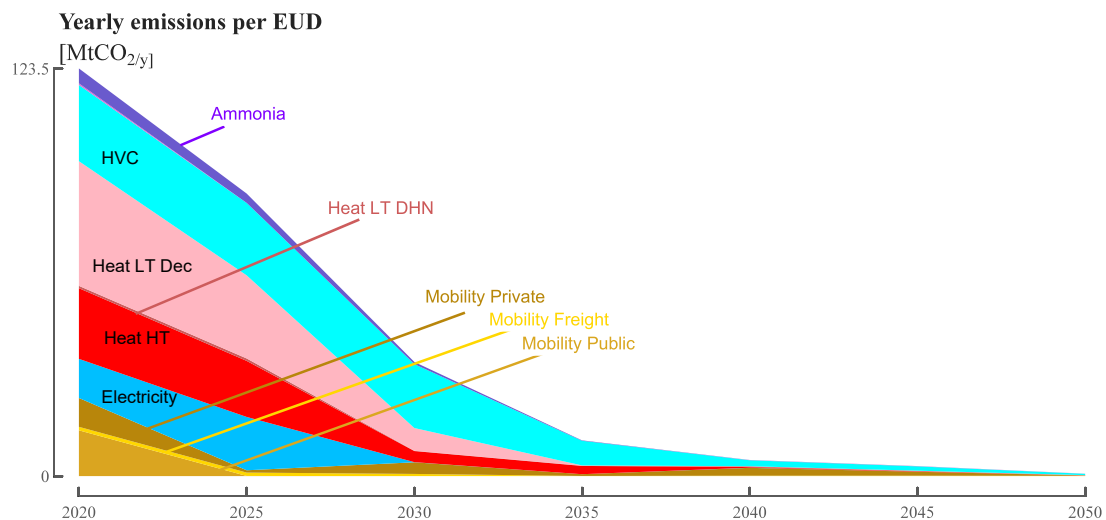


Figure 5: Yearly Emissions per EUD in Mt of CO₂. Freight transport, High Temperature heat (HT), and HVC are more complex and costly to decarbonize, while electricity, Decentralized heat Low Temperature (Dec LT), private and public transportation, and ammonia are being decarbonized more quickly. DHN stands for district heating network.

Ammonia, for example, is decarbonized in two ways: first, by changing how the hydrogen needed to produce this molecule is generated via the Haber-Bosch process: initially produced from natural gas (steam methane reforming), it is then imported directly as renewable hydrogen, and once this becomes feasible using electricity from carbon-free sources (electrolysis); and secondly, by importing renewable ammonia. Starting in 2040, it will be more economical to import it exclusively from renewable sources.

To explain, as with ammonia, the technological drivers behind these trajectories, each sector will be analyzed individually. Appendix H presents the layer graphs specific to each sector explained below.

4.2.1 Electricity layer

In the electricity sector, demand is rising steadily, highlighting the importance of electrification to decarbonize the various sectors. Indeed, the right graph on Figure 6 shows that many sectors are being electrified.

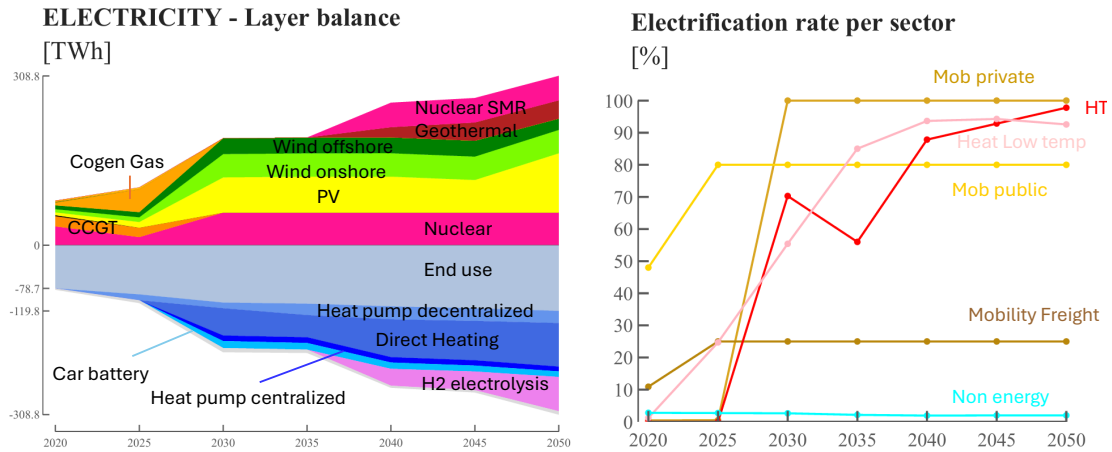


Figure 6: Electricity generation will be fully decarbonised by 2030. The graph on the right presents the percentage of direct electrification. The heating and passenger transport sectors are being massively electrified through the use of direct electrification - EV- HP – trains and trams. The freight transport sector, on the other hand, relies more on hydrogen and synthetic fuels. HVCs, meanwhile, rely on synthetic liquid fuels.

Starting in 2025, wind and solar power generation will increase dramatically, thereby displacing natural gas. Starting in 2035, geothermal energy, which can now be deployed, will support this renewable production and thus enable the completion of the electrification of high-temperature heating through the development industrial direct electrification. Regarding private mobility, this sector will be fully electrified

by 2030. Demand in this sector is low (and even decreases over time) thanks to the very high efficiency of electric motors. Finally, thanks to the deployment of geothermal energy and SMRs starting in 2035, electricity demand for electrolysis may increase. This hydrogen production then becomes a crucial decarbonization vector for sectors that cannot be directly electrified, as detailed below.

4.2.2 Mobility layer

Private and public mobility

The mobility sector is divided into three segments: private mobility, public mobility, and freight. The private mobility sector will be decarbonized by 2030 thanks to a massive shift toward electric vehicles and the use of green electricity. For public mobility, demand is initially met by trains, tramway & trolleys, and diesel buses. From 2030, as electricity production becomes carbon-free (Figure 5), trains, tramway & trolleys will also become carbon-free. Buses, on the other hand, will not be electrified (this sector will never be 100% electrified, see Figure 6); therefore, emissions reductions will come from another source: a shift from diesel to gas will take place between 2030 and 2035. At the same time, gas will consist either of imported renewable gas or gas produced by bio-hydrolysis from wet biomass, explaining why there will be only low emissions for this sector starting in 2035. In fact, while biomass combustion itself produces no emissions, its production and transport do (11.8 kg CO₂/MWh). Starting in 2040, gas is produced exclusively from wet biomass. Consequently, these emissions will persist until 2050 (approx. 98 kt) and will therefore be included in the residual emissions allowed in 2050.

Freight mobility

The freight sector is based on three modes of transport: road, waterways, and rail. Unlike private transportation, this sector is characterized by very limited direct electrification (see Figure 6).

- Road transport: The transition is based on the complete replacement of diesel trucks to truck fuel-cell by 2035. The hydrogen required is either produced through electrolysis using carbon-free electricity or imported in renewable form.
- Waterway transport: This segment will be realised by gas and diesel boats throughout the transition. For diesel boats, the switch to biodiesel (zero emissions) will begin in 2035. As for the shift in gas production methods, this follows the same logic as for gas buses: gas is gradually replaced by renewable gas produced from bio-hydrolysis between 2025 and 2035, and then

is produced exclusively from bio-hydrolysis starting in 2040, which explains the residual emissions.

- Rail transport: It is operated exclusively by electric trains. It is the only directly electrified component of the sector. It achieves carbon neutrality through the use of a low-carbon electricity mix.

4.2.3 Heat layer

Low temperature

The decentralized low-temperature heating sector will achieve carbon neutrality by 2035, primarily thanks to the widespread deployment of heat pumps and reduced heating needs resulting from improved building insulation. Initially, this sector consists of gas and oil boilers, a small number of wood boilers, and gas-powered heat pumps. Gradually, heat pumps will replace fossil fuel boilers. Following a transition phase using renewable gas heat pumps (2035–2040), heat pumps will become exclusively electric by 2040. Wood boilers are a transitional measure: since biomass resources are limited, they are subsequently allocated primarily to methanol production and thus disappear by 2035. Regarding centralized heat, the use of district heating networks increases between 2025 and 2035, thereby reducing the burden on decentralized heat production. Emissions from this sector are low [Figure 5] because it consists mainly of direct electrification and, to a lesser extent, wood boilers. It also benefits from waste heat generated by anaerobic digestion, methanol production, and electrolysis.

High Temperature

The high-temperature (HT) sector is undergoing a longer transition toward electrification. Coal and oil boilers are rapidly being replaced by a mix of gas cogeneration, waste-to-energy, and direct electrification. This strategy enables a massive reduction in initial emissions at a competitive cost. As a result, by 2030, emissions have already been significantly reduced. By 2040, waste boilers are completely phased out in favor of direct electrification. Gas boilers continue to produce residual emissions until 2050 because the gas is produced via biohydrolysis from wet biomass. By 2050, the complete phase-out of gas in favor of direct electrification brings the sector's electrification rate to nearly 100%. It is important to note that demand for high-temperature heat increases over the period to support the production of high-value chemicals (HVC) and hydrogen, from which it will be possible to recover a small portion of low-temperature heat, as explained above.

4.2.4 HVC layer

Emissions from the HVC sector will continue through 2050. This illustrates the technical complexity of the sector. In 2020, HVCs are produced from oil. This is then gradually phased out in favor of methanol, which will become the primary feedstock starting in 2040, combined with marginal HVC production from biomass. Methanol is produced from various sources: either imported from renewable sources, produced from biomass (biomass gasification), from methane, or via synthetic methanol production (from hydrogen). Emissions persisting through 2050 (400 KT) are attributable to methanol produced from methane derived from wet biomass and methanol produced directly from biomass (biomass gasification to methanol), whose emissions are low but not zero. Synthetic methanol production also requires a supply of CO₂, but this is not included in the emissions because it is captured directly from industry (CCU) and injected into the system.

The transition path was thus presented sector by sector for the grandfathering case. For mobility, the transition to carbon neutrality therefore relies on the shift to electric vehicles and biogas buses (using wet biomass) and the continued use of trains, tramway & trolley. For freight transport, it relies on the shift to fuel-cell trucks, biodiesel boats, biogas boats, and the continued use of electric trains. For low-temperature heating, it relies on the shift to electric heat pumps and direct electrification for high-temperature heating. Finally, for HVC production, it relies on the shift from LFO to methanol for its production.

4.3 Shared Socio economic Pathways

The detailed analysis of the Grandfathering case made it possible to identify the technological drivers and the model's internal substitution logic. The next step is to apply this mechanism to the various futures for Belgium represented by the SSP scenarios. The challenge here is first to present the trajectories obtained for the different SSPs before quantifying, with concrete numbers, the technologies to be deployed regardless of the future under consideration.

4.3.1 Emission trajectories for the different SSP

The emissions data for the various SSPs presented above [Table 3] are incorporated into the model, which allows to obtain the various emissions trajectories, as shown in Figure 7. Detailed emissions and costs for each phase of the transition are presented in Appendix I.

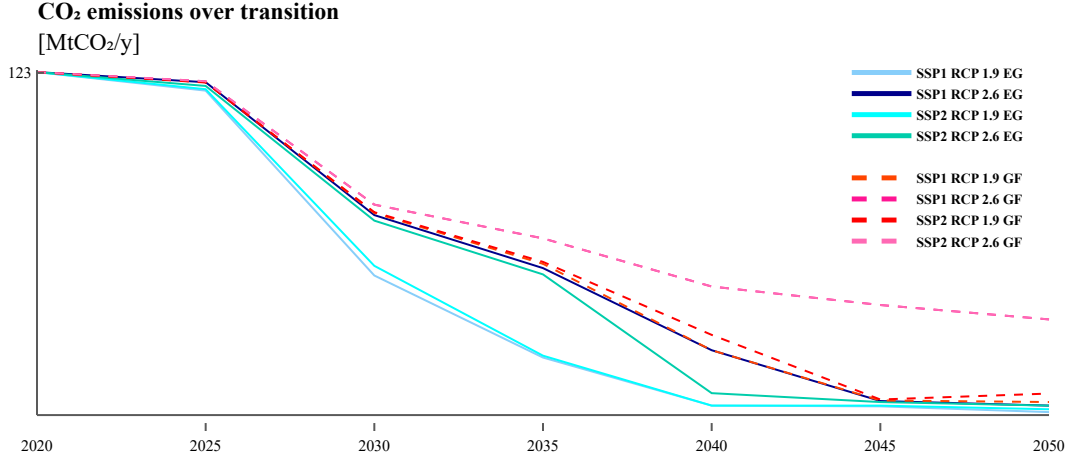


Figure 7: Emissions trajectories for each ssp from EnergyScope Pathway. The SSP1-RCP 2.6 GF and SSP2-RCP 2.6 GF trajectories show higher residual emissions than the other scenarios. They will be analysed as limit cases. EG stands for Egalitarian, GF for Grandfathering.

In Figure 7, between 2020 and 2025, emission reduction efforts are very limited. This finding is consistent with current Belgian data [31] and can be explained by the way the carbon budget constraint is set. Indeed, this constraint applies to the period from 2025 to 2050 and not from 2020. Since no constraint is applied during this period, the model maintains the existing situation to minimize its cost. Another important analysis specifically concerns the SSP1-RCP 2.6 GF and SSP2-RCP 2.6 GF curves, which show higher residual emissions than the other scenarios. Indeed, although they meet their 2050 emission limit constraint (53 and 49 Mt CO₂), their residual emissions amount to 34 Mt of CO₂, whereas those of the other scenarios range between 1 and 8 Mt. Climact, in its study conducted for the FPS Public Health [2], projects that, to achieve carbon neutrality, the negative emissions required in 2050 will need to range between 7 and 11 MtCO₂e. In this sense, the majority of emissions obtained through modeling appear consistent with the federal vision, with the notable exception of these two cases. Since these cases show “presumably high” residual emissions in 2050, they will therefore be analyzed as limit cases. A final note concerns the SSP 2 RCP 1.9 GF curve, which shows a slight increase in emissions between 2045 and 2050. This phenomenon, which may seem counterintuitive, is explained by the search for optimal cost under carbon budget constraints. Since the model made massive efforts earlier on, it takes advantage of its remaining carbon budget at the end of the period to minimize maintenance or investment costs in the final stage. This is discussed in more detail in Appendix J.

4.4 Policies for 2050

Now that the various emissions trajectories have been presented, the objective here is to identify policies regarding low-carbon and renewable technologies for the year 2050. These policies correspond to the minimum capacities (circled points in Figure 8) that the model installs in all scenarios. They form the foundation of energy planning. A presentation of new renewable capacity installed from 2020 to 2050 according to the different SSPs is provided in Appendix K and offers a detailed understanding of the various installation dynamics. The Policies for the year 2035, halfway of the transition, are also presented in Appendix L.

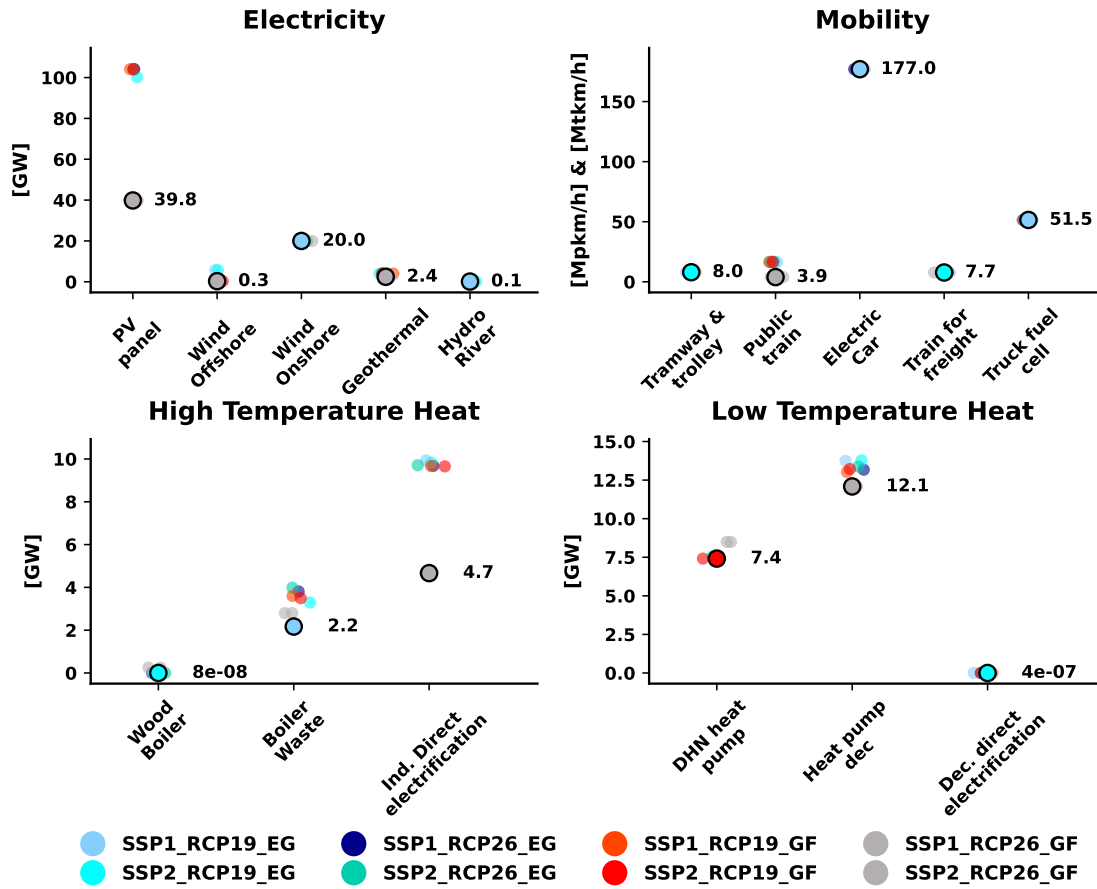


Figure 8: Baseline capacities in 2050. DHN for district heating network - Dec for decentralized and Ind for industrial.

The electrical sector:

The electricity sector is based primarily on four pillars: onshore wind, photovoltaic panels, nuclear and geothermal. Hydropower is present but plays a marginal role. Offshore wind is poorly installed.

- Onshore wind: This is the most stable technology. The model reaches its maximum capacity of 20 GW by 2035 and maintains that level through 2050 in all possible future scenarios. This limit is dictated by strict land-use and social acceptance constraints.
- PV: The minimum threshold increases from 10 GW in 2035 to approximately 40 GW in 2050. This reflects the indispensable role of solar power in supporting Belgium's energy transition. However, it's important to note that in all the "not extreme" scenarios, the full capacity of PV is needed [approx. 100 GW], which further highlights the indispensable role of this technology.
- Offshore Wind and Geothermal Energy: Offshore wind is very expensive; the model only includes it if electricity demand absolutely requires it, which explains its low installed capacity in 2050 (0.3 GW). Geothermal energy, on the other hand, becomes a necessity by 2050, with a minimum of 2.4 GW needed primarily to support the electrification of the high-temperature and public transportation sectors.
- Nuclear and SMR [not shown]: are maintained at their maximum installed capacity, 8 GW and 6 GW respectively, allowing for a continuous dispatchable technology.

Mobility sector:

The strategy is nearly the same regardless of the scenario, but this sector faces significant model's constraints.

- Electric vehicles: The vehicle fleet must account for at least 177 Mpkkm/h in 2050. By 2030, the private mobility sector will consist entirely of electric vehicles.
- Road freight: The deployment of fuel-cell trucks is essential starting in 2035 (31.4 Mtkm/h) and must increase to reach at least 51.5 Mtkm/h by 2050, thereby meeting 100% of road freight transport needs.
- Public transport: Tramway & trolley are operated at their maximum capacity in all scenarios, demonstrating their cost-effectiveness [8 Mpkkm/h]. Trains, on the other hand, are used more frequently when the carbon budget is strict

and electrification is therefore significant. Their use is thus limited by the two extreme cases, resulting in [3.9 Mtkm/h].

- Rail freight: Rail freight transport is operating at its maximum permitted capacity (25% of total demand) due to its highly competitive cost, which requires a minimum threshold of 7.7 Mtkm/h, common to all scenarios.

Heat sector:

- High Temperature: In 2035, the energy mix consists of wood boilers (1 GW) and waste boilers (1.9 GW), with the remainder coming from conventional fossil fuels (gas cogeneration and coal boilers). By 2050, wood will be phased out in favor of waste boilers (2.2 GW) and direct electrification, which will become mandatory with a baseline capacity of 4.7 GW. The trend is therefore marked by the phasing out of wood in favor of other solutions (minimum capacity of approximately 0 GW). This strategic choice stems from the limited availability of biomass resources (limited at 23 TWh/year), which are primarily reallocated to the production of HVC. This change necessitates a shift toward waste boilers (2.2 GW baseline) and direct electrification (minimum 4.7 GW).
- Low Temperature: Decarbonization relies on the widespread deployment of heat pumps. The minimum requirement is 12.1 GW for decentralized heat pumps and 7.4 GW for district heating heat pumps. Unlike the high-temperature sector, electric heating elements play only a marginal role here.

In conclusion, although these results are derived from a prospective study with its own modeling limitations, these minimum requirements have made it possible to identify the key technologies for the transition. These values should not be interpreted as infallible predictions, but rather as indicators of resilient trajectories: deviating significantly from these minimum levels by 2050 could complicate the achievement of carbon targets, potentially making it more costly or technically riskier for Belgium.

4.5 Sufficiency scenario

4.5.1 Application of the Clever scenario on the Egalitarian case

The Clever scenario developed earlier is first applied using a restrictive carbon budget of the Egalitarian type (604 Mt CO₂). However, despite a significant decline in demand, the model fails to converge to a solution that meets all the imposed

constraints. This infeasibility is mainly due to two factors: the model’s strong inertia and the high level of initial emissions, set at 123 MtCO₂ for the year 2020.

This impossibility highlights the fact that a simple reduction in demand cannot instantly compensate for the time required to deploy new infrastructure. In the model, this temporal dynamic is constrained by a maximum renewal rate imposed from one phase to the next. For example, the renewal rate for low-temperature heat is limited at 33% from one phase to the next. Specifically, the mathematical constraint requires that the difference in production, for each technology in a sector, between the start and end of a phase be less than the renewal rate (e.g., 33%) applied to the sector’s total demand in the year marking the start of the phase in question: $\Delta_{prod} \leq \text{Renewal-limit} \cdot \text{Sector demand}$. The mathematical modeling of the constraint for low-temperature heat is further developed in Appendix N.

The way this maximum rate of change is implemented reveals two important points. First, although there is a reduction in consumption between the two scenarios, the model cannot switch from one technology to another faster, which explains why many emissions remain unchanged between the two scenarios. Furthermore, due to the mathematical modeling used, a reduction in demand implies, in absolute terms, that fewer technologies are replaced per year than in the initial case. Next, and this is more surprising, the rate of change is even lower in the case of a low-consumption scenario. In fact, the rate of change—which must remain below 33% (again using the example of low-temperature heating)—depends both on the change in technology and on the reduction in production. Since production decreases under the demand reduction scenario, this will slow down the transition to new technologies. Specifically, if a low demand scenario reduces heating demand by 20%, the model will have only a residual margin of 13% to replace the remaining equipment during that same phase. While this formulation is relevant for scenarios based exclusively on incremental gains in energy efficiency, it highlights a modeling limitation when applied to a demand reduction one.

In addition to these inertia constraints, the initial 2020 emissions level fundamentally compromises the scenario’s viability. The egalitarian allocation approach is so strict that a significant portion of the budget is consumed in the early years of the transition, effectively requiring a near-complete elimination of emissions by 2030. Since demand-reduction measures do not take effect until 2025, with initial effects that are necessarily marginal, they prove insufficient to counterbalance the emissions curve in a manner compatible with this restrictive budget.

What if the carbon budget increased?

To address this infeasibility, the next step is to relax the emissions constraint. The objective was to determine the minimum increase in the carbon budget (initially set at 604 MtCO₂) required to generate a viable technical solution and define a transition pathway, both for the initial case and for the case with reduced demand. The results indicate that a mathematical solution is achieved for a minimum budget of 774 Mt of CO₂ with the initial demand, while the reduced-demand scenario requires a budget of 729 Mt of CO₂.

The difference between these two feasibility thresholds is only about 5%. This small variation can be explained, once again, by the combination of the inertia imposed by the model and the high emissions levels set for 2020. Furthermore, as explained earlier, the reduction in emissions is necessarily small at first.

However, the impact of sufficiency on the overall cost of the energy system is particularly significant. The demand reduction scenario amounts to 913 b€, compared to 1195 b€ for the baseline scenario, representing a savings of approximately 20%. This economic advantage stems from savings in both infrastructure investments (reduced need for new infrastructure) and long-term resource costs (particularly expensive e-fuels, which are more necessary in the baseline scenario to decarbonize sectors that are the most difficult to electrify).

4.5.2 Comparison between initial demand and Clever demand in the Grandfathering case

Unlike the previous analysis, the objective of this section is to assess the impact of reduced demand under the same emissions constraint. For this comparison, the grandfathering approach is selected (not anymore the Egalitarian one as in the previous paragraph) as the reference framework.

The first focus of the analysis is on the overall cost of the transition. This amounts to 980 b€ in the baseline scenario and drops to 750 b€ in the scenario incorporating sufficiency. This 23.5% reduction confirms the positive economic impact of sufficiency. As before, this economic gain is due to reduced CAPEX investments in the deployment of new infrastructure and, consequently, to lower purchases of primary resources. Part of the reduction in resource costs is also attributable to the model's optimization logic. Since the objective is to minimize costs, applying an equivalent carbon budget to lower demand gives the model greater flexibility in choosing resources and technologies. The model will thus maintain the use of the least expensive fossil fuels in the energy mix for a longer period, allowing it to smooth the investment trajectory and optimize the total cost of the transition.

The differences in primary energy consumption between the two scenarios are illustrated in Figure 9. The Appendix O shows the evolution of resources in the Grandfathering case with and without demand reduction. The overall dynamics are driven by two factors. On the one hand, the decline in demand leads to a reduction in the resources required. This effect is particularly pronounced in the long term for renewable energy sources, which then become the dominant sources. On the other hand, certain low-cost fossil fuel resources are extended, guided by the model's optimization logic. Indeed, with a reduction in demand, at equivalent carbon constraint, the model has a greater flexibility in emissions and can therefore afford to maintain fossil fuel less costly resources for longer than in the baseline scenario. It should be noted that this effect deviates from the original spirit of a policy of sufficiency, the goal of which is not to maintain fossil fuel resources in order to minimize costs.

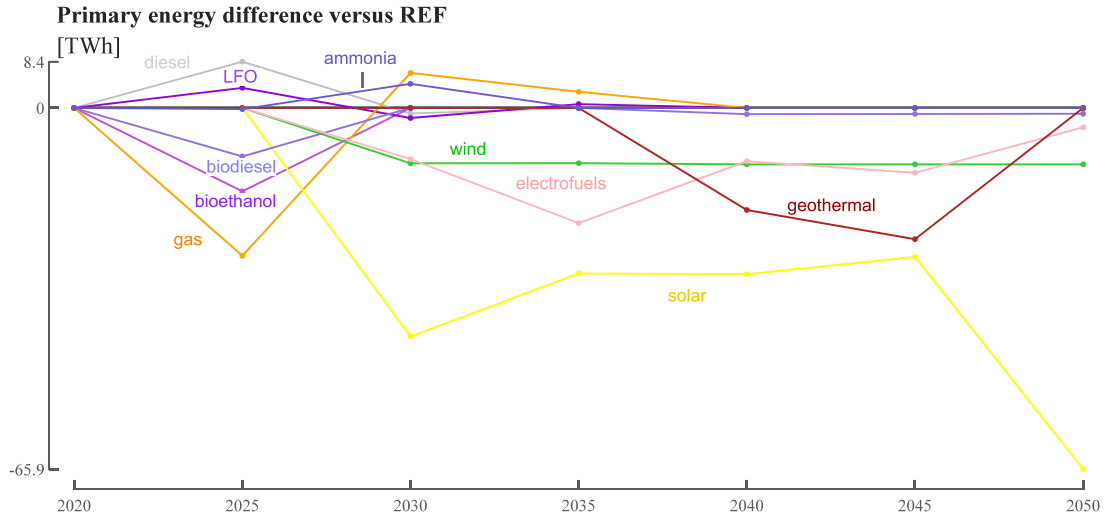


Figure 9: The decline in demand is delaying the phasing out of the least expensive fossil fuel resources. This decline also results in a lower deployment of solar and wind capacity compared to the baseline scenario, leading to a reduction in associated renewable resources. Although PV has a low LCOE compared to geothermal and nuclear power, its low load factor explains its decline. For offshore wind, its high LCOE explains the decline. *Note:* electrofuels refers to imported renewable H₂, ammonia, gas and methanol.

With regard to electricity generation, uranium reaches its production peak in both scenarios and therefore shows no variation (not shown). Conversely, solar suffers from a sharp decline (Figure 9) due to the overall reduction in electricity demand, the postponement of the electrification of certain applications (e.g., electric vehicles), and the non-reallocation of free photovoltaic areas to low-temperature

solar heat production. Wind energy also declines, only due to the phasing out of certain offshore capacities (costly), while onshore wind remains constant. Finally, geothermal energy follows a two-stage trajectory: the curve initially declines, which is explained by a slight increase in production from this technology compared to the initial scenario, as consumption is lower. In a second stage, it will increase to replace the more expensive offshore wind, thereby reaching the level of the baseline scenario.

For fossil fuels, optimization extends the use of the most cost-effective resources. Natural gas is a perfect example of this approach, despite an initial decline compared to the baseline scenario. Indeed, although the Clever applied scenario favors natural gas for certain technologies (CCGT, heat pumps, CNG vehicles, ships), this increase is largely compensated by the collapse in demand for high-temperature heat, drastically reducing the use of cogeneration. In a second phase, the trajectory reverses: relative gas consumption rises, as the model delays the adoption of decarbonized technologies compared to the initial scenario.

This extension of emitting technologies is equally evident for diesel, whose phase-out is delayed for passenger vehicles, and for light fuel oil (LFO). The latter is temporarily favored for HVC at the expense of methanol, which is more expensive. This choice leads to an initial slight increase in LFO, before the decline in non-energy demand eventually forces its reduction. Furthermore, the dynamics of ammonia are driven by investment trade-offs. As the contraction in demand makes local production via the Haber-Bosch process too costly, the model initially favors ammonia imports, before the overall reduction in demand gradually narrows the gap between the two scenarios to zero.

Finally, this prolonged reliance on fossil fuels directly slows the adoption of alternative fuels. The introduction of biodiesel and bioethanol is delayed: the first facing competition from road diesel and the second being displaced by LFO for the production of HVC. E-fuels, which are particularly expensive, are initially neglected in favor of their fossil fuel equivalents. If the consumption gap narrows as 2050 approaches, this is solely due to the cessation of e-fuel imports (excluding e-ammonia) in the baseline scenario, thereby bringing the values of the two scenarios closer together.

Looking now at the installed capacities, Figure 10 illustrates the proportion of installed capacity from the baseline scenario that is maintained in the Clever adapted scenario by 2050. It is immediately apparent that several sectors retain their full capacity (100%): nuclear power, SMRs, geothermal, onshore wind, Train for freight, and truck fuel cell³.

³As a reminder, freight transport demand has not been modified, which makes these last two

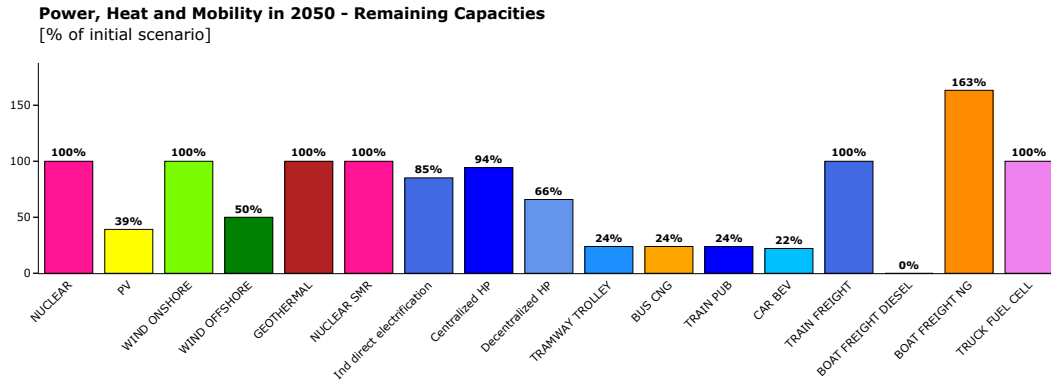


Figure 10: The decline in demand forces the model to maintain in priority controllable, low-cost electricity technologies: nuclear, geothermal, and onshore wind. Capacity for heat production and for private and public mobility drops due to reduced demand, while freight transport (for which demand remains constant) is characterized by a shift in fuel sources exclusively toward natural gas. *Note:* Ind for industrial, CNG for compressed natural gas and BEV for battery electric vehicles.

For electricity generation, the decline in demand means that technologies with the highest levelized cost of energy (LCOE) are not prioritized for deployment. As a result, offshore wind and solar photovoltaic (PV) capacity fall to 39% and 50% of their initial levels, respectively. While the purely economic merit order favors onshore wind, followed by PV, nuclear, geothermal, and finally offshore wind ([13], p. 73, fig. 4.7), the model’s overall optimization goes beyond this single financial criterion to incorporate controllability. Indeed, although geothermal and nuclear power require higher initial investments than PV, these technologies are retained because they ensure stable and continuous production. The model thus makes a fundamental technical trade-off: it limits solar energy, which is too intermittent, in favor of more expensive technologies that are indispensable for ensuring security of supply and system balance.

In the heating sector, the decline in heating demand has implied a widespread reduction in installed capacities. Industrial direct electrification drops to 85%, and decentralized heat pumps fall to 66%. However, this contraction is proportionally less pronounced for centralized heat pumps (district heating networks), which retain 94% of their capacity. This is due to a decrease in waste heat sources. Indeed, as overall demand for HVC (such as methanol) has fallen, industrial exothermic conversion processes, such as synthetic methanol production or the conversion of biomass into methanol, have declined. District heating networks must therefore rely more heavily on their own production capacities.

results less surprising.

Finally, public and private transportation continues to rely on the same range of technologies, but with reduced fleets due to travel restrictions. Tramway, natural gas (CNG) buses, and trains for passenger now account for only 24% of their original capacity, while the fleet of battery electric vehicles (BEVs) has dropped to 22%. However, a structural transformation is taking place, in maritime freight transport: diesel boats are completely phased out (0%) in favor of biogas boats, whose capacity surges to 163% compared to the initial scenario. This gas is produced through the bio-hydrolysis of wet biomass, the availability of which is limited. The decline in gas demand in other sectors, particularly for buses, release sufficient volumes of renewable gas to power the maritime fleet, allowing the model to avoid the use of biodiesel, whose production chain is more expensive.

5 Discussion

This study has identified various optimal transition pathways. Before discussing the key technologies identified for the different SSPs and the impact of the sufficiency scenario, this section begins by putting certain results into perspective in relation to the modelling assumptions.

5.1 Impact of the modeling assumptions on the results

The impact of perfect foresight on investment dynamics

The choice of a perfect foresight modeling approach delays certain investments for cost-saving reasons. This is illustrated, for example, in Figure 3, which shows the dynamics of the emissions trajectories obtained for the various principles of distributive justice. The Utilitarian scenario is particularly influenced by the chosen optimisation. Unlike a myopic approach, the model can anticipate falling costs for renewable technologies and e-fuel imports. Faced with a less restrictive overall carbon budget (2530 MtCO₂), the model logically chooses to delay the most costly investments in order to benefit from more mature and cheaper technologies as 2050 approaches. However, this concentration of decarbonisation efforts in the final years of the transition makes the trajectory vulnerable to unexpected events [32] (technological delays, economic crises, etc.), which could lead to a future in which the investments planned for 2045 never materialize. This example therefore shows that a higher carbon budget does not guarantee a successful transition, but may instead encourage a form of inaction that is risky in the short term.

Uncertainty: carbon budgets versus allocation factors

It is also important to revisit the difference in carbon accounting between the IPCC's AR6 database and that of the EnergyScope model, as detailed in the subsubsection 3.1.2. Although this difference constitutes a methodological limitation, its impact must be put into perspective given the significant uncertainty surrounding the allocation factors. Indeed, these are based on principles of distributive justice on which there is no universal consensus [33, 34]. These two studies demonstrate that a simple change in the mathematical rule radically alters the results. This is also the case in this study, where the choice of allocation principle (Egalitarian vs. Utilitarian) can quadruple Belgium's budget (see Table 2). This uncertainty regarding allocation factors thus far exceeds that associated with emissions accounting. Consequently, the approach adopted in this study, which consists of modelling a variety of allocation principles, is more relevant than seeking perfect consistency between how emissions are calculated in EnergyScope and in the IPCC database, as it provides a comprehensive assessment of the budget's impact on the results and helps to identify no-regret decisions from among all the possible options.

Nuclear power: the model versus reality

The results show that the maximum permitted capacity for nuclear energy (8 GW of conventional nuclear by 2030 and an additional 6 GW of SMRs by 2050) is consistently reached across all SSP scenarios. This highlights the fundamental role assigned by the model to this technology in supporting the massive electrification of the energy system. This result is directly driven by the assumption of a zero GWP to the use of uranium, making nuclear a highly competitive controllable source in the face of strict carbon constraints. Nevertheless, achieving such a capacity (14 GW in total) represents a considerable industrial and time-related challenge for Belgium, which currently has only 2 GW of operational capacity (Doel 4 and Tihange 3) until 2035 [35]. Moving from the current situation to the values optimized by the model implies a deployment rate that is almost logistically unfeasible over a 20-year horizon. Nevertheless, exploring "high nuclear density" scenarios is relevant given the recent shift in Belgian energy policy: the extension of the two existing units in 2023 [36], followed in May 2025 by the Bihet law [37] repealing the 2003 nuclear phase-out law, and recently reinforced (May 2026) by negotiations aimed at the nationalization of ENGIE's nuclear activities [38]. Consequently, although the deployment envisaged by the model is unrealistic, the current direction of the national roadmap confirms the strategic value of having assessed this lever.

5.2 Key technologies

This subsection now focuses on the key technologies emerging from the various SSP scenarios analysed previously. The results obtained are first summarised and then compared with those of other studies. Belgium’s current energy situation is then examined in order to assess whether the current pace of deployment of new infrastructure is sufficient to meet the targets set by this study.

As presented in subsection 4.4, the various SSP scenarios reveal that the most stringent climate trajectories require abrupt decarbonization coupled with massive and early electrification. Conversely, a more flexible carbon budget leads the model to postpone major investments, reduce the import of e-fuels, and extend the use of fossil fuels (e.g., coal boilers for industry, natural gas for transportation, etc.) in order to minimize short-term costs. Despite these differences, major technological convergences exist [Figure 8], making it possible to draw up a roadmap for the essential infrastructure needed by 2050.

- **Electrical sector:** Onshore wind power will reach its deployment limit (20 GW) from 2030 in all scenarios considered. Solar power will be essential, with a minimum capacity of 40 GW by 2050. Conventional nuclear power (8 GW) and SMR modular reactors (6 GW) will be installed at full capacity. Offshore wind power has a low installed capacity in 2050 (0.3 GW). At the beginning of the transition, its deployment is more significant in scenarios with the strictest emissions targets. When geothermal energy becomes feasible, it is preferred because it is less expensive. More flexible scenarios therefore tend to limit the deployment of offshore wind power due to its high cost and wait until geothermal energy is available, resulting in a minimum of 2.4 GW in 2050.
- **Low and high temperature heat:** Low-temperature heating requires a complete shift to heat pumps, a small portion of which will continue to be powered by biogas (no more than 13% of production across all scenarios). For high-temperature heating, direct electrification is essential (non-existent in 2020, reaching at least 4.7 GW by 2050), supported by the deployment of waste boilers (at least 2.2 GW). Wood boilers play a transitional role (1 GW in 2035) before the resource is reallocated.
- **Private mobility:** The private vehicle fleet will be fully electrified by 2030.
- **Public mobility:** Tramway and trolley must be operated at full capacity. Buses are powered by natural gas, becoming biogas by 2040. Passenger trains, meanwhile, will maintain their baseline operating levels in the most flexible climate scenarios and will see their capacity increase if the carbon budget tightens.

- **Road freight:** Freight transport requires a complete transition to hydrogen fuel cell trucks by 2050.

As a result, renewable electricity generation capacities, heat pumps, electric vehicles, and fuel cell trucks are emerging as essential structural pillars of tomorrow's energy system, regardless of the uncertainties surrounding the future carbon budget.

Comparison with other studies

With regard to PV, Elia's Blueprint 2035–2050 study [39] predict capacities ranging from 29.5 to 97.5 GW, depending on the level of electrification, which is consistent with the findings of the present study. For its part, the Path 2050 study, coordinated by Vito and EnergyVille [40], estimates these capacities at between 38 and 46 GW, which is similar to the results obtained in the current study (minimum of 40 GW). For onshore wind, forecasts range from 8 to 14 GW according to Elia, and from 10 to 17 GW for Path 2050 [41]. The result obtained here [20 GW regardless of the scenario] is therefore higher than those in both studies. As for nuclear power, both studies suggest maximum capacities of around 8 GW, which highlights the exceptional nature of the "nuclear pushed" scenario explored here.

Finally, with regard to offshore wind, the estimated installed capacity is low (0.3 GW). In contrast, the other two studies estimate a higher potential: 8 GW in both cases. This discrepancy could be explained in particular by differences in the technical and economic assumptions between the models, both in terms of the technologies considered for electricity production and the CAPEX used. In particular, unlike EnergyScope, the Elia study does not take geothermal energy into account for electricity production, which leads to a shift of this production towards other technologies. Furthermore, the EnergyScope model assumes an investment cost of 4650€₂₀₁₅/kW in 2050 for offshore wind, while Elia's study uses lower values, ranging from 810 to 2870 €₂₀₂₂/kW in 2050, thereby making this technology more competitive. It remains difficult, however, to pinpoint the exact source of this discrepancy without a more in-depth comparison of the models.

Nevertheless, Elia's study [39], through a sensitivity analysis, demonstrates that the choice between nuclear power and non-domestic offshore wind can shift depending on the cost assumptions used. In fact, in its central scenario, maximum nuclear deployment results in a total cost of the electricity system of 119€/MWh, meaning electricity is approximately 8% more expensive than in a scenario maximizing offshore wind (110€/MWh). Conversely, if investment and grid connection costs for offshore wind increase, the trend reverses: the cost of the all-offshore scenario rises to 123€/MWh, making the nuclear alternative approximately 2.5% cheaper (120€/MWh). Finally, if it is nuclear energy that has additional costs, the cost of

the system based on this technology rises to 145€/MWh, making it nearly 32% more expensive than the offshore option (110€/MWh). Although this observation does not directly concern domestic offshore wind power, it suggests that this point deserves further analysis here, as a revision of costs could be sufficient to make it competitive again, thereby facilitating its re-emergence among the solution space. It therefore seems appropriate, for future work, to verify whether offshore wind power should truly be excluded or if it is absent solely because a single cost-optimal solution is considered here. In this perspective, one promising approach to evaluate would be to use the MGA (Modeling to Generate Alternatives) method [42]. By allowing for a slight relaxation of the optimal cost, this method makes it possible to explore “near-optimal” designs. This would make it possible to determine whether or not offshore wind power incorporates these alternative solutions, thereby establishing whether it remains a viable option or not.

The results of this study therefore appear to be consistent with those obtained by other studies, with the notable exception of offshore wind and nuclear power.

What is the actual situation?

For its low-carbon electricity generation, Belgium currently has 2 GW of nuclear capacity (Doel 4 and Tihange 3), the operation of which has been extended until 2035 [35]. Installed renewable capacity stands at 2.2 GW for offshore wind and 3.6 GW for onshore wind [43], while solar photovoltaic account for approximately 14 GW of installed capacity [41]. The transportation sector is largely dominated by fossil fuels (essentially diesel) [44]. In 2026, electric vehicles account for only a small share of 7.5% of the Belgian vehicle fleet [45]. Building heating is primarily provided by natural gas and heating oil, with only 3% supplied by electricity [44]. Furthermore, district heating networks remain underdeveloped [44]. The industrial sector also shows a high dependence on fossil fuels, particularly natural gas and coal [44].

Is the current deployment sufficient?

Given the current situation and the targets to be met by 2050, are the current measures sufficient? To this end, the trends set out in the 2025 National Energy and Climate Plan (PNEC) [46] are compared with the infrastructure requirements identified by this study.

With regard to electricity generation, the roll-out of solar PV appears to be in line with the results achieved here. The PNEC indicates that Wallonia plans to install 5.55 GW between 2018 and 2030, while Flanders is aiming for a rate of 0.5 GW per year giving approximately 1 GW/year for the whole country (a bit more because

the Brussels-Capital Region installed some capacities too). This rate is driven by a range of regional measures, such as installation requirements for certain buildings, their inclusion in PEB scores, financial incentives and administrative simplification. If this deployment rate were to remain unchanged, the current 14 GW (2025) would rise to 38 GW by 2050, which is in line with the minimum 40 GW required by the current study. However, this finding must be put into perspective: although it meets the minimum requirements, all the "non-extreme" scenarios in the study require a capacity of around 100 GW, thus showing that the pace of photovoltaic panel deployment will need to accelerate in the coming years.

For onshore wind, regional projections forecast the installation in Flanders of 150 MW/y from 2026 to 175 MW/y from 2028, and an additional 3.41 GW in Wallonia between 2018 and 2030. If these rates were to continue, the current national capacity of 3.6 GW (2025) would rise to 14.5 GW by 2050. This result remains below the 20 GW ceiling targeted by the current study, although the regional forecasts already take into account the repowering of existing wind farms and a hypothetical acceleration in the granting of permits. Indeed, the slowness of the permit-granting processes constitutes a major obstacle, as highlighted by ELIA [39], as does social acceptability. It is precisely to speed up the permitting process that the European Union adopted the RED III Directive [47]. This directive imposes the creation of "renewable energy acceleration zones" (which also apply to other renewable energy sources) where authorization deadlines are limited to 12 months for onshore projects (2 years outside these zones). In these zones, projects are exempt from the requirement to conduct a specific environmental impact assessment. However, transposing these European obligations at the regional level is complex: as their impact is cross-cutting, it requires the adaptation of several legal texts at the decree level [46]. These measures are currently still in the process of being transposed in both regions.

Finally, nuclear power remains a major uncertainty. The PNEC does not specify any deployment pathway, as small modular reactors (SMRs) are still an emerging technology. Elia nevertheless mentions the installation of a very first Generation III SMR by 2036 in its most ambitious scenario [39]. Furthermore, Elia also points out that the development of a new nuclear fleet must address the issue of long-term waste management, as well as concerns about excessively long construction times and significant cost overruns, which have historically been observed in Europe. Since this type of technology takes a considerable amount of time to become operational, it is essential to establish a clear and concrete vision as soon as possible.

Beyond production, the decarbonization of end-use sectors faces significant obstacles. According to the PNEC [46], the adoption of heat pumps remains particularly low despite the financial incentives provided. The main obstacle is the high price of

electricity compared to that of gas. To address this, regions are considering several measures such as a phased ban on fossil fuel boilers, maintaining a reduced VAT rate of 6%, and a tax shift. This economic assessment is shared by the IEA [48], which also identifies non-financial barriers such as the administrative complexity of building permit, the lack of information enabling individuals to make informed choices, and the shortage of qualified installers. It is therefore necessary to assess whether the incentives are sufficient to accelerate the uptake of heat pumps and to remove the remaining barriers, thereby enabling the widespread deployment of this technology in the coming years.

With regard to mobility, regulatory frameworks vary across regions: Wallonia and Flanders are aiming for 100% "zero-emission" new vehicles (not exclusively electric) by 2035, while Brussels has opted for a total ban on diesel (2030), CNG and LPG (2035) vehicles. Since current measures focus solely on new vehicles, with the exception of the Brussels-Capital Region, they do not enable the achievement of a 100% electric vehicle fleet by 2050. Furthermore, voluntary adoption by the public is hampered by the still insufficient roll-out of public charging infrastructure and by anxiety regarding autonomy and charging times [49]. It is therefore necessary to either tighten measures concerning private vehicles or to accelerate public adoption by working on the remaining obstacles. The latter seems to have started with the current installation of numerous charging points in Wallonia and Brussels [50].

Finally, with regard to road freight transport, the federal vision [44] aligns with the findings of this study by advocating for a fleet of hydrogen-powered trucks. However, this domestic hydrogen production requires significant decarbonized electricity generation capacity. While the modeling done here manages to meet this demand by relying on a massive expansion of nuclear and geothermal power, any delay in these production sectors could result in local supply falling short. In such a scenario, heavy reliance on imports will become inevitable to relieve pressure on the national electricity system. The main challenge then becomes securing international supply chains and developing import infrastructure.

In conclusion, while current policies are on the right track, achieving the 2050 targets will demand a significant acceleration of these measures post-2030, supported by stronger inter-regional coordination and massive grid upgrades.

5.3 Sufficiency as an additional driver of the transition

The integration of the Clever scenario into the Belgian case study has identified the benefits of an approach based on reducing demand: Alleviating grid congestion, reduced need for new infrastructure (lower photovoltaic and offshore wind capacity by 2050), lower total system costs (23.5% savings at equivalent carbon constraints through the avoidance of heavy investments and the reduction of e-fuel imports).

However, modeling has revealed that reducing demand is not a silver bullet for overcoming the physical inertia of the transition (permit delays, installers shortages, etc.), demonstrating that this approach must complement the levers presented earlier, rather than replace them, in order to achieve the desired technological deployments. Furthermore, a mathematical rebound effect was observed: by offering greater flexibility to the model, it extends the use of the cheapest fossil fuels (natural gas, diesel), thereby delaying the transition to renewable. This paradox serves as a reminder that the goal of energy sufficiency is not to postpone the technological transition by relying solely on citizen efforts, but rather to act in parallel with the deployment of renewable technologies. Moreover, Figure 10 confirms that the infrastructure previously identified as essential (heat pumps, EVs, etc.) remains indispensable even with a decline in demand.

Although this approach offers significant advantages, it requires a profound transformation of our behaviors and lifestyles that should not be overlooked. Whereas the technology-based strategy proposes, for example, subsidizing the purchase of electric vehicles, the sufficiency approach flips this by questioning the very necessity of owning a personal vehicle. The CLEVER report [24] outlines the expected changes, including, for example: a reduction in living space, lower target temperatures in buildings, a shift toward sustainable transportation and carpooling, as well as a transition to an industry that produces less but better. This approach inevitably faces resistance from the public, often due to the perception of a loss of comfort, and should therefore not be viewed as a simple mathematical reduction in needs, but as a strategy capable of yielding significant benefits at the cost of significant individual effort.

The gap between the current energy mix and the climate targets for 2050 is so vast that we cannot afford to rule out any solution. The sufficiency approach is therefore an essential complementary lever to the measures mentioned above. We must act on both fronts: rationalizing our consumption and accelerating the deployment of low-carbon technologies.

Conclusion

This study identified optimal transition pathways for the Belgian energy system by 2050, subject to various carbon budgets developed from principles of distributive justice and Shared Socioeconomic Pathways (SSPs). These pathways, together with a sufficiency scenario, have enabled the translation of climate imperatives into a technology roadmap and to assess whether the current pace of deployment is sufficient to achieve these objectives.

The analysis of these different pathways highlights several key lessons. Firstly, implementing a carbon budget based on the Egalitarian principle is physically unfeasible given the accumulated delay since 2020. This finding underlines past inaction and the urgent need to drastically reduce emissions without further delay.

Second, regardless of the future scenario foreseen, a set of unavoidable technological solutions consistently emerges. Achieving carbon neutrality will require massive electrification of end-use sectors, necessitating significant deployment of onshore wind, solar PV, geothermal, and nuclear power. The latter, consistently selected by the model, requires clear strategic planning and rapid decision-making given the industrial, financial, and time-related challenges involved in building new reactors. This massive electrification is vital for decarbonizing the heating and mobility sectors. For sectors where electrification is insufficient (freight, HVC, high-temperature heating), the use of hydrogen, biomass, and waste boilers is necessary.

Third, the inclusion of the sufficiency scenario has shown that reducing final demand is an essential lever. Although it raises significant challenges in terms of social acceptability, this approach helps reduce the total cost of the transition and eases the pressure on infrastructure deployment. It must, however, complement technological development, rather than replacing it.

However, it is important to keep in mind that the success of the transition goes beyond solely the mathematical feasibility of the model. Although current policies are heading in the right direction, a massive acceleration of these measures is essential to have any hope of achieving the set objectives. It is urgent to remove the remaining barriers to the adoption of the key transition technologies.

Finally, this study has, nevertheless, certain limitations that pave the way for future works, particularly regarding how to define an “optimal trajectory” and how to account for climate impacts.

Indeed, the study focused on identifying a single solution, for each scenario analyzed, that minimizes costs. However, focusing exclusively on the economic optimum tends to obscure other technological configurations that might prove more acceptable

from a political and social point of view. For example, while this model does not identify offshore wind as strictly indispensable in terms of costs, exploring “near-optimal” solutions, at a slight additional financial cost, could reveal its value. This is the challenge of MGA (Modeling to Generate Alternatives) approaches, which are currently attracting growing interest.

Moreover, the optimisation in this study has focused on the climate emergency solely through the prism of CO₂ emissions. To enrich this approach, future studies should incorporate an assessment of all planetary boundaries. Indeed, the transition to carbon neutrality and massive electrification, even when reduced by sufficiency measure, will inevitably exert new material and environmental pressures. Lithium, a critical resource essential for a 100% electric vehicle fleet, is one such example. Expanding the scope of the analysis beyond emissions alone would allow for a more comprehensive assessment of the environmental impact of these trajectories.

Combining this more comprehensive approach with the MGA method would thus make it possible to develop other technological configurations capable of providing more sustainable and widely relief for the energy system of the future.

APPENDICES

Appendix A EnergyScope Pathway: Explanation of the model

A.1 EnergyScope: TD to Pathway

EnergyScope Pathway is an extension of the “EnergyScope TD” model developed by Gauthier Limpens ⁴. EnergyScope TD (typical day), [12], is an open-source, bottom-up linear optimization model applied to a target year, known as a “one-shot model.” It allows, for this target year, the optimization of the design and operation of an urban or regional energy system, taking into account all energy sources and demand at hourly resolution. More specifically, the model’s objective (objective function) is to find the optimal configuration that minimizes the total system cost for a given year between 2015 and 2050 while ensuring compliance with technical and environmental constraints through a linear formulation. This model is unique in that it integrates and links all energy sectors - heat, electricity, and transportation - and represents them with an equivalent level of detail.

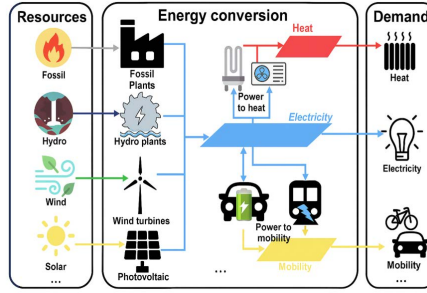


Figure A1: Overview of EnergyScope TD - figure from Limpens et al. [12]

In order for the optimization to take place, the model must be provided with a set of parameters (efficiency, CO₂ emissions, cost of energy resources, hourly energy demand, etc.). Once this is done, EnergyScope TD identifies the decision variables that allow the objective function to be met while satisfying the model’s constraints. A typical constraint is that production must equal consumption at all times.

The Figure A1 provides a simplified overview of the EnergyScope framework. The model is divided into three main parts: Resources, Conversion Technologies, and End-use Demand. The demand from each of the three sectors (Heat, Mobility, and Electricity) must be met every hour of the year, requiring the use of a certain

⁴The code is available at: <https://github.com/energyscope/EnergyScope/tree/v2.0>, and pre-loaded data are about Belgium.

amount of resources. The link between the resources used and final demand is established through a series of conversion technologies.

A.2 EnergyScope : The Pathway model

The EnergyScope TD model focuses on identifying an optimal system configuration for a single target year. While effective for defining a final state, this “snapshot” approach does not allow for the modeling of long-term transition pathways. To address this limitation, the model has been extended to its Pathway version⁵, a system planning tool designed to cover the 2020–2050 horizon [Figure A2]. A full research paper on the model is available [4].

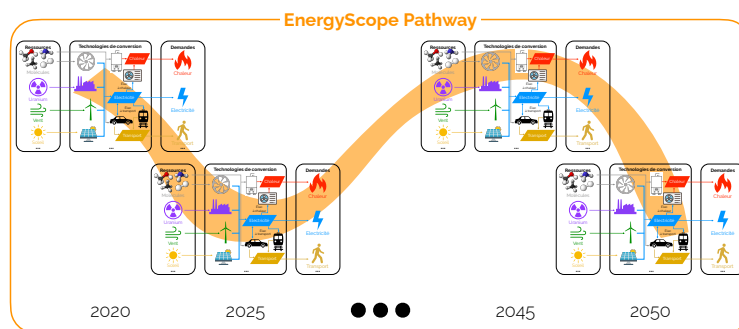


Figure A2: Extended model from TD to Pathway - figure from Xavier Rixhon [51]

The strength of EnergyScope Pathway lies in its ability to integrate investment strategies rather than simply optimizing for a single target year. This approach directly addresses the central challenge of this work: defining the optimal pathway for transitioning from the current energy mix to a carbon-neutral target by 2050.

The shift from a one-year optimization to a 30-year transition requires some adjustments compared to its parent model, EnergyScope TD. First, the optimization is not performed for every year of the transition from 2020 to 2050, but rather for 7 representative years. In fact, the 30-year period has been divided into 5-year periods (called phases), and within each phase, a target year is optimized. In total, 7 target years are optimized, hence “7 years of the EnergyScope TD model.” Second, an annual dimension had to be added to all variables and parameters. This was done to account for differences in inputs and outputs across years.

To ensure consistency across the different phases, constraints also had to be added. These constraints take into account the investment strategies and various choices

⁵The source code is available on GitHub: https://github.com/energyscope/EnergyScope_pathway, and pre-loaded data are for Belgium.

made in one phase and carry them over to the next phase so that they are taking into account in the optimization. Constraints also limit the speed of changes from one phase to the next to account for social inertia and prevent shifts in technology and supply that are not possible in reality. New long-term storage technologies have also been added.

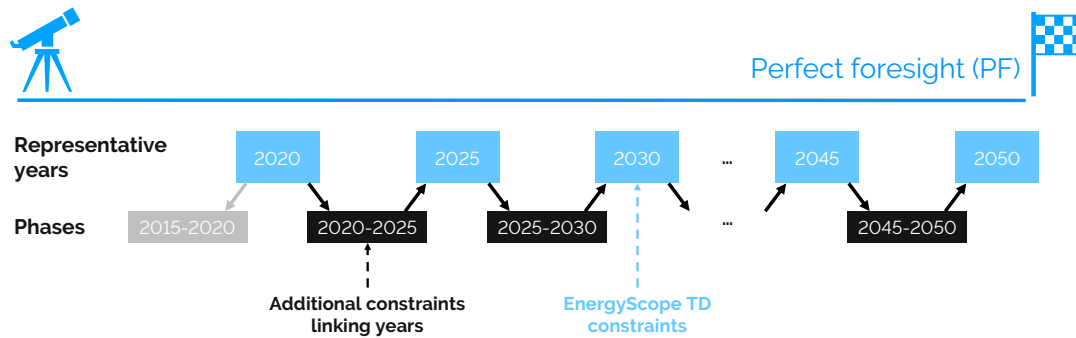


Figure A3: Transition from Snapshot model to Energyscope Pathway - figure from Xavier Rixhon [52]

Figure A3 provides a schematic overview of the adjustments described. The seven representative years are shown in blue. For each of these years, the EnergyScope TD model is applied using a series of inputs: demand, costs, emissions, etc. The additional constraints that had to be added are shown in black and bridge the gap between the representative years. The period between two representative years is called a phase. The model's initial state is shown in gray, allowing the model to start from an existing situation rather than a blank paper.

Figure A3 also introduces the term "Perfect Foresight" (PF), which defines the nature of the global optimization performed by the model over the thirty-year transition period. Unlike a "myopic" approach, the PF approach is based on a single optimization in which all future parameters are considered known from the starting point in 2020 (changes in demand, resource price trajectories, improvements in technological efficiency, etc., through 2050). This methodological choice simplifies the modeling of the energy system compared to the myopic approach, but it represents a major simplification of reality. In particular, this choice may lead the model to delay certain investments due to the anticipation of future cost reductions. It is therefore crucial to interpret the results of this model while taking this simplification into account.

Appendix B Formulation of the objective function and emissions accounting

In this section, we will briefly present the formulation of the objective function and the emissions accounting, based on the work of Xavier Rixhon [52]. The complete formulation is available in Gauthier Limpens’s thesis [13] or in the repository [53].

These two indicators - GWP and total transition cost - are two very important metrics for optimizing the energy system. Indeed, the goal is to analyze viable options for Belgium to achieve its climate target in an economically sustainable manner.

Objective function

The goal is to minimize the total cost of the system. That means to minimize the sum of all capital expenditures and all costs associated with facility operations and resource extraction, as shown in the formula below. All costs are expressed in euros 2015, which is why an annualization factor is used sometimes.

$$\min C_{\text{tot,trans}} = C_{\text{tot,capex}} + C_{\text{tot,opex}} \quad (5)$$

This formula is very important because all the choices made by the model will be influenced by it. It will affect every decision, whether it involves choosing one technology over another, one resource over another, ...

Capital expenditures (CAPEX) are calculated by summing all capital expenditures incurred during the transition period (30 years in this case) and subtracting the residual values of “unused” assets at the end of the transition (in 2050).

$$C_{\text{tot,capex}} = \sum_{p \in PHASE \cup \{2015_2020\}} C_{\text{inv,phase}}(p) - \sum_{j \in TECH} C_{\text{inv,return}}(j), \quad (6)$$

For operating and maintenance costs, the 2020 value is calculated by taking the average C_{Opex} between the start and end of the 2015–2020 phase and multiplying it by 5. For the other phases, the same logic regarding the average value ($C_{\text{Opex}}(p)$) is followed, but a price annualization factor is taken into account [Equation 7].

$$C_{\text{tot,opex}} = C_{\text{opex}}(2020) + t_{\text{phase}} \cdot \tau_{\text{phase}}(p) \cdot \sum_{p \in PHASE} C_{\text{opex}}(p), \quad (7)$$

The two terms appearing in Equation 6 are explained below. First, $\mathbf{C}_{\text{inv,phase}}$ is equal to the sum of all technologies j , represented by their newly installed capacity in a phase (p), multiplied by the annualization factor for the phase and by the average investment cost of the technologies (obtained by averaging the cost of the technology at the beginning and end of the phase). The annualization factor is obtained using Equation 9. i_{rate} is set equal to 1.5% (based on [13]).

$$\mathbf{C}_{\text{inv,phase}}(p) = \sum_{j \in \text{TECH}} \mathbf{F}_{\text{new}}(p, j) \cdot \tau_{\text{phase}}(p) \cdot c_{\text{inv}}(p, j) \quad \forall p \in \text{PHASE}, \quad (8)$$

$$\tau_{\text{phase}}(p) = 1 / (1 + i_{\text{rate}})^{\text{diff}_{2015_year}(p)}, \quad (9)$$

As for the residual investment cost at the end of the transition, it is calculated using Equation 10. Each technology is associated with a parameter that specifies its estimated lifespan. If this lifespan has not been fully reached by the end of the transition, a return value is calculated in proportion to the number of remaining years. However, technologies that are retired prematurely are excluded from this calculation. No costs are recovered in this case, as this is a mathematical formula designed to avoid hindering investments at the end of the transition period, not to allow for the removal of technologies that are already installed but no longer in use in order to recover the investment.

$$\begin{aligned} \mathbf{C}_{\text{inv,return}}(j) = & \sum_{p \in \text{PHASE} \cup \{2015_2020\}} \tau_{\text{phase}}(p) \cdot c_{\text{inv}}(p, j) \cdot \\ & \frac{\text{remaining_years}(j, p)}{\text{lifetime}(y_{\text{start}}, j)} \left(\mathbf{F}_{\text{new}}(p, j) - \sum_{p2 \in \text{PHASE}} \mathbf{F}_{\text{decom}}(p2, p, j) \right) \quad \forall j \in \text{TECH}. \end{aligned} \quad (10)$$

Turning now to operating and maintenance costs [Equation 7], the annual operating cost ($C_{\text{opex}}(y)$) includes the maintenance and operating costs of technologies j as well as the costs associated with purchasing resources i over the year y , as shown in Equation 11.

$$\mathbf{C}_{\text{opex}}(y) = \sum_{j \in \text{TECH}} \mathbf{C}_{\text{maint}}(y, j) + \sum_{i \in \text{RES}} \mathbf{C}_{\text{op}}(y, i) \quad \forall y \in \text{YEARS} \quad (11)$$

The two terms of Equation 11 are presented below. $\mathbf{F}$ represents the installed capacity for each technology j , and $\mathbf{F}_t$ is the hourly consumption of resource i . c_{op}

represents the cost of a resource, and c_{maint} represents the operating expenses of a technology; both are fixed parameters for each representative year.

$$\mathbf{C}_{\text{maint}}(y, j) = c_{\text{maint}}(y, j)\mathbf{F}(y, j) \quad \forall y \in YEARS, \forall j \in TECH \quad (12)$$

$$\mathbf{C}_{\text{op}}(y, i) = \sum_{t \in T} c_{\text{op}}(y, i)\mathbf{F}_{\mathbf{t}}(y, i, t)t_{\text{op}}(t) \quad \forall y \in YEARS, \forall i \in RES \quad (13)$$

CO₂ budget over the transition

In the context of this work, a particularly important constraint is that related to CO₂ emissions during the entire transition (i.e., $\mathbf{GWP}_{\text{tot,trans}}$). In fact, this must comply with an imposed carbon budget (i.e., $gwp_{\text{lim,trans}}$), as shown by the constraint presented in Equation 14. The carbon budget boundary is difficult to define and is, in fact, a key focus of this work.

The term GWP (Global Warming Potential) is used because it takes into account not only the CO₂ emitted by each resource, but also its CO₂ equivalent. It considers the CO₂ equivalent emitted during extraction, transportation, and combustion. In fact, a life cycle assessment (LCA) approach is followed, known as cradle-to-use. However, emissions at the end of a resource's life are not accounted for, nor are emissions related to the construction of various technologies, making this a partial LCA.

To obtain these values, Gauthier Limpens [13] used the “GWP100a-IPCC2013” indicator. This indicator accounts for the contribution of greenhouse gases over a 100-year period. The impact of each resource is considered equivalent at any point during the transition. Therefore, unlike cost, no annualization factor is taken into account here. These values have not been modified in this study unless specifically noted.

$$\mathbf{GWP}_{\text{tot,trans}} \leq gwp_{\text{lim,trans}}, \quad (14)$$

$GWP_{\text{tot,trans}}$ is calculated using Equation 15. Starting with a system representative of the year 2020, $GWP_{\text{tot}}(2020)$ represents the 2020 emissions of that specific system. To this must be added the emissions associated with each of the other phases. The methodology used is to calculate the average emissions between the start year of a phase and the end year of the same phase and multiply this by the duration of the phase, which is 5 years. The 6 values obtained must then be summed.

$$\mathbf{GWP}_{\text{tot,trans}} = \mathbf{GWP}_{\text{tot}}(2020) + t_{\text{phase}} \sum_{p \in PHASE} \mathbf{GWP}_{\text{tot}}(p) \quad (15)$$

Total emissions per representative year are calculated using Equation 16. This corresponds to the sum of the $GW P_{op}$ of each resource over the year. This annual value is obtained using Equation 17 by multiplying the $GW P_{op}$ emissions (in $\text{ktCO}_{2,\text{eq}}/\text{GWh}$) of each resource by the hourly consumption of each resource i and by its operating time t_{op} . Emissions associated with imported electricity are also included in the $GW P_{op}$.

$$\mathbf{GWP}_{\text{tot}}(y) = \sum_{i \in RES} \mathbf{GWP}_{\text{op}}(y, i) \quad \forall y \in YEARS \quad (16)$$

$$\mathbf{GWP}_{\text{op}}(y, i) = \sum_{t \in T} gwp_{op}(y, i) \mathbf{F}_t(y, i, t) t_{op}(t) \quad \forall y \in YEARS, \forall i \in RES \quad (17)$$

Appendix C Details about Shared Socioeconomic Pathways

Five SSPs were selected to cover a sufficiently broad range of uncertainties regarding future societies [9]. These five SSPs correspond to specific combinations of socio-economic challenges, making mitigation (emissions reduction) either easier or more difficult. The same applies to adaptation (reducing vulnerability), as shown in Figure A4.

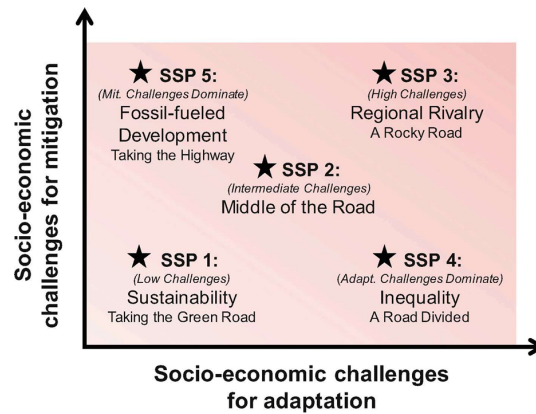


Figure A4: SSP's: Challenge to mitigation and adaptation - figure from O'Neil et al. [9]

Based on O'Neil et al. [9], each of the five SSPs shown in Figure A4 is briefly defined.

- SSP 1 - Sustainability - Taking the green road: The world is shifting toward a more sustainable way of life and prioritizing human well-being, education, and the reduction of inequality. Economic growth is not the primary concern. The world is aware of environmental limits, thereby promoting the use of renewable energy, and is also moving toward a more resource-efficient approach. The challenges are low for both mitigation and adaptation.
- SSP 2 - Middle of the road: This scenario follows historical economic, social, and technological trends. The environment continues to deteriorate. The challenges are moderate for both mitigation and adaptation.
- SSP 3 - Regional Rivalry - A Rocky Road: The world is becoming increasingly divided, with national interests taking precedence over global interests. Poverty is on the rise, economic growth is slowing, and environmental issues

are not a top priority. The challenges are significant for both mitigation and adaptation.

- SSP 4 - Inequality - A road divided: There are very high levels of inequality both within and between countries. On one side, there is a wealthy, educated elite, and on the other, there are poor, less educated people. The challenges for mitigation are low thanks to low-carbon technologies developed by a wealthy elite, but the challenges for adaptation are high due to significant inequalities.
- SSP 5 - Fossil-fuel development - Taking the highway: The world is relying heavily on fossil fuels, and economic growth is strong. Massive investments in infrastructure are helping to mitigate adaptation challenges. However, the important use of fossil fuels is making mitigation challenges particularly significant.

Appendix D World carbon budget for each SSP from AR6 database

This appendix presents the assumptions used to derive the data for the various SSPs. As explained in subsection 2.3, the following scenarios were retained for the study:

- SSP1 SPA1 19I LIRE LB
- SSP1 SPA1 26I LIRE
- SSP2 SPA1 19I LIRE LB
- SSP2 SPA2 26I LIRE

Emissions for these scenarios were obtained using a specific IAM (Integrated Assessment Model), in this case “IMAGE 3.2”. The data are sourced from the “AR6 Scenario Explorer” database [21]. The SSPs and radiative forcing were explained in subsection 2.3.

According to Van Vuuren et al. [54], LIRE stands for “Lifestyle and Renewable.” “Lifestyle” implies that a change in lifestyle is taken into account: Demand for heating and cooling is reduced, as is the use of household appliances. Public transportation is used more frequently, and air travel is reduced. For “Renewable,” the price of renewable energy is assumed to decline more rapidly than in the reference scenario, and its integration into the power grid is facilitated. The electrification of end-use sectors is more extensive than in the other scenarios.

The term “LB” is not defined by the IAM model but refers to post-processing performed on the “AR6 Explorer” dataset, standing for “Lower Bound.” Since this concept only makes sense when compared to other IAM models, it will not be discussed further.

For the selected scenarios, data on CO₂ emissions [MtCO₂/y] in the energy sector are taken into account, as well as CO₂ capture in that same sector.

For emissions in the energy sector, these are emissions related to categories 1A and 1B (see documentation in [21] of the IPCC report), covering emissions from fuel combustion and leaks. Categories 1A and 1B are discussed in [26].

These emissions, however, are net emissions, meaning that CO₂ capture has been removed. To ensure these data are used correctly in EnergyScope Pathway, the decision was made to switch to gross emissions and to require the EnergyScope Pathway optimization model to remain within the carbon budget for the period 2025–2050 as well as below the remaining emissions limit in 2050. To do this,

emissions related to “Carbon Sequestration” (CCS) in the energy sector are added to net emissions. According to [21], these are the total emissions of CO₂ captured following the use of fossil fuels and stored (buried). This is how the emissions are calculated. The values are presented in Table A1.

World CO ₂ Emissions - Energy field [GT CO ₂]		
Carbon budget 2025–2050	CO ₂ in 2050	Scenario
463.64	13.78	SSP 1 - RCP 1.9 - LIRE
730.37	22.84	SSP 1 - RCP 2.6 - LIRE
481.31	15.10	SSP 2 - RCP 1.9 - LIRE
659.78	20.96	SSP 2 - RCP 2.6 - LIRE

Table A1: World carbon budgets and CO₂ emissions in 2050 under different SSP-RCP scenarios.

Appendix E How the Clever data are adapted to EnergyScope Pathway model

To integrate the Clever sufficiency scenario into EnergyScope, we apply Clever’s relative demand reductions to the model’s baseline. This approach accounts for the discrepancies in how sectors are defined in both frameworks. Additionally, because Clever’s final consumption units differ from EnergyScope units (e.g., passenger-km or tonne-km instead of TWh), a relative method is necessary to ensure consistency.

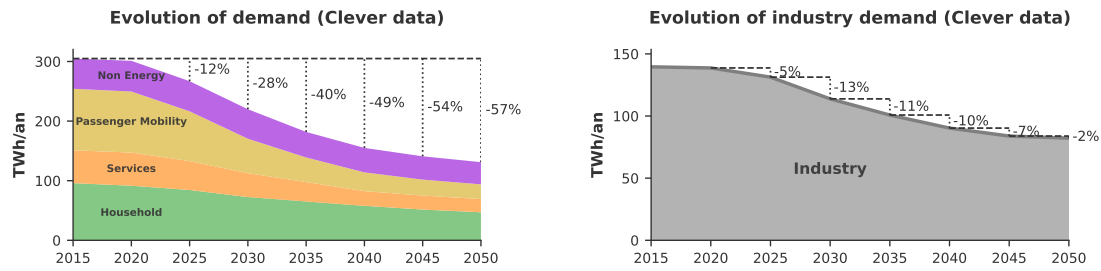


Figure A5: Methodology to adapt Clever demand to EnergyScope - based on Belgium Clever data [29]. (Left) Non-energy, passenger mobility, services, and household sectors, calculated via relative changes from 2015. (Right) Industrial sector, using relative changes compared to the previous reference year to account for initial growth in EnergyScope trajectories.

Appendix F Calculation of Belgium allocation factors

1. **Egalitarian principle:** CO₂ are divided around population number.

- Belgium population number in 2020: 11.54 millions [55]
- World population in 2020 : 7.86 billions [55]

$$\alpha_{\text{egal,Belgium}} = \frac{\text{pop}_{\text{Belgium}}}{\text{pop}_{\text{world}}} \quad (18)$$

2. **Grandfathering principle:** CO₂ are divided around actual and past emissions.

- World emissions in 2020 : 49.33 GtCO₂ [56].
- Belgium emissions in 2020 : 92.27 MtCO₂ [56].

$$\alpha_{\text{AR,country}} = \frac{\text{CO2}_{\text{country}}}{\text{CO2}_{\text{world}}} \quad (19)$$

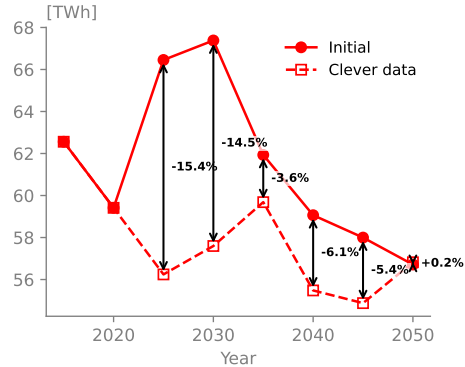
3. **Utilitarian principle :**

$$\alpha_{\text{util,Belgium}} = \frac{\text{GDP}_{\text{Belgium}}}{\text{GDP}_{\text{world}}} \quad (20)$$

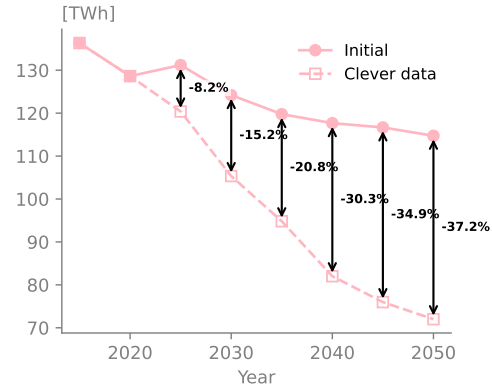
- The World GDP is 86 116 billions dollars US in 2020 [55]
- The GDP for Belgium is 554 billions dollars US in 2020 [55].

Appendix G Clever and initial EnergyScope data

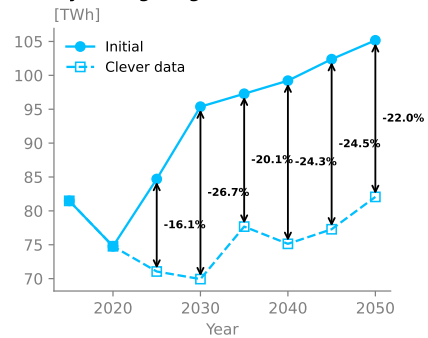
High Temperature sector - Demand reduction



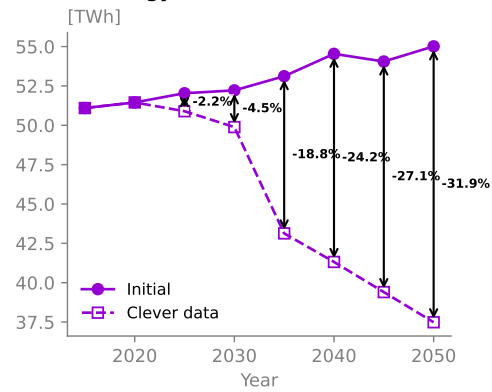
Low Temp sector - Demand reduction



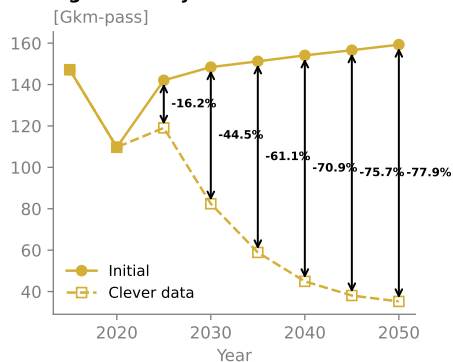
Electricity and lighting sector - Demand reduction



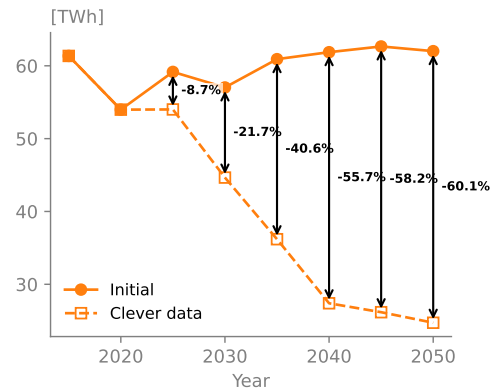
Non Energy sector - Demand reduction



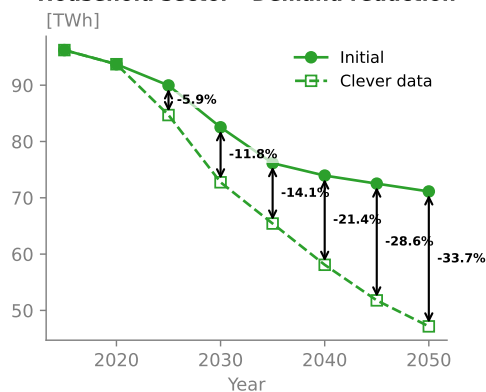
Passenger Mobility sector - Demand reduction



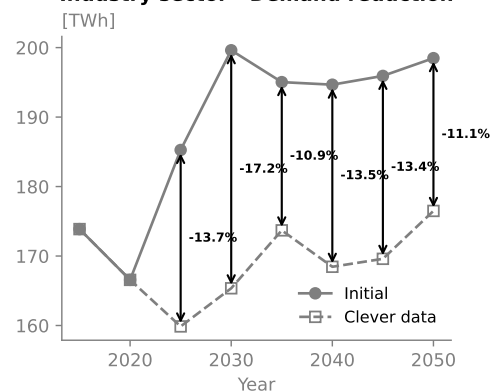
Services sector - Demand reduction



Household sector - Demand reduction



Industry sector - Demand reduction



Appendix H Layer balance of the Grandfathering case - 966 Mt CO₂

The graph layers illustrate the balance between production by technology (positive side) and consumption or final demand (negative side).

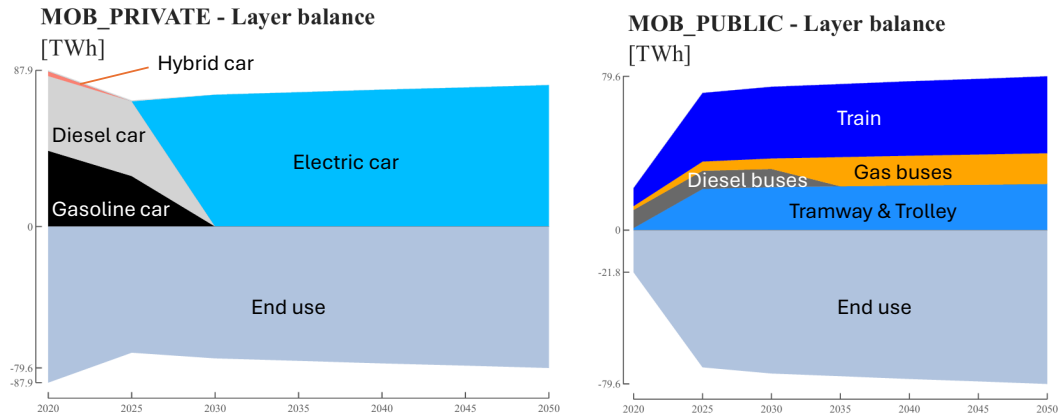


Figure A7: Private transportation will be fully electrified by 2030. Public transportation will continue to rely on gas for buses. Achieving carbon neutrality therefore requires a change in how this gas is produced.

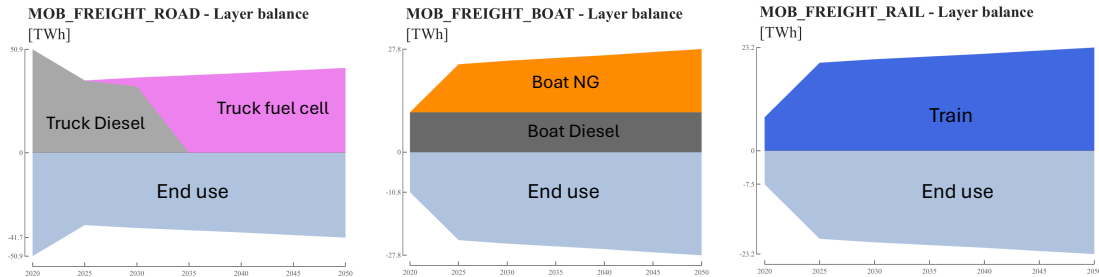


Figure A8: The road transport is undergoing a major technological transition in their trucks, shifting from diesel engines to fuel cells. In the maritime sector, the technological breakthrough is taking place in fuel production, with a shift from conventional hydrocarbons to synthetic fuels. Rail transport is still carried out by trains.

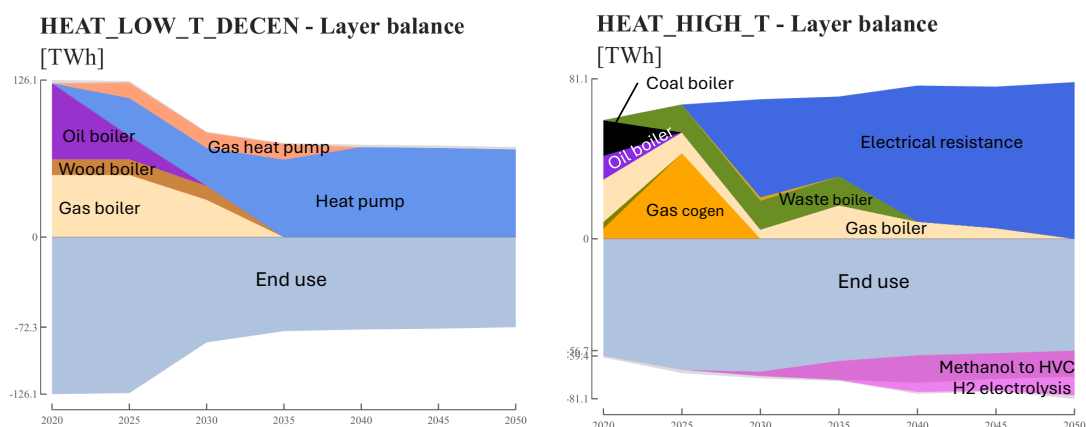


Figure A9: Reducing emissions requires a significant shift toward electrification in heat production: heat pumps for the LT sector and direct electrification for the HT sector. The growing use of centralized production facilities explain the decline in demand between 2025 and 2035.

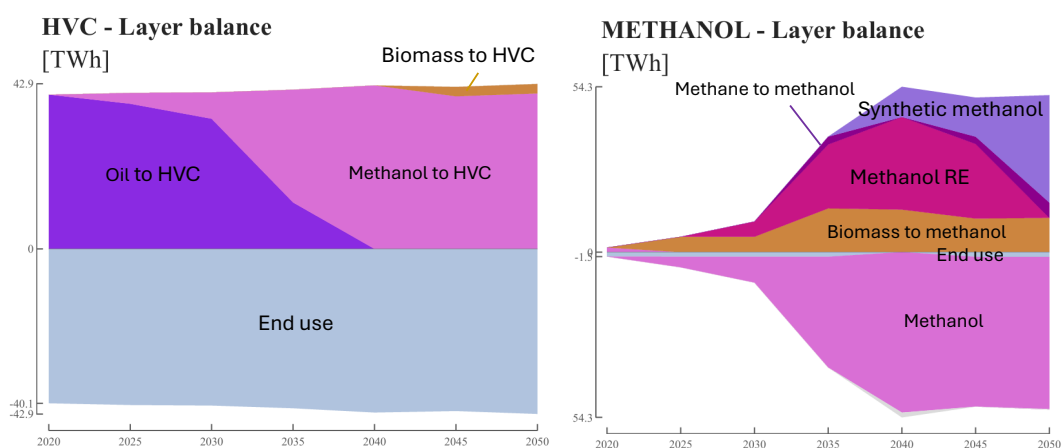


Figure A10: Transition of HVCs from oil-based to methanol-based. Methanol is imported, produced from methane or biomass, or via synthetic methanol. The residual emissions are due to the fact that biomass has non-zero emissions.

Appendix I Details about SSP's emissions and cost for each phase of the transition

CO2 related to energy [MT of CO ₂]				
/	CB 2025–2050	Target CO ₂ in 2050	Model CO ₂ in 2050	Scenario
Egalitarian	681.06	20.24	1.07	SSP 1 - RCP 1.9
Grandfathering	1088.64	32.36	4.69	
Egalitarian	1072.87	33.55	3.41	SSP 1 - RCP 2.6
Grandfathering	1714.92	53.63	34.38	
Egalitarian	707.01	22.19	2.09	SSP 2 - RCP 1.9
Grandfathering	1130.12	35.46	7.74	
Egalitarian	969.18	30.79	3.41	SSP 2 - RCP 2.6
Grandfathering	1549.17	49.21	34.38	

Table A2: Carbon budgets and CO₂ emissions (Targets vs Model) under different SSP-RCP scenarios

Scenario	Trans. Limit [Mt CO ₂]	2050 Limit [Mt CO ₂ /y]	Trans. Cost [b€]	Year	Total CO ₂ [Mt CO ₂ /y]	Total Cost [b€/y]
SSP1-RCP 1.9 EG	681.06	20.24	932.13	2020	123.25	43.02
				2025	116.60	41.12
				2030	50.16	38.55
				2035	20.68	39.65
				2040	3.41	39.74
				2045	3.14	40.15
				2050	1.07	41.18
SSP1-RCP 2.6 EG	1072.87	33.55	902.23	2020	123.26	43.01
				2025	119.63	41.06
				2030	71.87	37.06
				2035	52.82	36.91
				2040	23.31	37.79
				2045	5.05	39.60
				2050	3.41	40.51
SSP2-RCP 1.9 EG	707.01	22.19	929.29	2020	123.26	43.02
				2025	117.12	41.14
				2030	53.64	38.24
				2035	21.35	39.62
				2040	3.41	39.71
				2045	3.41	40.06
				2050	2.09	40.97
SSP2-RCP 2.6 EG	969.18	30.79	908.10	2020	123.26	43.01
				2025	118.28	41.16
				2030	69.88	37.12
				2035	50.55	36.99
				2040	7.88	39.02
				2045	4.68	39.65
				2050	3.41	40.54
SSP1-RCP 1.9 GF	1088.64	32.36	901.44	2020	123.26	43.01
				2025	119.66	41.06
				2030	72.63	37.06
				2035	54.36	36.87
				2040	23.30	37.77
				2045	5.26	39.57
				2050	4.69	40.39
SSP1-RCP 2.6 GF	1714.92	53.63	888.65	2020	123.26	43.01
				2025	119.97	41.06
				2030	75.63	37.12
				2035	63.50	36.88
				2040	46.20	36.65
				2045	39.56	37.62
				2050	34.38	38.57
SSP2-RCP 1.9 GF	1130.12	35.46	899.45	2020	123.26	43.01
				2025	119.52	41.05
				2030	72.92	37.06
				2035	55.06	36.86
				2040	28.82	37.35
				2045	5.60	39.54
				2050	7.74	40.13
SSP2-RCP 2.6 GF	1549.17	49.21	888.65	2020	123.26	43.01
				2025	119.97	41.06
				2030	75.63	37.12
				2035	63.50	36.88
				2040	46.20	36.65
				2045	39.56	37.62
				2050	34.38	38.57

Table A3: Evolution of CO₂ and Costs under various SSP-RCP scenarios (EG: Egalitarian, GF: Grandfathering)

Appendix J Details of SSP 2 - RCP 1.9 GF case

In the SSP2 RCP 1.9 GF scenario, emissions increase between 2045 and 2050. This is because, in the model, it is more economically advantageous to invest massively before 2045 and then ease up on emission reduction efforts between 2045 and 2050 (thereby reaching exactly the limit of its carbon budget). This may seem illogical, but it is simply a result of seeking the lowest possible cost.

This increase is due to the rise in coal use over this period (left graph in Figure A11). This resource will be used for industrial boilers, as shown in Figure A12, which explains why emissions from the high-temperature sector are increasing (right graph of Figure A11).

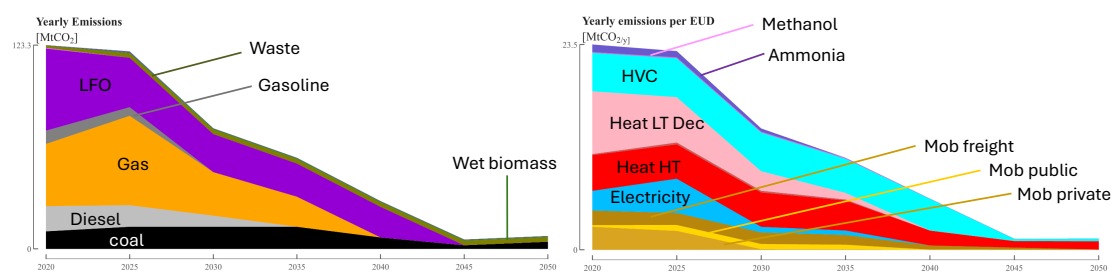


Figure A11: Yearly Emissions and Emissions per EUD - SSP2 - RCP 1.9 - GF

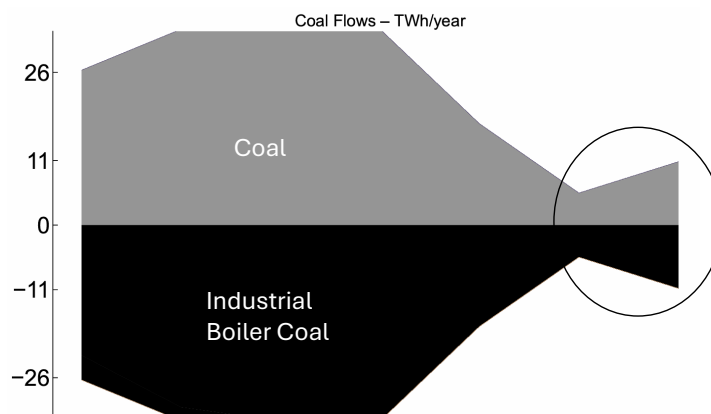


Figure A12: Coal: Year Balance

But why isn't a low-carbon technology chosen instead of one that uses coal? When the heat balance is analyzed [Figure A13], it appears that the demand for high-

temperature heat increases between 2045 and 2050. Indeed, a massive increase in hydrogen production - which will be used for methanol production - is visible (H₂ electrolysis – methanolization – methanol – HVC)

It is economically more advantageous to operate existing coal boilers (since the carbon budget allows it) rather than invest in direct electrification that are expensive to purchase and whose electricity generation poses challenges during a period when electrification is significant.

This is why the model decides to reinvest in fossil fuels rather than in more expensive low-carbon fuels. It was decided not to add a constraint to the model to avoid a rise in emissions, as the goal is to let cost optimization occur by imposing only a carbon budget for the entire transition. Indeed, adding more constraints would risk producing results dictated more by the modeler's choices than by the model's own logic.

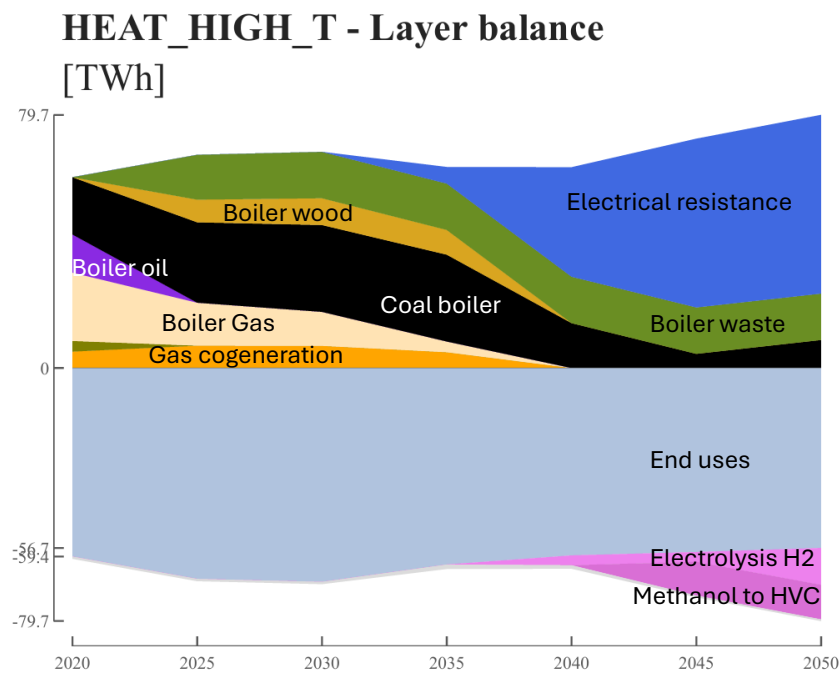


Figure A13: Layer of High temperature heat - SSP2 - RCP 1.9 - GF

Appendix K New capacity installed for the different SSP

This appendix reviews new installed capacity, that is, the technologies added by the model for each representative year. It is important to note that a zero value for a given year does not indicate a lack of capacity, but rather the absence of new investments. The analysis focuses on renewable technologies and separates them by sector.

Electricity

Figure A14 shows the dominance of onshore wind and solar PV in electricity generation. For solar PV, there is a clear consensus in favor of its deployment, although the more stringent scenarios begin this effort earlier. Between 2045 and 2050, a massive installation takes place, reaching 71 GW. For onshore wind power, all scenarios agree: the model consistently reaches the maximum authorized capacity (20 GW due to land-use constraints and social acceptability) through cyclical reinvestments. Geothermal energy, available and introduced starting in 2040, exhibits divergent installation dynamics across the SSP scenarios, depending on the level and pace of electrification. In fact, all scenarios, with the exception of our two limit cases (in gray), reach an installed capacity of 4 GW by 2050; however, the implementation timeline for reaching this 4 GW varies depending on the pace of electrification in the sectors, particularly those of high-temperature heat and public transportation. For the two limit cases, the predominance of fossil fuels in these sectors means that reaching 4 GW of geothermal capacity by 2050 is not necessary. Finally, the deployment of offshore wind power is marked by a sharp acceleration starting in 2030 in the most ambitious scenarios (SSP1-RCP 1.9 EG and SSP2-RCP 1.9 EG), reaching the limit of available capacity. The other trajectories also include installations, but to a much more marginal extent. Installed capacity in 2050 is, moreover, less than 1 GW for all scenarios except SSP 1 and 2 - RCP 1.9 EG and SSP 2 - RCP 2.6 EG.

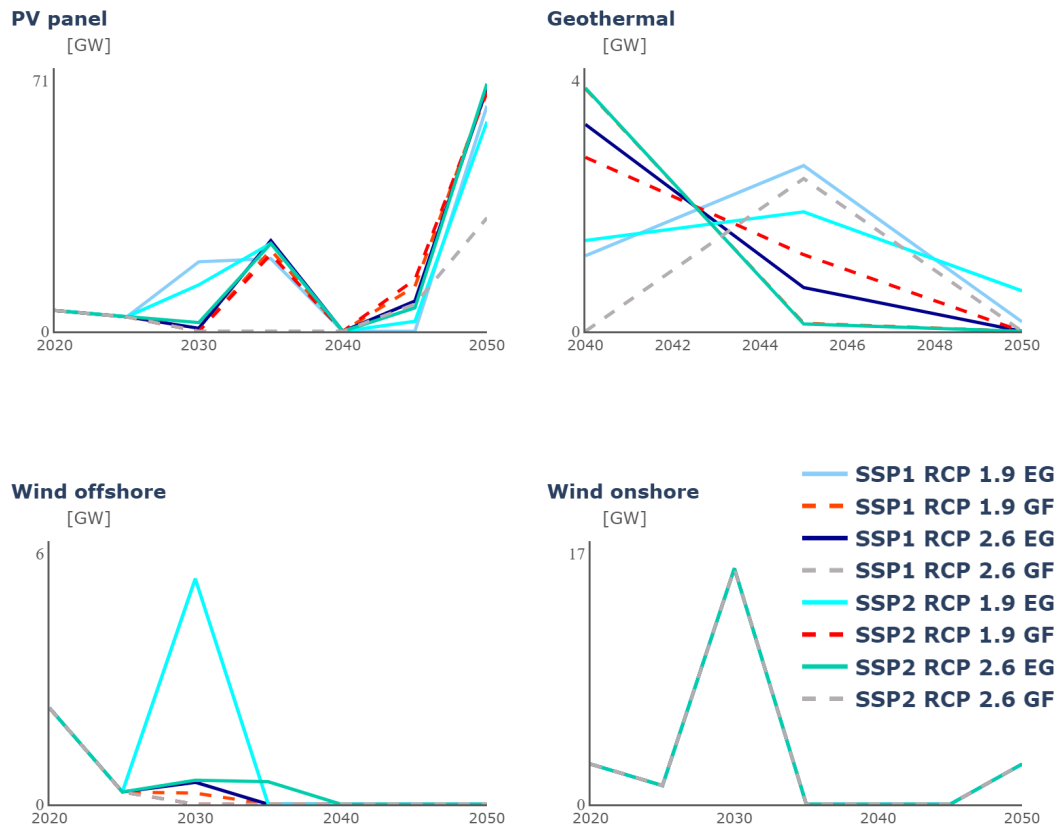


Figure A14: New capacity installed in electricity sector: Massive installation of PV towards the end of the transition, reaching 71 GW with the exception of the two limit cases (32 GW). The onshore wind installation schedule follows the same timeline regardless of the scenario. For geothermal energy, with the exception of the two limit cases, all scenarios reach 4 GW installed by 2050, but the implementation schedule varies. Offshore wind, which is expensive, is only installed if electricity demand requires it.

Mobility

With the exception of the two gray cases, the period from 2030 to 2035 marks the complete transition from diesel trucks to truck fuel cells. In the two limit cases, diesel is replaced by natural gas and hydrogen. This explains the deployment trends shown in Figure A15. By 2050, for all scenarios, freight transport by truck is entirely carried out by fuel cell trucks, and since the estimated lifespan is 15 years, a second peak is observable. The remainder of freight transport is carried out via trains as well as boats running on natural gas (not shown here). Rail transport remains at its maximum threshold of 25% of total freight transport demand due to the attractive cost of rail, explaining the uniformity of the trajectories. The

significant increase in freight transport demand from 2020 to 2025, followed by a more gradual rise through 2050, explains why new capacity continues to be added. No replacements are made because their lifespan is estimated at 40 years. Regarding private mobility, the full electrification of the vehicle fleet emerges as an essential lever for decarbonization. From 2025 to 2030, the complete replacement of the private vehicle fleet takes place, and since the lifespan of electric vehicles is estimated at 10 years, various peaks can be observed.

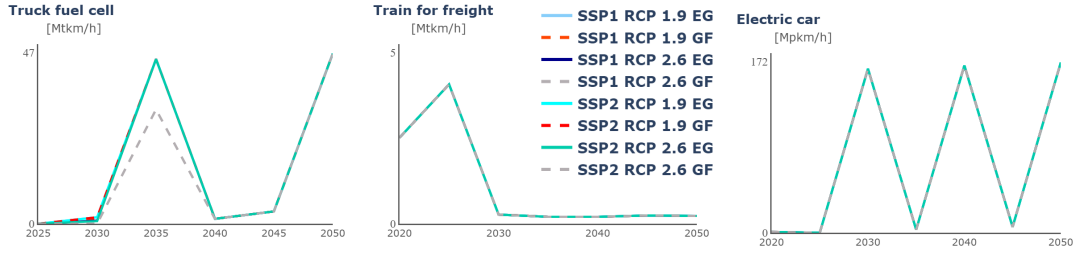


Figure A15: New capacity installed in mobility sector: Freight transport is a sector where various scenarios converge. Fuel-cell trucks are becoming the norm for road freight transport, while electric vehicles are becoming the norm for private transport. Rail transport is being utilized to its full potential throughout the transition due to its cost-effectiveness.

High temperature

All scenarios are initially powered by technologies that use high-carbon resources (LFO, gas, coal) and will subsequently shift toward the technologies shown in Figure A16, with an importance and speed that vary depending on the scenario considered. However, depending on the flexibility of the carbon budget, coal boilers may be maintained in varying quantities to achieve the optimal cost. It should also be noted that wood boilers are only transitional. This strategy stems from the limitation of the wood resource to 23 TWh/year, which is subsequently reallocated primarily to the production of HVC. This phase-out requires the sector to shift toward waste boilers, for which a massive installation peak is observed in 2040 across nearly all scenarios. In addition to this, electric resistance heaters are also installed, although the pace of their deployment depends directly on the severity of the carbon constraint. More specifically, the two extreme cases (shown in gray) rely largely on fossil fuel technologies during the transition, which explains why their new installed capacities for wood boilers, waste boilers, and direct electrification are lower than in the other scenarios. Conversely, the most ambitious scenarios (SSP1-RCP 1.9 EG and SSP2-RCP 1.9 EG) install wood and waste boilers from the start of the transition. For wood boilers, capacity will initially

increase, reflecting the fact that new installations will continue until they are phased out after 2035. Installations that have not reached the end of their lifespan (17 years, but installed in phase 1 and decommissioned in phase 4⁶) will then be decommissioned between 2040 and 2045. Waste boilers continue to be installed until 2040, thereby increasing the share generated via this technology. In both of these scenarios, electric resistors will eventually become the primary technology; they are therefore installed throughout the transition. The peak between 2040 and 2045 is due to the fact that the first resistors installed are reaching the end of their lifespan, and the trend continues afterward as the second batch also reaches the end of their lifespan. The other scenarios follow similar trends. Their mix in 2050 consists of waste boilers (explaining the peak between 2035 and 2040), direct electrification, and a small proportion of coal boilers.

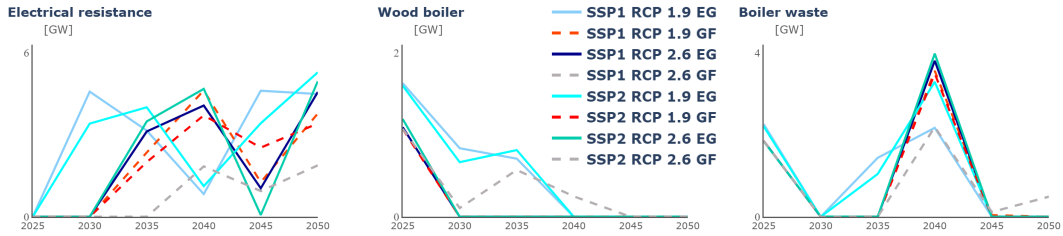


Figure A16: New capacity installed in high temperature sector. There are three types of cases: two ambitious scenarios in which the energy mix moves towards full direct electrification (electrical resistance), and a transition involving wood and waste boilers. Two limit cases (shown in grey), where the energy mix in 2050 still relies heavily on coal boilers, explaining the lower capacity of other technologies. And finally, intermediate scenarios which, by 2050, rely on waste boilers, with coal boilers in minority, and direct electrification.

Low temperature

The decarbonization of low-temperature heating relies on the widespread deployment of heat pumps (HPs), both centralized and decentralized [Figure A17]. This strategy is common to all scenarios, although gas-fired heat pumps will still be in use in 2050 regardless of the scenario (approximately 10% of total installed capacity). The use of electric resistors, meanwhile, is marginal. Given a technical lifespan of 18 years (considered installed in phase 1 and decommissioned in phase 4) for decentralized heat pumps, the model plans for replacement cycles for this

⁶Capacities are considered installed in the middle of the phase; thus, a capacity installed between 2020 and 2025 will be taken as 2022.5 and with a lifespan of 17 years, will be decommissioned in 2039.5 (at the end of the phase between 2035 and 2040).

equipment throughout the transition. The first units, installed between 2020 and 2025, will therefore reach the end of their service life between 2035 and 2040.

Concerning centralized production, the model complies with the imposed maximum production constraint (40% of low-temperature heat production). However, due to the capacity limit imposed before 2030 at 0.2 GW, the model cannot produce at maximum limit production. That explains the installation peak in 2030 reaching the upper limit of the production constraint. A divergence emerges, however, for the two limit scenarios (shown in gray): these limit the use of synthetic methanol. This choice therefore deprives the system of the waste heat normally recovered during methanation and synthesis processes, forcing the model to compensate for this thermal deficit by installing a larger number of heat pumps. Since their lifespan is 25 years, they will reach the end of their life cycle between 2050 and 2055, having been installed between 2025 and 2030, which explains why a second peak is not present in Figure A17.

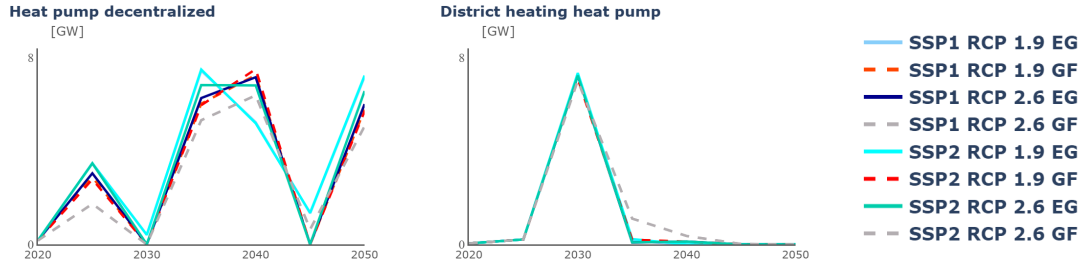


Figure A17: New capacity installed in low temperature sector: The decarbonisation of low-temperature heating relies on the deployment of heat pumps (HP), both centralised and decentralised. Decentralised HP will begin to be installed from the start of the transition but will follow a gradual growth, while centralised HP will follow a massive expansion between 2025 and 2030.

Appendix L Policies in 2035

The year 2035 marks the halfway point toward the 2050 goal. This appendix provides an analysis of the minimum capacities required for this intermediate step. This helps identify the necessary investments to be made in the short and medium term.

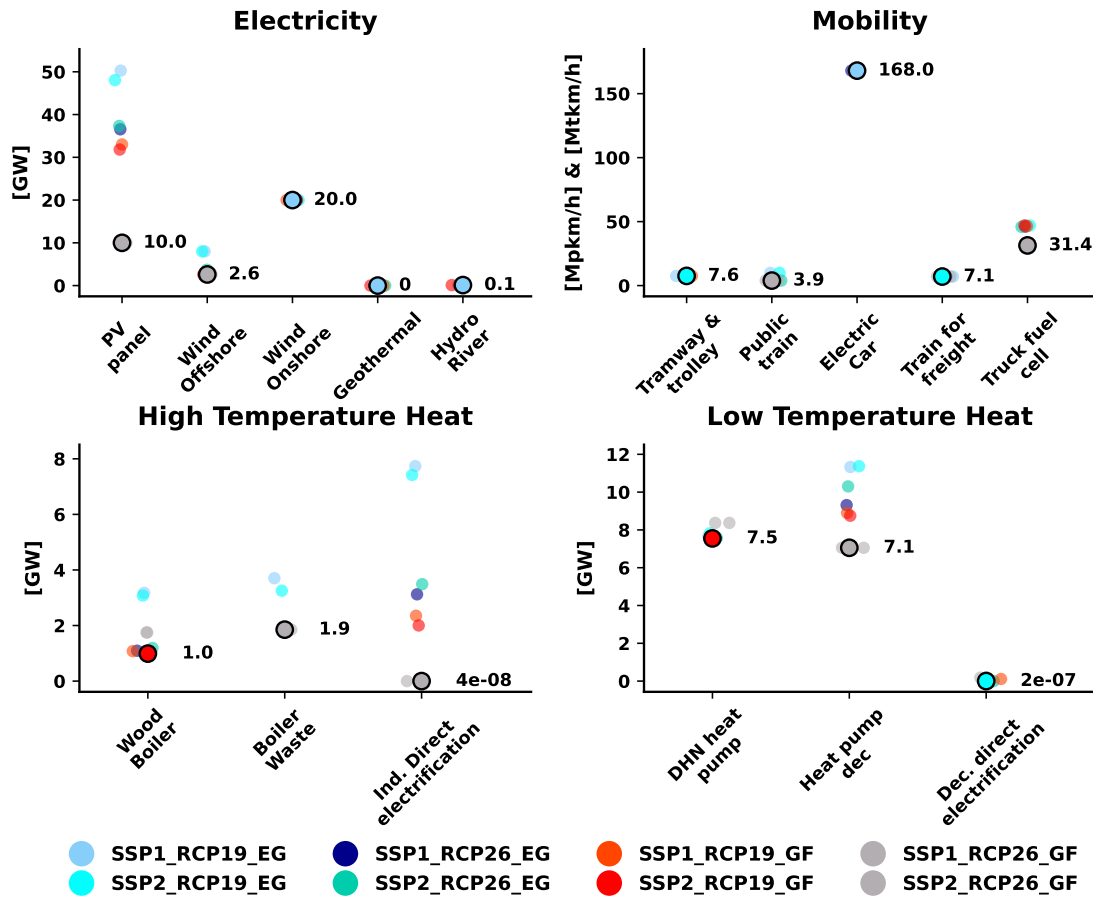


Figure A18: Baseline capacities in 2035

Electrical sector:

- Onshore wind: The model is already operating at the maximum permitted capacity of 20 GW. This shows that onshore wind power must be installed as quickly as possible.
- PV: The minimum target is 10 GW, Nevertheless, all ‘non-extreme’ scenarios exceed this (minimum 32 GW). This shows that a sustained rate of installation

is needed starting now.

- Offshore wind: Unlike in 2050, offshore wind has a minimum capacity of 2.6 GW here. Although this technology is very expensive, it is essential in the short term for rapidly decarbonizing the electricity mix, which means we must rely on costly technologies until other, cheaper technologies, take over.
- Geothermal: Its deployment is permitted only after 2035 (0 GW).
- Nuclear and SMRs [not shown]: Conventional nuclear power has reached its maximum capacity: 8 GW. SMRs can be deployed only after 2035.

Mobility sector:

The mobility sector is undergoing a radical transformation at a very early stage of the transition.

- Electric vehicles: The electrification of the private vehicle fleet is a top priority. The model sets a minimum target of 168 Mpkm/h from 2035, corresponding to the complete replacement of combustion-engine vehicles.
- Road freight: The shift towards hydrogen trucks (31.4 Mtkm/h) is beginning. 2035 marks the end of diesel in the truck freight sector, but some scenarios envisage an intermediate phase involving gas trucks before the switch to hydrogen.
- Public transport: Trams and trolleybuses are operating at full capacity (7.6 Mpkm/h), while rail transport is not yet highly developed (all scenarios still limit its potential, although this is not the case in 2050, when the scenarios diverge regarding its development). Rail freight is also operating at full capacity (7.1 Mtkm/h).

Heat sector:

- High Temperature (HT): The mix relies on waste boilers (1.9 GW) as well as wood boilers (1.0 GW). Unlike in 2050, when wood is phased out, it plays a crucial role here as a transition fuel to decarbonize industry rapidly. Direct electrification is not yet an absolute prerequisite (approx. 0 GW).
- Low Temperature (LT): The roll-out of heat pumps is already well underway. The minimum requirement stands at 7.1 GW for decentralized heat pumps and 7.5 GW for heat pumps in district heating networks. Between 2025 and 2035, district heating networks are expanding rapidly.

In conclusion, the 2035 policy framework highlights the importance of investing in low-carbon technologies to achieve Belgium's first step reduction targets. This is an intermediate step that must be achieved in order to continue the effort towards carbon neutrality by 2050.

Appendix M Detail about passenger mobility demand reduction

The Belgium Clever data are presented in Table A4. These data have been integrated into the model using a relative reduction methodology. This Appendix do a small comparison between Clever real data and the adapted Clever data in the model for the mobility sector. The Figure A19 shows the production related to electric cars [private mobility] while Figure A20 presents the consumption of public mobility thanks to the dedicated layer graph. The sum of the two consumption gives 35 Twh which is more than in Clever data (24.7 Twh).

Sector (TWh)	2015	2020	2025	2030	2035	2040	2045	2050
Residential	95.90	91.60	84.40	72.50	65.20	57.90	51.60	47.00
Tertiary	55.10	55.60	48.50	40.10	32.50	24.60	23.50	22.20
Industry	139.60	138.70	131.30	113.80	100.80	90.30	83.90	82.20
Domestic transport	103.20	102.40	83.50	57.80	41.30	31.50	26.70	24.70
Non energy	50.70	51.50	50.50	49.50	42.80	41.00	39.10	37.20

Table A4: Evolution of final demand per sector - Clever data [29]

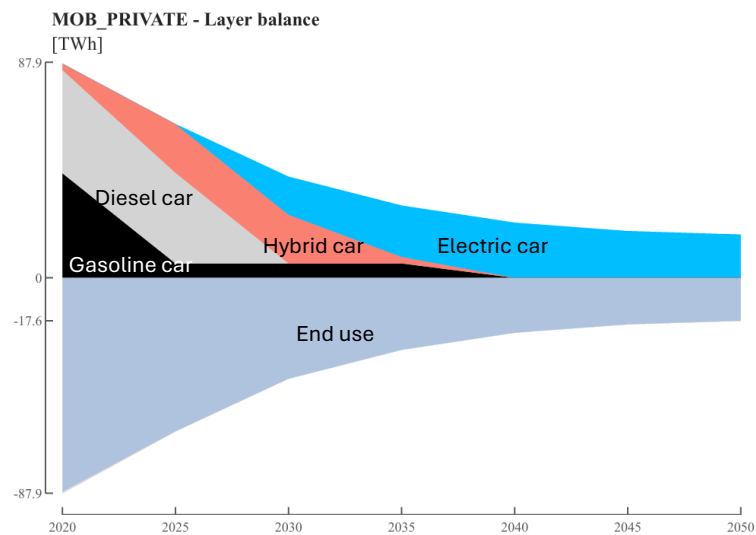


Figure A19: For the demand reduction case with 729 Mt of CO₂, the consumption in 2050 is 17.6 Twh.

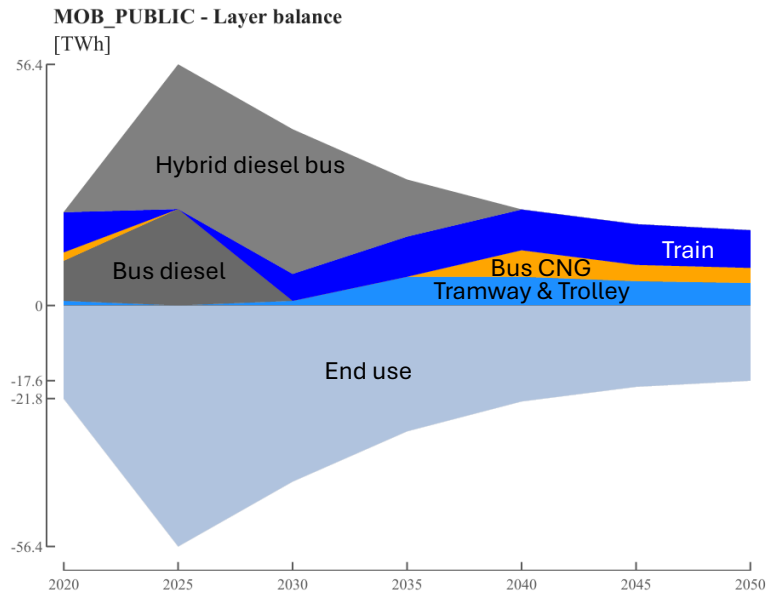


Figure A20: For the demand reduction case with 729 Mt of CO₂, the consumption in 2050 is 17.6 TWh.

Appendix N Explanation of the limited inertia of the system

To avoid changes that are too abrupt and unrealistic, constraints are built into the model. The Equation 21 and Equation 22, for example, prevent the model from unrealistically eliminating and replacing all low-temperature heating systems over a 5-year period.

The delta change (Equation 21) is equal to the difference between the production at the beginning of a phase - calculated by summing the total heat supplied by each technology - and the production at the end of the phase. Next, the constraint modeled by the Equation 22 applies the physical limit (i.e., 33%). On the left-hand side, the sum of all reductions from the low-temperature sector is calculated and must be less than the term on the right-hand side, representing the renovation limit applied to the total low-temperature heat demand (domestic hot water and space heating) at the start of the phase.

These two equations therefore require the model to account for a gradual replacement of technologies and a gradual increase in insulation, over several successive periods.

$$\Delta_{\text{change}}(p, i) \geq \sum_{t \in T | \{h, td\} \in T_H_TD} (\mathbf{F}_t(y_{\text{start}}, i, h, td)) - \sum_{t \in T | \{h, td\} \in T_H_TD} (\mathbf{F}_t(y_{\text{stop}}, i, h, td))$$

$$\forall j \in TECH, p \in PHASE, y_{\text{start}} \in Y_START(p), y_{\text{stop}} \in Y_STOP(p) \quad (21)$$

$$\sum_{euc \in EUT_OF_CAT(HeatLowT), i \in TECH_OF_EUT(euc)} \Delta_{\text{change}}(p, i) \leq \lim_{LT, ren} \cdot (eui(y_{\text{start}}, HotWater) + eui(y_{\text{start}}, SpaceHeat)) \quad (22)$$

Thus, this cap limits both technological upgrades (e.g., replacing a gas boiler with a heat pump) and reductions in energy demand (e.g., building insulation).

Appendix O Resources for Clever grandfathering scenario [966 Mt]

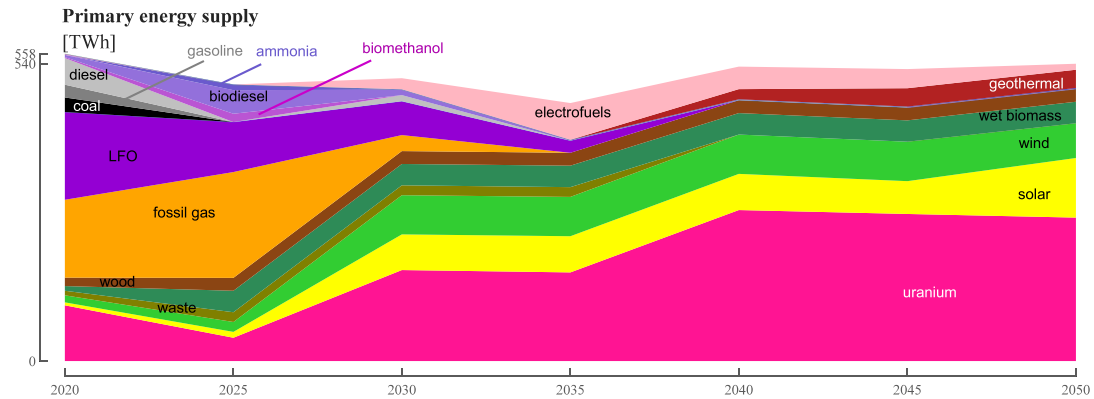


Figure A21: Primary energy supply remains roughly stable (558 to 540 TWh), but is shifting from fossil fuels to renewables. Starting in 2025, solar and wind power will expand to power low-temperature heating and public and private transportation. For sectors that are difficult to decarbonize, electrofuels are used, particularly to meet the demand for ammonia, for part of the methanol supply, or as a transitional solution for the hydrogen needed by freight trucks.

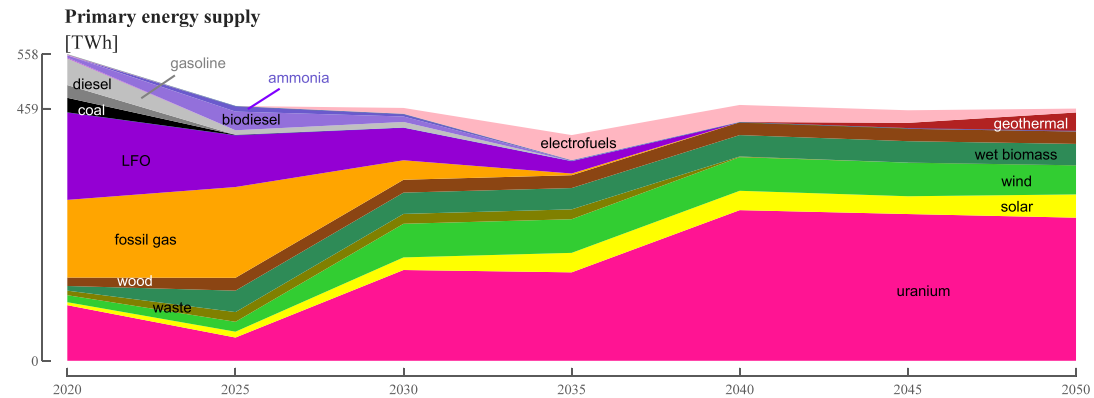


Figure A22: Under the sufficiency scenario applied to grandfathering case, primary energy consumption falls from 558 TWh in 2020 to 459 TWh in 2050. Compared to the baseline scenario, the least expensive fossil fuels - oil and gas - are used for longer. Due to lower demand, the use of solar and wind energy, as well as imported electrofuels, declines. Wet biomass and wood are retained for the production of low-emission gas, methanol, and HVC. *Note* : electrofuels refers to imported renewable H₂, ammonia, gas and methanol.

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Declaration of AI usage

For this work, several artificial intelligence (AI) tools were utilized to assist with literature review and writing. Initially, ChatGPT and NotebookLM were used to identify relevant sources. During the writing phase, Gemini and ChatGPT were used to suggest rephrasing of paragraphs. Finally, a comprehensive review of the text was conducted using Gemini to correct spelling and typographical errors. The author, however, assumes full responsibility for the final content of this work.

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