UCLouvain

École polytechnique de Louvain

Exploring sufficiency scenarios pathways towards 2050 for Belgium, using EnergyScope Pathway

Author: **Margaux Hanut**
Supervisor: **Hervé Jeanmart, Sébastien Meyer**
Reader: **Xavier Rixhon, Martin Colla, Sylvain Quoilin**
Academic year 2024–2025
Master [120] in Mechanical Engineering

Abstract

Sufficiency refers to reducing energy demand by focusing on meeting essential needs. It offers several advantages for achieving carbon neutrality, as planned by the European Union. This work was carried out in collaboration with negaWatt Belgium, an organisation that promotes sufficiency as a cornerstone of a fair and sustainable energy transition. The following research was conducted with this perspective in mind.

This study aims to explore a scenario that integrates sufficiency. To do so, two pathways are analysed: the reference and the Clever one, which incorporates sufficiency. The reference scenario is based on projections from the European Commission, while the Clever scenario is an adaptation of the original CLEVER scenario coordinated by the négaWatt France association. Here, a distinction is made between the scenario developed in this study, referred to as "Clever," and the scenario developed by negaWatt, referred to as the "original CLEVER" scenario. The Clever and reference scenarios are the result of optimisation using the EnergyScope Pathway model. This model provides a comprehensive view of the energy transition and allows for the analysis of its dynamics over the 2025–2050 period. One strength of this work is that both scenarios start in 2025, making the baseline year closely aligned with the current situation.

The Clever scenario is based on a significant reduction in demand, providing greater flexibility with respect to the total emissions limit. It ends up being relatively more carbon-intensive than the reference scenario. This stems from the model being built on cost optimisation. The increased flexibility in Clever leads to the selection of cheaper but more polluting resources.

The Clever scenario was then modified to comply with lithium extraction limits, which were previously exceeded. As a result, the number of electric vehicles was limited, and alternative solutions such as fuel cell and natural gas vehicles were used.

Subsequently, the infrastructure costs of the vehicles were integrated into the model. This addition helped nuance the economic advantage of electric vehicles and brought to light the economic viability of alternative vehicle options.

Since EnergyScope Pathway relies on cost optimisation, environmental objectives take a secondary role to economic ones. However, a more comprehensive integration of sufficiency must also include these environmental goals, along with factors such as appropriate policies, collective actions, and behaviour change.

Acknowledgments

I would like to express my sincere gratitude to the people who supported me throughout the writing of this thesis.

I would first like to thank Prof. Hervé Jeanmart for his guidance in helping me define my research topic, for encouraging me to ask critical questions, and for helping me develop a more analytical mindset.

I also wish to thank Sébastien Meyer for closely following my work, offering valuable advice, and engaging in many insightful discussions that greatly enriched this project.

My thanks also go to Xavier Rixhon, who helped me to understand how EnergyScope Pathway works and also helped me to go beyond the results obtained.

I would like to thank Tareen Muhammed Umair of ULiège for discussing the current data and helping me to complete my database.

I would also like to acknowledge the responsible use of assistive AI tools during the proofreading process of this manuscript.

Finally, a heartfelt thank you to my father and my brother for their support and assistance in proofreading my writing.

List of abbreviations

BEV Battery Electric Vehicle

CAPEX Capital Expenditures

CCGT Combined Cycle Gas Turbine

OPEX Operating Expenditures

CNG Compressed Natural Gas

DHN District Heating Network

EU European Union

EUD End-Use Demand

EV Electric Vehicle

GWP Global Warming Potential

HEV Hybrid Electric Vehicle

HVC High-Value Chemicals

LFO Light Fuel Oil

LULUCF Land-Use, Land Use Change and Forestry

NG Natural Gas

NRE Non-Renewable Energy

PHEV Plug-in Hybrid Electric Vehicle

RE Renewable Energy

VRE Variable Renewable Energy

Contents

Abstract i

Acknowledgement ii

List of abbreviations iii

1 Background 3
- 1.1 Focus on previous research . . . 3
- 1.2 Sufficiency . . . 4
  - 1.2.1 What is sufficiency? . . . 4
  - 1.2.2 Why sufficiency? . . . 4

2 Literature review 6
- 2.1 Existing scenarios . . . 6
  - 2.1.1 Presentation of existing scenarios . . . 6
  - 2.1.2 Summary of sectors included in the scenarios . . . 9
- 2.2 Comparison of existing scenarios . . . 10
  - 2.2.1 Energy demands comparison . . . 11
  - 2.2.2 VRE capacities comparison . . . 12
  - 2.2.3 Flexibility capacities in electricity grid comparison . . . 13

3 Methodology 15
- 3.1 Presentation of case studies . . . 15
  - 3.1.1 Reference scenario . . . 15
  - 3.1.2 Clever scenario . . . 16
- 3.2 Cost of vehicle infrastructure . . . 19

4 Results 21
- 4.1 Impact of demand reduction: Clever vs reference scenario . . . 22
  - 4.1.1 Reduction rates across both scenarios . . . 22
  - 4.1.2 Analysis of resource allocation . . . 23

4.1.3 GWP emissions per sector 28
4.1.4 Evaluation of the total cumulative cost of the transition 30
4.1.5 Assessment of the cumulative investment costs 31
4.2 Impact of the lithium constraint on the Clever scenario 34
4.2.1 Installed capacity overview 34
4.2.2 Evaluation of the total cumulative cost of the transition 35
4.2.3 Analysis of resource allocation 36
4.2.4 GWP emissions per sector 37
4.3 Result including vehicle infrastructure costs 38
4.3.1 Impact on the choice of technology 38
4.3.2 Consequences for annual system costs 38
4.3.3 Effect on the installed capacity of the infrastructure 39
4.3.4 Total cumulative cost for the Clever scenario with lithium constraints 40

5 Discussion **41**
5.1 The Clever scenario 41
5.1.1 Challenge in integrating sufficiency into the Clever scenario using EnergyScope Pathway 41
5.1.2 Comparison of trajectories with the newly developed Clever scenario and the original CLEVER scenario 43
5.2 The lithium constraint 45
5.2.1 Compliance with environmental limits for lithium in the Clever scenario and the role of vehicle occupancy 45
5.2.2 Economic impact of the lithium constraint 45
5.2.3 Benefits of the lithium constraint in the Clever scenario 46
5.3 Trends in transport infrastructure 47
5.3.1 Focus on infrastructure for NG cars 47
5.3.2 Focus on infrastructure for fuel cells cars 48
5.3.3 Comparison of results obtained with current trends 48
5.4 Discussion on biomass potential in EnergyScope Pathway 50
5.4.1 Primary energy mix under realistic wet biomass 51
5.5 Putting the results into perspective with the literature 52
5.5.1 Limits of the model used 52
5.5.2 Positioning the proposed scenarios in the landscape of existing scenarios 53

A Model description **58**

B Vehicle infrastructure constraints **61**

Introduction

The EU (European Union) has committed to achieving carbon neutrality by 2050. This study explores two different scenarios for reaching this objective in Belgium: the reference scenario and the Clever scenario. The latter incorporates the concept of sufficiency.

Sufficiency involves setting ambitious reductions in future energy demand. This approach considers that technological progress will play a crucial role in achieving this goal. However, it will not be sufficient on its own; collective actions and behavioural changes are also essential. This study is conducted in collaboration with negaWatt Belgium. According to this association, sufficiency is the first and most fundamental step towards carbon neutrality, as shown in figure 1. Then, negaWatt shows that the energy transition will also rely on efficiency and the integration of renewable energy (RE) sources [1].

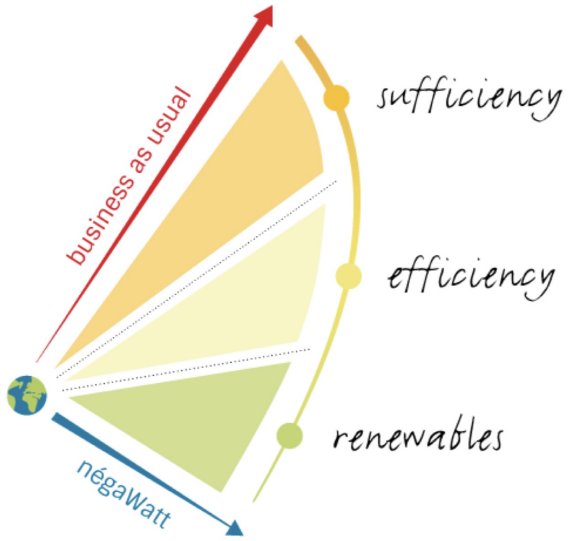

Figure 1: negaWatt's approach [1]

The EnergyScope Pathway model is used to generate the scenarios. It provides a comprehensive view of the energy transition and captures the pace of change in resource

consumption. The reference scenario is based on projections from the European Commission and serves as the baseline [2]. The Clever scenario developed here is an adaptation of the original CLEVER scenario coordinated by negaWatt France [3]. In this study, the adapted version is referred to as "Clever," while the negaWatt scenario is referred to as the "original CLEVER" scenario. It assumes a significant reduction in energy demand. This reduction strongly influences resource choices and the speed of transitions determined by the model. The EnergyScope Pathway is based on cost optimisation. This characteristic will therefore also influence the resource choices in the Clever scenario.

The Clever scenario, in addition to including major assumptions about demand reduction, also incorporates environmental objectives. To best meet these objectives, a case study will be conducted with a limited number of EVs (electric vehicles) in order to respect lithium extraction limits. This limit is based on a lithium extraction cap for the EU and then reduced and calculated for Belgium. In this case study, alternative technologies to EVs will be highlighted, as well as their impact on the cost of the transition, on dependency toward other countries, and on equity gains. The choice of these alternative technologies will be greatly influenced by their cost. For this reason, special attention will be given to the infrastructure costs of the vehicles used.

In summary, two scenarios are studied and developed here using the EnergyScope Pathway model. The central focus of this study is to examine how sufficiency will impact the energy transition and the resource choices made by the EnergyScope Pathway model.

Chapter 1

Background

1.1 Focus on previous research

This work builds on the research initiated in the master dissertations of Hugo Baudson and Pierre Verstraeten. This research serves as a starting point for this study.

Hugo Baudson's research focused on analysing Belgium's energy demand in detail, by sector and by need [4]. To optimise the energy system for the 2050 horizon, the EnergyScope Typical Days snapshot model was used. This model optimises the energy system for a target year. The assumptions of his work included carbon neutrality and a 100% RE mix by 2050. The complete phase-out of nuclear energy by 2050 was also assumed. The focus was placed on local renewable potentials, with an unlimited possibility of importing e-fuels or fossil fuels.

Pierre Verstraeten's work then extended the work of Hugo Baudson, but this time with a specific focus on the industrial sector [5]. The study outlines different potential evolutions for this sector. Industrial emissions were counted using a territorial approach, as opposed to the 'carbon footprint' approach used in Baudson's work. Energy system optimisation was also carried out using the EnergyScope Typical Days snapshot model. In this optimisation, special attention was paid to potential energy savings, distinguishing between reduced consumption, material substitution, recycling, and the energy efficiency of processes.

The aim of this work is to extend the previously mentioned studies. This time, the EnergyScope Pathway model is used [6]. This method provides a fast computational optimisation tool for exploring various energy transition scenarios across the entire energy system. It extends a snapshot model into a pathway model by integrating a linear formulation that captures the system's evolution over time. Specifically, it divides

transition scenarios into 5-year phases, allowing for a step-by-step analysis of energy pathways. The key advantage of this approach is its ability to offer insights into the evolution of the energy system between these phases. Another feature of this research is the incorporation of sufficiency into the scenarios. The next section defines sufficiency and explains why its inclusion is important.

1.2 Sufficiency

1.2.1 What is sufficiency?

Sufficiency should not be confused with efficiency. While both involve reducing energy demand, they do so through different means. Efficiency relies on technological advancements that reduce resource use. On the other hand, sufficiency focuses on meeting people's needs to ensure a good quality of life. It does so by narrowing down to more essential needs, thereby reducing overall demand and resource consumption [7]. To illustrate this concept, consider the following example: a typical person goes to work. What sufficiency levers can be applied in this context? They might take public transportation, live closer to their workplace, or use car sharing.

Sufficiency therefore leads to significant societal and behavioural changes. This requires structural changes, such as: adequate public transport infrastructure that is accessible and affordable for all, vehicles adapted to specific needs, shared living spaces, services, and workplaces closer to homes, better quality clothes, and other measures that contribute to a more sustainable lifestyle [3]. To make these changes feasible, they must be supported and encouraged by policies aligned with these concepts.

1.2.2 Why sufficiency?

There are several reasons why Belgium, and more globally the EU, would benefit from adopting sufficiency [7].

The first reason is that by reducing demand and the need for resources, Belgium would become less reliant on imports. Consequently, this would offer greater resilience. This issue is especially relevant today and has already become a significant concern. In 2022, with the war in Ukraine, natural gas (NG) prices surged, triggering an energy crisis. This highlighted Belgium's current energy dependence and the price instability associated with it.

The second reason is economic. Sufficiency helps reduce costs by cutting resource consumption and minimising waste. This, in turn, reduces the need for investments in

unnecessary infrastructure, and instead promotes the reindustrialisation of the country by focusing on more strategic sectors. As a result, Belgium could become more competitive in certain industries.

The next reason is that by focusing on essential and vital needs, it becomes easier to meet everyone's needs. This, in turn, helps ensure a better quality of life for society as a whole and fosters greater equity.

The final reason is that by reducing our consumption of resources and energy, it becomes easier to meet the climate targets set by the EU. This significantly increases the likelihood of achieving decarbonisation goals. Additionally, it becomes easier to remain within planetary boundaries.

By way of a brief conclusion, sufficiency is increasingly recognised as an essential lever for meeting the challenges of sustainability. A growing number of scientific articles refer to it. The concept was even highlighted in a recent IPCC report [8], underlining its growing importance in global climate discussions.

Chapter 2

Literature review

2.1 Existing scenarios

Before developing the scenarios analysed in this study, it is useful to review existing scenarios in the literature aiming for carbon neutrality in Belgium by 2050. These include the McKinsey, EnergyVille (Central), EnergyVille (Shift), Elia (Electrification), CLEVER, Climact PAC2.0 and BEHAVIOUR scenarios.

2.1.1 Presentation of existing scenarios

McKinsey scenario

McKinsey's scenario is based on a large-scale energy transition [9]. Firstly, a reduction of more than 50% in primary energy demand is expected. The McKinsey scenario is for a transition starting in 2019 and ending in 2050. This scenario relies on improvements in energy efficiency and electrification to achieve the targeted reduction. Interestingly, as this scenario relies heavily on electrification, electricity demand is expected to double. This will also require significant investment to build new infrastructure and technologies. This, in turn, is expected to significantly reduce energy imports, leading to greater energy independence for Belgium. At present, Belgium produces only 5% of its energy consumption. By 2050, the scenario envisages that Belgium will produce 50% of its energy needs through the development of REs and an overall reduction in demand. At the end of the transition, this scenario envisages the complete elimination of fossil fuels. Note that this scenario does not include maritime (national and international) or aviation transport.

Energyville (Central) scenario

The Energyville (Central) scenario envisions a balanced approach at all levels, integrating various technological options such as energy efficiency, fuel substitution, electrification, the use of synthetic molecules like hydrogen, and carbon removal technologies [10].
Additionally, several key assumptions have been made for this scenario. First, the CO_2 price is set higher than its current level, reaching 350€ per ton CO_2 by 2050, in alignment with the European Fit for 55 model [11]. In the industrial sector, production levels are assumed to remain the same, considering planned investments. An exception is made for refineries, where production is expected to decline as fossil fuel demand decreases.
Population growth will drive higher energy demand in the residential and transport sectors. However, in the residential sector, building renovations are modelled, leading to a reduction in heating demand. The model assumes that the current nuclear capacity will be extended by 10 years, from 2025 to 2035. No further investments in nuclear energy will be made after 2025. A significant increase in RE production is also projected, especially for sources with high technical potential.
An exogenous assumption in the model is the expansion of electricity interconnection capacity, rising from 6.5 GW in 2020 to 13 GW by 2040, in line with Ten-Year Network Development Plan (TYNDP) scenarios [12]. The TYNDP, drafted biennially by ENTSO-E[1] (and a similar one by ENTSO-G [2]), evaluates future transmission and storage projects based on cost-benefit, socio-economic, and environmental criteria. After consultations, the European Commission adopted this model.
The Energyville (Central) scenario does not take into account the international maritime transport sector, aviation, or Land-Use, Land Use Change and Forestry (LULUCF)[3]. Nevertheless, it does consider the costs of modernising electrical infrastructure and hydrogen-related infrastructure.

Energyville (Shift) scenario

The key feature of EnergyVille's (Shift) scenario is the reduction of final energy demand through systemic changes in the transport, residential, and industrial sectors [10]. This scenario integrates behavioural changes in transportation. It assumes a doubling of public transport use and a significant increase in active mobility (walking and cycling).
Additionally, it plans a structural transformation in the industrial sector by transitioning to a more circular economy. This leads to higher rates of recycling, reuse, and product repair. The scenario also considers a reduction in living space per person, lowering energy demand in the residential sector. These combined assumptions result in an overall decrease in energy demand, thereby also reducing the need for additional RE capacity.

[1] European Network of Transmission System Operators for Electricity
[2] European Network of Transmission System Operators for Gas
[3] LULUCF : accounts for carbon emissions and sequestration from forest and agricultural ecosystems

This scenario builds on the EnergyVille (Central) scenario. It adds the option to invest in 16 GW of additional offshore wind in the North Sea starting from 2030 onward. Notably, societal shifts of this kind are already integrated into national strategies and the EU's Circular Economy Action Plan (CEAP).
Like the central scenario, the Energyville (Shift) scenario does not take into account international maritime transport, aviation transport and the LULUCF sector.

Elia (Electrification) scenario

The Elia (Electrification) scenario forecasts a decarbonisation of Belgium by 80-95% by 2050 [13]. To achieve the decarbonisation, the scenario relies mainly on electrification. This will lead to a significant increase in the production of RE. What is somewhat surprising, compared with other scenarios also based on electrification, is the absence of any forecast for an increase in electricity demand. This is linked to the assumptions concerning e-energy efficiency considered by the Elia (Electrification) scenario. As RE production increases, the scenario shows a growing need for energy storage and therefore a significant increase in infrastructure costs.
The scenario explores various short-term options for maintaining security of supply. It assumes a nuclear phase-out in 2025, but provides for sufficient replacement capacity to ensure grid stability.
The Elia (Electrification) scenario does not take into account maritime transport (domestic and international), aviation transport, the agricultural sector or the LULUCF sector.

CLEVER scenario

The 'Collaborative Low Energy Vision' (CLEVER) scenario is a European collaboration involving 20 countries, coordinated by the négaWatt France association [3]. As presented by négaWatt France, the scenario is built around three key pillars of the energy transition (see figure 1): sufficiency, efficiency, and REs. In other words, the transition is driven by demand reduction through societal behaviour changes and technological improvements that further reduce demand. The remaining demand is then supplied with RE sources. One of the most important levers for achieving neutrality and sustaining sufficiency in this scenario is electrification.
The CLEVER approach is based on the Doughnut Economics theory [14]. In this context, the CLEVER scenario achieves carbon neutrality with a 100% RE mix, without relying on carbon capture technologies, nuclear energy, or imports from non-EU countries. This scenario starts in 2015 and ends in 2050. The values for 2015 are historical values, and the other years are predicted values. Nevertheless, the 2020 values are close to the actual EUROSTAT data.
Instead of applying the same EUD (End-Use Demand) reduction to all countries, CLEVER sets upper and lower limits, corridors, that nations should strive for. Higher-

consuming countries must reduce more, while some low-consuming nations may even increase their usage if below the lower limit. This approach ensures a fair transition, preventing wealthier countries from gaining an advantage. Fairness is key to CLEVER's vision. It should be noted that only the scenario for Belgium is examined here. In the next sections of this report, this scenario will be referred to as the original CLEVER scenario. This scenario does take maritime and aviation transport, as well as the agriculture and LULUCF sectors, into account.

Climact PAC2.0 scenario

The first PAC scenario was developed by Climate Action Network (CAN) Europe and the European Environmental Bureau (EEB) [15]. The PAC 2.0 scenario, later released and designed by Climact, aims to provide a national scenario for each EU member country. In this work, only the Belgian scenario is considered. It aligns with the Paris Agreement, aiming to keep global warming well below 1.5°C, with a 65% reduction in GHGs by 2030 and carbon neutrality by 2040. It assumes a 100% RE-based energy system by 2040.
This scenario focuses on efficiency, sufficiency, REs, and transforming energy infrastructure to support a decentralised, flexible system. It also addresses the cost of transition by integrating macroeconomic indicators and infrastructure needs.
It includes sectors such as industry, buildings, transport, and agriculture, but excludes international maritime transport.

BEHAVIOUR scenario

The BEHAVIOUR scenario is a scenario developed by the FPS Public Health using Climact's 2050 Pathway Explorer [16]. As its name suggests, this scenario is based on behavioural changes, such as transformational shifts in mobility, housing, and dietary habits. The scenario starts in 2015 and ends in 2050. By 2050, it achieves a demand reduction of -52% compared to 2015. To reduce emissions and eliminate fossil fuels, the scenario relies on significant electrification as well as carbon-neutral fuels. This scenario also foresees a decrease of more than 50% in metal demand. While the scenario leads to additional investment costs, these are mitigated through behavioural changes and the development of a circular economy.
The BEHAVIOUR scenario includes all sectors of interest except international maritime transport.

2.1.2 Summary of sectors included in the scenarios

Table 2.1 provides a summary of the sectors considered in all the previously presented scenarios.

Scenario	Power	Industry	Domestic Transport	Maritime Transport (Domestic)	Maritime Transport (International)	Aviation Transport	Agriculture	Residential & Tertiary	LULUCF
McKinsey	V	V	V	X	X	X	V	V	V
Energyville (Central)	V	V	V	V	X	X	V	V	X
Energyville (Shift)	V	V	V	V	X	X	V	V	X
Elia (Electrification)	V	V	V	X	X	X	X	V	X
CLEVER	V	V	V	V	V	V	V	V	V
Climact PAC 2.0	V	V	V	V	X	V	V	V	V
BEHA-VIOUR	V	V	V	V	X	V	V	V	V

Table 2.1: Summary table of sectors taken into account in the scenarios

2.2 Comparison of existing scenarios

A comparison will be conducted between the various scenarios available in the literature. The Climact PAC2.0 scenario is excluded due to insufficient data.

2.2.1 Energy demands comparison

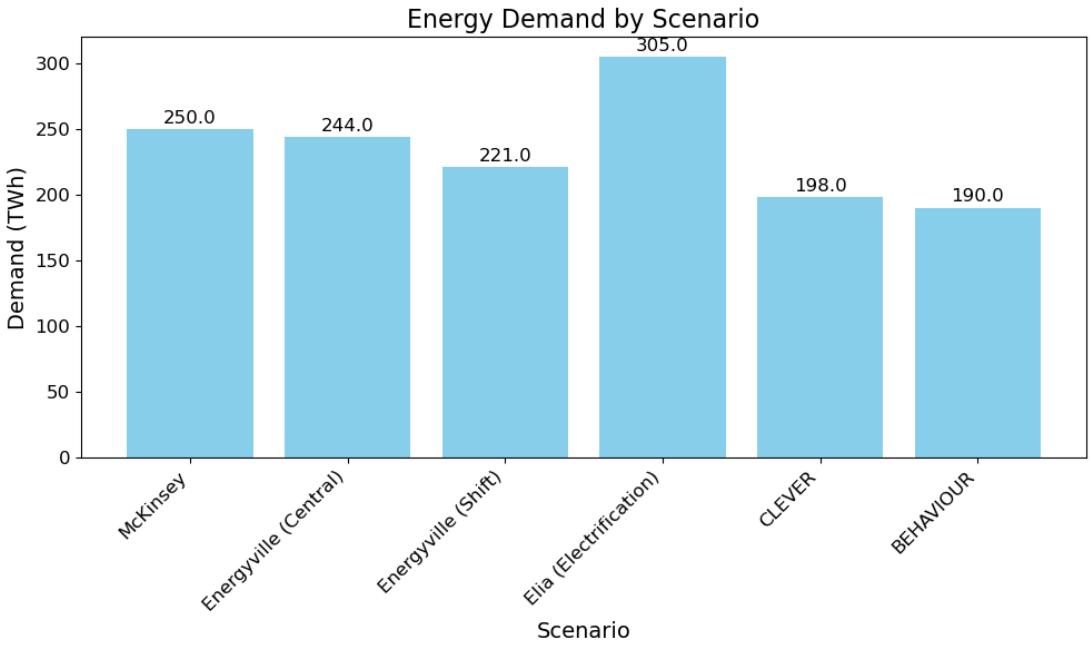

Figure 2.1: BEHAVIOUR, CLEVER, and the EnergyVille (Shift) scenarios have the lowest final energy demands due to their sufficiency assumptions.

The figure 2.1 shows the final energy demand for the different scenarios. The demand for the Elia (Electrification) scenario is projected to reach 305 TWh. It is the scenario with the highest final energy demand. Moreover, as the Elia (Electrification) scenario excludes some sectors, the increase is even more pronounced than shown in figure 2.1 when all are considered.

The CLEVER and BEHAVIOUR scenarios have the lowest final energy demands, at 198 TWh and 190 TWh respectively. This reflects the importance they place on demand reduction and therefore the significance of sufficiency within these approaches. Furthermore, the demand in the Energyville (Shift) case (221 TWh) lies between the CLEVER and Energyville (Central) ones (244 TWh). This result is predictable, as Energyville (Shift) mainly differs from Energyville (Central) in its sufficiency assumptions. Finally, the McKinsey scenario shows a final energy demand of 250 TWh.

2.2.2 VRE capacities comparison

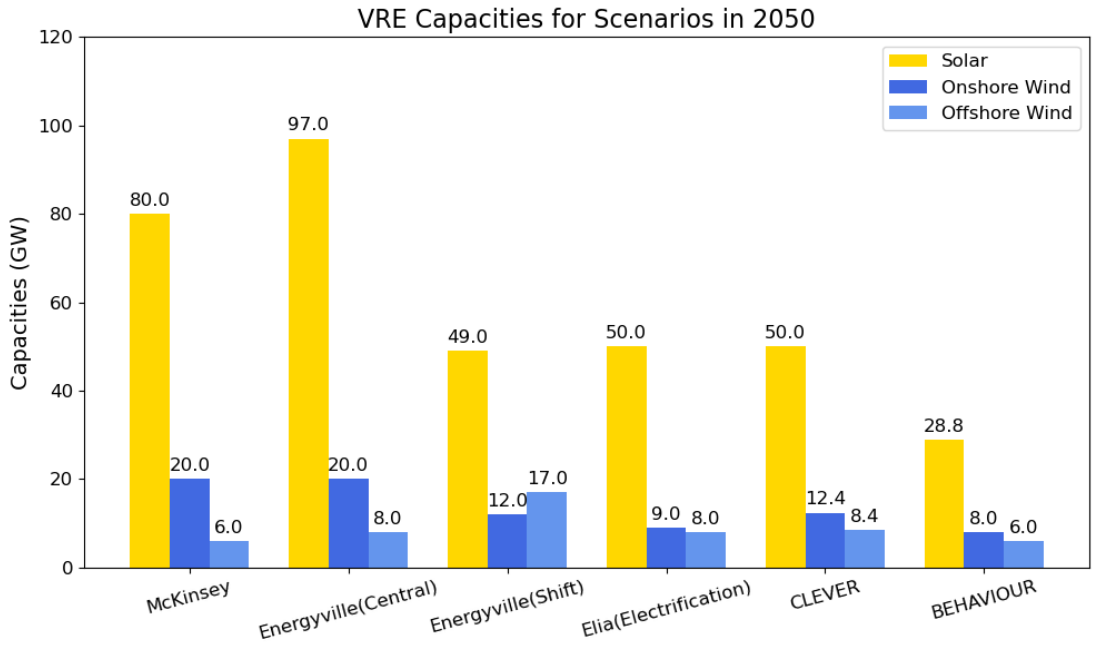

Figure 2.2: Comparison of installed capacity for solar, wind offshore and wind onshore

This section analyses the Variable Renewable Energy (VRE) capacities of the different scenarios (see figure 2.2).

Solar capacities

The highest solar capacity is found in EnergyVille (Central), with 97 GW of solar energy. McKinsey also has a relatively high installed capacity. EnergyVille (Shift) and CLEVER have lower capacity due to their incorporation of sufficiency. Elia (Electrification) also has low solar capacity, as it does not forecast any increase in electricity demand. At an even lower level is BEHAVIOUR, with 28.8 GW of installed solar capacity. This is due to its integration of sufficiency through structural, systemic, and behavioural changes, leading to reduced demand. As seen previously, this approach results in the lowest final energy demand. The lower solar capacity is also partly explained by the allowance for 20% to 30% electricity imports, resulting in less installed capacity for the BEHAVIOUR scenario.

Wind onshore capacities

The highest onshore wind capacity is found in McKinsey and EnergyVille (Central), both reaching 20 GW, consistent given the lack of sufficiency assumptions in these scenarios. Capacities in EnergyVille (Shift) and CLEVER are relatively similar, both around 12 GW, due to their sufficiency assumptions. Elia (Electrification) shows a lower capacity level, as it does not project an increase in electricity demand. BEHAVIOUR is roughly at the same level as Elia (Electrification) due to its lower final energy demand and the possibility of importing part of its electricity.

Wind offshore capacities

The trend is reversed for offshore wind. McKinsey and EnergyVille (Central), with the highest onshore wind capacities, have among the lowest offshore wind capacities, at 6 GW and 8 GW respectively. The highest offshore wind capacity is found in EnergyVille (Shift), at 17 GW, consistent with its assumptions, including the option to invest in an additional 16 GW in the North Sea from 2030. As for the others, Elia (Electrification) and CLEVER both have relatively similar offshore wind capacities, around 8 GW. BEHAVIOUR has the lowest installed capacity, at 6 GW.

2.2.3 Flexibility capacities in electricity grid comparison

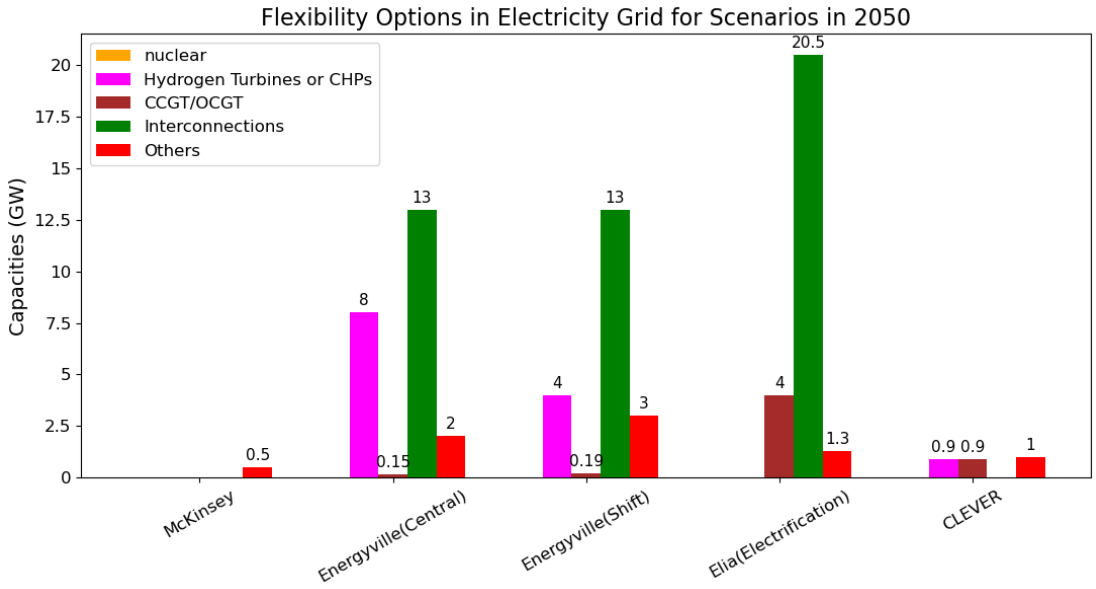

Figure 2.3: Scenario flexibility capacities in electricity grid comparison

In the figure 2.3, a comparison of different flexibility and production technologies across the various studied scenarios can be observed. The BEHAVIOUR scenario is not represented due to the lack of information on these technologies.

Interconnection technologies

For interconnection technologies, the capacity level is higher in the Elia (Electrification) scenario. These capacities exceed those in the other cases because this one relies on electricity imports and exports to balance supply and demand. This approach offers greater flexibility during the transition, but also increases dependence on other countries. This explains the higher interconnection capacity in Elia (Electrification). The CLEVER and McKinsey pathways have 0 GW of interconnections. They aim to reduce electricity imports and achieve greater energy autonomy.

Nuclear energy phase-out

The figure 2.3 also shows all scenarios have phased out nuclear energy.

Hydrogen turbines and CHPs

Regarding Hydrogen Turbines and CHPs (Combined Heat and Power plants), the installed capacities are:

- 8 GW in the Energyville (Central),
- 4 GW in Energyville (Shift),
- 0.9 GW in CLEVER,
- The other scenarios do not use this technology.

Hydrogen turbines are used to produce electricity, while CHPs generate both heat and electricity simultaneously. Both technologies use hydrogen as a fuel. Scenarios incorporating these technologies assume significant development of hydrogen production and storage infrastructure.

CCGT and OCGT technologies

Finally, regarding CCGT (Combined Cycle Gas Turbine) and OCGT (Open Cycle Gas Turbine) technologies, these are used for electricity production. They help ensure grid stability, as REs are inherently intermittent. All scenarios use this technology to varying degrees, except for the McKinsey scenario. Elia (Electrification) relies on it the most, with 4 GW of capacity. CLEVER integrates 0.9 GW, while EnergyVille (Shift) and EnergyVille (Central) report only 0.19 GW and 0.15 GW, respectively.

Chapter 3

Methodology

This study, conducted in 2025, faces an initial challenge as the EnergyScope Pathway simulations originally started in 2020. As a consequence, the values for 2025 were already projections. These projections no longer reflect current realities. To address this issue, the most recent available data had to be gathered. The latest data obtained corresponds to the year 2023. EnergyScope Pathway is a phased model, with each phase representing a five-year period. Previously, the model covered the period from 2020 to 2050. To facilitate the integration of 2023 data, 2023 is assumed to be representative of 2025. As a result, the model now starts in 2025 and runs through to 2050.

3.1 Presentation of case studies

Two case studies are examined here to demonstrate the potential and limitations of a sufficiency-based scenario developed with the EnergyScope Pathway model. These are the reference and Clever scenarios.

3.1.1 Reference scenario

The reference scenario assumes that no effort is made to achieve sufficiency. It serves as the baseline, drawing on projections from the European Commission [2]. The figure 3.1 shows the primary energy supply for this reference case.

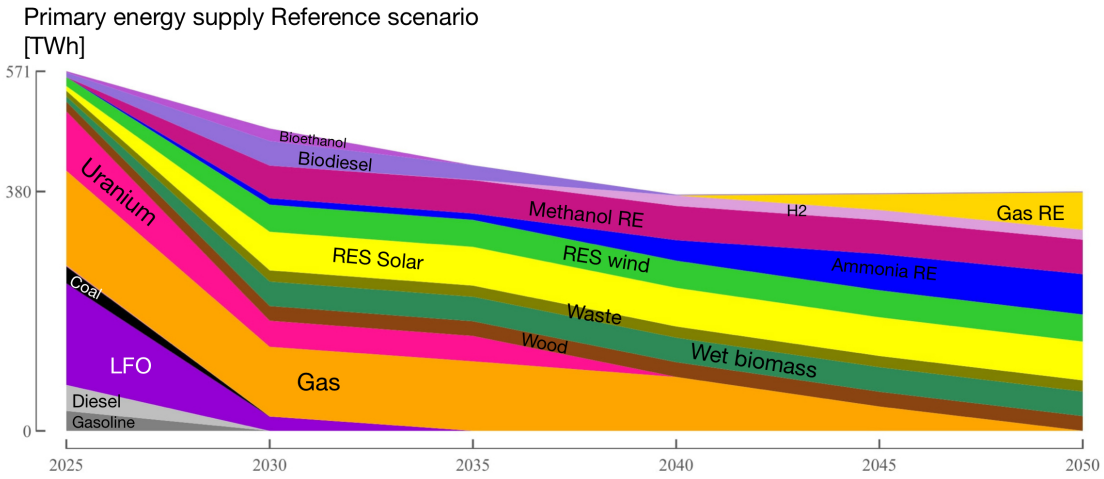

Figure 3.1: Primary energy supply for the reference scenario

3.1.2 Clever scenario

The Low Demand scenario, developed in Hugo Baudson's 2021-2022 thesis, was deliberately excluded. Based on the article 'Providing Decent Living with Minimum Energy: A Global Scenario' [17], it deviates significantly from current trends. It is considered overly ambitious, so it will not be studied in this work. The CLEVER scenario (see section 2.1) was chosen as a more realistic, yet still ambitious, alternative. The data from the original CLEVER scenario was adapted for the EnergyScope Pathway model to develop the 'Clever' scenario. The primary energy supply for this scenario is shown in figure 3.2.

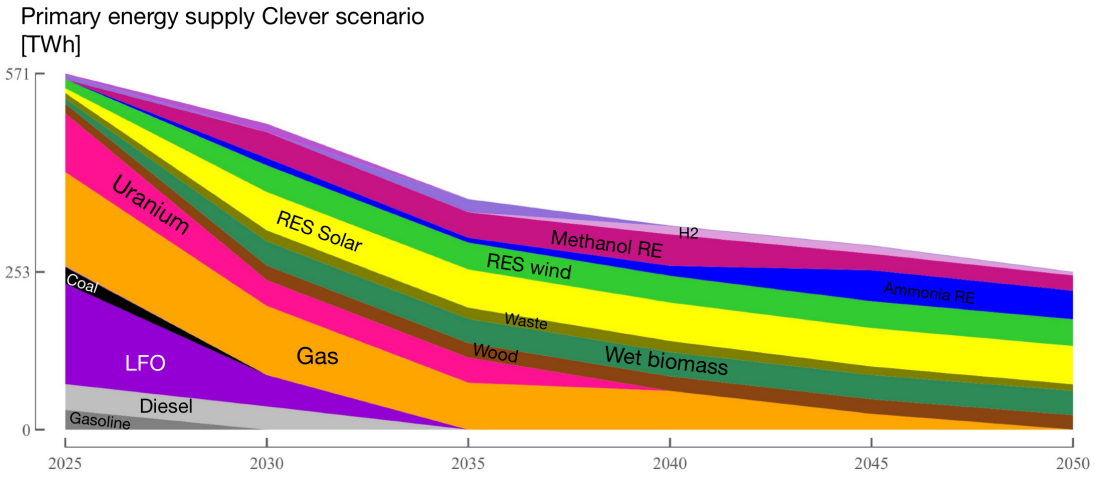

Figure 3.2: Primary energy supply for the Clever scenario

Clever scenario with lithium limit

The Clever scenario is a sufficiency-based pathway with ambitious reduction targets. Nevertheless, it does not fully comply with planetary boundaries, represented by the Doughnut Economy theory [14]. This theory is illustrated (see figure 3.3) by two concentric circles. The first represents the social foundation, ensuring basic human needs are met. The second is the ecological ceiling, which prevents humanity from exceeding planetary boundaries to keep the planet livable. Staying within these limits guarantees a fair and sustainable environment for humanity.

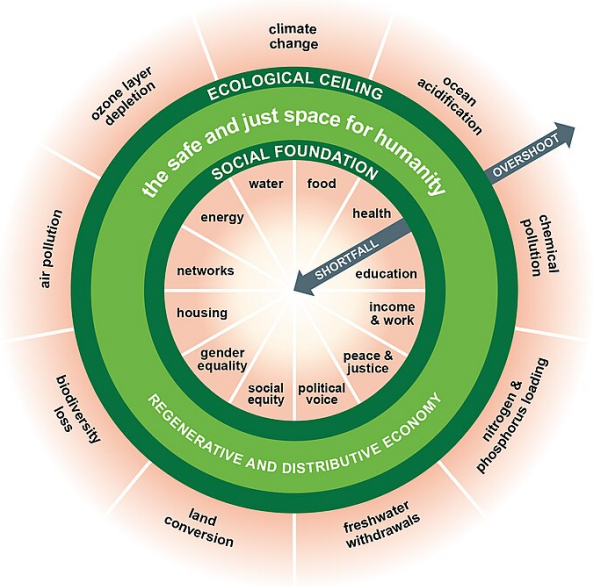

Figure 3.3: Doughnut Economy theory [14]

The Clever scenario exceeds certain environmental limits, though not across all categories of the ecological ceiling. Notably, it places significant pressure on resources, especially lithium. Since a key aspect of this scenario is electrification, the demand for batteries, and consequently for lithium, increases significantly. To address this issue, the Clever scenario with limits on lithium imposes a cap on the number of EVs allowed during the energy transition. In this case study, this means setting a limit on the number of cars in circulation by 2050.

The maximum number of EVs was calculated based on the report 'Lithium: A Major Ecological Challenge for Decarbonized Mobility' by the négaWatt France association

[18]. This report establishes a sustainability corridor to define a fair lithium consumption level for 2050 in relation to other countries. More specifically, it sets an ecological extraction budget of 20,000 tonnes of lithium for the EU, calculated to stay within planetary boundaries. It is interesting to note that this figure relates only to the use of lithium in the batteries of electric and hybrid vehicles.
To determine the maximum number of EVs in Belgium by 2050, this 20,000 tonnes EU budget first needs to be adjusted for Belgium's share. Since Belgium represents 2.61% of the European population [19], its lithium budget for 2050 is:

$$20,000 * 0.0261 = 521.74[\text{tonnes}] \tag{3.1}$$

Next, considering an average EV battery of 24 kWh, where each kWh of storage capacity requires approximately 113 grams of lithium [20], the total lithium content per vehicle is:

$$24 * 113 = 2.7[\text{kg per car}] \tag{3.2}$$

Therefore, the maximum number of EVs in Belgium in 2050 is:

$$\frac{521,744[\text{kg}]}{2.7[\text{kg per car}]} = 193,238.5[\text{vehicles}] \tag{3.3}$$

The total number of EVs should not exceed 193,238 by 2050. In order to integrate this constraint into the model, a passenger occupancy rate of 1.26 [pass/vehicle] and an average speed of 40 [km/h] were considered. These values allowed the determination of f_{max_EV}, expressed as follows:

$$f_{max_EV}[Mpass * km/h] = 193,238.5[vehicles] \times 1.26[pass/vehicle] \times 40[km/h] \times 10^{-6}$$

$$f_{max_EV} = 9.739[Mpass * km/h]$$

This new parameter will be considered constant throughout the transition period and will define a new constraint, expressed as:

$$F[y,"CAR_BEV"] + \frac{F[y,"CAR_PHEV"]}{2} + \frac{F[y,"CAR_HEV"]}{2} \leq f_{max_EV}[y];$$

This constraint limits the number of vehicles with electric batteries. The lithium content of batteries in Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) is considered to be half that of batteries in Battery Electric Vehicles (BEVs). As mentioned earlier, an average BEV contains approximately 2.7 kg of lithium. HEV and PHEV have a 11.1 kWh battery, corresponding to an average of 1.25 kg of lithium [21]. Consequently, the assumption that lithium content is half in hybrid vehicles compared to EVs is valid.
By integrating this constraint into the model, the Clever scenario is able to respect the environmental limits regarding lithium extraction.

3.2 Cost of vehicle infrastructure

Three new parameters have been added to account for infrastructure costs: GRID2 for electric vehicles (EVs), GRID_NG for NG vehicles, and GRID_FUELCELL for fuel cell vehicles. The definitions of the constraints associated with these parameters are provided in appendix B. The assumptions made to define these three parameters are presented below. In each case, four sub-parameters must be specified:

- *c_grid_extra*: Cost of reinforcing the grid due to intermittent RE penetration.
- *c_inv*: Total annualized investment cost over the phase.
- *c_maint*: Total annualized maintenance cost over the phase.
- Lifetime: The lifetime of the technology, in years.

Assumption for GRID2

The values in the GRID2 constraint were set equal to the existing GRID values in EnergyScope Pathway. GRID represents grid costs in the electricity sector. Consequently, it seemed logical to align these costs with EV infrastructure costs.

Assumption for GRID_NG

- Investments costs: According to Mathieu Vander Paelt from Mattheeuws, the investment cost for a NG station is estimated at 1.5M€, with profitability achieved at 20 trucks per day. Given that small stations operate with 20 trucks daily, their power capacity ranges from 30 kW to 80 kW, resulting in a cost range of:

$$18.75 - 50 \text{ G€/GW} \tag{3.4}$$

  For a station with an average power capacity of 55 kW, the cost is:

$$27.3 \text{ G€/GW} \tag{3.5}$$

- Maintenance costs: Annual maintenance costs are estimated at 2.3% of the station's Capital Expenditures (CAPEX), leading to:

$$625 \text{ M€/GW} \tag{3.6}$$

- Lifetime: The lifespan of a NG station can reach up to 20 years [22]. This information was also confirmed by Mathieu Vander Paelt of Mattheeuws.

Assumption for GRID_FUELCELL

- Investments costs: For hydrogen refueling stations with a compressor capacity of 30-50 kW, the investment cost is estimated at 1M€, yielding a cost range of [23]:

$$20 - 33 \text{ G€/GW} \tag{3.7}$$

  Taking an average value, we obtain:

$$26.5 \text{ G€/GW} \tag{3.8}$$

- Maintenance costs: Annual maintenance costs are estimated at 5% of the CAPEX [24], resulting in :

$$1325 \text{ M€/GW} \tag{3.9}$$

- Lifetime: The lifetime of a hydrogen refueling station can reach up to 20 years [25].

Summary of assumptions

Below is the summary table of assumptions:

	GRID2	**GRID_NG**	**GRID_FUELCELL**
c_grid_extra (M€/GW)	368	0	0
c_inv (M€/GW)	74919.06	27300	26500
c_maint (M€/GW)	0	625	1325
Lifetime (y)	80	20	20

Table 3.1: Summary table of assumptions

In addition, fuel prices will also impact the cost of these infrastructures. The following table 3.2 presents the evolution of energy costs between 2025 and 2050 in €/MWh.

Cost [€/MWh]	**2025**	**2050**
Electricity	57	105
Gas	43	69
Renewable gas	30	53
Hydrogen	74	96
Renewable hydrogen	144	101

Table 3.2: Change in energy costs between 2025 and 2050 in €/MWh

Chapter 4

Results

In this chapter, the results obtained for the different scenarios are explored. First, section 4.1 will focus on the advantages of the Clever scenario compared to the reference scenario obtained using the EnergyScope Pathway model. The aim in this section is to find answers to the questions: What are the advantages of having a scenario with a significant reduction in demand? What are the disadvantages, and what is the impact on the choice of resources used?

Then, section 4.2 will contrast the Clever case under a lithium constraint to limit the number of EVs. Here, alternative solutions to EVs will be highlighted, along with their advantages and disadvantages.

Finally, section 4.3 will integrate additional costs into the simulations. These include the infrastructure costs of EV, NG, and fuel cell vehicles. Such costs will allow for a more complete representation of the real costs of the transition. They will also help put the economic advantage of EVs into perspective.

4.1 Impact of demand reduction: Clever vs reference scenario

4.1.1 Reduction rates across both scenarios

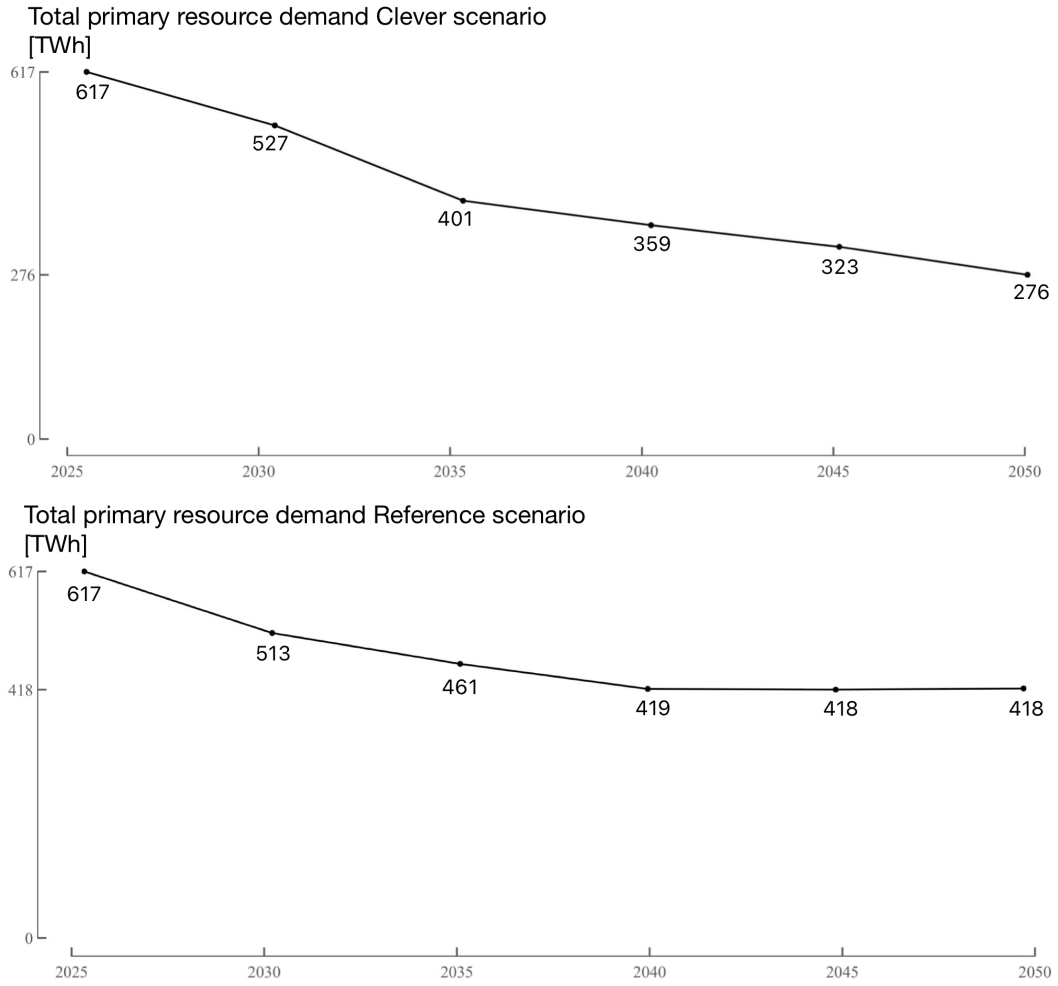

Figure 4.1: Comparison of reduction trends for resources in the Clever and reference scenarios.

The figure 4.1 illustrates the pattern of total primary resource demand reduction for the Clever scenario (top graph) and the reference scenario (bottom graph). A first observation can be made regarding the scales of these graphs. The total primary resource demand at the end of the transition reaches 276 TWh for Clever, compared to 418 TWh for the reference case. Notably, the reduction from the 2025 demand in Clever to 2050 is about

55%, in line with the assumptions of the original CLEVER scenario.

Next, comparing the trend of total demand reduction between the two is interesting. The curve for Clever roughly follows an S-curve. Due to this S-shape, the case undergoes a ramp-up period between 2025–2030. This means a slower start to the reduction than in the reference. As a result, resource demand in Clever is higher than in the reference case by 2030. Then, the reduction accelerates, and the demand drops significantly between 2030 and 2035. After that, the trend appears more linear, decreasing by about 40 TWh per year. The reference case, on the other hand, undergoes a more gradual reduction between 2025 and 2040, before starting to plateau around 2040.

Understanding how these scenarios reduce their demand is crucial for analysing how the model will respond to these changes.

4.1.2 Analysis of resource allocation

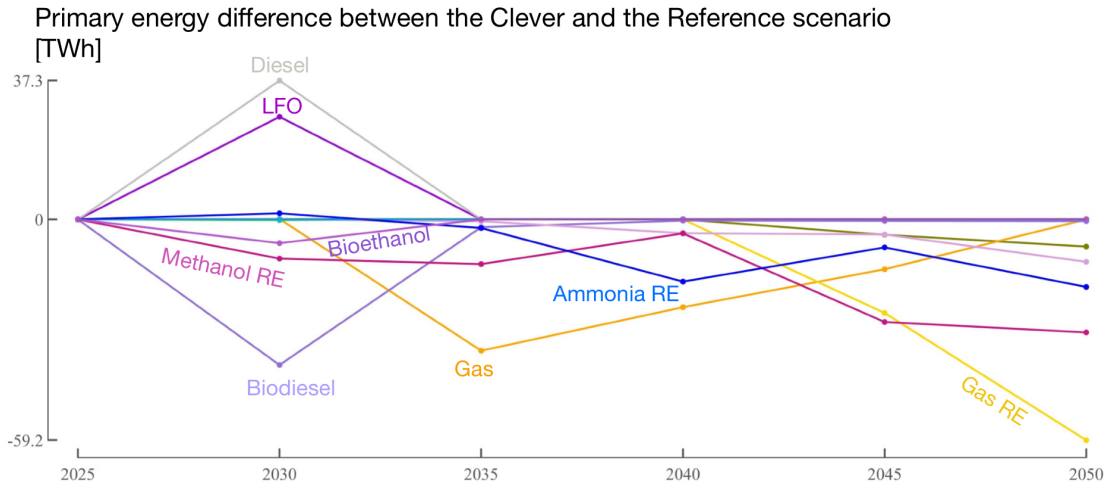

Figure 4.2: The Clever scenario has more freedom in relation to the GWP (Global Warming Potential) emissions limit. It therefore allows itself to opt for less costly but more polluting options in 2030. The reference scenario has a greater demand, which leads it to consume more resources and consequently rely more on RE resources.

The graph in figure 4.2 shows the subtraction of primary energy supplies between the Clever scenario and the reference scenario: positive values indicate that the Clever scenario uses more resources than the reference scenario, while negative values indicate the opposite.

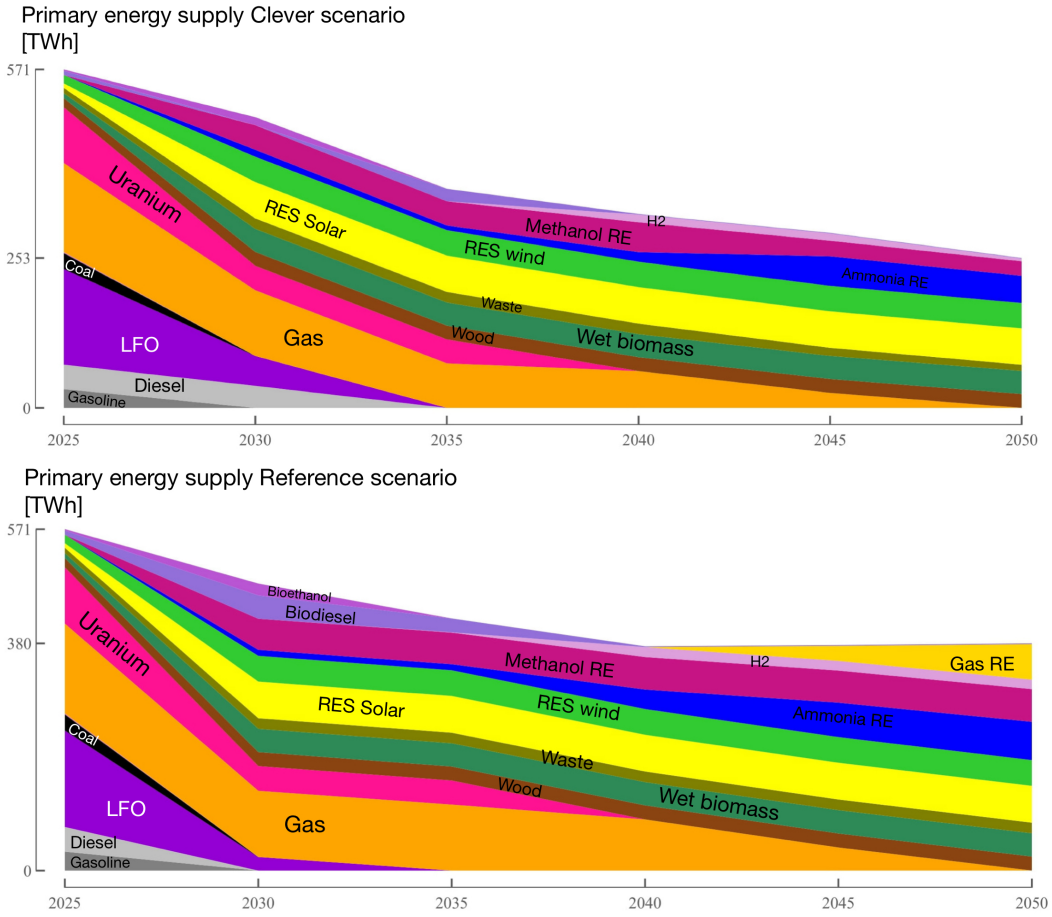

Figure 4.3: Graph of resources for the Clever scenario (top graph) and the reference scenario (bottom graph). This graph gives an absolute representation of resource consumption. It shows the resources that are equal in both scenarios and are therefore not displayed in the figure 4.2.

By examining the primary energy mix (see figure 4.3), it is possible to see an increase in Light Fuel Oil (LFO) in 2030. In this figure, the energy demand for LFO is shown to be 50 TWh in the Clever scenario, compared to 22 TWh in the reference one. Both foresee a gradual phase-out of this fuel by 2035. The reference scenario shows a decrease from 161 TWh to 22 TWh between 2025 and 2030. This reduction in LFO use is unrealistic, as it would require a rapid transition of all LFO-related technologies within that short timeframe. Both experience a sharp reduction in LFO consumption by 2030. The Clever scenario appears slightly more realistic due to its more gradual decline between 2025 and 2030.

The model operates through cost optimisation and must comply with a total Global

Warming Potential (GWP)[1] emissions budget (see model description in appendix A). Since the Clever scenario reduces demand more significantly, it has greater flexibility with respect to the GWP emissions limit. As a result, the model opts for cheaper but more polluting solutions in the Clever case. The reference scenario, on the other hand, cannot afford this. It must rely more on RE fuels to stay within the GWP emissions budget.

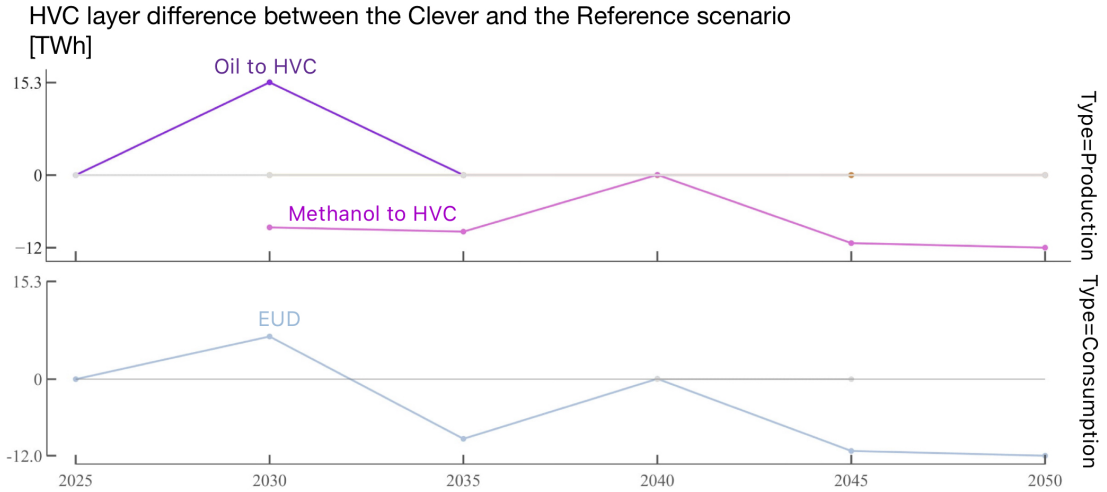

Figure 4.4: The Clever scenario uses more LFO in 2030 to produce HVCs because it has more freedom in relation to the GWP emissions limit. This is not the case for the reference one, which uses more RE methanol to produce HVCs (High-Value Chemicals).

This explains why, in 2030, the model chooses to produce High-Value Chemicals (HVCs) with more LFO in the Clever scenario and with more RE methanol in the reference one (see figure 4.4). In 2035, the reference scenario still consumes more RE methanol due to higher HVC demand that year, as RE methanol is used to produce HVCs. The increase in HVC demand is caused by a rise in non-energy demand in the industrial sector in the reference case. To give context, the term "non-energy" refers to energy products used as raw materials in various sectors rather than being consumed as fuels or transformed into other fuels. In Belgium, the non-energy sector mainly consists of HVCs, ammonia, and methanol. Hence the increase in HVC demand with rising non-energy demand.

The fact that the Clever version is more flexible with regard to the GWP emissions limit also explains why, in 2030, there is more diesel in this case. It also explains why there is more biodiesel in the reference one.

[1]The Global Warming Potential (GWP) is a metric used to describe the relative potency of a greenhouse gas. It does so by considering both its ability to trap heat and the duration it remains in the atmosphere. The GWP of carbon dioxide is 1 and is taken as reference [26].

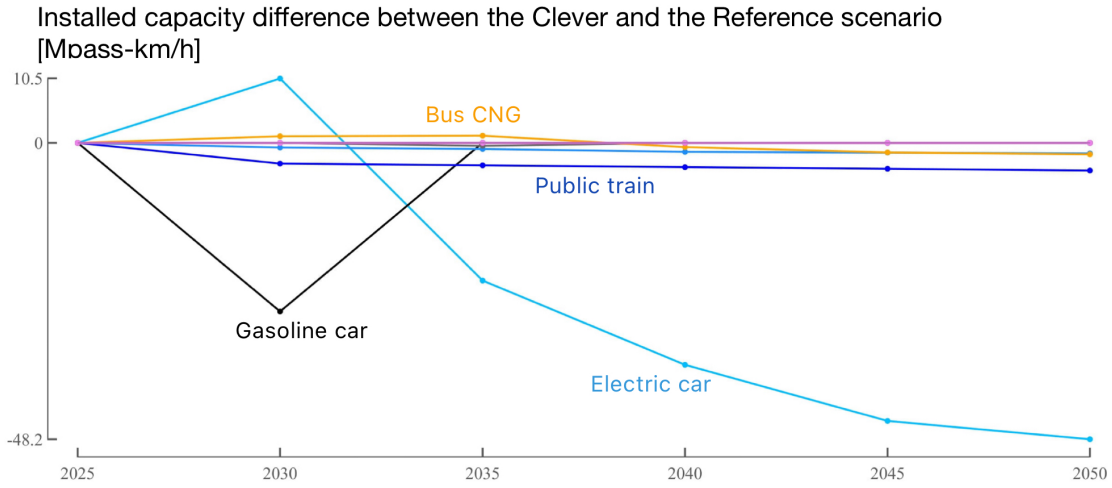

Figure 4.5: There are more gasoline-powered cars in 2030 in the reference scenario.

In figure 4.2, it can be seen that the reference scenario uses more bioethanol in 2030. This is due to higher private mobility demand in that case that year, resulting in a greater installed capacity of gasoline cars (see figure 4.5). More cars require more fuel, hence the increase in bioethanol consumption in the reference version. Bioethanol is chosen by the model to ensure compliance with the GWP emissions limit.

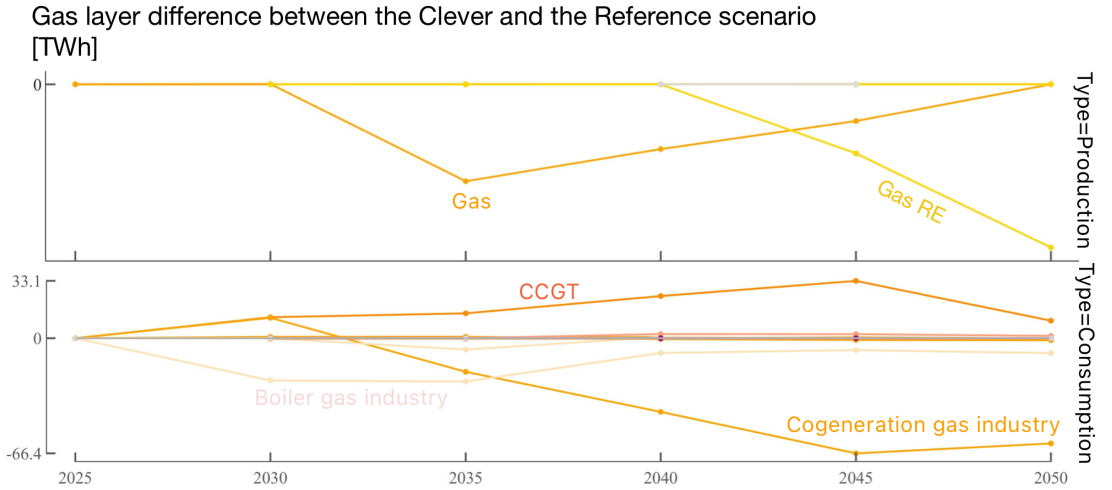

Figure 4.6: The reference scenario consumes more gas due to higher demand in the high-temperature heat sector. This translates into more gas-fired cogeneration in this case. In 2040, this scenario must reduce its GWP emissions and replace gas with RE gas.

From 2030 onwards, gas use increases in the reference scenario (see figure 4.2) due to higher energy demand, especially for high-temperature heat production. Between 2030

and 2050, it consumes more gas than the Clever case for cogeneration in the gas industry (see bottom graph in figure 4.6). Meanwhile, Clever, with lower high-temperature heat demand, uses more gas for electricity generation via CCGTs. Nevertheless, the amount of gas used for CCGTs is less than that used for cogeneration. This results in higher overall gas consumption in the reference scenario.

Looking at the gas production graph (top of figure 4.6), a significant increase in RE gas production between 2040 and 2050 is visible in the reference scenario compared to Clever, also shown in figure 4.2. This is because the reference case has less flexibility with the GWP emissions limit, while high-temperature heat demand remains high. To remain within the GWP emissions budget, the model is forced to replace fossil gas with RE gas to reduce emissions and achieve carbon neutrality by 2050.

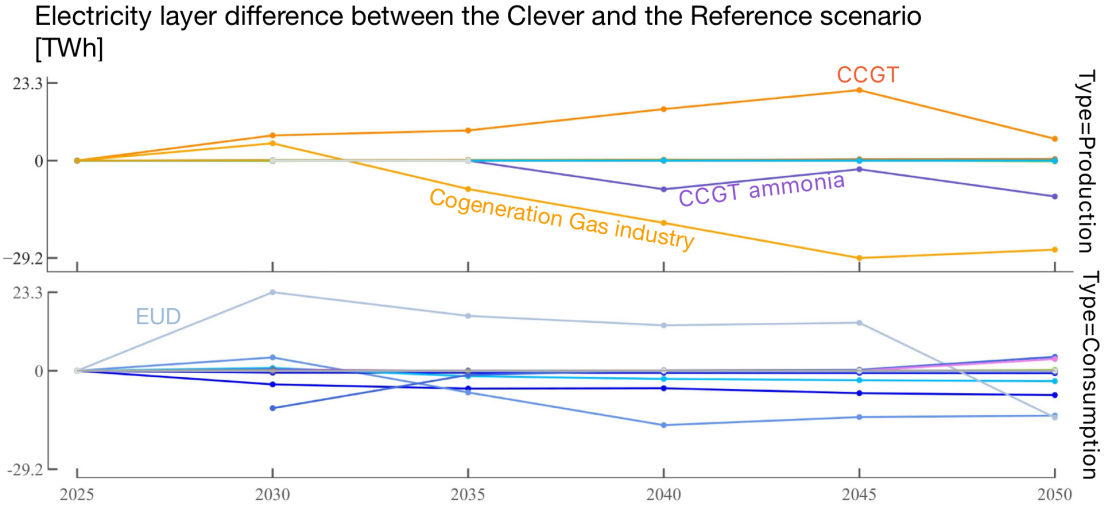

Figure 4.7: Use of ammonia CCGT to produce the remaining electricity for the reference scenario.

The increase in RE ammonia observed in figure 4.2 between 2040 and 2050 can be linked to the electricity production graph (top of figure 4.7). As mentioned earlier, the reference scenario must reduce its GWP emissions starting in 2040. To meet the remaining electricity demand, the model opts for ammonia CCGTs, which contribute to lowering emissions. This explains the rise in RE ammonia consumption over that period.

To conclude this sub-section, the model's resource choices are guided by both cost and the GWP emissions limit. The Clever scenario, with its greater demand reduction, allows for the use of cheaper but more polluting resources.

4.1.3 GWP emissions per sector

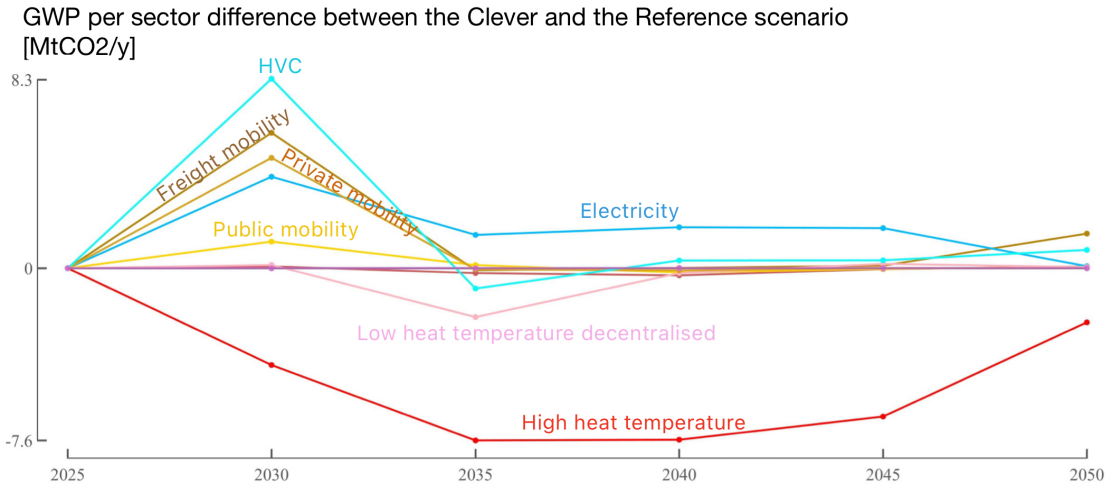

Figure 4.8: The Clever scenario emits more in certain sectors because it has more flexibility regarding the GWP emissions limit. It can therefore afford more polluting and cheaper options. The reference scenario has higher emissions for high-temperature heat and decentralised low-temperature heat due to higher demand in these sectors.

The graph in figure 4.8 compares the GWP by sector between the Clever and reference scenarios by subtracting the GWP emissions of the two scenarios. It is not surprising to see that the Clever case emits more in several sectors. Since it significantly reduces overall demand, it has more flexibility regarding the GWP emissions budget. As a result, it uses more polluting resources.

First, emissions from HVC increase significantly in the Clever scenario, reaching a peak of 8.3 $MtCO_2$ per year in 2030. This peak can be better understood by looking at the top graph in figure 4.4, showing HVC production. In 2030, Clever uses more LFO to produce HVC, while the reference case relies more on RE methanol. This explains why emissions in the HVC sector increase that year.

Next, a peak can be observed in 2030 for freight mobility in the Clever scenario compared to the reference. This increase is explained by the comparative resource graph (see figure 4.2), where a peak in diesel consumption is visible for Clever and a peak in biodiesel consumption appears for the reference. Since diesel emits more GWP emissions, it is logical to observe a peak in emissions in 2030 for the freight mobility sector.

GWP emissions from private mobility also peak in 2030, as shown in the mobility graph (see figure 4.5). On this graph, a decrease in gasoline cars and an increase in EVs can

be observed in the Clever scenario. To understand the origin of this increase in GWP emissions for private mobility, it is useful to know how EnergyScope calculates these emissions. The model calculates them based on the GWP of the resource used by each technology, called gwp_{op} [27]. According to figure 4.2, gasoline consumption is the same in both cases. However, slightly more bioethanol is consumed in the reference scenario due to the higher number of gasoline cars. The emissions increase does not come from this aspect, since the gwp_{op} of bioethanol is zero. The increase in emissions is due to the rise in the number of EVs in the Clever scenario. Indeed, in 2030, for the Clever case, electricity is mainly produced from gas cogeneration and CCGT (see figure 4.7). This means that the electricity is not produced from green sources and instead comes from NG. NG has a gwp_{op} of 0.267 $[MtCO_2/GWh]$. Its use consequently contributes to GWP emissions. The increase in emissions for private mobility is therefore due to the rise in EVs in the Clever scenario. It is important to remember that for EVs to contribute to emission reductions in the system, the electricity mix must be green.

To understand why the Clever scenario includes more EVs in 2030, it's helpful to look at fuel prices that year. Indeed, in the 2030 model, the price of gasoline is €78.5/MWh and the price of bioethanol is €115/MWh, while the price of NG is €41.5/MWh. As previously discussed, the EVs run on electricity mainly from NG, leading to higher GWP emissions in the Clever scenario. For this scenario, the model takes advantage of its flexibility within the GWP emissions budget to reduce costs by choosing the most economical option, even if it results in higher emissions. In this case, the model prioritises EVs in order to use electricity generated from natural gas. This helps reduce overall costs.

Next, electricity-related emissions are higher throughout the transition in the Clever scenario compared to the reference. This is due to the higher EUD for electricity consumption in the Clever case, as shown in the bottom graph of figure 4.7. This higher EUD stems directly from the demand matrices provided as input. These matrices assume greater electricity consumption due to the strong electrification of the system (see section 2.1.1). The increase in EUD leads to a rise in emissions in this sector, given that both scenarios rely on polluting production methods such as CCGT and cogeneration.

Finally, the reference scenario has higher GWP emissions for the high-temperature heat sector and the decentralised low-temperature heat sector. This is due to the fact that the reference case has a higher demand for these two sectors, which leads to higher GWP emissions.

4.1.4 Evaluation of the total cumulative cost of the transition

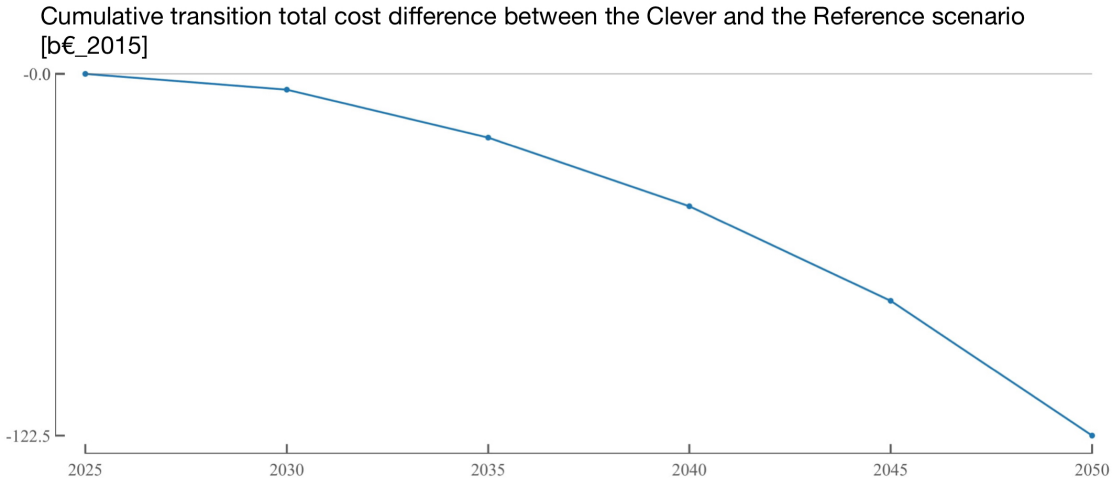

Figure 4.9: The Clever scenario is cheaper than the reference one due to its demand reduction and freedom from GWP emissions limit.

The graph in figure 4.9 compares the total cumulative transition cost between the Clever scenario and the reference one by subtracting the costs of the two. The graph decreases into the negative range. This indicates that the Clever scenario is less expensive than the reference one. Indeed, this cost reduction can be explained by two phenomena. The first reason is the Clever approach itself. In fact, it is based on a reduction in demand due to its sufficiency assumptions. When demand is lower, this leads to cost reductions due to lower resource requirements. The second reason is that, by reducing its demand, the Clever version gains some flexibility regarding the GWP emissions limit. This allows it to opt for less expensive but more polluting technologies. The choice of these technologies also reduces the total cumulative cost of the transition.

In the end, the system saves 122.5 $[b€_{2015}]$ with the Clever scenario, resulting in a total cumulative transition cost of 1,076.45 $[b€_{2015}]$. In comparison, the reference case has a total cumulative cost of 1,198.95 $[b€_{2015}]$. This means the Clever approach achieves a significant cost reduction of approximately 10.2% compared to the reference case. This underscores the economic advantage of sufficiency-based scenarios.

4.1.5 Assessment of the cumulative investment costs

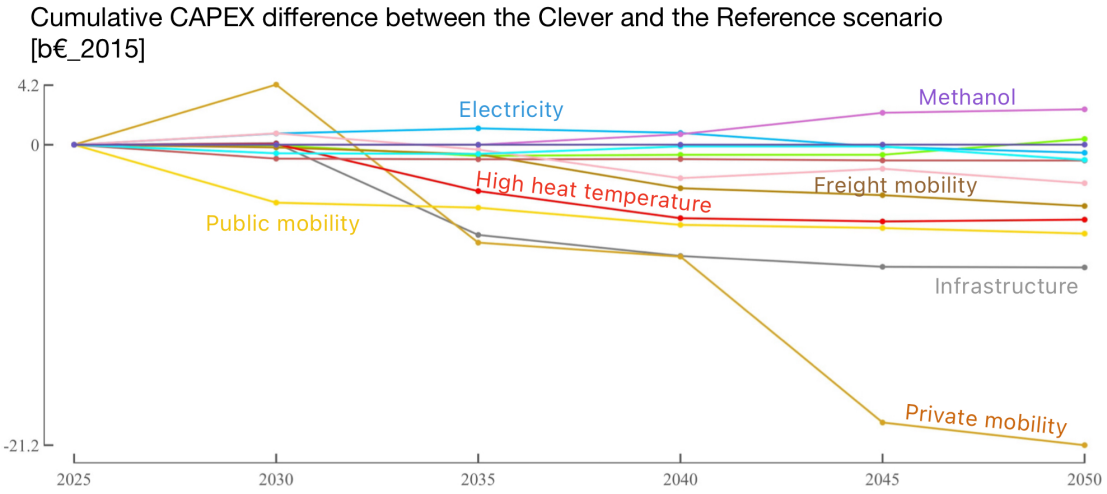

Figure 4.10: The differences in cumulative investment costs by sector between the two scenarios depend on the technology choices made for the sector. They also depend on the demand within the sector for each.

The figure 4.10 compares the cumulative investment costs, or CAPEX, between the Clever and reference scenarios. This is done by subtracting the CAPEX of the two scenarios. It can be observed that, overall, the Clever one has lower investment costs.

In 2030 (see figure 4.10), private mobility has higher investment costs in the Clever scenario. This is explained by figure 4.5, showing the installed capacity for passenger mobility. In 2030, the Clever case increases the installed capacity of EVs. Since EVs are a new technology, this leads to an increase in CAPEX for private mobility. Afterwards, the trend reverses, and investment costs for private mobility become higher in the reference case. This is because the reference scenario has more EVs than the Clever one after 2030, along with greater installed capacity. Consequently, investment costs for private mobility are higher in the reference scenario.

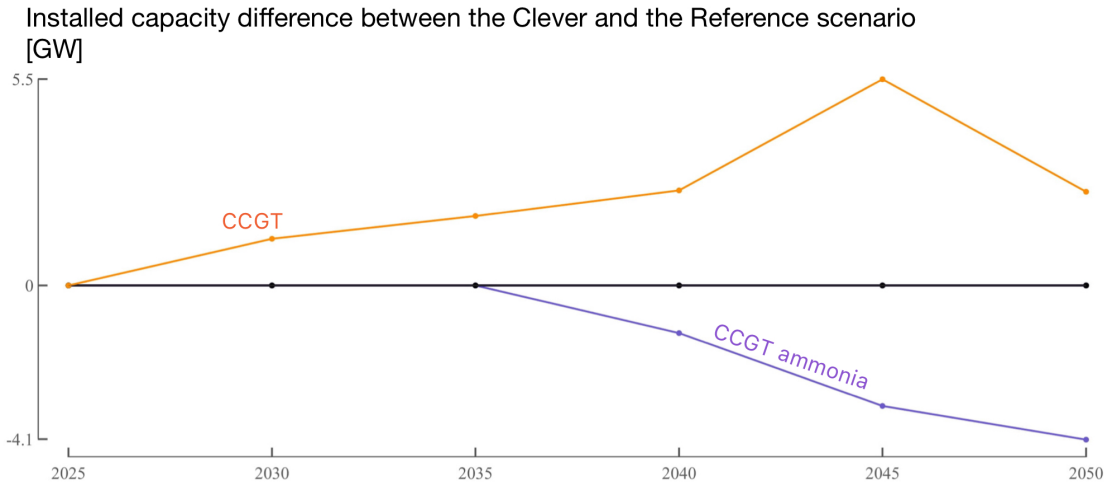

Figure 4.11: Increase in installed capacity in the electricity sector for the Clever scenario between 2025 and 2040.

The Clever scenario has higher electricity expenditures between 2025 and 2040. As shown in figure 4.11, there is more installed capacity for electricity during these years. This is due to higher demand in the Clever scenario. However, by 2045 and 2050, both scenarios have similar installed capacity, resulting in equal investment costs in those years.

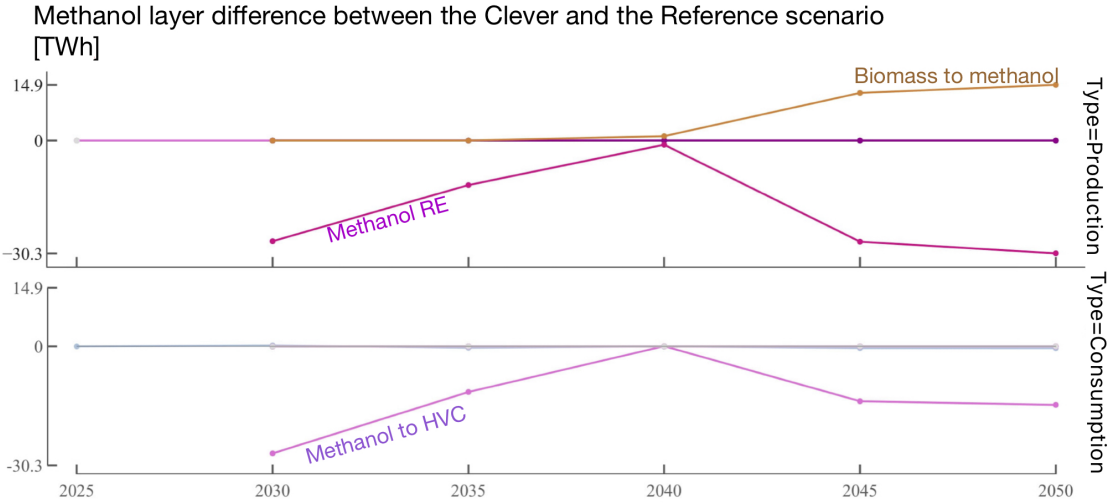

Figure 4.12: Increase in the production of methanol from biomass between 2040 and 2050 for the Clever scenario.

Between 2040 and 2050, there is also an increase in investment costs for methanol in the Clever scenario. The methanol production graph (top graph in figure 4.12) shows the

rise in biomass use for methanol production between 2040 and 2050. This increase in biomass for methanol production explains why investment costs for methanol are higher during these years. Indeed, before this period, this method of methanol production was not used. Thus, an infrastructure deployment is necessary, reflected by an increase in CAPEX for methanol during these years.

Next, the investment cost in public mobility decreases in the Clever scenario. This can be explained by the fact that, throughout the transition, installed capacity for public mobility is greater in the reference scenario (see figure 4.5). Moreover, the reference case relies more on public trains, whereas the Clever case uses more CNG (Compressed Natural Gas) buses. CNG buses are more polluting but have the advantage of being less expensive. This further explains why the investment cost for public mobility is higher in the reference scenario.

Regarding infrastructure[2] investment costs, they are higher in the reference scenario between 2035 and 2050. This increase is mainly due to the infrastructure costs for the DHN (District Heating Network). Higher investment costs in this scenario are explained by greater demand in the high-temperature heat sector. This leads to a higher need for expanded heat distribution networks and increased infrastructure costs.

Finally, investment costs for high-temperature heat and freight mobility are decreasing. Indeed, demand for these two sectors decreases significantly in the Clever scenario. This leads to a reduction in investment costs in these sectors.

This has therefore illustrated how the choice of technologies impacted the cumulative investment costs.

[2]The infrastructures include DHNs, the electricity grid, SMR (Steam Methane Reforming), biomethanation, biohydrolysis, methanation synthesis, hydrogen production from ammonia, hydrogen electrolysis, CCS (Carbon Capture and Storage), and energy efficiency technologies.

4.2 Impact of the lithium constraint on the Clever scenario

4.2.1 Installed capacity overview

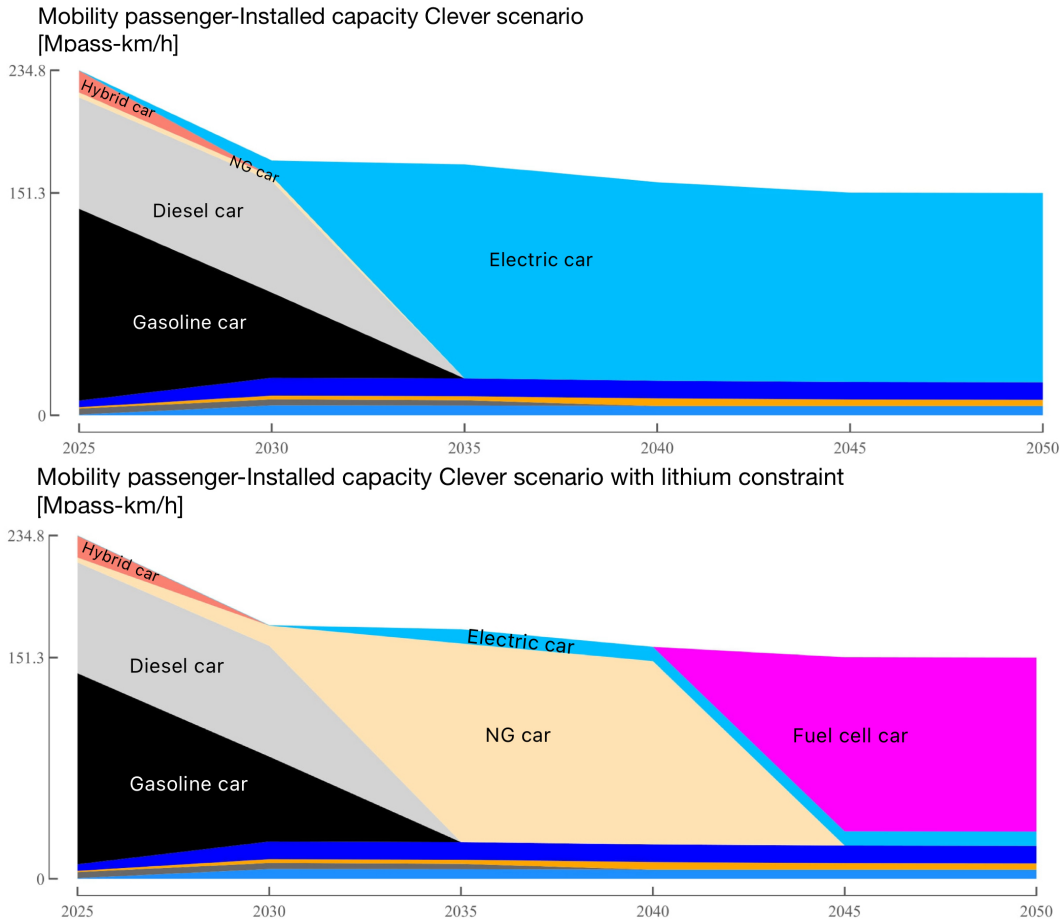

Figure 4.13: With the lithium constraint (bottom graph), the system is opting for NG and fuel cell cars to compensate for the lack of EVs.

When the lithium constraint is included in the model, it is possible to obtain the installed capacity for passenger mobility for the Clever scenario (see figure 4.13). The constraint has a significant impact on installed capacity. Unlike the scenario without constraints, NG and fuel cell vehicles are used much more intensively. Interestingly, NG cars appear as early as 2025, indicating that this technology is already available. In contrast, fuel cell cars do not appear until 2040.

Moreover, NG and fuel cell vehicles precisely compensate for the difference between the number of EVs before the constraint and the number allowed by this constraint. This raises the question: if some of the EVs are replaced by NG and fuel cell vehicles, what will be the impact on the transition costs? This point will be addressed in the next section.

Eventually, to compensate for the lack of EVs, NG vehicles are initially chosen. However, due to their higher carbon footprint, some are gradually replaced by fuel cell cars, which are carbon-neutral. In 2050, the system will consist solely of fuel cell cars and EVs.

4.2.2 Evaluation of the total cumulative cost of the transition

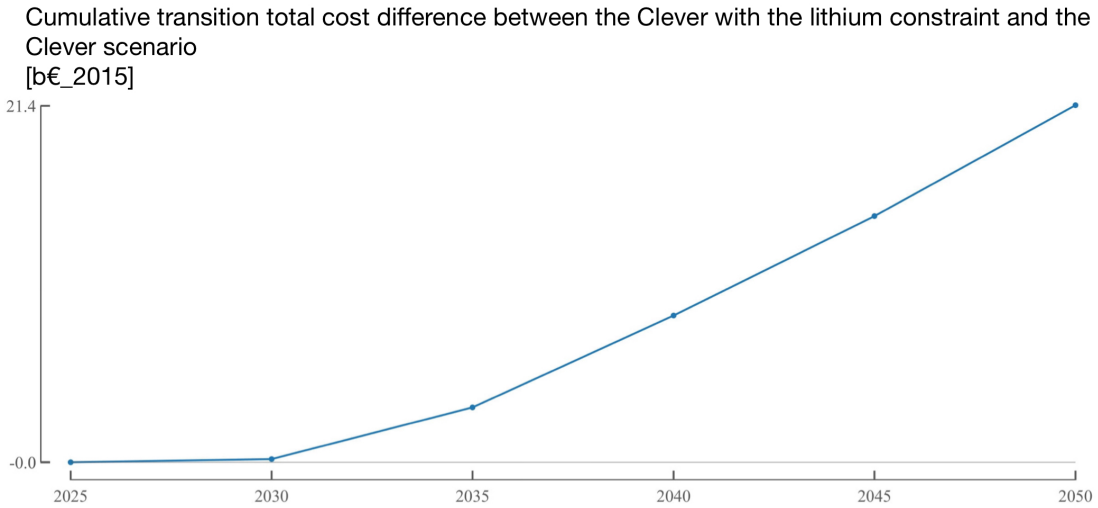

Figure 4.14: The reduction in the use of EVs increases the total cumulative cost of the transition.

The figure 4.14 compares the total transition cost between the scenario with the lithium constraint and the one without, by subtracting the costs of the two scenarios. The costs increase in the positive direction, indicating that the case with the lithium constraint is more expensive. In the end, the Clever scenario with the lithium limitation increases by 21.4 $b[€_{2015}]$. This corresponds to a 2% increase in the total cumulative cost of the transition. The Clever case with the lithium limitation now has a total cumulative transition cost of 1,097.85 $[b€_{2015}]$ compared with 1,076.45 $[b€_{2015}]$ before the limitation. This highlights the economic advantage of EVs.

4.2.3 Analysis of resource allocation

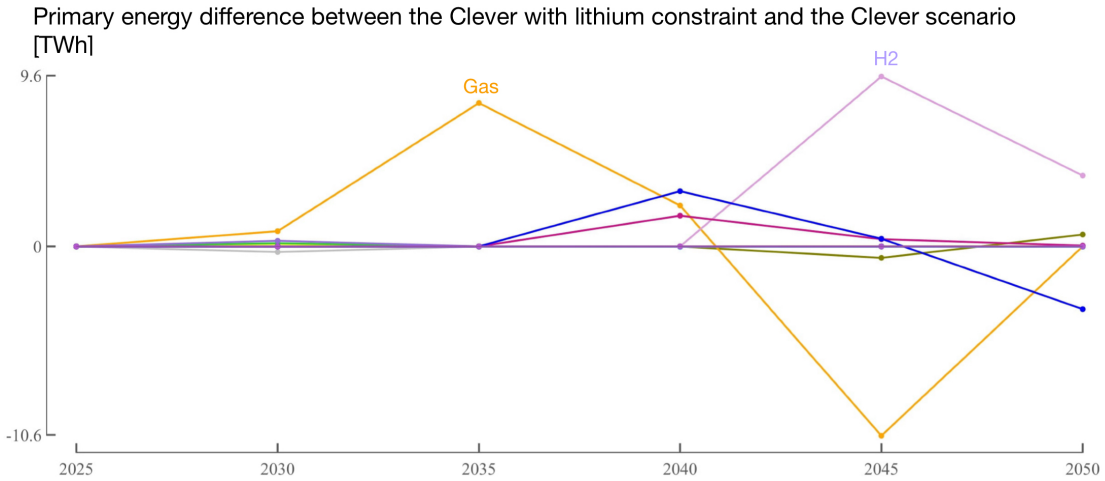

Figure 4.15: The scenario with the constraint uses more gas in 2035–2040 due to more NG cars. It also uses more hydrogen in 2045 due to more fuel cell cars.

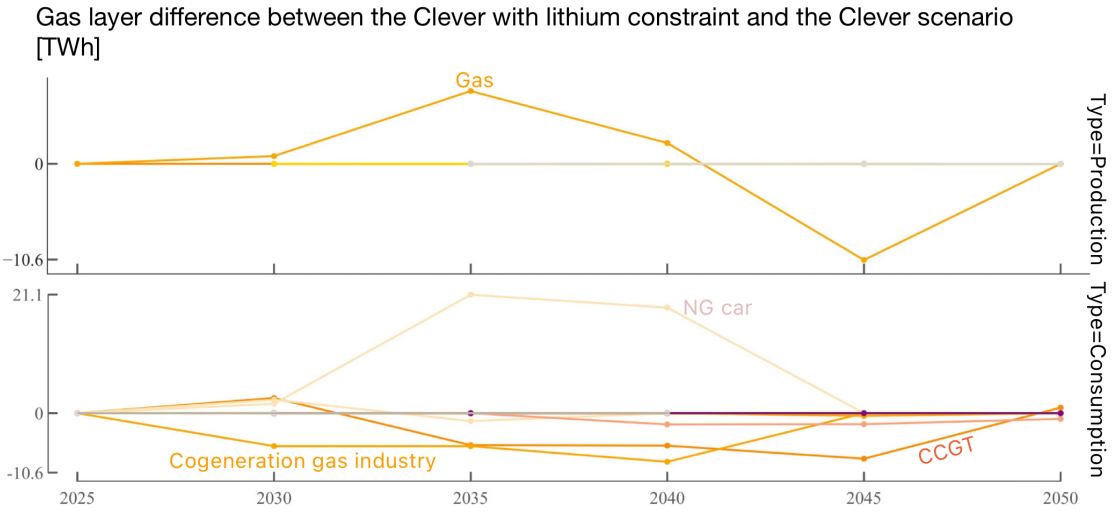

Figure 4.16: Gas is mainly used to produce electricity in the scenario without the constraint. In the scenario with the constraint, gas is mainly used for NG cars.

The graph in figure 4.15 shows that gas consumption initially increases between 2035 and 2040. This corresponds to the period when the Clever scenario, under lithium constraints, has the highest number of NG vehicles. Afterwards, the trend reverses, with a negative peak in 2045.

This pattern can also be observed in the gas production graph (top graph in figure 4.16) and is explained by the gas consumption graph (bottom graph in figure 4.16). Between 2035 and 2040, gas consumption is higher in the lithium-constrained scenario due to the greater number of NG vehicles (see figure 4.16). Then, in 2045, there are no more NG cars in either scenario (see figure 4.13). This leads to the same level of gas consumption for this type of vehicle that year. However, there is still a negative peak in gas consumption in that year. This can be explained by the fact that the unconstrained scenario still includes EVs. To supply part of their electricity, the model chooses to produce electricity with CCGTs (see figure 4.16), leading to the negative peak in 2045.

A peak in H2 consumption can also be observed in 2045 in the figure 4.15. This is due to the increase in the number of fuel cell vehicles in that year for the Clever scenario with the lithium limit.
Finally, it is not worth analysing other resources in this diagram because the variations are very small, of the order of 3 TWh.

4.2.4 GWP emissions per sector

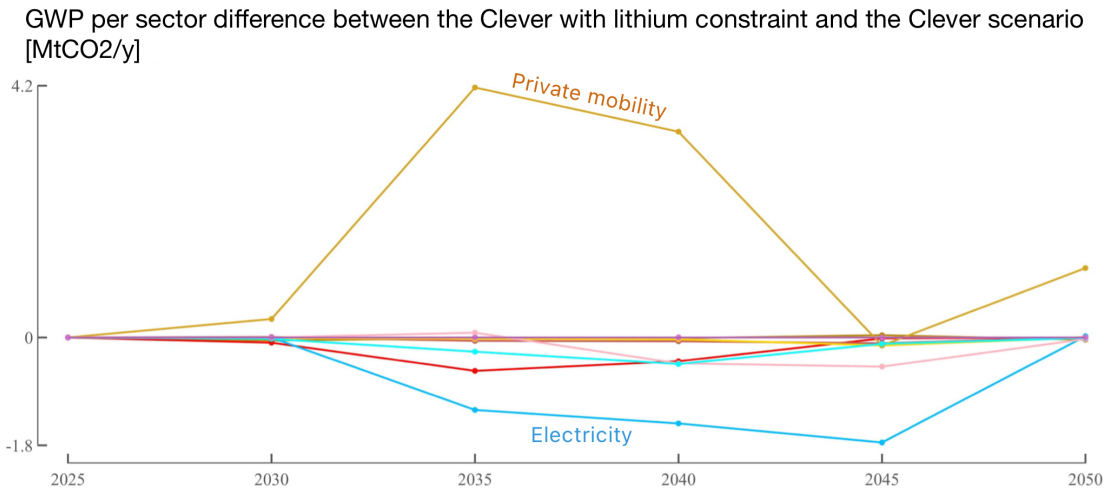

Figure 4.17: The GWP emissions increase in the lithium-constrained scenario due to greater use of NG cars. These cars emit more than EVs. Additionally, GWP emissions in the electricity sector decrease under the lithium constraint scenario.

The figure 4.17 compares GWP emissions by sector between the Clever scenario with and without the lithium constraint, by subtracting the GWP emissions of the two scenarios. Emissions are higher in the private mobility sector in the constrained case between 2030 and 2045. This is due to the fact that during these years, some EVs were replaced by NG

vehicles, which have a higher GWP.

The unconstrained Clever scenario includes more EVs between 2030 and 2050. In this scenario, the electricity mix is not green. Therefore, the electricity consumed for EVs emits GWP emissions.

4.3 Result including vehicle infrastructure costs

4.3.1 Impact on the choice of technology

With the inclusion of vehicle infrastructure costs in the model, the first result shows that these costs had no impact on technology choices. The selected technologies remain unchanged for both passenger and freight mobility. This means the primary mix is the same as before (see figure 4.3).

4.3.2 Consequences for annual system costs

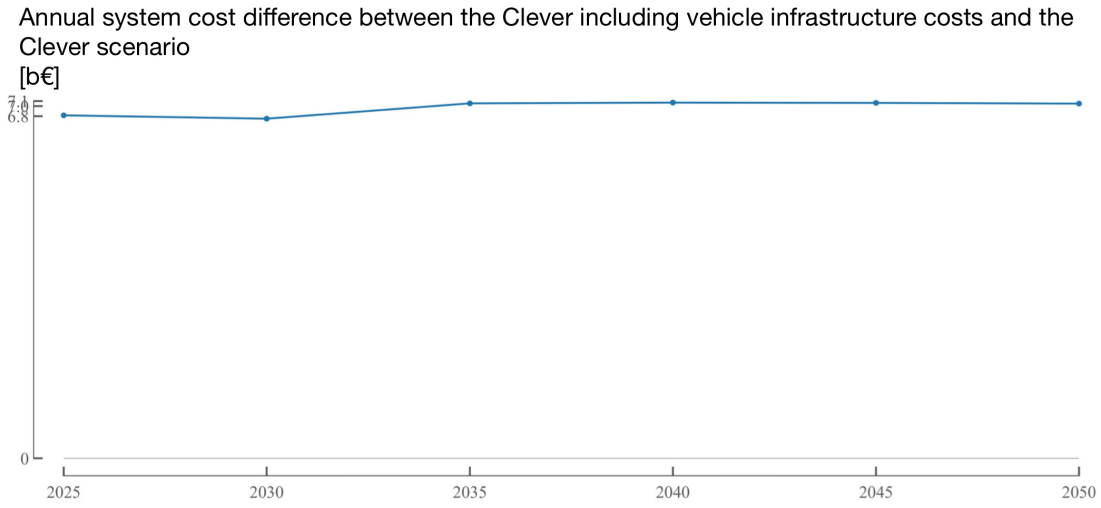

Figure 4.18: Increase in annual cost with the inclusion of infrastructure costs for EV, NG, and fuel cell vehicles.

The inclusion of these costs increases the system's annual cost. The graph in figure 4.18 compares the Clever scenario with its three new infrastructure costs to the initial Clever scenario. This is done by subtracting the costs of the two scenarios. It can be seen that all values are positive, indicating an overall increase in costs due to the addition of infrastructure costs. This increase ranges between 6.8 and 7.1 billion euros and remains

relatively constant throughout the transition. The initial Clever case has a total annual cost of 33.6 [$b€$] in 2050. With the addition of these costs, the Clever scenario now has a total annual cost of 40.7 [$b€$] in 2050, representing an increase of 21%.

Here, it is important to note the necessity of accounting for all system costs to obtain an order of magnitude as close to reality as possible. The integration of infrastructure costs therefore already enables system costs to be refined.

4.3.3 Effect on the installed capacity of the infrastructure

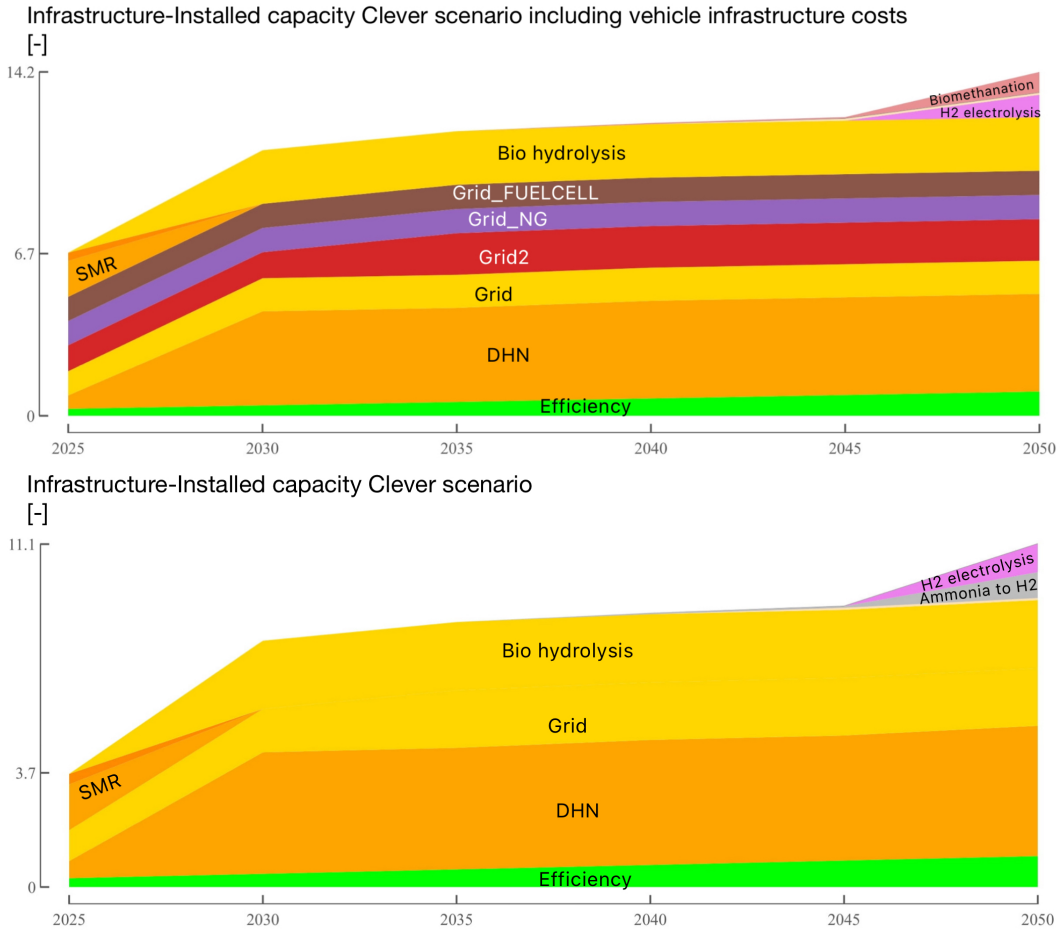

Figure 4.19: More complete representation of the installed capacity of infrastructures with the integration of infrastructure costs for these 3 types of vehicles.

The graphs in figure 4.19 show that, with the addition of these vehicle infrastructure costs, the installed capacity is now more complete. While the previously considered technolo-

gies remain unchanged, the installed capacities for EV infrastructure (GRID2), NG vehicle infrastructure (GRID_NG), and fuel cell vehicle infrastructure (GRID_FUELCELL) are now taken into account. This results in a clearer and more accurate representation of installed capacities for infrastructure.

4.3.4 Total cumulative cost for the Clever scenario with lithium constraints

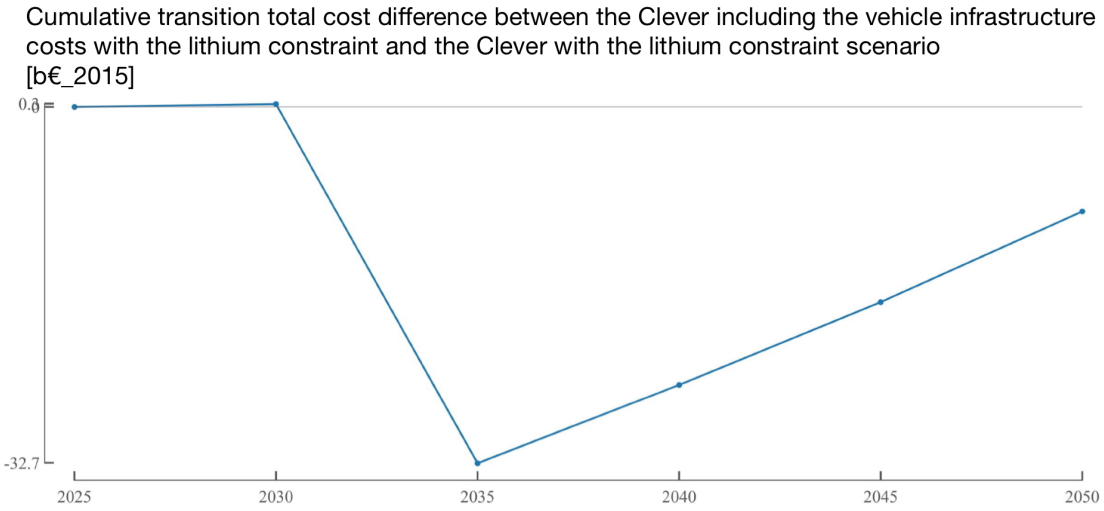

Figure 4.20: The inclusion of infrastructure costs in the total cumulative cost comparison between the Clever scenario with the lithium limit and the one without shows a change. The version with the lithium limit becomes the least expensive.

In the figure 4.20, the graph shows the total cost difference between the Clever scenario with the lithium limit and its version without this constraint. Both now include the infrastructure costs for EV, NG, and fuel cell vehicles. It seemed relevant to integrate these costs, given that the lithium-constrained version includes NG and fuel cell vehicles to replace some EVs. When vehicle infrastructure costs are taken into account, the lithium-limited Clever scenario becomes the more cost-effective scenario, reversing the previous conclusion. This results in a final saving of 9.6 $[b€_{2015}]$. Its total cumulative transition cost is 1,066.85 $[b€_{2015}]$, representing a 0.9% decrease compared to the reference Clever scenario. This phenomenon can be explained by the fact that the infrastructure costs for NG and fuel cell vehicles are lower than those for EVs (see section 3.2). Although EVs are more efficient and less expensive themselves, their infrastructure is more costly.
This underlines the value of developing other types of vehicle, such as NG and fuel cell vehicles, and the importance of considering all the costs associated with a technology.

Chapter 5

Discussion

5.1 The Clever scenario

5.1.1 Challenge in integrating sufficiency into the Clever scenario using EnergyScope Pathway

The reduction in demand in the Clever scenario strongly influences the resources selected by the model. With lower overall demand, the scenario provides greater flexibility regarding the GWP constraint. This leads the model, driven by cost optimisation, to favour more carbon-intensive but cheaper resources (see figure 4.2). As a result, the Clever case achieves substantial savings, with a total cost reduction of 122.5 $[b€_{2015}]$ over the entire transition. The increase in NRE (Non-Renewable Energy) fuels leads to higher GWP emissions in some sectors. Although the original CLEVER scenario aims to reduce emissions, the model tends to reach the GWP emissions limit to minimise costs in the Clever scenario. This raises questions regarding what is considered desirable in a sufficiency scenario. A clear trade-off between cost optimisation and environmental objectives must be addressed.

The Clever scenario was developed based on the original CLEVER scenario. This original CLEVER pathway defines energy demands and technology choices exogenously. In this work, to avoid constraining EnergyScope Pathway, technology selection was left to the model. As a result, the chosen technologies differ from the expertise-based choices of the original CLEVER scenario. The Clever scenario can be discussed in this regard, as it does not follow the initial technology assumptions of the original CLEVER scenario.

Another important point relates to the objectives of negaWatt. The Clever scenario developed here with EnergyScope Pathway uses demand reduction to delay the phase-out of fossil fuels and save money. However, negaWatt's vision is based on three pillars (see

figure 1): sufficiency, efficiency, and RE. Here, insufficient weight is given to the third pillar, the development of RE. Indeed, delaying the phase-out of fossil fuels also delays the development of RE. Once again, this flaw stems from the cost-optimisation logic of the model.

One interest of EnergyScope Pathway is its ability to observe the speed of resource changes. The figure 4.3 shows that the reduction of LFO in the Clever scenario appears more realistic than in the reference. Nevertheless, diesel demand remains constant until 2030 before decreasing. This is due to the greater flexibility of the Clever case regarding the GWP emissions limit. Still, since the reference reduces diesel earlier, it is unfortunate that Clever does not follow the same path. Both trajectories phase out coal and gasoline in 2030, uranium in 2040, and NG in 2050. Table 5.1 summarises resource demands for Clever in 2025 and 2050, giving absolute values.

Energy Source	**2025 (TWh)**	**2050 (TWh)**
Gasoline	31.7	0
Diesel	41.3	0
Light Fuel Oil (LFO)	161.3	0
Coal	26.9	0
Natural Gas	150.5	0
Uranium	94.0	0
H2	0.1	0
Methanol	1.5	0
Wood Biomass	15.5	23.4
Wet Biomass	8.4	38.9
Waste	8.8	10.5
Solar	7.6	61.3
Wind	14.3	42.7
Bioethanol	2.2	0
Biodiesel	7.1	1.0
Ammonia (RE)	0.0	46.0
Methanol (RE)	0.0	24.5
H2 (RE)	0.0	4.5

Table 5.1: Energy sources and their consumption in 2025 and 2050 (in TWh)

A scenario like Clever, with significant demand reduction, also implies behavioural changes in society. If the energy mix is not greener, the population might not understand the role of sufficiency or the need to reduce demand. For such societal change to occur, politics, education, and awareness-raising are crucial. Changing society's perception of sufficiency is necessary. It must be seen not as technological regression, but as an

opportunity. An example is slow heat [28], which promotes heating bodies rather than homes. This can cut energy use and heating bills, while supporting a move from fossil fuels to local electric options like heated capes, mattress toppers, or blankets. Openness to new habits is essential, and the benefits of sufficiency must be clear.

However, integrating sufficiency into the system relies more on collective choices than on individual behaviours. According to the study "Faire sa part ? Pouvoir et responsabilité des individus, des entreprises et de l'État face à l'urgence climatique", published by Carbone 4 in 2019 [29], even if all citizens adopted "heroic behaviour" (giving up flying, going vegetarian, using soft mobility, etc.), the maximum individual carbon footprint reduction would be 25%. The remaining 75% depends on systemic transformations supported by the State, companies, and local authorities. The report emphasizes that all actors must play their part. In the Clever scenario, which includes sufficiency, collective actions are a key lever for its successful implementation.

In summary, demand reduction leads to a more polluting scenario due to the cost-driven selection of resources. A scenario like Clever, which incorporates sufficiency, should also strengthen the development of RE, set stronger environmental goals, and rely on both collective action and behavioural change. The Clever scenario obtained with EnergyScope Pathway can be criticized on all these aspects.

5.1.2 Comparison of trajectories with the newly developed Clever scenario and the original CLEVER scenario

It is interesting to compare the trajectory of the Clever scenario with that of the original CLEVER. The latter envisages a reduction of 23% in 2030, 45% in 2040, and 55% in 2050 compared with 2015 (see figure 5.1)[3].

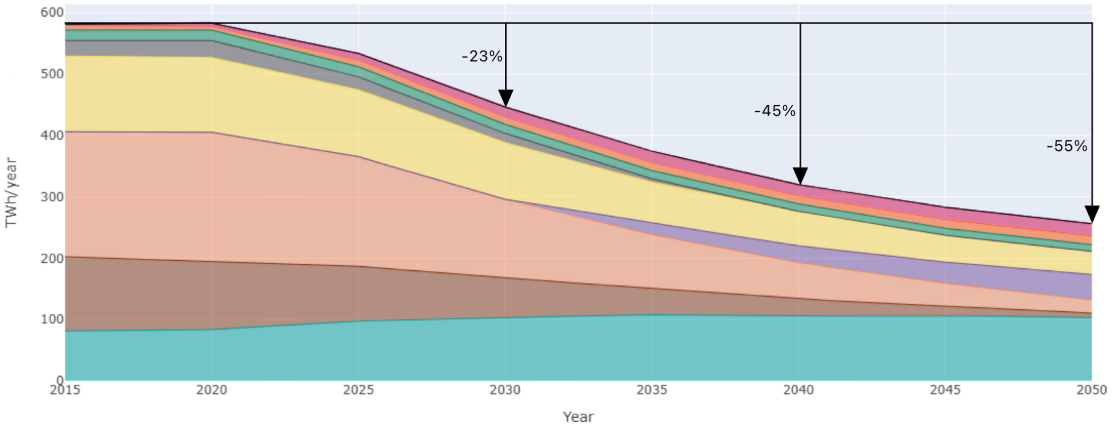

Figure 5.1: Original CLEVER scenario with the associated reduction path [3].

The figure 5.1 shows the S-curve trajectory for the original CLEVER scenario, as explained in section 4.1.1. The start-up period runs from 2015 to 2020. The Clever pathway developed in this work begins in 2025. Therefore, the start-up period was taken from 2025 to 2030.
It is interesting to note that the original CLEVER scenario includes sectors not covered by the one developed with EnergyScope Pathway, such as aviation, international maritime transport, and agriculture. It should also be noted that figure 5.1 for the original CLEVER corresponds to final energy consumption, whereas the one obtained here (see figure 5.2) represents the primary energy mix. Nonetheless, despite these differences, it is interesting to compare these graphs in terms of trends and trajectories.

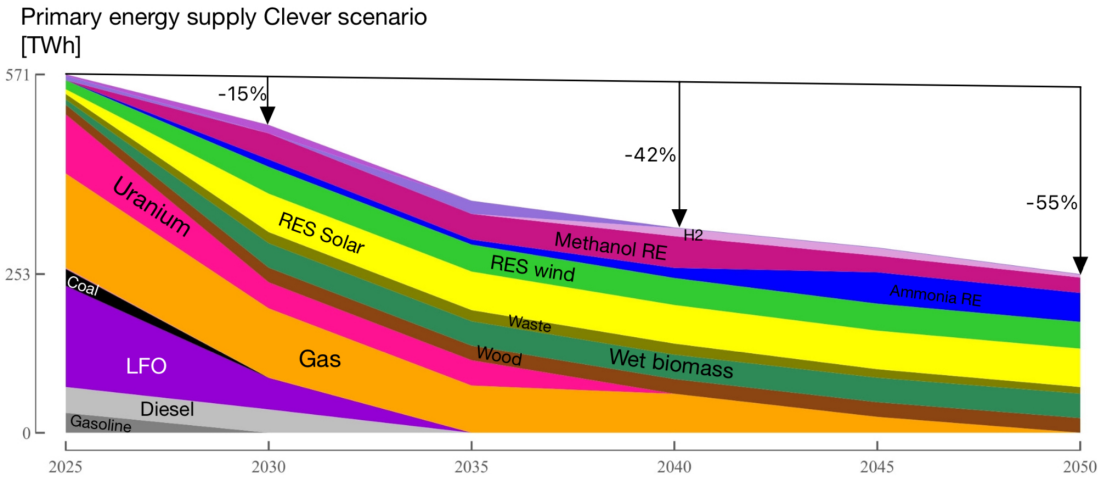

Figure 5.2: Clever scenario developed in this work with the associated reduction path

For the Clever scenario developed here with EnergyScope Pathway, a reduction of 15% in 2030, 42% in 2040, and 55% in 2050 can be observed (see figure 5.2). This trajectory differs slightly from the original CLEVER (see figure 5.1). It begins in 2025 rather than 2015, so these changes are logical. Achieving a 25% reduction by 2030 when starting in 2025 seems very ambitious. The version developed here foresees a 15% cut in 2030, likely more realistic. In 2040, both trajectories converge to similar reduction levels. By 2050, each reaches a 55% reduction, an unsurprising outcome, as this endpoint is inherent to the Clever assumptions.

The key takeaway is that the trajectory of the Clever scenario obtained with EnergyScope Pathway is an adaptation of the original CLEVER trajectory. The transition starts in 2025, offering an updated path with 2025 historical data, allowing a more realistic reduction.

5.2 The lithium constraint

5.2.1 Compliance with environmental limits for lithium in the Clever scenario and the role of vehicle occupancy

The constraint on lithium is based on a lithium extraction budget for the EU, set at 20,000 tonnes by 2050 [18] (see description in section 3.1.2). From this, a specific limit was calculated for Belgium, amounting to 521.74 tonnes.
The constraint imposed on the model was then determined and is expressed as:

$$f_{max_EV} = 9.739[Mpass * km/h]$$

By reasoning in reverse and determining the minimum number of tonnes of lithium required for the Clever scenario, it is possible to find that:

$$f_{max_EV} = 16.4[Mpass * km/h]$$

This means that in 2050, there will be 3,254 million EVs, which will require 8785.7 tonnes of lithium. This represents 44% of the EU's lithium budget, highlighting that even a demand-reduction scenario like Clever still relies heavily on lithium and exceeds the resource limits. Achieving carbon neutrality while respecting environmental boundaries will be a major challenge.

The vehicle occupancy rate considered here is 1.26. In the original CLEVER scenario, it is assumed to increase over time, reaching 2 in 2050 [3]. The figure of 3.254 million EVs can thus be compared with a scenario using the higher occupancy rate of 2. Applying this rate to the number of EVs gives 2.050 million vehicles, representing 5,535 tonnes of lithium, 27.7% of the EU's total allocation. Clearly, the Clever scenario still exceeds what is required to meet environmental limits. However, actions such as car sharing have a significant impact on these figures. Vehicle occupancy is a key factor in representing sufficiency. A weakness of the Clever scenario developed here with EnergyScope Pathway is that the occupancy rate does not vary over time. To better include sufficiency, this rate should increase as the transition progresses.

5.2.2 Economic impact of the lithium constraint

The Clever scenario with the lithium limitation has a restricted number of EVs. Consequently, it must compensate for this shortage with NG vehicles and fuel cell vehicles. Nevertheless, since EVs are the most efficient and the cheapest option, reducing their number increases the overall cost of the transition. The Clever scenario sees an increase of $19.1 b€_{2015}$ compared to the Clever scenario without the lithium limit.

By including the infrastructure costs (see section 4.3.4), it was shown that the Clever scenario with the lithium limit actually became the cheapest one, leading to a total saving of 9.6 $b€_{2015}$ by 2050. This cost reduction directly depends on the infrastructure cost values found in section 3.2, which introduces a degree of uncertainty to this result. The main point here is not to determine the exact cost reduction of the transition. Rather, it is to understand that by including vehicle infrastructure costs, the cost advantage of EVs is nuanced. The interest in developing alternative vehicle types is highlighted.

In addition, the Clever scenario with the limit on lithium could offer an additional economic advantage. A significant uncertainty is associated with lithium prices due to supply and demand imbalances, geopolitical tensions, and even political decisions [30]. The energy transition will increase lithium demand, especially because of the rise in EVs and the growing need for energy storage. This rising demand could drive up lithium prices, potentially increasing the cost of the transition. A scenario like the one developed here, with fewer EVs, could as a result offer greater resilience against future uncertainties related to lithium prices.

Finally, the economic advantages of EVs must be viewed with nuance. To find a balance between lithium extraction limits and transition costs, alternative solutions like fuel cell and NG vehicles appear to be a wise choice.

5.2.3 Benefits of the lithium constraint in the Clever scenario

In this work, the Clever scenario was developed with a constraint on lithium in order to respect environmental limits for this special resource. Indeed, neither the version obtained with EnergyScope Pathway, nor the original CLEVER version respects this constraint on lithium. This limit was calculated based on both environmental and social floors. The social floor was determined by essential mobility needs and lithium requirements [18]. This highlights that lithium extraction is both an environmental and social issue.

The Clever scenario with the lithium limit allows us to show what the energy system would look like under such a constraint. This is especially relevant in the context of a scenario that promotes sufficiency and aims for energy justice in comparison with other countries. Indeed, nearly 80% of the world's lithium reserves are located in fairly poor territories. In these areas, the consent of indigenous peoples is regularly ignored. The goal of this limit is to ensure social and geopolitical justice for the populations affected by the extraction.

This limit is based on the study 'Lithium: a major ecological challenge for decarbonized mobility' [18]. In this study, key action levers are highlighted to respect the lithium

extraction limit: sufficiency, technological efficiency, recycling, and substitution. The results obtained here show that sufficiency alone does not solve everything. Even with a significant reduction in demand, the number of EVs required to respect the lithium limit is still far from meeting the system's needs. Substitution is therefore crucial in this context. EVs must be replaced by other types of vehicles, such as NG and FUEL CELL cars, to meet the lithium limit. In addition, the recycling of EV batteries has not been taken into account in this study. This is unfortunate, as a circular economy with recycled batteries could help the system meet the lithium limit more easily.

The results from this study raise new questions, such as: How can we consume less lithium? How can we increase vehicle occupancy rates? How can we avoid relying on a single technology for mobility? Which technology is the most advantageous to choose?

5.3 Trends in transport infrastructure

Infrastructure costs were considered for electric, NG, and fuel cell vehicles. It's interesting to explore the current trend and the most likely technologies to be chosen. The EnergyScope Pathway model does not take into account current societal trends. To account for them, one solution would be to impose specific technology choices. However, this would undermine the value of using the model. The value lies in observing the technologies and resources it selects to optimise the system.

After consulting several experts in this field, it has been observed that the industry is leaning more towards EVs. This is due to their economic advantage and efficiency. In general, when the industry considers NG or fuel cell technology, it is mainly for heavy-duty vehicles. NG vehicle appears to be a wise choice only if it comes from biogas and is used as a transitional solution. In the long term, it does not seem to be a viable solution because biogas will be in high demand for other applications such as industry, energy production, and agriculture. Hydrogen can also be used for heavy-duty vehicles in specific cases. For example, for long-haul transport in isolated areas without nearby charging stations or for trucks with specific functions such as refrigerated trucks or construction vehicles.

5.3.1 Focus on infrastructure for NG cars

Here, it will look at what already exists and the projects planned for the future. Regarding NG infrastructure, there were already 150 CNG stations across Belgium in 2018. A few years ago, the CREG published an article [31] in which it reported that for the period 2019-2020, 18 projects were planned in Flanders, 14 in Wallonia, and 3 in the Brussels-Capital Region. Furthermore, an article published by IDETA [32] indicates that

there are already 200 operational CNG service stations and that new projects are under development.
NG-powered vehicles are not the preferred solution for most of the industry. Even so, this option is already being utilized. There are reasons to believe that its use could increase in the coming years.

5.3.2 Focus on infrastructure for fuel cells cars

Regarding infrastructure for fuel cell vehicles, several hydrogen refueling stations are already installed and managed by DATS24 [33]. These stations are located in Halle, Wilrijk, Haasrode, Ollignies, Erpe-Mere, and Herve. Additionally, the EU has planned the construction of 35 hydrogen refueling stations [34]. Some of these will be in Belgium. Pilot projects, such as those conducted by Virya Energy and Taxis Verts [35], have been carried out to assess whether this technology could be a viable option for taxis. One study showed that a hydrogen-powered taxi covered more than 55,000 kilometers. This demonstrates its potential for passenger mobility.
Despite these initiatives, the hydrogen refueling network in Belgium remains limited. While interest in such projects may grow in the future, the industry currently appears to be moving primarily toward EVs.

5.3.3 Comparison of results obtained with current trends

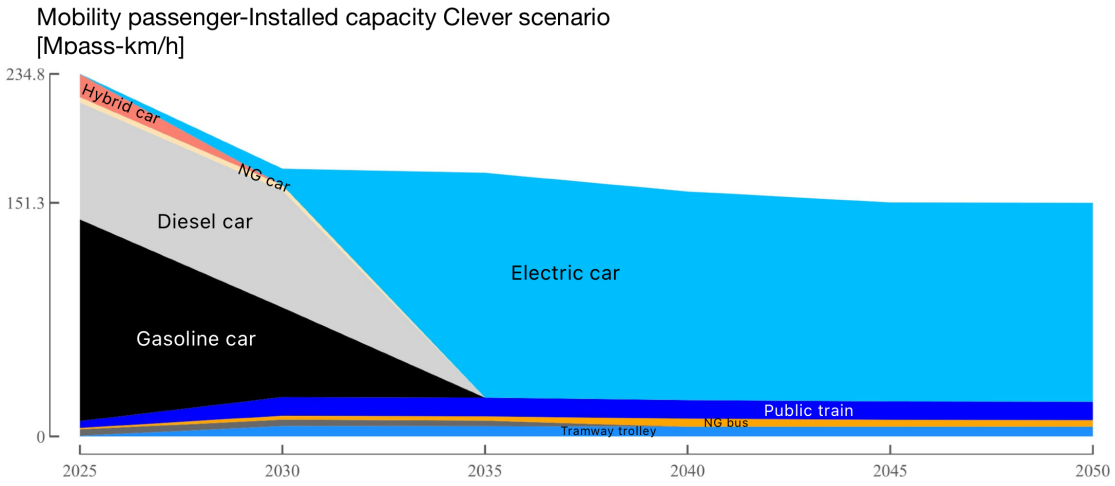

Figure 5.3: In the Clever scenario, private mobility consists exclusively of EVs by 2050, while public mobility includes a share of NG buses.

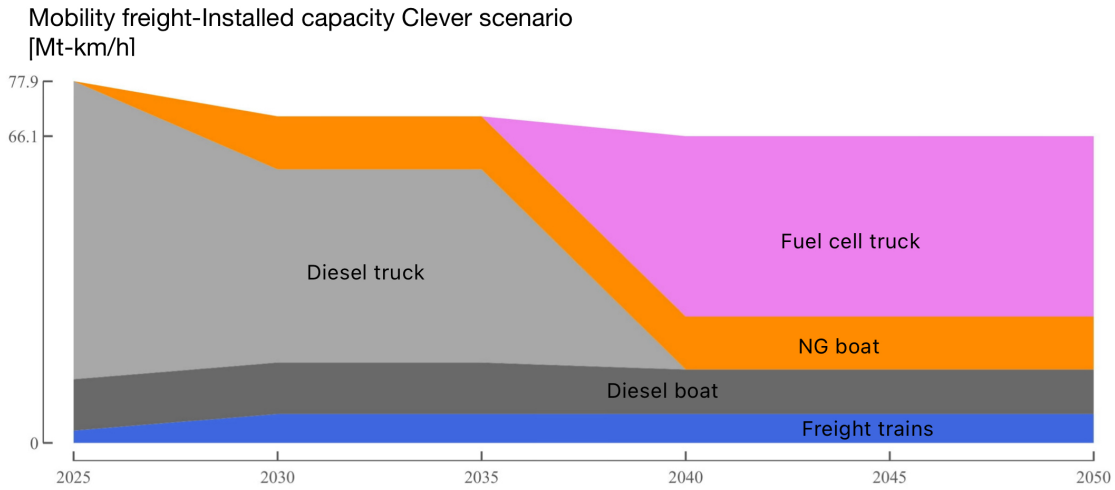

Figure 5.4: In the Clever scenario in 2050, freight mobility consists of fuel cell trucks, NG boats, diesel boats, and freight trains.

Now that the current trends have been reviewed, the next step is to compare them with the model's results. In the Clever scenario, the model fully opts for EVs for private mobility (see figure 5.3). For public mobility, part of the installed capacity is covered by CNG buses (see figure 5.3). Regarding freight mobility (see figure 5.4), the model primarily selects fuel cell trucks, along with NG boats, diesel boats, and freight trains. Diesel was completely phased out of the system by 2035 in the Clever scenario. As a result, biodiesel is used to power the diesel boats. EVs are therefore not favored by the model for freight mobility. This contradicts the current industry trends and makes these results open to criticism.

When a lithium constraint is introduced in the model, it compensates by favoring NG and fuel cell cars. This happens due to the reduction in the number of EVs (see figure 4.13). This replacement strategy can even be economically beneficial, as discussed in section 5.2.2. Therefore, the importance of including all three technologies, electric, NG, and fuel cell, in private mobility was highlighted.

Looking at ongoing projects, it is clear that NG and fuel cell vehicles are not currently the leading options, but the door remains open. If the economic advantages of these alternatives are emphasized, their adoption could increase in the future. The evolution of these trends will largely depend on future policies and subsidies.

5.4 Discussion on biomass potential in EnergyScope Pathway

The biomass potential in Belgium, considered by EnergyScope Pathway, is important as it directly impacts the primary energy mix. The model, in fact, has a limit on the maximum amount of energy it can produce from biomass. For the Clever scenario and the reference one, this limit is reached as early as 2030. This indicates that from the very first optimisation phase, the model hits this maximum limit. One should question whether this maximum limit accurately represents the real biomass potential in Belgium. To do so, it is useful to examine the maximum potential given by four studies: CONCAWE, ENSPRESO, OUTLOOK, and S2BIOM (see table 5.2). This comparison of studies is taken from the work of Colla et al. [36].
The summary table of values used by EnergyScope Pathway (see table 5.3) shows that the imposed wood biomass limit is realistic compared to those in the literature. However, the limit for wet biomass is higher, indicating that the model is overestimating the amount of energy it can produce from wet biomass. It is therefore important to know that in the primary energy mix, probably more than 14.9 TWh cannot be produced from wet biomass.

Study	**Wood Biomass (TWh)**	**Wet Biomass (TWh)**
CONCAWE	11	24
ENSPRESO	28	21
OUTLOOK	23	15
S2BIOM	18	12

Table 5.2: Maximum potential of wood and wet biomass in Belgium according to 4 studies for the year 2030 [36]

In EnergyScope Pathway	**Energy (TWh)**
Wood biomass	23.4
Wet biomass	38.9

Table 5.3: Maximum potential values for wood and wet biomass considered in the model

5.4.1 Primary energy mix under realistic wet biomass

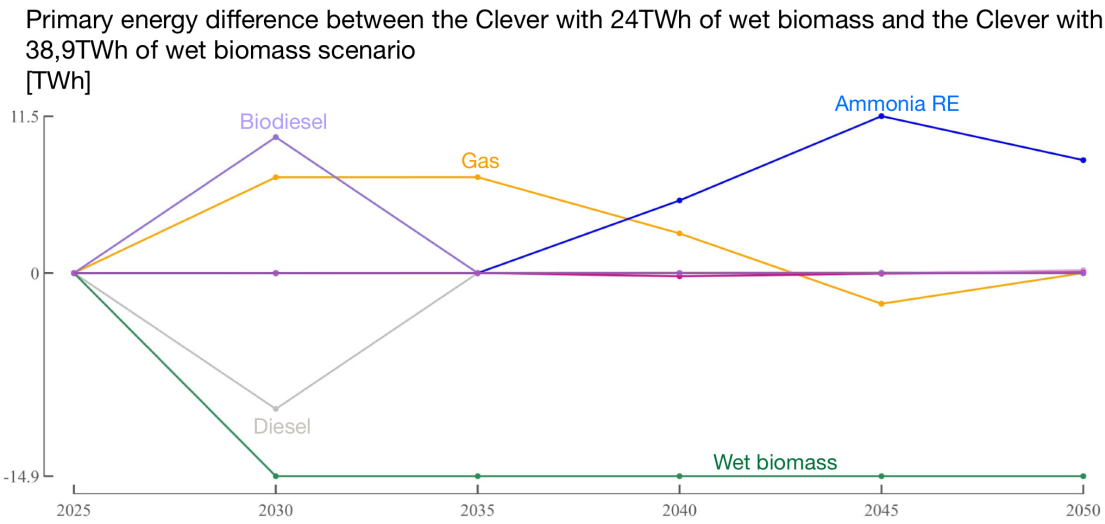

Figure 5.5: The decrease in wet biomass with a maximum potential of 24 TWh leads to an increase in NG. The portion of high-temperature heat that was previously produced with wet biomass is now produced with NG.

In figure 5.5, the comparison of the primary resource mix between the Clever scenario with a maximum wet biomass potential of 24 TWh and the Clever scenario with a maximum wet biomass potential of 38.9 TWh is shown. This comparison helps observe the resources selected by the model when the maximum wet biomass potential is not overestimated. The 24 TWh maximum potential was chosen based on table 5.2.

In 2030, wet biomass decreases. As this biomass helped reduce GWP emissions, the system must compensate by lowering emissions elsewhere to stay within the total budget. This explains the increasing peak of biodiesel and the decreasing peak of diesel in 2030. The use of biodiesel allows the system's emissions to be reduced.

The additional wet biomass in the second scenario was partly used for biohydrolysis, hence for electricity production. This electricity was then used directly to produce high-temperature heat. Another part of the additional wet biomass was used in an industrial wood boiler, also for producing high-temperature heat. Now, with a maximum wet biomass potential of 24 TWh, the model covers this unmet high-temperature heat demand with industrial gas cogeneration. Gas consumption increases between 2025 and 2040 in figure 5.5, due to this.

This increase in gas consumption results in additional GWP emissions. To respect the total GWP emissions budget, the model then chooses, between 2040 and 2050, to replace electricity production from CCGT with CCGT running on ammonia. This explains why gas consumption decreases and RE ammonia consumption increases during these years in figure 5.5.

Next, the reduced share of wet biomass in the system has an impact on the cost. The total cumulative transition cost increases by €5.4 billion. This corresponds to a 0.5% rise.

In summary, the portion of wet biomass is replaced by gas. This biomass was previously used for high-temperature heat production. As the model substitutes wet biomass with NG, which has a higher gwp_{op}, it leads to an increase in system emissions. As a result, the model must compensate by reducing emissions elsewhere. Wet biomass consequently proves to be both an effective option for reducing emissions and a sound economic choice.

5.5 Putting the results into perspective with the literature

5.5.1 Limits of the model used

The model used is the EnergyScope Pathway model. It introduces a linear formulation to extend the EnergyScope snapshot version [2]. Compared to the snapshot version, this model has the advantage of representing the entire energy system transition and not just a single representative year. It therefore allows us to observe the speed of the transition. It also enables visualizing transitions over time for indicators such as resources, installed capacity of energy systems, and GHG emissions by sector.

The results obtained in this work were generated using the monthly version of EnergyScope Pathway, MO. One weakness of this version is its lack of hourly resolution. Hourly resolution allows for a more accurate consideration of seasonality and energy storage, as is the case in the hourly model [6]. However, the monthly version remains sufficiently granular to capture significant seasonal variations. In this version, intermittent REs are aggregated at the monthly scale. This results in a loss of detail regarding hourly production profiles. The scenarios for achieving neutrality are based on RE fuels. A significant share of these fuels comes from intermittent technologies like wind and solar. Some uncertainty remains regarding these intermittent RE sources in the monthly version. Here, EnergyScope MO was chosen for its fast computation time, one of its strengths. In this way, it is easy to explore and compare different scenarios quickly.

The developed scenarios rely on demand projections, formulated as input assumptions. Since the demand matrices are used as inputs, their values may be subject to criticism. They directly influence the results, demand evolution, and model decisions. In this context, the matrices enable the implementation of the two scenarios, reference and Clever, by varying future demand.

The EnergyScope Pathway model is not designed for detailed cost analysis of the energy system. It provides an order of magnitude estimate of the energy transition's cost. It is consequently not suited for in-depth economic assessments.

A final point is that the model must comply with a GWP emissions budget to meet environmental objectives. Still, environmental objectives are not limited to a GWP emissions budget. Considering the emissions limit does not necessarily imply addressing air pollution reduction [37]. This air pollution includes NOx, SO_2 and fine particles which can have a very harmful effect on public health. There is also no integration of the notion of biodiversity. The model neglects the impact on the degradation of natural environments [38]. As already mentioned, the model does not take into account the respect of environmental boundaries regarding resource consumption, as discussed in section 3.1.2 with the limit on lithium. Linked to these resources, the model does not consider geopolitical dependencies, potentially impacting the system's sustainability [7]. The environmental objectives go beyond the GWP emissions limit, revealing a weakness of the EnergyScope Pathway model.

5.5.2 Positioning the proposed scenarios in the landscape of existing scenarios

To put the previously obtained results into perspective, it is useful to reflect on the assumptions underlying the developed scenarios. This allows for a comparison with the scenarios previously mentioned in the literature review. The Clever and reference scenarios developed here include the power sector, the industry sector, domestic transport, domestic maritime transport, the residential sector, and the tertiary sector. However, these scenarios do not include international maritime transport, aviation transport, agriculture and LULUCF.

VRE capacities comparison

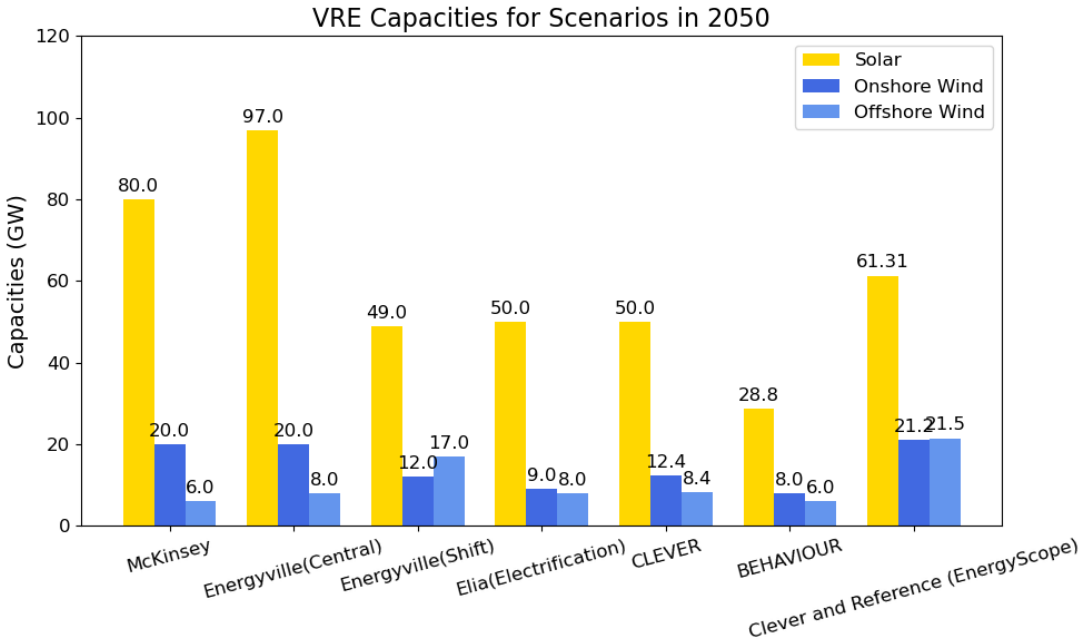

Figure 5.6: The scenarios developed with EnergyScope always reach the maximum VRE capacity limit, resulting in identical VRE capacities in the Clever and reference scenarios.

The figure 5.6 compares the installed capacities of VRE technologies. The installed capacities are identical for the two scenarios developed with EnergyScope. These technologies are limited by a maximum installation capacity. The model always reaches this maximum due to the benefits it offers in reducing system emissions.
The installed solar capacities in these two EnergyScope cases are higher than in the sufficiency-based scenarios from existing literature, such as EnergyVille (Shift), CLEVER, and BEHAVIOUR. This difference results from the assumptions made by the model regarding maximum installable capacity limits. The solar capacity values in the EnergyScope cases fall within a mid-range compared to those in existing literature. The offshore wind capacity in the EnergyScope scenarios is similar to that in the EnergyVille (Shift) case. Similarly, the onshore wind capacity aligns closely with the values in the McKinsey and Energyville (Central) cases.

Finally, both the Clever and reference scenarios reach the maximum installation limit for these technologies. Nonetheless, this result is debatable, as it depends heavily on future project developments, especially for offshore wind.

Conclusion

This study analysed two pathways for achieving carbon neutrality in Belgium by 2050: the reference and Clever scenarios. Both were obtained using the EnergyScope Pathway model. The reference scenario, based on the European Commission's projections, serves as the baseline. The second pathway developed in this study is called 'Clever' and is based on the 'original CLEVER' scenario coordinated by négaWatt France.

The Clever scenario allows for a 55% reduction in demand, in line with the original CLEVER version. A key strength of this work is that both pathways start in 2025. Clever adjusts the initial assumptions accordingly for a 2025–2050 transition. This allows the starting year to closely reflect the current situation.

The Clever scenario shows the impact of integrating sufficiency into an energy transition using the EnergyScope Pathway model. The model is based on cost optimisation while respecting a total Global Warming Potential (GWP) emissions budget. The Clever scenario is based on a significant reduction in demand. This reduction in demand has allowed the model to gain flexibility regarding the emissions budget. As a result, it has selected less expensive resources despite their higher carbon intensity. In the end, the Clever scenario has a lower total transition cost but is relatively more carbon-intensive.

The EnergyScope Pathway model is based on cost optimisation and is not designed to minimise emissions. However, in a scenario built around sufficiency, like the original CLEVER one, environmental goals are prioritized over economic ones. The model accounts for environmental objectives through a Global Warming Potential (GWP) emissions limit. Nevertheless, these objectives go far beyond a simple emissions limit. They include other key issues such as air pollution, loss of biodiversity, and depletion of resources. In this context, EnergyScope Pathway is thus limited in its ability to account for broader environmental boundaries.

The original CLEVER scenario defines energy demands and technology choices exogenously. In this study, the Clever scenario was developed based on the original scenario's demands but adapted for the EnergyScope Pathway model. The model was left free

to select technologies independently. This explains why the technologies in the Clever scenario differ from those in the original CLEVER scenario.

Furthermore, the negaWatt vision is based on three pillars (see figure 1): sufficiency, efficiency and renewable energy. The Clever scenario relies more on non-renewable energy technologies. This delays the phasing out of fossil fuels and, consequently, the integration of renewables. As a result, it does not integrate renewable energy technologies sufficiently or quickly enough.

Subsequently, a limit on the number of electric vehicles was integrated into the Clever scenario. The objective was to develop a scenario that not only incorporates sufficiency but also respects planetary boundaries. Both the original CLEVER scenario and the newly developed Clever scenario did not respect planetary boundaries regarding lithium extraction. Therefore, a cap on the number of electric vehicles was imposed. This limit, based on the European Union's lithium extraction constraints, was then adjusted and calculated to provide a cap for Belgium. The result of implementing such a constraint is that the maximum allowed number of electric vehicles is far from sufficient to meet the total passenger mobility demand. The model then compensated for this shortfall by selecting natural gas and fuel cell vehicles. This highlighted the benefits of alternative solutions to electric vehicles. Currently, electric vehicles remain the most efficient technology. In this study, the advantages of electric vehicles were nuanced. A system based on fewer electric vehicles may offer greater stability in lithium prices and reduce dependence on certain countries.

This new constraint on electric vehicles also underscored the importance of vehicle occupancy rates in a sufficiency-based scenario. This factor can significantly influence the results. If the occupancy rate increases, it becomes easier to stay within lithium extraction limits. Higher vehicle occupancy rates can be achieved through behavioural changes such as car sharing.

There was also special attention given in this work to the integration of infrastructure costs. Integrating these costs allowed for a system that more accurately represents reality. This integration of infrastructure costs also showed a certain economic advantage of natural gas and fuel cell vehicles compared to electric vehicles.

One must keep in mind that EnergyScope Pathway does not take current realities into account. The industry is mainly moving towards electric vehicles. Interestingly, in the Clever scenario, the model does not choose electric vehicles for the freight mobility sector and relies instead on other technologies such as fuel cell trucks. One limitation of the model is its inability to reflect current and emerging trends. One way to account

for these trends is to impose technology choices. Still, this removes the benefit of using EnergyScope Pathway. The benefit lies in its ability to show the model's selection of resources and technologies. In this case, the model's choices do not align with current trends. However, these trends may shift significantly and will be influenced by the policies and subsidies implemented.

A final point of attention was addressed after obtaining the results. It was observed that the maximum potential of wet biomass was overestimated in EnergyScope Pathway. When this potential is corrected to a more realistic level, the model replaces wet biomass with natural gas to meet the demand for high-temperature heat. This substitution increases the system's emissions. It thereby requires reductions elsewhere to stay within the emissions budget. Such a result highlights the significant advantage biomass offers in reducing overall system emissions. Wet biomass also helped reduce the costs of the transition, therefore offering a certain economic advantage.

Finally, it is important to emphasize that the successful integration of sufficiency into the system will also depend on adopted policies, collective action, and societal behavioural change. These are factors that are not currently captured by the model. A promising direction for future research would be to adapt EnergyScope Pathway to better account for sufficiency. This could be done by integrating these societal dimensions and aligning more closely with ambitious environmental targets.

Appendix A

Model description

The EnergyScope Pathway model is a model based on cost optimisation [2]. More specifically, this model will try to reduce the total cost of the transition $C_{tot,trans}$. This corresponds to minimising the sum of Operating (OPEX) and Capital Expenditures (CAPEX). This is expressed as:

$$\min C_{\text{tot,trans}} = C_{\text{tot,capex}} + C_{\text{tot,opex}}. \tag{A.1}$$

The CAPEX is based on the following assumptions:

$$C_{\text{tot,capex}} = \sum_{p \in \text{PHASE}} C_{\text{inv,phase}}(p) - \sum_{j \in \text{TECH}} C_{\text{inv,return}}(j) \tag{A.2}$$

$$C_{\text{inv,phase}}(p) = \sum_{j \in \text{TECH}} F_{\text{new}}(p,j) \cdot \tau_{\text{phase}}(p) \cdot c_{\text{inv}}(p,j) \quad \forall p \in \text{PHASE} \tag{A.3}$$

$$\tau_{\text{phase}}(p) = \frac{1}{(1+i_{\text{rate}})^{\text{diff_2025_year}(p)}} \tag{A.4}$$

$$C_{\text{inv,return}}(j) = \sum_{p \in \text{PHASE}} \tau_{\text{phase}}(p)\, c_{\text{inv}}(p,j)\, \frac{\text{remaining_years}(j,p)}{\text{lifetime}(y_{\text{start}},j)} \left(F_{\text{new}}(p,j) - \sum_{p_2 \in \text{PHASE}} F_{\text{decom}}(p_2,p,j) \right) \tag{A.5}$$

- $C_{\text{tot,capex}}$ corresponds to the difference between the total investments made during the transition ($C_{\text{inv,phase}}$) and the residual value of the equipment ($C_{\text{inv,return}}$).
- $C_{\text{inv,phase}}$ is calculated as the product of the new installed capacities and the discounted investment costs.
- $C_{\text{inv,return}}$ takes into account the residual value at the end of the transition according to the remaining years of use.

- $F_{\text{new}}(p, j)$ is the new installed capacity of technology j in phase p.
- $F_{\text{decom}}(p_2, p, j)$ represents the amount of installed capacity of technology j decommissioned during phase p_2, initially commissioned in phase p. This term is used to exclude capacity no longer operational when calculating salvage value or other metrics.
- $F(y, j)$ is the installed capacity of technology j in year y.
- The annualisation factor, τ_{phase} adjusts future expenditures to reflect their value in a reference year, considering a constant discount rate i_{rate}.
- The discount factor (i_{phase}) is uniform for all technologies and is intended to reflect the depreciation of future expenditure. It is set at 1.5%.

The OPEX is based on the following assumptions:

$$C_{\text{tot,opex}} = C_{\text{opex}}(2020) + t_{\text{phase}} \cdot \sum_{p \in \text{PHASE}} \tau_{\text{phase}}(p) \cdot C_{\text{opex}}(p) \tag{A.6}$$

$$C_{\text{opex}}(y) = \sum_{j \in \text{TECH}} C_{\text{maint}}(y, j) + \sum_{i \in \text{RES}} C_{\text{op}}(y, i) \quad \forall y \in \text{YEARS} \tag{A.7}$$

$$C_{\text{maint}}(y, j) = c_{\text{maint}}(y, j) \cdot F(y, j) \quad \forall y \in \text{YEARS}, \forall j \in \text{TECH} \tag{A.8}$$

$$C_{\text{op}}(y, i) = \sum_{t \in T} c_{\text{op}}(y, i) \cdot F_t(y, i, t) \cdot t_{\text{op}}(t) \quad \forall y \in \text{YEARS}, \forall i \in \text{RES} \tag{A.9}$$

- $C_{\text{tot,opex}}$ includes the operational costs in 2025. These also include those of the various transition phases, calculated as the average of the costs at the beginning and end of each phase.
- The annual operating cost $C_{\text{opex}}(y)$ includes maintenance costs (C_{maint}) and resource consumption costs (C_{op}).
- $C_{\text{maint}}(y, j)$ is the maintenance cost for technology j in year y.
- $C_{\text{op}}(y, i)$ is the cost of using resource i in year y.
- $c_{\text{maint}}(y, j)$ is the unit maintenance cost for technology j in year y.
- $F(y, j)$ is the installed capacity of technology j in year y.
- $c_{\text{op}}(y, i)$ is the cost per unit of resource i in year y.

- $F_t(y,i,t)$ is the hourly consumption of resource i at time t during year y.
- $t_{\text{op}}(t)$ is the number of hours represented by time step t (e.g., summing up to 8760 hours).
- $\tau_{\text{phase}}(p)$ is the discount factor for phase p.
- t_{phase} is the duration of a phase, i.e., 5 years.

To account for emissions during the transition, the model uses the parameter $GWP_{\text{tot,trans}}$. This parameter is calculated as an average of representative years at the beginning and end of each phase and is expressed as follows:

$$GWP_{\text{tot,trans}} = GWP_{\text{tot}}(2025) + t_{\text{phase}} \cdot \sum_{p \in \text{PHASE}} GWP_{\text{tot}}(p)$$

Where:
- $GWP_{\text{tot}}(2025)$ covers all operational emissions for the year 2025.
- $GWP_{\text{tot}}(p)$ represents the arithmetic mean of annual emissions at the beginning and end of each phase.
- The annual emissions $GWP_{\text{tot}}(y)$ result from the sum of emissions related to the resources used for energy production:

$$GWP_{\text{tot}}(y) = \sum_{i \in \text{ERES}} GWP_{\text{op}}(y,i)$$

- $GWP_{\text{op}}(y,i)$ depends on the specific GWP of each resource, multiplied by the quantity used.

In this work, the GWP_{tot} budget is set at 1,020,779.5 [ktCO$_2$,eq].

Appendix B

Vehicle infrastructure constraints

For the electric vehicle

Previously, the model did not take into account the cost of EVs in terms of infrastructure expenditure. To incorporate this cost, a new parameter will be created in the model, called GRID2. This new parameter will allow us to define a new constraint. This constraint is formulated as follows:

$$F[y,\text{"GRID2"}] \geq 1 + \frac{c_grid_extra2}{c_inv[y,\text{"GRID2"}]} \Big(\sum_{v \in \{\text{"CAR_BEV"},\text{"CAR_PHEV"},\text{"CAR_HEV"}\}} (F[y,v] - f_min[y,v]) \Big)$$

Where:

- $c_grid_extra_2$ [M€/GW]: is the cost to reinforce the grid due to intermittent RE penetration.
- c_inv [M€/GW]: is the phase total annualized investment cost.
- F [GW]: is the additional installed capacity during a phase.
- f_min [GW]: is the minimum installed capacity during a phase.

This equation imposes a constraint on the variable $F[y,\text{“GRID2”}]$ for each year y. It takes into account all vehicles equipped with batteries, namely BEV, PHEV, and HEV cars. The constraint specifies that the value of $F[y,\text{“GRID2”}]$ must be greater than or equal to 1, adjusted by a factor that depends on the ratio between the additional infrastructure cost and the investment cost of this infrastructure. This factor is multiplied by a term representing the difference between the additional and minimum installed capacity during a phase.

For the natural gas vehicle

$$F[y,\text{"GRID_NG"}] \geq 1 + \frac{c_grid_extra_NG}{c_inv[y,\text{"GRID_NG"}]} \Big(\sum_{v \in \{\text{"CAR_NG"},\text{"TRUCK_NG"}\}} (F[y,v] - f_min[y,v]) \Big)$$

For the constraint on NG (natural gas) vehicles, the same logic used for EVs is applied. It is worth noting that *c_grid_extra_NG* is set to 0, as this parameter represents additional costs related to RE intermittency. Since NG is not considered intermittent, no extra grid reinforcement costs are included.
Another important point is that this constraint applies not only to cars, but also to trucks. The decision was made to include infrastructure costs for trucks in order to provide a more accurate cost assessment. Trucks were therefore included under this constraint, based on the reasonable assumption that cars and trucks will share the same infrastructure.

For the fuel cell vehicle

$$F[y,\text{"GRID_FUELCELL"}] \geq 1 + \frac{c_grid_extra_FUELCELL}{c_inv[y,\text{"GRID_FUELCELL"}]} \cdot \left(\sum_{v \in \{\text{"CAR_FUEL_CELL"},\text{"TRUCK_FUEL_CELL"}\}} (F[y,v] - f_min[y,v]) \right)$$

For fuel cell vehicles, the same logic is applied in formulating the constraint. The parameter *c_grid_extra_FUELCELL* is set to 0 because hydrogen is not considered an intermittent energy source in this context. As a result, no additional costs related to intermittency need to be accounted for.
A similar reasoning was used to decide on the inclusion of cars and trucks in the constraint. The goal, once again, is to provide a more accurate representation of vehicle infrastructure costs.

Bibliography

[1] Association negaWatt Belgique. *La démarche négaWatt*. https://www.negawatt.be/la-demarche-negawatt/. 2023.

[2] Xavier Rixhon. "Exploration of Uncertainty-Aware Energy Transition Pathways: Reinforcement Learning and Principal Component Analysis-Based Methods". Doctoral dissertation. UCLouvain, Sept. 2024. URL: http://hdl.handle.net/2078.1/291459.

[3] CLEVER Project Team. *CLEVER Final Report*. https://clever-energy-scenario.eu/wp-content/uploads/2023/10/CLEVER_final-report.pdf. 2023.

[4] Hugo Baudson. "Impact of demand reduction on the Belgian energy system in 2050". Supervised by Hervé Jeanmart. Mémoire de master. Louvain-la-Neuve, Belgium: École polytechnique de Louvain, Université catholique de Louvain, 2022. URL: http://hdl.handle.net/2078.1/thesis:35632.

[5] Pierre Verstraeten. "Impact of sufficiency in industry on the Belgian energy system in 2050". Supervised by Hervé Jeanmart. Mémoire de master. Louvain-la-Neuve, Belgium: École polytechnique de Louvain, Université catholique de Louvain, 2023. URL: http://hdl.handle.net/2078.1/thesis:40590.

[6] Gauthier Limpens et al. "EnergyScope TD: A novel open-source model for regional energy systems". In: *Applied Energy* 255 (2019). Available online 12 September 2019, p. 113729. DOI: 10.1016/j.apenergy.2019.113729. URL: https://doi.org/10.1016/j.apenergy.2019.113729.

[7] *Manifesto: A Resilient and Resource-wise Europe: Sufficiency at the Heart of the EU's Future*. Available at https://friendsoftheearth.eu/wp-content/uploads/2024/01/Sustainable-Resource-Use.pdf. Friends of the Earth Europe, Mar. 2024.

[8] IPCC. *Climate Change 2022: Mitigation of Climate Change. Working Group III Technical Summary*. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_TechnicalSummary.pdf. Intergovernmental Panel

on Climate Change (IPCC) Sixth Assessment Report (AR6), Working Group III. 2022.

[9] McKinsey & Company. *Net Zero or Growth? How Belgium Can Have Both*. https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zero-or-growth-how-belgium-can-have-both. Accessed February 22, 2025.

[10] Enya Lenaerts, Wouter Nijs, and Pieter Valkering. *Scenario towards a climate neutral Belgium by 2050: Introducing the SHIFT scenario – A PATHS2050 comparison*. Tech. rep. A study commissioned by Ecolo-Groen. Thor Park 8310–8320, 3600 Genk, Belgium: EnergyVille, 2024. URL: https://energyville.be/wp-content/uploads/2024/03/Full-Fledged-Report_1.pdf.

[11] Council of the European Union. *Fit for 55*. https://www.consilium.europa.eu/en/policies/fit-for-55/. 2024.

[12] ENTSO-E and ENTSOG. *Executive Summary – TYNDP 2024 Scenarios*. https://2024.entsos-tyndp-scenarios.eu/#executive-summary. 2024.

[13] Elia. *Electricity Scenarios for Belgium Towards 2050: Elia's Quantified Study on the Energy Transition in 2030 and 2040*. Rapport PDF, novembre 2017. Disponible sur le site d'Elia. 2017. URL: https://www.elia.be/-/media/project/elia/elia-site/electricity-market-and-system---document-library/adequacy---studies/2017/20171114_electricity-scenarios-for-belgium-towards-2050.pdf.

[14] Doughnut Economics. *About Doughnut Economics*. 2025. URL: https://doughnuteconomics.org/about-doughnut-economics.

[15] Climate Action Network (CAN) Europe. *PAC Scenario 2.0 in a nutshell – Frequently Asked Questions*. Organisme : CAN Europe, Bruxelles (Belgique). Disponible sur https://caneurope.org. June 2022.

[16] *Scenarios for a Climate Neutral Belgium by 2050*. Federal Public Service Health, Food Chain Safety and Environment - DG Environment, Climate Change Service, May 2021. URL: https://climat.be/doc/climate-neutral-belgium-by-2050-report.pdf.

[17] Joel Millward-Hopkins et al. "Providing decent living with minimum energy: A global scenario". In: *Global Environmental Change* 65 (2020), p. 102168. DOI: 10.1016/j.gloenvcha.2020.102168. URL: https://www.sciencedirect.com/science/article/pii/S0959378020307512.

[18] Judith Pigneur et al. *Le lithium : un défi écologique majeur pour une mobilité décarbonée*. Rapport. Avec le soutien de l'ADEME et de l'European Climate Foundation. Valence, France: Association négaWatt, 2024. URL: https://www.negawatt.org.

[19] Statbel. *Infographie : La présidence belge du Conseil de l'Union européenne 2024*. https://statbel.fgov.be/sites/default/files/images/Presidence/BEPresidencyInfographic_FR.pdf. 2024.

[20] ByMyCar. *Combien de lithium dans une batterie de voiture électrique ?* Aug. 2024. URL: https://www.bymycar.fr/webzine/combien-de-lithium-dans-une-batterie-de-voiture-electrique/.

[21] Hélène Seynaeve. *Quelles différences entre voiture électrique, voiture hybride et voiture hydrogène ?* June 2024. URL: https://www.automobile-propre.com/dossiers/differences-voiture-electrique-voiture-hybride-hydrogene/.

[22] Gaz-Mobilité. *Sécurité GNV : est-il dangereux ?* https://www.gaz-mobilite.fr/dossiers/securite-gnv-est-il-dangereux/.

[23] *Costs and Financing of Hydrogen Infrastructure*. https://h2stationmaps.com/costs-and-financing. Consulté le 23/03/2025.

[24] *Operation and Maintenance of Electric Vehicle Charging Infrastructure*. https://afdc.energy.gov/fuels/electricity-infrastructure-maintenance-and-operation.

[25] *Hydrogen Infrastructure Report*. https://hydrogeneurope.eu/wp-content/uploads/2024/10/2024.10_HE_Hydrogen-Infrastructure-Report.pdf.

[26] Eurostat. *Glossary: Global-warming potential (GWP)*. 2023. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Global-warming_potential_(GWP).

[27] Gauthier Limpens. "Generating Energy Transition Pathways: Application to Belgium". PhD Thesis. Louvain-la-Neuve, Belgium: Université catholique de Louvain, 2023. URL: https://dial.uclouvain.be/pr/boreal/object/boreal:249196.

[28] SlowHeat Project. *SlowHeat — Heat People, Not Spaces*. 2024. URL: https://www.slowheat.org/.

[29] *Faire sa part ? Pouvoir et responsabilité des individus, des entreprises et de l'État face à l'urgence climatique*. Carbone 4, 2019. URL: https://www.carbone4.com/publication-faire-sa-part.

[30] Oxford Institute for Energy Studies. *Lithium Price Volatility: What's Driving it and What it Means for the Energy Transition*. Oxford Energy Insight No. 145. Feb. 2024. URL: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/02/Insight-145-Lithium-Price-Volatility.pdf.

[31] CREG. *Étude sur la compétitivité du gaz naturel utilisé en tant que carburant (F1919FR)*. Disponible sur https://www.creg.be/sites/default/files/assets/Publications/Studies/F1919FR.pdf. 2018.

[32] IDETA. *Plan stratégique 2023–2025*. Disponible sur https://ideta.be/wp-content/uploads/2024/01/IDETA-plan-strategique-2023-2025-DEF.pdf. 2023.

[33] Touring Belgique. *Voiture à hydrogène : avantages, fonctionnement et où faire le plein*. 2023. URL: https://carselect.touring.be/fr/blog/voiture-hydrogene-avantages-fonctionnement-et-ou-faire-le-plein-2/.

[34] H2 Mobile. *L'Europe finance de nouveaux projets de stations hydrogène*. 2024. URL: https://www.h2-mobile.fr/actus/europe-finance-nouveaux-projets-stations-hydrogene/.

[35] Virya Energy. *L'hydrogène durable : une solution viable pour les flottes de taxi*. 2023. URL: https://virya-energy.com/fr/actualit%C3%A9s/hydrogene/lhydrogene-durable-une-solution-viable-pour-les-flottes-de-taxi/.

[36] Martin Colla et al. "Navigating bioenergy horizons: a critical examination of Europe's potential, with Belgium as a case study". In: *Sustainable Energy Research* 11.17 (2024). DOI: 10.1186/s40807-024-00108-0. URL: https://doi.org/10.1186/s40807-024-00108-0.

[37] Sciensano. *Qualité de l'air — Belgique en bonne santé*. 2024. URL: https://www.belgiqueenbonnesante.be/fr/etat-de-sante/determinants-de-sante/qualite-de-lair.

[38] Sécurité de la Chaîne alimentaire et Environnement SPF Santé publique. *Biodiversité — Conséquences des changements climatiques*. 2024. URL: https://climat.be/changements-climatiques/consequences/biodiversite.

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