

École polytechnique de Louvain

Impact of sufficiency in industry on the Belgian energy system in 2050

Author: **Pierre VERSTRAETEN**

Supervisors: **Hervé JEANMART, Sébastien MEYER, Paolo THIRAN**

Reader: **Sylvain QUOILIN**

Academic year 2022–2023

Master [120] in Mechanical Engineering

Abstract

While a significant downward trend in greenhouse gas emissions from the Belgian industrial sector was observed until around 2012, they have been stagnating for the last decade. It seems that the easiest efficiency measures have already been leveraged in most industries. Breakthrough technologies could lower the emissions further, but they come with a high level of uncertainty, and they may not suffice to reach net carbon neutrality by 2050. Another strategy, that is gaining in attention, is to decrease production volumes, directly decreasing emissions and allowing a more rapid transition. This approach is based on sufficiency, aiming at redefining our material needs in order to meet the social foundations for every individual, without collectively overshooting Earth's planetary boundaries.

In this master thesis, a scenario is built for the Belgian industry in 2050 with ambitious assumptions regarding sufficiency, based on previous work in the residential, tertiary and transportation sectors. The global Belgian scenario, including all sectors, is compared with different existing global Belgian scenarios towards 2050 with varying sufficiency ambitions, leading to varying energy demand. All the scenarios are then modeled using EnergyScope Typical Days, which optimises the design and operation of all energy sectors. The results are compared with the energy systems from the original scenarios, and the impact of demand reduction on the energy system is studied, with a focus on the industrial sector.

It was observed that as the lower demand scenarios have the main advantage of relying less on uncertain and expensive imported e-fuels, their higher shares of intermittent renewable electricity generation from wind and solar are a real challenge for the operation of the energy system. On top of storage technologies, flexibility in the industrial sector was identified as a promising way to overcome this challenge.

Acknowledgments

I would like to thank Sébastien Meyer, who proposed this interesting subject.

I would also like to thank him, as well as Paolo Thiran, for their supervision throughout my master thesis, their precious advice and feedback on my work.

Thank you to Professor Hervé Jeanmart for supervising this thesis and for the interesting discussions we had about the topic, challenging my vision and helping me forward.

I am grateful for the meetings I had with external experts from various fields, who gave me different perspectives on the complex subject : Luc Norga from CSC-BIE, Tycho van Hauwaert from BBL, and Yves Marenne from ICEDD.

Thank you to Professor Sylvain Quoilin, who immediately accepted with enthusiasm to be an external reader of this thesis.

Thank you to my sister, for the discussions that helped me structure my master thesis.

A special thank you to my parents for their support, and especially for their proofreading and feedback on my work.

Contents

Abstract	i
Acknowledgments	ii
Contents	iii
List of Figures	v
List of Tables	vii
1 Introduction	1
2 Literature review	4
2.1 Major technologies in the industry of 2050	4
2.1.1 Steel	4
2.1.2 High-value chemicals	5
2.1.3 Ammonia	6
2.1.4 Other sectors	7
2.2 Energy system modeling	8
2.2.1 EnergyScope Typical Days	8
2.2.2 Other energy system models	12
2.3 Existing scenarios towards 2050	13
2.3.1 Hugo Baudson "Low Demand" scenario	13
2.3.2 FPS Public Health and Climact "Behaviour" scenario	15
2.3.3 CLEVER Belgian scenario	19
2.3.4 EnergyVille "Paths 2050" central scenario	23
2.3.5 EU reference scenario	25
2.3.6 Bond Beter Leefmilieu and Climact "Hoe creëren we een klimaatneutrale Vlaamse industrie?" scenario	26
3 Methodology	30
3.1 Adjusted Low Demand scenario	30
3.2 Simulations with EnergyScope TD	33
3.2.1 Obtaining the EUD matrix	33
3.2.2 EnergyScope simulation	35
3.2.3 Defining Final Energy Consumption from EnergyScope results	35
4 Results	37

4.1	Comparison of the original scenarios	38
4.1.1	Sufficiency and efficiency assumptions	38
4.1.2	Industrial final energy consumption	39
4.1.3	Global final energy consumption by sector	42
4.1.4	End-use demand	42
4.2	Comparison of the industrial sector in the existing scenarios with EnergyScope simulations	45
4.2.1	FPS and Climact Behaviour scenario	45
4.2.2	CLEVER Belgian scenario	46
4.2.3	EnergyVille scenario	46
4.2.4	EU reference scenario	47
4.3	Comparison of EnergyScope simulations for the global energy system	48
4.4	Industrial sector in EnergyScope simulations	51
4.4.1	Final Energy Consumption	51
4.4.2	A focus on high temperature heat	53
4.5	Emissions in EnergyScope simulations	59
4.6	Costs in EnergyScope simulations	60
5	Discussion	62
5.1	Main findings	62
5.1.1	General findings	62
5.1.2	Operating of the energy system in the industrial sector	63
5.2	Limitations	64
5.3	Further work	66
6	Conclusion	68
A	Industry adjustments for the Low Demand scenario	70
B	EnergyScope input for the different scenarios	80
C	Sankey diagrams	83
	Bibliography	89

List of Figures

1.1	The Doughnut of social and planetary boundaries	2
1.2	Evolution of the shares of the buildings, transportation, and industrial sector of the total energy demand in 2050 (vs 2015)	3
2.1	2050 industrial FEC (excl feedstock) in the Low Demand scenario	15
2.2	Overview of the FPS and Climact scenarios	17
2.3	Final energy consumption in the industry per vector	18
2.4	Calculation of FEC in 2050 with simplified corridors	20
2.5	Calculation of FEC in 2050 with detailed corridors	20
2.6	2050 industrial FEC (excl feedstock) in the CLEVER scenario	22
2.7	Evolution of the industrial FEC (excl feedstock) in the EnergyVille central scenario	24
2.8	Evolution of the EU energy mix of the industrial FEC (excl feedstock) in the EU reference scenario 2020	26
2.9	Evolution of FEC in the BBL scenario and 2050 FEC in the MIX-scenario	28
2.10	Evolution of feedstock consumption in the BBL scenario and 2050 feedstock consumption in the MIX-scenario	29
4.1	Reductions in material production for different industrial sectors between 2015 and 2050	38
4.2	Reductions in energy intensity for different industrial sectors between 2015 and 2050	39
4.3	Industrial final energy consumption in 2050 excluding feedstock for different scenarios	40
4.4	2050 primary feedstock consumption for different scenarios	41
4.5	Comparison of FEC by sector for the various scenarios	42
4.6	2050 EUD of the different scenarios in households, services and industry, and NED	43
4.7	2050 EUD for passenger transportation and freight	44
4.8	Comparison of FEC and feedstock consumption in the original FPS and Climact Behaviour scenario, and in the EnergyScope simulation	45
4.9	Comparison of FEC in the original Belgian CLEVER scenario, and in the EnergyScope simulation	46
4.10	Comparison of FEC and feedstock consumption in the original EnergyVille central scenario, and in the EnergyScope simulation	47
4.11	Comparison of FEC and feedstock consumption in the original EU reference scenario, and in the EnergyScope simulation	48
4.12	Total primary energy consumption in the EnergyScope simulations	49
4.13	Industrial final energy consumption in 2050 excluding feedstock in EnergyScope simulations	52
4.14	Primary feedstock consumption in 2050 (excluding secondary / recycled feedstock) in EnergyScope simulations	52

4.15	Energy mix over one year for the high temperature heat supply of the different scenarios in EnergyScope simulations	53
4.16	Installed capacities of various technologies for the supply of high temperature heat in EnergyScope simulations	54
4.17	High temperature thermal storage capacities in the different scenarios in the EnergyScope simulations	55
4.18	Overview of the characteristics of the 4 selected typical days	56
4.19	Comparison of the HT heat supply over 24 hours : TD 1	57
4.20	Comparison of the HT heat supply over 24 hours : TD 4	57
4.21	Comparison of the HT heat supply over 24 hours : TD 6	58
4.22	Comparison of the HT heat supply over 24 hours : TD 9	59
4.23	Cost of the energy system simulated with EnergyScope for the five scenarios	60
C.1	Sankey diagram of the adjusted Low Demand scenario	84
C.2	Sankey diagram of the FPS and Climact Behaviour scenario	85
C.3	Sankey diagram of the CLEVER Belgian scenario	86
C.4	Sankey diagram of the EnergyVille PATHS2050 central scenario	87
C.5	Sankey diagram of the EU reference scenario 2020 (NED 2016)	88

List of Tables

2.1	EUD matrix input for EnergyScope TD	10
4.1	Installed energy conversion capacities for some of the main technologies	50
4.2	Installed storage capacities	50
4.3	Curtailment over a year by scenario	51
4.4	Emissions related to the construction of technologies in the EnergyScope simulations	59
A.1	Reduction in floor area in the residential and tertiary sectors	71
A.2	Private mobility	72
A.3	Public mobility	72
A.4	Reduction of steel FEC	73
A.5	Reduction of cement FEC	73
A.6	Reduction of ammonia FEC	74
A.7	Reduction of HVC FEC	75
A.8	Reduction of transport equipment FEC	75
A.9	Reduction of NFM, other chemicals, ceramics and machinery FEC	76
A.10	Reduction of wood, glass and textile FEC	76
A.11	Reduction of food FEC	77
A.12	Reduction of paper FEC	77
A.13	Reduction of other industrial sectors FEC	78
A.14	Total reduction of FEC in the adjusted Low Demand scenario	78
A.15	Calculation of Adjusted Low Demand EUD	78
A.16	Reduction of non-energy demand	79
A.17	Reduction of the freight mobility in the adjusted Low Demand scenario	79
B.1	EUD matrix of the adjusted Low Demand scenario	80
B.2	EUD matrix of the FPS and Climact Behaviour scenario	80
B.3	EUD matrix of the CLEVER Belgian scenario	81
B.4	EUD matrix of the EnergyVille PATHS2050 central scenario	81
B.5	EUD matrix of the EU reference scenario	81
B.6	Shares of the NED for the different scenarios	82
B.7	Shares of public mobility for the different scenarios	82

List of Abbreviations

BECCS	Bioenergy with Carbon Capture and Storage
BEH	FPS and Climact's Behaviour scenario
BF-BOF	Blast Furnace with Basic Oxygen Furnace
BTX	Mixtures of Benzene, Toluene and Xylene isomers
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CHP	Combined Heat and Power (cogeneration)
CO ₂ e	Carbon Dioxide Equivalent
COP	Coefficient Of Performance (of a heat pump)
DAC	Direct Air Capture
DHN	District Heating Network
DLS	Decent Living Standard
EAF	Electric Arc Furnace
ES(TD)	EnergyScope (Typical Days)
EUD	End Use Demand
EUI	End Use Input
EUT	End Use Type
FEC	Final Energy Consumption
GBPN	Global Building Performance Network
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWP _{op}	Global Warming Potential related to resources (operation)
H2-DRI	Hydrogen-based Direct Reduction of Iron

HT	High Temperature (heat demand)
HVC	High Value Chemicals
IEA	International Energy Agency
ktoe	thousand tonne of oil equivalent (unit for energy)
LD	Low Demand scenario
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
LT	Low Temperature (heat demand)
MTO	Methanol To Olefins
Mtoe	Million tonne of oil equivalent (unit for energy)
NED	Non-energy demand
NH ₃	Ammonia
P/C	Production / Consumption ratio
PDH	Propane Dehydrogenation
pkm	passenger kilometer
PV	Photovoltaic
SMR	Small Modular (nuclear) Reactor
SNG	Synthetic Natural Gas
tkm	tonne kilometer

Chapter 1

Introduction

While emissions from the industrial sector decreased steadily until around 2012, they have been stagnating in the following years, and until the COVID pandemic [10, 35, 14]. Companies and authorities are focusing primarily on efficiency to reduce these emissions. The plateau from the last decade does however show that this approach will probably not suffice to reduce emissions from the industrial sector fast enough [10]. Breakthrough changes will be needed in the industrial processes, in order to move away from fossil fuels. But even these changes, which come with a high degree of uncertainty, will probably not be enough.

A solution to reduce emissions further is then to reduce the production volumes in the industry. This has both direct and indirect impacts. First, scaling down processes directly leads to scaling down emissions proportionally. Second, the investments needed to transform the industry will be more moderate, and the transition could occur more rapidly. As we will see, it also allows to rely less on uncertain and expensive importation of e-fuels.

The reduction of production volumes, without delocalising the industry abroad, is possible when relying on various levers, including measures to promote a circular and sharing economy and to increase the lifetime of products. In this context, the value of materials and products could increase, including at their end-of-(first)-life, and the reduction of material production would thus not necessarily lead to less value added in the Belgian industry [10, 13].

This master thesis was made in partnership with "negaWatt Belgium" [65], which develops Belgian scenarios towards carbon neutrality in 2050. It is part of the CLEVER (Collaborative Low Energy Vision for the European Region) network [5], aiming at an ambitious and realistic European scenario towards 2050, based on a 100% renewable energy mix, and high ambitions regarding sufficiency.

The CLEVER network defines sufficiency as "the aim to redefine our needs for resource-intensive services as individuals and societies, in order to adjust their nature and quantity at a level compatible with the Earth's capacity" [5], putting an emphasis on demand-side measures. In the industrial sector, sufficiency assumptions generally imply reduction of the production volumes.

This approach can be illustrated by the "Doughnut of social and planetary boundaries" [18], shown in figure 1.1. It consists of an inside ring, the "social foundation", defining the key social rights that every individual should have, and an outside ring, the "ecological ceiling", defining the planetary boundaries, inside of which Earth could remain safe for humanity. The

planetary boundary that is covered in this work, is climate change related to emissions from the energy system. The Doughnut does however make clear that this is only one aspect of the issue. The other ecological ceilings, that are not covered in this work, should thus also be taken into account.

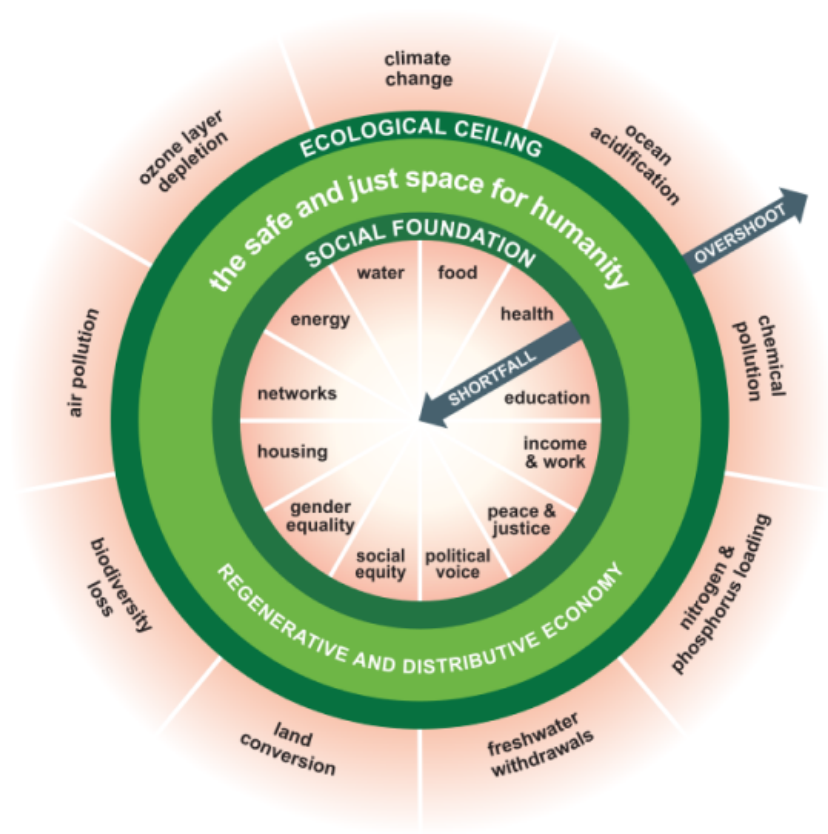


Figure 1.1: The Doughnut of social and planetary boundaries. From [18]

Different scenarios towards 2050 differ greatly regarding technical ambitions, and even more so regarding sufficiency ambitions, but they all project an increase of the share of the industrial sector in the total energy consumption. Belgium is currently one of the European countries with highest energy consumption per capita [36], mainly due to the high concentration of industries [10]. While important changes in buildings and in the transportation sector, like the switch to electric vehicles and the insulation of buildings are projected to allow important reductions in most scenarios, improvements in the industrial sector are projected to be less significant, leading to an increase of its share of the total energy demand. Figure 1.2 shows the evolution of its share in the different scenarios considered in this work. From the current 45%, the scenarios project an increase of the industrial share to 55% up to 70%. The study of the industrial sector for the Belgian energy transition towards 2050 is thus of particular importance.

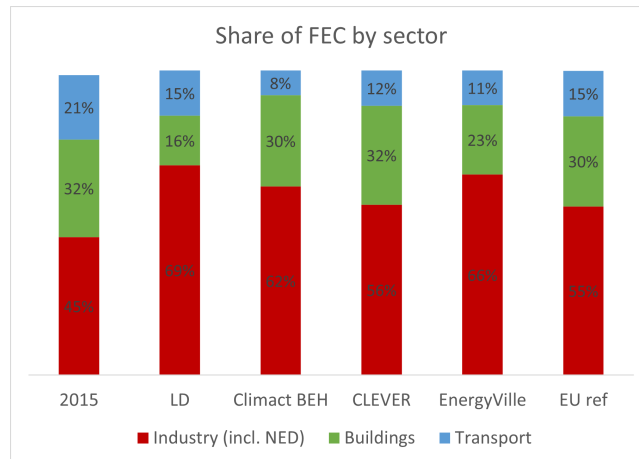


Figure 1.2: Evolution of the shares of the buildings, transportation, and industrial sector of the total energy demand in 2050 (vs 2015)

In late May 2023, production of electricity from solar and wind energy in Belgium set a new record, while the demand was relatively low. Using negative electricity prices, industries were payed to increase their consumption. It is becoming clear that the industrial sector will have an important role to help regulate the future energy system.

In his 2021-2022 master thesis, Hugo Baudson already built a Low Demand scenario regarding the Belgian global energy consumption [7], based on the article "Providing decent living with minimum energy: a global scenario" [63]. He analysed an appropriate energy system for this scenario using EnergyScope TD, an open-source model for regional energy systems [46].

In this work, we will improve the industrial assumptions of the Low Demand scenario further, compare it with various existing scenarios, and go deeper into the analysis of the energy systems modeled, especially in the industrial sector.

First, we will briefly introduce some of the main industrial processes of the Belgian industry, in order to better interpret and critically analyse further results. We will then describe the energy system modeling tool used in this work, EnergyScope TD. Furthermore, different scenarios for the global Belgian energy system in 2050 will be presented.

We will describe the methodology that was used to build our own adjusted "Low Demand" scenario, as well as a new methodology to obtain the "End Use Demand" for the different scenarios, which is a specific input required by EnergyScope TD to define the energy demand.

We will then analyse and compare the different existing scenarios. The different scenarios have also been simulated with EnergyScope TD, and the resulting energy systems will be compared with the energy systems from the existing scenarios. Finally, the results from the EnergyScope simulations will be analysed and compared with each other, and a more in-depth analysis of the industrial sector will be performed.

These results will then be discussed, making concrete conclusions for the Belgian transition towards 2050 with a focus on sufficiency and on the industrial sector. They will be critically analysed to identify the strengths and weaknesses of our approach and the tools used.

Chapter 2

Literature review

2.1 Major technologies in the industry of 2050

In order to better understand and critically analyse scenarios for a Belgian energy system in 2050 from an industrial perspective, it is important to understand the processes taking place in these industries. This section aims at presenting both the current and potential future processes for some of the main industrial sectors in the Belgian industry.

2.1.1 Steel

The steel sector consumes over 20% of the Belgian industrial energy demand (excluding fuels used as feedstock in the chemical industry, see 2.1.2), and over 30% of industrial GHG emissions [14]. It is thus one of the main sectors to decarbonise. Currently, two routes are used for steel production :

- **Blast Furnaces with Basic Oxygen Furnaces (BF-BOF).** This process can be simplified as follows. Coal is heated to transform it into coke in a coke plant. Iron ore (Fe_2O_3) and coke (C) are then introduced at the top of the blast furnace (BF), and a hot air blast is injected from the base of the furnace. Iron oxide, carbon and oxygen react to produce pig iron and CO_2 . This 'pig iron' is however too rich in carbon, so a second step is needed : the Basic Oxygen Furnace (BOF). Oxygen is blown on the hot metal, oxidises the carbon, and CO or CO_2 is produced. Other elements are then added in order to produce specific alloys. The heat required at various steps of the process is currently mainly provided by fossil fuels, like natural gas. The process is thus complex and implies emissions at various steps of the process, both from combustion of fuels to provide heat, and from the process itself. While efficiency improvements are possible, and substitution of fossil fuels by renewable fuels or electricity can reduce the energy-related emissions, the process-related emissions are inherent to this process.
- **Electric Arc Furnace (EAF).** This route relies on an input of recycled scrap steel, which is melted in a furnace by an electric current going through the material. Lime and fluorspar are added in order to form a slag with impurities and remove them. Oxygen is blown in the furnace in order to react with carbon and produce CO_2 .

The EAF route has four advantages compared to the BF-BOF route :

1. It relies on scrap steel rather than a primary resource like iron ore.
2. Process emissions are much lower.
3. The energy is provided by electricity and not by a fossil fuel.
4. Total energy intensity is significantly lower.

Currently, in Belgium, about 68% of steel is produced through the BF-BOF process, and 32% through the EAF process [53]. A moderate increase of steel production through EAF towards 2050 is conceivable, but it is unlikely that 100% of the production could happen through recycling. In order to reduce process emissions of the BF-BOF route, carbon capture could be used, but this implies important extra energy consumption, and 100% of the CO₂ cannot be captured. Other climate-friendly routes for primary steel making thus need to be considered :

- **Hydrogen-based direct Reduction of Iron (H₂-DRI).** In this route, iron ore is reduced by a reducing gas below its melting temperature. It is currently already used in other countries, but with fossil fuels like natural gas. These fossil fuels could be replaced by renewable hydrogen. The obtained iron could then be fed in an EAF to produce steel. This technology allows emissions reductions up to 95% [42].
- **Electrolysis of iron ore.** This technology also allows emissions reductions up to 95% [42].
- **Smelting reduction.** It is a more efficient process than BF-BOF, but it still relies on coal. Without carbon capture, it only allows for emissions reductions up to 35% [42].

The technology considered to be the most promising by the majority of the scenarios used in this work is the H₂-DRI process, which allows important emissions reductions, and has the highest technology readiness level [42].

2.1.2 High-value chemicals

High value chemicals cover olefins, such as ethylene, propylene and C₄, as well as BTX (a mixture of aromatics). Ethylene and propylene are produced in largest quantities [53]. These molecules are mainly used for plastic production. Olefin production consumes around 11% of industrial energy demand (excluding feedstock), and emits about 20% of industrial greenhouse gases [14]. HVC production is also the main consumer of the non-energy demand, also called feedstock, which is defined by Eurostat [37] as follows :

***Non-energy** consumption [or demand] includes fuels that are used as raw materials and are not consumed as fuel or transformed into another fuel (for example, chemical reactions or bitumen for road construction).*

The main process currently used in Belgium for HVC production is **steam cracking**. A fossil feedstock, like naphtha or LPG, is mixed with steam and heated to high temperatures, without oxygen. The hydrocarbons are then broken down into smaller hydrocarbons like ethylene and propylene.

Another process used in Belgium, at a smaller scale, is **propane dehydrogenation (PDH)**.

Propane is heated to high temperatures, with the presence of a catalyst, to produce propylene and hydrogen.

These technologies currently rely on fossil fuels for heat production, on top of the fossil feedstock.

While the fossil feedstock does not directly lead to carbon emissions, as the carbon is 'locked' in the produced material, the conservative approach is to assume that it will end up in the atmosphere at its end of life (incineration).

A first way to reduce the carbon footprint from HVC production, is to improve the efficiency of the current processes, and to switch to lower-CO₂ fuels or to electrify crackers [59]. These improvements do however not address the fossil feedstock, which is why new processes are needed.

Mechanical recycling is already common in our society, but it could be pushed to another level. It consists in the sorting, shredding, cleaning, melting and reprocessing of plastics. Its main benefit is that it avoids emissions from incineration, and the need for a primary feedstock. The process temperatures are much lower, lowering the energy consumption [59]. Collection and sorting of plastic waste however stays a major challenge.

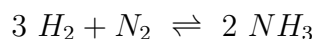
Chemical recycling is much less mature. The polymers from the plastics are broken down into simpler molecules, creating a feedstock for producing new plastics. It allows to produce higher-quality plastics than mechanical recycling, but generally consumes more energy.

Like for the steel sector, it is unlikely that 100% of the demand could be met by recycling only. There is thus need for carbon-neutral feedstock. A first option is biomass, which can be processed into bio-ethanol, bio-methanol, bio-gas or bio-naphta [59]. Methanol seems to be promising as a future 'platform chemical'. Several routes allow to produce methanol from biomass. Green methanol can also be produced from CO₂ and green hydrogen. Methanol is relatively easy to transport, so it could be an imported resource as well. The **methanol-to-olefins (MTO)** process then allows to make olefins from methanol, with the presence of a catalyst and at high temperatures.

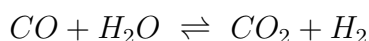
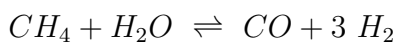
2.1.3 Ammonia

About 90% of European ammonia production is used for fertilisers [59]. Its production consumes about 5% of the industrial energy demand, and emits about 4% of their greenhouse gas emissions [14].

The main process for ammonia production is the Haber-Bosch process. Hydrogen and nitrogen are heated and react to produce ammonia :



Currently, the hydrogen needed for the Haber-Bosch process is obtained from a natural gas feedstock. The natural gas is purified, and then reacts with steam through catalytic steam reforming :



This process thus inherently emits carbon dioxide.

A solution is to replace the hydrogen obtained from natural gas through steam reforming by green hydrogen, produced through electrolysis from green electricity. The Haber-Bosch process remains identical.

2.1.4 Other sectors

The other main industrial energy consumers are the food industry (14%), non-metallic minerals, including lime, glass, cement, ceramic (13%), other chemical sectors (11%) and paper (7%) [14]. Most of these industries still heavily rely on fossil fuels, in particular for heat production. Fossil fuels could be substituted by electricity for the low temperature and medium temperature heat demands. For the low temperature demand, heat pumps could improve efficiency significantly. Electrification is more complicated for the high temperature heat demand. Here, e-fuels and bio-fuels are a promising alternative [10].

2.2 Energy system modeling

Various energy system scenarios will be analysed in this thesis. These scenarios may use different assumptions as input, but also use different energy system models, both of which can lead to different results. In order to compare and discuss these scenarios, it is thus important to understand some of the particularities of the model that was used to produce them. EnergyScope Typical Days, the main tool used in this thesis, is described in section 2.2.1, while some other models are briefly introduced in section 2.2.2.

2.2.1 EnergyScope Typical Days

The energy system model used in this thesis is EnergyScope Typical Days (TD)¹. The model is developed through a collaboration between UCLouvain and EPFL. It was originally created by EPFL for Switzerland, and then adapted to the Belgian case by Gauthier Limpens (UCLouvain). It optimises the design and operation of the energy system for minimal cost. Limitations on the greenhouse gas emissions constrain the model to meet environmental goals. Compared to other energy system models, it has four **main advantages** [57] :

1. It models the **whole energy system** : the residential, tertiary, transportation and industrial sectors are modeled. Resources and technologies needed to provide the demand for these sectors are distributed between the sectors in a way that optimises the total cost, without preference for any sector. The optimal global system is not necessarily the sum of optimal systems for each sectors.
2. The model has an **hourly resolution**. Variability of the weather, and thus of the renewable resources, is taken into account, using 'Typical Days', described hereunder. The variability of the demand is also taken into account. This concerns both hourly and seasonal variabilities. This makes the model particularly appropriate for the integration of intermittent renewable resources, taking into account storage technologies.
3. The model has a **short computational time** of around one minute, which is very useful, for modeling and comparing various scenarios with different assumptions (what-if analyses), and for uncertainty quantification.
4. The model is **open-source** and documentation is available. This enables collaboration between researchers and its use for educational purposes.

Typical Days

Running the model for the 8760 different hours of the year would be too computationally expensive. That is why Typical Days (TD) are used. Generally, 12 typical days are selected for this model. They represent a various set of conditions, like availability of renewable resources and demand. To each of the 365 days of the year is then assigned one of these 12 typical days, in order to represent the real conditions over a year as closely as possible. All decision variables (e.g. the operation of wood boilers vs direct electricity) are then optimised for the 24 hours of each TD, except for the energy storage, that is optimised for the whole year [46].

¹Documentation for the model can be found at [46]

End-use demand

The energy demand is mostly expressed as the Final Energy Consumption (FEC). It is defined by the European Commission as "the energy which reaches the final consumer's door" [30]. Energy losses in the energy sector are thus excluded, but energy losses occurring at the consumer's side are included in the demand (for example inefficient boilers used by an industry).

EnergyScope has another approach : the demand is defined by the End-Use Demand (EUD). This is the useful energy (or other service) that is required by the consumer. For example, in case of a boiler, the FEC is the fuel consumed by the boiler, while the EUD is the useful heat available for the consumer.

As losses occur in most technologies, the EUD is usually lower than the FEC. The only exception is heat pumps. The energy that heat pumps draw from ambient air is not considered to be energy consumption (as the "resource" is free and always available). The EUD/FEC ratio of heat pumps is defined by their Coefficient of Performance (COP), usually between 3 and 4 in EnergyScope.

The EUD in the transport sector is not expressed in units of energy, but of mobility : passenger-kilometers (pkm) and tonne-kilometers describe the service of displacing one person or one tonne over one kilometer, whatever the vehicle.

The main advantage of the use of EUD rather than FEC is that it allows the model to not only optimise the energy sector, but also the technologies and resources used to meet the EUD. It favours the use of most efficient technologies, and technologies that help the complex hourly-varying system to obtain a minimal annual cost as a whole. At the end of the day, what consumers are interested in, is the service that the energy they use provides (EUD), and not the energy needed to provide it (FEC).

The EUD from each of the sectors is divided into eight different End-Use Types (EUT). For each sector and each EUT, a demand could be defined. The eight EUT are described hereunder.

- The **electricity demand** is distributed in a **constant** and a **variable** share, also called 'electricity' and 'lighting', even though the variable share does not only concern lighting.
- The **high temperature heat**, or process heat, is defined only for the industrial sector. As the technologies used for providing low temperature heat (like heat pumps) can not be used to provide high temperature heat, a separate EUT is needed.
- The **low temperature heating** demand concerns space heating, considered as a **variable** demand, and hot water, considered as a **constant** demand.
- The **passenger mobility** and **freight mobility** only consider the transportation sector, and are expressed in pkm and tkm.
- A **non-energy demand** (NED) is defined for the industrial sector. As the demand is expressed as an EUD and not a FEC, it does not represent the feedstock consumption of the industry, but the lower heating value (LHV) of the products from the industry. It is distributed in a demand for HVC, ammonia and methanol.

An overview of the EUD matrix used by EnergyScope as input is shown in table 2.1. A cross indicates each combination of EUT and sector where a demand can be defined.

	Households	Services	Industry	Transport	Units
Electricity constant	X	X	X		[GWh]
Electricity variable	X	X	X		[GWh]
High temperature heat			X		[GWh]
Low T heat variable	X	X	X		[GWh]
Low T heat constant	X	X	X		[GWh]
Passenger mobility				X	[pkm]
Freight mobility				X	[tkm]
Non-energy demand			X		[GWh]

Table 2.1: EUD matrix input for EnergyScope TD

Other inputs

Besides the EUD, EnergyScope TD takes various other inputs :

- A list of available **resources**, their yearly availability, their price and related emissions.
- The available **transformation technologies**, their investment cost, maintenance cost, lifetime, yearly capacity factor, maximum potential, efficiencies.
- The available **storage technologies**, charge time, discharge time, losses, efficiencies.
- **Time series** regarding electricity, heating, passenger and freight EUD, and time series for renewable energy resources and technologies (wind, PV, hydro).
- A limit on emissions (see section regarding emissions hereunder).

Cost

The objective of the model is to minimise the cost of the system. This cost takes into account the cost of the resources ($C_{op}(i)$), as well as the annualised cost of investment of the used technologies ($\tau(j) C_{inv}(j)$) as well as their yearly maintenance and operation cost (C_{maint}). It can be expressed as [46] :

$$\min C_{tot} = \sum_{j \in TECH} (\tau(j) C_{inv}(j) + C_{maint}(j)) + \sum_{i \in RES} C_{op}(i)$$

As the optimal system is not the sum of optimal systems for all sectors, it would be necessary to have incentives to motivate all the actors to move towards this optimal system and to balance the advantages or disadvantages for each sector. This is however out of the scope of this work and can be considered as a second step. Still, it is important to remember it when comparing energy system scenarios from EnergyScope with other sector-specific scenarios.

Emissions

In EnergyScope TD, the total emissions are defined by the global warming potential (GWP) of the used resources. It is calculated using following equation [56].

$$GWP_{tot} = \sum_{i \in RES} GWP_{op}(i)$$

Each resource, like natural gas, oil, or biomass, has a fixed value of GHG emissions related to their use ($GW P_{op}(i)$, expressed in $ktCO_2e/GWh$). It accounts for production, transport and combustion of the resource. Emissions related to construction and end-of-life of the technologies used are not accounted for (unlike their cost). This is in line with official reports estimating territorial emissions. Combustion of imported e-fuels physically releases carbon in Belgium, but it is compensated by the carbon used for their production (even if it happens in another country). The convention is thus to consider their emissions to be zero when calculating territorial emissions.

The use of fuels for **non-energy demand** is a special case : when producing plastics for example, the fuel is not immediately combusted, so the carbon is not immediately released in the atmosphere, it is 'locked' inside the produced material. Official GHG accounting rules don't account for carbon embedded in the materials at the industrial stage, but at their end-of-life, if and when they are incinerated [41]. This is where EnergyScope TD differs : emissions are considered from the moment that a resource is used, even if it is used for the non-energy demand. It is justified by the fact that, at the end of the day, if the material is not recycled, the carbon will probably be released in the atmosphere, and it is thus easier to consider emissions only once at manufacturing [67], even though the emissions could take place years or decades later. With high recycling ambitions, the material could even go through several use cycles before the emissions take place. EnergyScope's accounting mechanism is thus conservative, as it is more likely to overestimate the emissions related to the non-energy demand.

Limitations of EnergyScope TD

As any model, beside its advantages cited above, EnergyScope TD also has several limitations [46].

1. While it represents the whole energy system and the interactions between sectors very well, it does not model each sector in great detail. In the industrial sector, which is the object of this work, for example, high temperature heat includes all process heat that can not be qualified low temperature heat. There are however various different processes at very different "high" temperatures, which can be more or less hard to electrify. EnergyScope considers all these demands to be equal. It also doesn't take into account specific processes that need particular fuels, like steel making through H2-DRI.
2. Only emissions related to the energy system and the non-energy demand are accounted for. This is a major limitation in the industrial sector, where an important share of the emissions are process-related (cement, steel, ...).
3. The demand is an input of the model which is not part of the optimisation. In reality the demand would react to the market and the price of energy, by changing the total demand or by changing the distribution in time of the demand. No flexibility of the demand can be considered. For example, oversized industrial factories, which would run when energy is cheapest and thus help stabilise the energy system, can't be modeled.
4. It is a snapshot model. It seeks the optimal state of the energy system for a specific year, without taking into account its current state and the pathway to get from the current state to the projected optimal state.
5. Some sectors, like agriculture, aviation and refineries, are not included in the model.

6. It only considers a single area (so-called cell). Import of fuels and electricity is assumed to be possible at a certain price, but the energy systems from the countries from which these resources are imported are not modeled.
7. The optimisation is deterministic. A single optimum is reached, assuming all parameters known for sure. The possibility to make uncertainty quantification with the model compensates for this limitation.

2.2.2 Other energy system models

Many other energy models exist, each having its advantages and limitations. Some of the models that were used to build the scenarios discussed in the next section are briefly introduced hereunder.

- The **PRIMES** model is used in the EU reference scenario. It is developed by E3Modeling. It finds a market equilibrium solution for energy supply and demand [3]. Hourly adequacy is assured. More information in section 2.3.5.
- The **TIMES** model, and its Belgian version TIMES-Be is used in the EnergyVille scenarios. It also finds a market equilibrium solution for energy supply and demand [3]. On top of the residential, tertiary, transport and industrial demand, it also models the demand of agriculture and refineries. Hourly adequacy is assured as well. Import-export cost curves of electricity or fuels are time-sliced [22].
- Climact's **Pathways Explorer** does not optimise the system for minimal cost, but is based on levers set by the user. This is a complementary approach that has some advantages to cost optimisation, as explained in section 2.3.2. It does however not model the issue of intermittency, no hourly adequacy is verified. This is the model used for the FPS-Climact scenarios.

2.3 Existing scenarios towards 2050

Various energy system scenarios towards 2050 were analysed. All scenarios concern the whole Belgian energy system, except the scenario presented last, from Bond Beter Leefmilieu, which only concerns the Flemish industrial sector. The latter scenario is very interesting because of its high ambitions regarding circular economy and the great level of detail of the industry, taking into account more specificities of the Flemish industry. All the scenarios, except for the EU reference scenario, reach net carbon neutrality by 2050. The strategies used to reach this objective are however very different. The main focus of this study is sufficiency, so the measures regarding sufficiency and circular economy are the ones that will mainly interest us. The five Belgian scenarios are presented hereafter in order of increasing demand, i.e. decreasing level of ambition regarding sufficiency. There is a factor 4 between the demand from the scenario least ambitious regarding sufficiency (EU reference scenario) and the most ambitious one (Hugo Baudson's Low Demand scenario).

2.3.1 Hugo Baudson "Low Demand" scenario

The first considered scenario is also the one with the highest ambitions regarding sufficiency towards 2050. It was built by Hugo Baudson in 2022, for his master thesis [7], on which this section is based. The scenario is based on the article "Providing Decent Living with Minimum Energy: A Global Scenario" from Millward-Hopkins et al. [63, 51]. This article follows a bottom-up approach, defining each service that any individual needs in order to have "decent living", the so-called "Decent Living Standards" (DLS) and the related energy needs. This means that it is considered that any individual has access to these same services, and that no one has access to more services, which would induce more energy needs. Equality is a key value of the approach. No cultural or economic considerations are made. The only differences taken into account are outdoor temperature, age structure, climate, degree of urbanisation, population density and water scarcity [7]. Hugo Baudson applied the article, which only contains global assumptions, valid for the whole world, to the Belgian case. Most parameters that were used to establish the energy demand of the scenario come directly from the "Decent Living" article. Some needed to be adapted to the Belgian reality, or were found using other sources.

Each of the Decent Living Standards imply direct energy consumption in the residential, tertiary and transport sectors. The industrial demand is considered to correspond to the embodied energy from all the DLS from these three sectors (and other). The defined industrial demand thus corresponds to the energy needed to provide the DLS to the Belgian population. It thus corresponds to an "energy footprint", comparable to a "carbon footprint", of the Belgian population, rather than territorial energy consumption, which is needed to model a national energy system. The "energy footprint" corresponds to the territorial consumption if all materials and products needed in the country are produced locally, and nothing more is produced than needed locally. It means there are no imports or exports of products. This is obviously very far from the current Belgian reality, and that is why another approach is considered in this work, presented in section 3.1.

The assumed Belgian population in 2050 is 11.9 million, which is the same assumption as the one made in the EU reference scenario [29] (see section 2.3.5).

The number of persons per **household** is projected to increase from 2.3 to 2.5, which goes against the current downward trend. An important decrease of floor space per capita is assumed : from the current 55 m²/cap to 28 m²/cap, which allow important reductions for domestic heating but also for the industry, which provides the construction materials. New buildings with state-of-the-art energetic standards are considered. Heating intensities are estimated by the Global Building Performance Network (GBPN) [47]. Electricity needs are defined by the consumption of appliances considered as DLS (cooking, cold storage, washing, phones, computers, illumination). Hot water is limited to 20L/day.

In the **tertiary** sector, education, health, retail, offices and other services (restaurants, hotels, ...) are considered. A slight decrease (-7%) in floor area is assumed. Space heating accounts for half of the tertiary demand. Heating intensity is once again defined by the GBPN. Remaining consumption are allocated to hot water and electricity.

The demand for the **transportation** sector is expressed in passenger-kilometer (pkm) and tonne-kilometer (tkm). The passenger mobility is adapted to the assumed Belgian degree of urbanisation (82%). The global assumed mobility is 4300km/cap/year, which is a two thirds decrease compared to the current mobility. This number does not include soft mobility (walk, bike). 80% of displacements are assumed take place with public transport (train, bus), 20% with cars, and no aviation is assumed. Currently, only 20% of the mobility excluding aviation and soft mobility takes place with public transport, and 80% with cars. Occupancy in cars is supposed to increase from 1.5 person/vehicle to 3 persons/vehicle. Regarding the freight transport, 2309 tkm/cap/year, a 61% decrease, is assumed.

In the **industrial** sector, various sources are used to calculate the embedded energy for the buildings, vehicles and other goods required for the previous sectors, distributed over their assumed lifetime (in years for buildings, kilometers for vehicles, ...). Infrastructure, for example for transportation (roads, rail) is also taken into account. Consumption of goods is limited to phones, computers, fridges, cookers and clothes. Public services, like network infrastructure, water supply, waste management and power supply are considered. Finally, the food industry is also considered, in order to meet a calorie consumption of 2000 kcal/cap, a 25% decrease of the current mean consumption in Belgium.

The obtained industrial demand is assumed to exclude the non-energy demand. Its share of the total industrial demand is estimated to be the same as in the EU reference scenario.

An energy system satisfying the demand from these four sectors was then modeled using EnergyScope TD. Ratios between constant and variable electricity, constant and variable low temperature heat, and high temperature heat from the EU reference scenario are used for each sector, to obtain the EUI (end-use input) needed by EnergyScope TD. The transportation demand is already expressed as an EUD (pkm and tkm). For the heating, electricity and non-energy demand, the EUD is approximated by the FEC (which is what was obtained in previous paragraphs).

The obtained energy system of the Low Demand scenario relies for 79% on local renewable resources (mainly wind, solar and biomass), for 4% on imported electricity and for 17% on imported renewable fuels, used exclusively as feedstock. The low temperature heat for all sectors

is provided by heat pumps. Hydrogen is used for the freight transport, it is produced locally through electrolysis.

Regarding the industrial sector, the high temperature heat is provided by wood boilers and direct electricity. As in other sectors, low temperature heat is provided by heat pumps. There is thus a shift towards electrified technologies for the heating demand. The non-energy demand for HVC is provided by the methanol-to-olefin technology, using imported renewable methanol. The ammonia demand is met by import of renewable ammonia (no local production). The global FEC mix for industry is represented in figure 2.1.

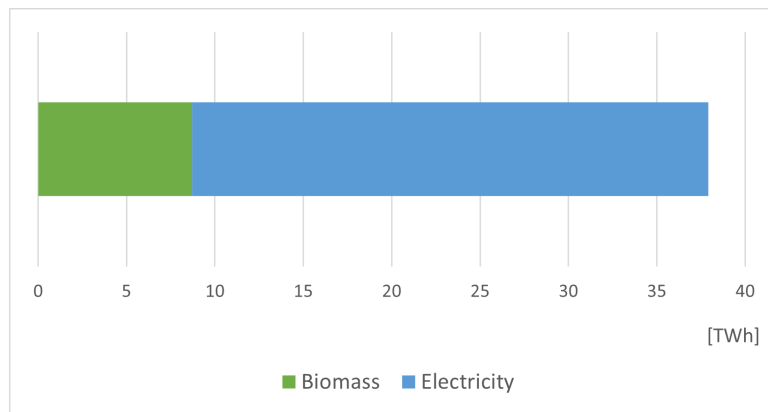


Figure 2.1: 2050 industrial FEC (excl feedstock) in the Low Demand scenario. From Hugo Baudson's data [7]

2.3.2 FPS Public Health and Climact "Behaviour" scenario

The FPS Public Health published its report "Scenarios for a *carbon neutral* Belgium by 2050" [41] in 2021. It presents several scenarios for reaching carbon neutrality in Belgium by 2050. The most ambitious of these scenarios in terms of behaviour change is called the "Behaviour" scenario (abbreviated BEH), and it is the one that will interest us in this work. This section is based on the report.

The Climate Change service of the federal administration of Belgium first published its "Scenarios for a *low carbon* Belgium by 2050" in 2013. The online model underpinning the scenario was also published. In the meantime, the work faced several shortcomings and was updated by the report from 2021. These new scenarios use the latest data available, and aim at reaching net carbon neutrality by 2050, while the previous ones only aimed at an 80 to 95% emissions reduction. The new scenarios also take other dimensions than energy-related emissions into account, such as natural resources and biodiversity.

The modelling tool used for the scenarios is the "2050 Pathways Explorer"[14], developed by Climact. It is a model of the energy system, but also of the land, materials, product and food systems. Unlike other models, it is not an optimisation model, but a driver and lever-based model, allowing the user to choose a level of ambition for any parameter. This makes the model less vulnerable to uncertainties (e.g. cost of future technologies). The parameters, also called "levers", include behavioural levers, like the distance travelled per person per year

or the living space per person; technological levers, like efficiency improvements in industrial processes; demographic levers, like the share of the population living in cities; and more. Based on the levers set by the user, the model calculates the amount and type of energy required, as well agricultural and industrial practices, and the related GHG emissions.

The online model of the "2050 Pathways Explorer" used for the scenarios from the 2021 report is available at <https://becalc.netzero2050.be/>. "Example pathways" can be selected. These contain the scenarios from the report. A newer version developed by Climact is also available at <https://pathwaysexplorer.climact.com/pathways?region=BE>.

Different scenarios, all reaching carbon neutrality in 2050 using different strategies (except for the reference scenario), were developed.

- The **REFERENCE** scenario supposes a "business-as-usual" evolution. Emissions stay similar to their current level.
- The **CORE 95** scenario is a balanced scenario including both behaviour changes and technological changes. A 95% reduction of GHG emissions in 2050 w.r.t. 1990 is achieved. The 5% remaining emissions are compensated by negative emissions (carbon capture, land use, ...), in order to reach carbon neutrality. All of the following scenarios are based on the CORE 95 scenario.
- The **TECHNOLOGY** scenario sets more ambitious goals in terms of technological change, and less ambitious ones in terms of behavioural change.
- The **BEHAVIOUR (BEH)** scenario, sets the most ambitious goals regarding "behaviour, lifestyle and societal changes in the way people move, house, feed themselves and consume", and less ambitious goals for technological change. This is the scenario that will be used in this work.
- The **ELEC**, **H2**, **EFUELS**, and **BIO** scenarios rely more heavily on electrification, hydrogen, e-fuels or biomass.
- The **HIGH ENERGY DEMAND** scenario studies the implication of a lower reduction of the energy consumption.

An important question to ask ourselves when making scenarios for the evolution of the industrial sector, is "How does material production relate to material demand?". One approach is to define industrial production levels exogenously. This can be justified by the fact that the Belgian industry is strongly interconnected internationally, and a change of consumption in Belgium would not necessarily have an important impact on the demand perceived by the industry. However, other countries are expected to go through similar change, as decarbonisation is an international objective in the context of the Paris agreement and the EU Green Deal. The BEH scenario is based on this last approach, linking the material production evolution to the (national) material demand evolution, keeping a constant P/C^2 ratio. The "HIGH DEMAND" scenario follows the former approach, industrial production is defined exogenously.

²Production / Consumption : if $P/C > 1$, the industrial sector is a net exporter, if $P/C < 1$, the sector is a net importer

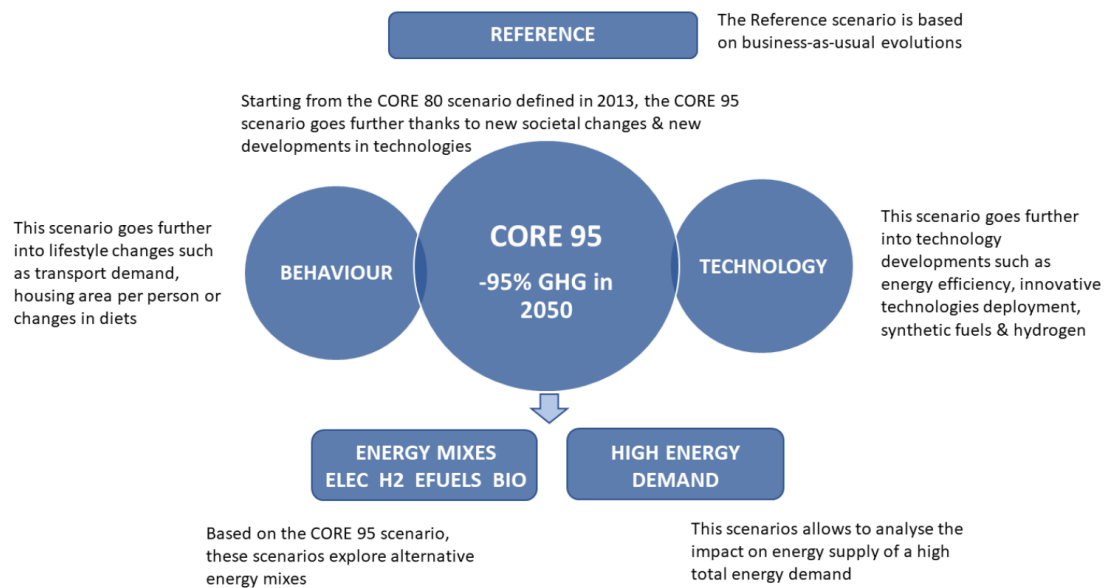


Figure 2.2: Overview of the FPS and Climact scenarios. From FPS study [41]

The model contains several levers regarding behavioural and societal change, as well as levers related to the circular economy, the sharing economy³ and the economy of functionality⁴. These are well developed compared to other models, and are most impactful in the BEH scenario, leading to a 34% reduction of the material demand, and thus a significant reduction of the energy demand and GHG emissions. The behavioural changes include "reducing paper and plastic packaging, reducing food waste and adopting more sustainable consumption patterns". In the agriculture sector, the BEH scenario makes the strong assumption of a generalisation of agro-ecology practices and a complete phase-out of the use of fertilisers, which are currently an important consumer of the chemical sector. Technical levers are also used. Material efficiency allows lowering the amount of material used per product, without reducing its functionality, by "improving product design, reducing material losses and using more efficient materials". Material substitution consists in replacing materials by less GHG-intensive materials or materials allowing a longer lifetime of the product. It is also possible to put levers on shares of the technologies used for producing certain materials. These include recycling technologies. They are however only available for the steel, cement and paper industry. Finally, levers regarding the industrial process efficiencies are used (considering no drastic change of technology type).

The study shows that the hardest to abate sectors are the industry and agriculture. All scenarios consider electrification of the industrial processes at its full potential, even though the electrification potential in the industry is less important than in other scenarios. Substitution of fossil fuels by e-fuels and bio-fuels are also needed. This allows a very important reduction of emissions, but doesn't allow to reach zero-carbon. As all of the emissions of these sectors

³"The sharing economy is an economic model defined as a peer-to-peer based activity of acquiring, providing, or sharing access to goods and services that is often facilitated by a community-based online platform." [71]

⁴According to the Belgian Federal Government, "the functionality economy replaces the sale of a product with the sale of a service fulfilling the same functions as the product. It is based on the value of using the product and not of owning of the product." [8]

do not originate from energy use, like process emissions, it is often more difficult to decarbonise the source of these emissions. This is why there are around 5% of remaining emissions that need to be offset by sequestration. As an example, in the "Behaviour" scenario, BECCS (Bio-energy with Carbon Capture and Storage) allows to store around 3 Mt CO₂ per year. This technology allows to capture and store CO₂ from combustion of biomass, which contains carbon captured from the atmosphere. Direct air capture (DAC) is also used to provide the carbon for producing e-fuels from hydrogen. Even though a lot of research is performed on these last two technologies, they have not yet been demonstrated at a large scale, so they come with a large degree of uncertainty. Other scenarios are more cautious about the use of these uncertain technologies.

The industry is also the only sector where fossil fuels are still used. They are used as feedstock for the chemical industry, and for certain processes (like coal for steel production with a blast furnace). As the official GHG accounting rules only consider emissions directly taking place in the country, embedded carbon in the products from the chemical sector (like plastics), made out of fossil feedstock are not accounted for at manufacturing. They are only accounted for when and if they are incinerated. The scenarios consider fossil feedstock substitution by carbon neutral feedstock (biomass, e-fuels, hydrogen), thus capturing carbon in these products during their lifetime. The conservative approach of the study doesn't account for this emission reduction.

The final energy consumption and feedstock consumption in industry for each scenario, as well as their energy mix, are shown at figure 2.3.

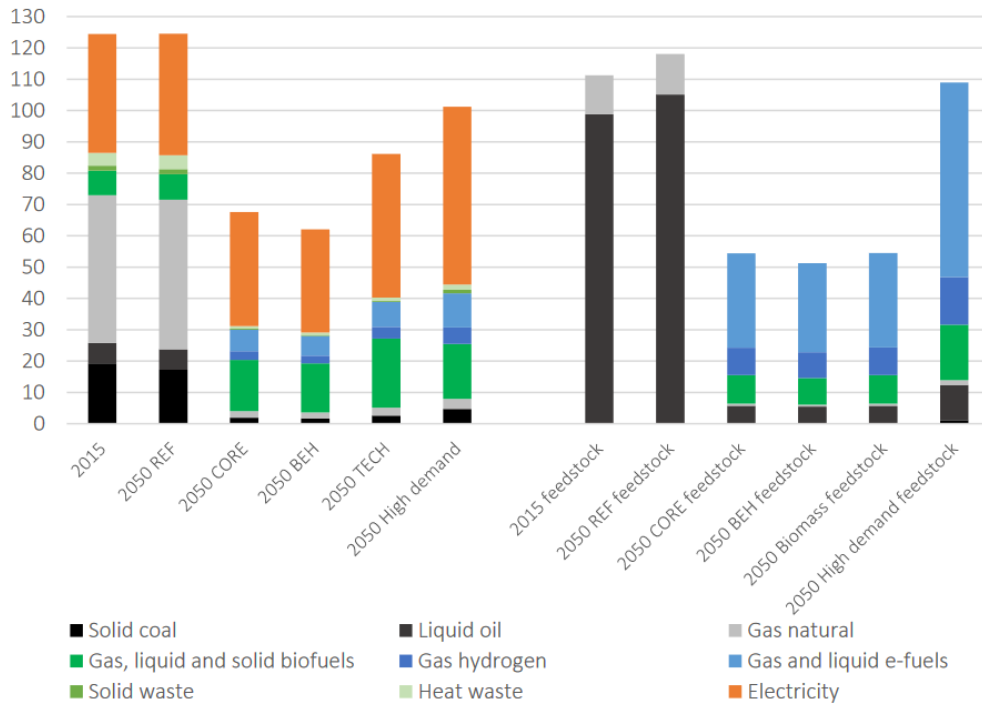


Figure 2.3: Final energy consumption in the industry per vector without feedstocks (left) and feedstocks only (right) (in TWh). From FPS study [41]

The behavioural changes taking place in the BEH scenario allow to keep the cost of the decarbonisation relatively low compared to other scenarios. It should be noted that the use of hydrogen and e-fuels, which are particularly costly and come with an important degree of uncertainty, make the total cost more uncertain. Here again, the BEH scenario is the one relying the least on these resources.

2.3.3 CLEVER Belgian scenario

CLEVER [5] is a European collaboration between various national associations, aiming at proposing a coherent European vision for the decarbonisation in Europe. It stands for "a Collaborative Low Energy Vision for the European Region". More than 20 "national partners" from different European countries participate in the project. Each of the national partners constructs a scenario for its own country, following certain recommendations to ensure coherence between the countries, with the goal of combining these scenarios to construct a European scenario, while taking advantage of coordination between countries. The CLEVER project is leaded by the French négaWatt association [4]. The Belgian partner developing the Belgian scenario is negaWatt Belgium [65].

One of the particularities from this project compared to other ones, is its high ambition in terms of energy demand reduction, which is driven not only by efficiency, but also by sufficiency. Sufficiency is understood as focusing on "quality of life instead of quantity of services" [5], promoting measures that enable to keep a good quality of life while reducing the energy demand through changes at the demand-side. An example is the use of smaller cars. This approach is inspired by the "Doughnut economy" theory. The aim is also to reach carbon neutrality through a 100% renewable mix, rather than relying on carbon capture or nuclear energy.

The CLEVER approach can be summarised as follows :

1. Reduce the demand by prioritising the essential energy needs (sufficiency)
2. Reduce the energy needed to provide the same services (efficiency)
3. Meet the energy demand with a 100% renewable mix, and no importations from outside of the EU

Rather than imposing the same reduction in end-use demand in all countries, CLEVER proposes lower and upper limits on the EUD, so-called corridors, that all countries should aim at. This means that the most consuming countries will need to make higher reductions than less consuming countries. Some of the least consuming countries could even have a current consumption below the lower limit and could increase their consumption. The goal is to ensure a fair transition, where wealthiest countries are not advantaged. Fairness is a central part of the CLEVER vision, also within a country : renovated buildings reduce energy poverty, better public transport makes mobility available to everyone, ...

CLEVER published a sectoral note for its partners regarding the industry [1]. The remaining of this section is based on this note. It defines so-called detailed corridors for four sectors : steel, cement, paper and chemicals (itself divided in ammonia, HVC and other chemicals).

Simplified corridors are defined for the glass, food and non-ferrous metals industries. Remaining industries are grouped together under "Other industries", for which simplified corridors are defined. Simplified corridors only define a relative reduction of the final energy consumption in each sector. Detailed corridors define the production reduction for each industrial sector, as well as its energy intensity (how much energy is needed to produce a certain mass of the product). Simplified corridors allow to calculate the final energy consumption of a sector in 2050 based on historical data of its final energy consumption in 2015, which is used as base year, while detailed corridors allow to calculate the final energy consumption from historical data of material production (in kt) in 2015. Both approaches are illustrated in figure 2.4 and 2.5. The corridors are based on data from studies from Fraunhofer ISI [43], Material Economics [59], négaWatt [6], Umwelt Bundesamt - RESCUE [73] and others. Each national partner can then choose its own objective for production reduction, energy intensity and/or energy consumption reduction within the corridor, taking into account specificities in each country. The Belgian national trajectories chosen by négaWatt Belgium are based on the CLEVER corridors as well as other sources, the BBL-study, presented in section 2.3.6, being the main one.

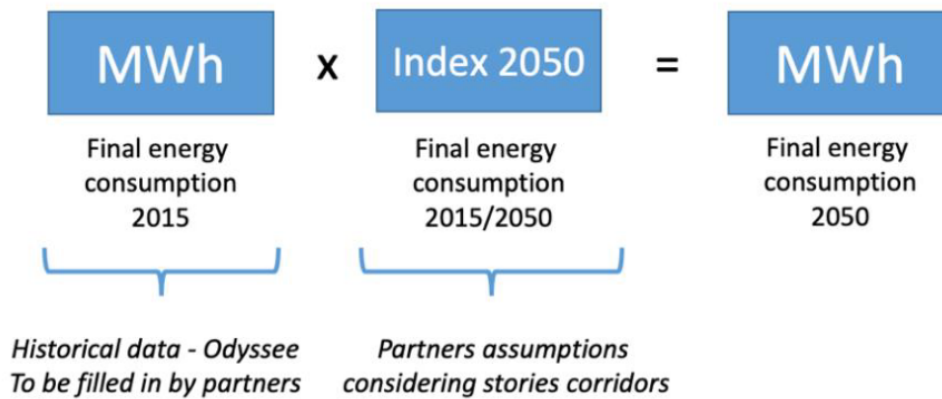


Figure 2.4: Calculation of FEC in 2050 with simplified corridors. From CLEVER report [1]

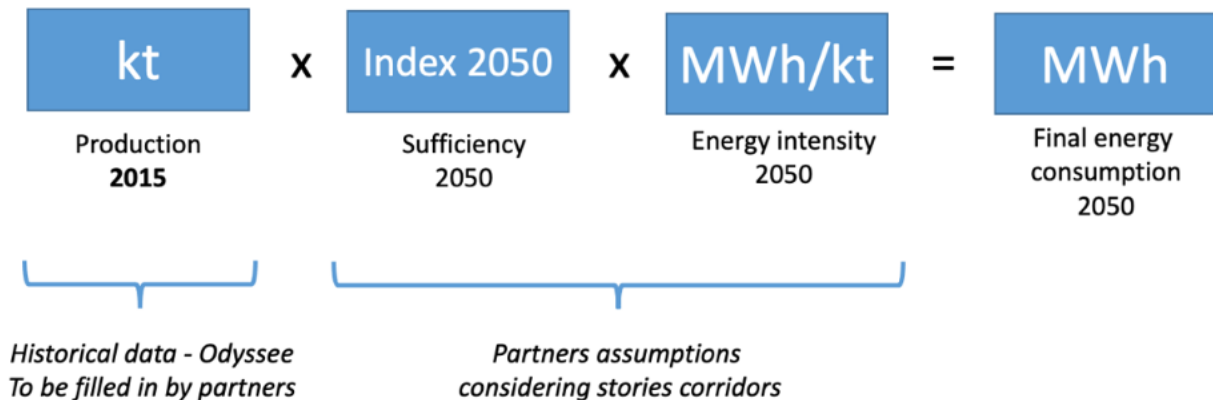


Figure 2.5: Calculation of FEC in 2050 with detailed corridors. From CLEVER report [1]

The CLEVER scenario is based on energetic balances. No hourly adequacy is verified.

Steel production

The corridor for steel production reduction lies between 8% and 26%. The studies from Fraunhofer ISI, Material Economics, négaWatt as well as the RESCUE study all forecast a reduction that lies in this corridor. This reduction is possible thanks to lower building surfaces, longer lifetime of buildings, especially in the industrial and commercial sector, less and smaller vehicles. Material substitution is also important : in construction some steel could be replaced by wood, in transport some steel will be substituted by aluminium. Reduction of overspecification in construction is another important lever. The Belgian production reduction objective fixed by négaWatt Belgium within the corridor is 15%, it is also coherent with the BBL scenario.

The energy intensity corridor for steel production is calculated supposing the average share of recycled steel in the EU (39%). As energy intensity of recycled steel is around 3 to 4 times lower than primary steel, the energy intensity corridors are only valid for countries with a share of scrap steel production similar to the average EU share. The Belgian share of recycled steel is only slightly lower than the EU average, so these corridors can be used. Using the same four studies as previously, the CLEVER corridor for energy intensity is between 2690 MWh/kt and 2060 MWh/kt, which corresponds to a reduction between 15% and 30% for the primary production and 15% to 45% for the secondary production. This is made possible by a switch from blast furnaces with basic oxygen furnaces to other technologies like hydrogen-based direct reduction (H₂-DRI), HIsarna (smelting process) and DR-electrolysis (direct reduction using only electricity). For the remaining BF-BOF production, some efficiency improvements are expected, as well as some fuel substitution, replacing coal by gas and/or biomass. Finally, all scenarios forecast an increase in scrap usage, both by increasing the share of secondary steel and by increasing the use of scrap steel for primary steel, where up to 25% of scrap steel could be used. The Belgian scenario supposes an energy intensity of 2300 MWh/kt, well within the corridor.

Chemicals production

The chemical sector is divided in three subsectors in the CLEVER scenario :

- High Value Chemicals (HVC) : here, these do not only contain olefins and aromatics, but also methanol
- Ammonia
- Other chemicals

For **HVCs**, the CLEVER corridor for production reduction is 2% (Fraunhofer ISI) to 40% (négaWatt). 40% of the produced HVCs are used for packaging. There is thus a high potential of reduction thanks to less single-use plastics and reuse of products as plastic bags and bottles. Material efficiency can also lower the demand with no change to the functionality of the product. Finally, material substitution, for example by fibre-based alternatives, could also play a role. The reduction in Belgium chosen by négaWatt Belgium is 10%, which is consistent with the BBL study.

The corridor for energy intensity is 3140 MWh/kt to 5680 MWh/kt. The expected switch to hydrogen technologies such as MTO allows to decarbonise the production, but increases the

energy intensity. Other considered technologies are electrical steam crackers and limited reliance on biomass-based solutions. Finally, mechanical and chemical recycling could also have an important impact, reaching up to 62% of the production. The Belgian expected energy intensity, within the corridor, is 4400 MWh/kt.

The CLEVER corridor for **ammonia** production reduction is 20% (Fraunhofer ISI) to 42% (Material Economics). 82% of ammonia production is used for producing fertilisers. Its demand can be reduced in two ways :

1. By reducing food waste, and thus food demand and production.
2. By reducing the use of synthetic fertilisers. This requires an important change in the agricultural sector, including implementation of agro-ecological practices.

The Belgian scenario supposes a 30% decrease of ammonia production.

Energy intensity for ammonia could see higher reductions. The corridor is 1580 MWh/kt to 2500 MWh/kt. In this case, the expected switch to hydrogen technologies has a positive impact on the energy intensity. However, considering feedstock, it increases the energy intensity. Use of biogas instead of natural gas is considered to a lesser extent. The Belgian scenario supposes an energy intensity, within the corridor, of 2000 MWh/kt.

Other sectors

A 15% reduction of production is assumed for both glass and paper. For cement, a 25% reduction is assumed, taking into account some material substitution by wood for houses. Important efficiency improvements are assumed in all three sectors, especially in the glass industry, thanks to electrification of the furnaces. For other chemicals (all excl. HVC and ammonia), food, non-ferrous metals and other industries, no specific assumptions regarding sufficiency and efficiency are made. The "simplified" corridors are used (see above). Sufficiency and efficiency are considered at the same time through reductions in final energy consumption. Important reductions, from 21% for other chemicals, to 55% for food, are considered.

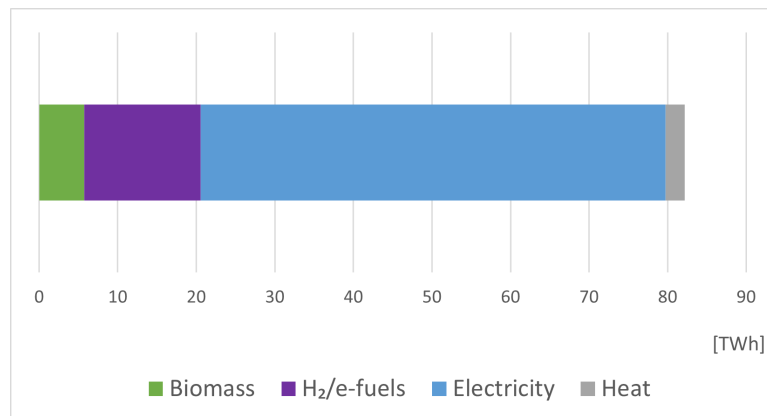


Figure 2.6: 2050 industrial FEC (excl feedstock) in the CLEVER scenario. From CLEVER data [68]

Energy system

The industrial sector is highly electrified in the CLEVER scenario : 72% of the FEC is met by electricity. Hydrogen and e-fuels are also used, and biomass to a lesser extent. The energy mix of the FEC in 2050 of the industrial sector is shown at figure 2.6.

2.3.4 EnergyVille "Paths 2050" central scenario

EnergyVille is a collaboration between the Flemish universities KULeuven and UHasselt and institutions VITO and imec. It develops "technology and knowledge to support public and private stakeholders in the transition to an energy efficient, decarbonised and sustainable urban environment" [23]. Their researchers collaborate closely with partners from industry and public authorities.

The "Paths 2050" study [22] was modeled by EnergyVille on demand from Febeliec, the Federation of Belgian Industrial Energy Consumers, and some of its results were made public. The modeled scenarios explore different possible pathways towards carbon neutrality in Belgium by 2050. Three scenarios are explored. Their difference mainly originates from technological assumptions, impact of production levels and behavioural changes are thus not compared by these scenarios. The results are available on EnergyVille's website. The scenarios were modeled by the TIMES-Be model, developed by the IEA, which calculates net-zero emissions scenarios based on the evolution of technical and economic parameters. The model calculates pathways to get from the current energy system to the 2050 net-zero scenario in the most cost-effective way. The model also has a high level of industrial process detail, taking into account the specifics of the processes in different industries. EnergyVille published a document that "aims to provide more details on the modelling approach, the method and the values of the model parameters" [53]

The three scenarios presented in the EnergyVille scenario are :

- The **Central** scenario, where a balanced set of ambitions and technological assumptions are made. It is the scenario that will be considered in this work.
- The **Electrification** scenario considers 16 GW extra offshore wind capacity, as well as investment in a new generation of nuclear Small Modular Reactors (SMRs), that would be operational in 2050. This leads to a larger share of electricity in the energy mix, but as the central scenario is already very electrified, the difference is limited.
- The **Clean Molecules** scenario, which considers lower costs for imported synthetic fuels (hydrogen and e-fuels), but a more limited access for cross-border CO₂-storage for storing captured carbon. Storage for at most 5 Mt of CO₂ every year is considered available. Use of clean molecules thus slightly increases. What is more astonishing, is the fact that electrification is as high as in the Electrification scenario. This is caused by the limited carbon storage capacity, which forces the industry to switch to less carbon-intensive processes, that are often electrical.

The projected industrial production levels in 2050 are at the same level as in 2020, adding the production of some future investments that are already planned today. There is thus no reduction in volumes thanks to sufficiency measures (circular economy, economy of functionality, ...)

like in the "Behaviour" scenario from the FPS and the CLEVER scenario, but also no production increase due to economic growth as forecasted in the EU reference scenario. Petroleum production from refineries, which are considered in the transformation sector and not in the industrial sector, is however expected to follow a downward trend. The production volumes in the EnergyVille scenario are obtained from various sources, including public institutions, industrial federations and industries themselves.

In the Central scenario, industrial processes are highly electrified in 2050. However, some sectors rely on clean molecules to produce high temperature heat : mainly the chemical, glass and ceramic industries, as well as steel finishing; the lime and cement industries to a lesser extent. The Electrification scenario allows further electrification of the steam crackers in the chemical sectors. In the central scenario, these crackers still use fossil fuels. The Clean Molecules scenario is the only one using methanol-to-olefins (MTO) for HVC production. The evolution of the energy mix of the central scenario is shown at figure 2.7

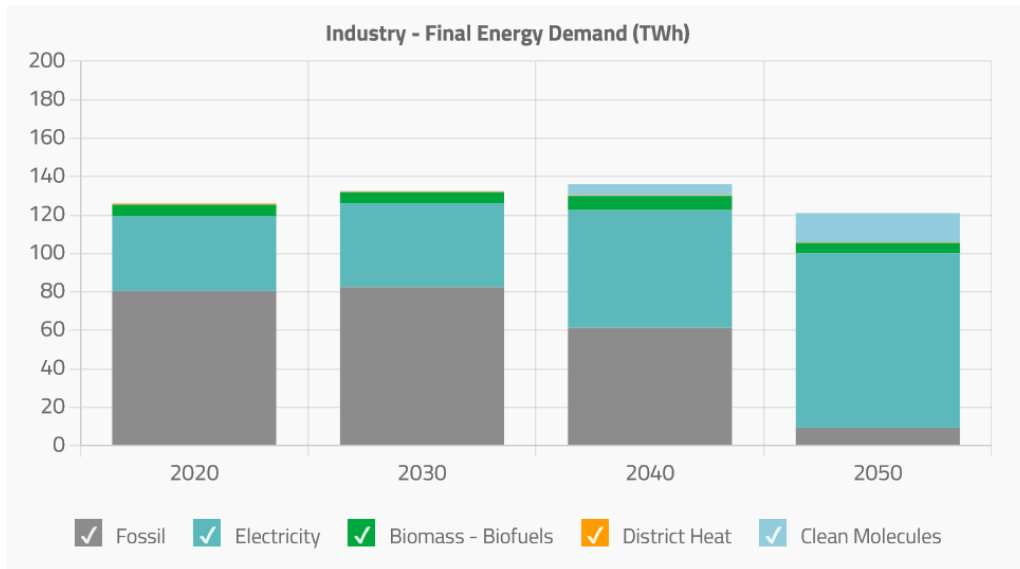


Figure 2.7: Evolution of the industrial FEC (excl feedstock) in the EnergyVille central scenario. From EnergyVille website [22]

The Central scenario strongly relies on carbon capture. The captured carbon is highest in 2040, accounting for 18.5 Mt per year. This technology is considered a temporary solution for reducing emissions quickly, but doesn't allow reaching net-zero. Its use thus diminishes towards 7.4 Mt in 2050, as fossil fuels are replaced by synthetic fuels or electrified processes. Its use in 2050 is limited to the chemical sector and for covering process emissions in the cement and lime industry. In the Clean Molecules scenario, the captured carbon that cannot be stored because of the limited storage capacity, is used for methanol synthesis, which is used in the MTO process.

2.3.5 EU reference scenario

The last and least ambitious scenario covered in this work is the EU reference scenario, published by the European Commission. It was already used as the upper bound of the demand in Hugo Baudson's master thesis [7]. The last version of the EU reference scenario is the "EU reference scenario 2020" [29]. It updates the previous "EU reference scenario 2016" [31].

The EU reference scenario makes a projection of the EU energy system, transport system and GHG emissions. It was made by a group of experts from different member states, with the input of stakeholders from the industry and non-governmental organisations. The central model that is used for the scenario is the PRIMES model [20]. It combines an economic and a technical approach. It is interconnected in a complex web with several other models, which provide specific projections regarding demography, economy, agriculture, transport and others. Industrial processes are modeled in detail, 10 different sectors with 31 subsectors are modeled, with each its own processes, fuels, equipment, boilers, etc. Projections for the 27 Member States are made across Europe, but also individually on a country-by-country basis.

Unlike the other scenarios, the EU reference scenario does not aim at carbon neutrality by 2050. It is also not a forecast of the most plausible evolution of the energy system. It is a projection of what the energy system could look like, taking into account only *current* policy context, on top of other economic, demographic, and technological assumptions. No new policies are assumed. Only current policies are assumed to intensify until 2030, and then stay stable until 2050. The aim of the reference scenario is to give a "reference point" for comparison to other projections that do take into account new policies in order to reach carbon neutrality by 2050. At an European scale, the 2020 scenario only projects a 60% reduction of GHG emissions, which is far from enough in order to reach carbon neutrality.

GDP growth is assumed in the EU Reference Scenario. For the energy-intensive industry, it is assumed that a significant part of the production will remain in the EU. A gradual shift towards high value-added industrial products, which are less energy-intensive, is however assumed. This means that the production volumes increase more slowly than the GDP, but an increase of production volumes is still assumed.

The Reference Scenario takes into consideration the Circular Economy Action Plan from 2015 [26], but it does not take into consideration the new one from 2020 nor the New Industrial Strategy for Europe [27]. These action plans and strategies favour recycling, and thus less energy-intensive processes. Some improvements are also expected regarding global energy efficiency of the processes.

At an European scale, between 2015 and 2050, an 8% decrease in FEC in the industry is projected. At a Belgian scale, however, a 17% increase is projected. Although the model has no carbon neutrality objective, the EU ETS system [28] is taken into account and favours a gradual shift to cleaner resources in industry. This shift is however much slower than in the previously considered scenarios. Globally, while efficiency improvements and a shift away from solid and liquid fossil fuels is projected in most scenarios, no breakthrough changes, like a switch to H₂-DRI in the steel industry for example, take place. No decrease is expected for the use of natural gas at EU level. Electricity shares rise slightly. The evolution of the EU energy mix of the FEC in industry is shown on figure 2.8

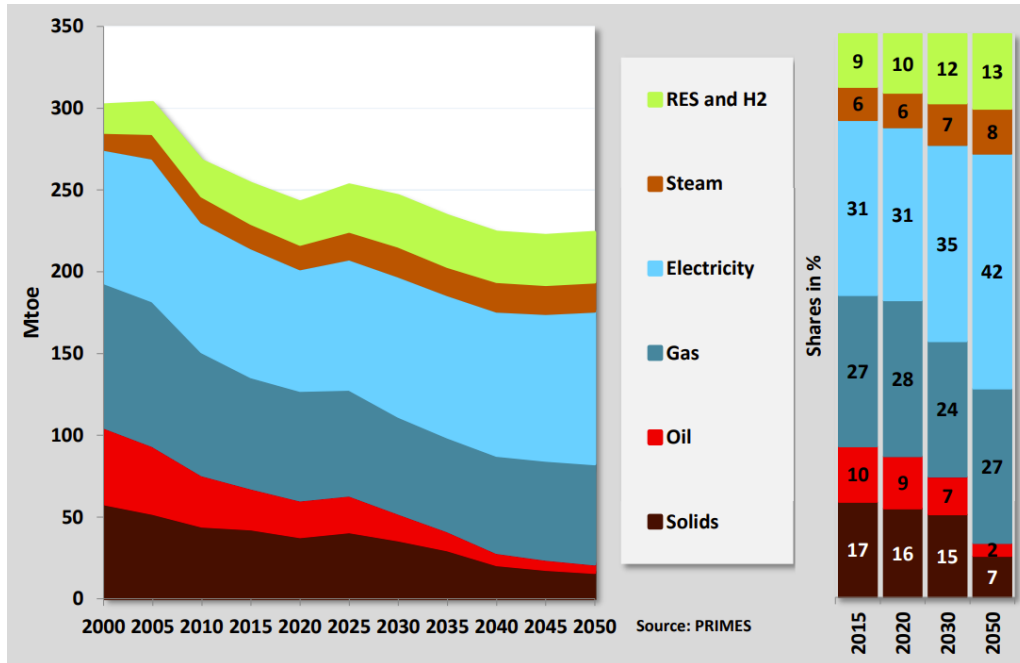


Figure 2.8: Evolution of the EU energy mix of the industrial FEC (excl feedstock) in the EU reference scenario 2020. From EU reference scenario 2020 [29]

2.3.6 Bond Beter Leefmilieu and Climact "Hoe creëren we een klimaatneutrale Vlaamse industrie?" scenario

Unlike previous scenarios, this scenario does not consider the whole energy system, but only the industrial sector, and it does not consider the Belgian, but only the Flemish industrial sector !

In November 2020, "Agentschap Innoveren & Ondernemen" (VLAIO), a Flemish institution supporting entrepreneurship, in collaboration with Climact and other organizations, published its study "Naar een koolstofcirculaire en CO₂-arme Vlaamse industrie" (Towards a *carbon circular and low-CO₂* Flemish industry) [2]. It is a roadmap study that aims at showing possible pathways for the transition of the energy-intensive Flemish industry, and the conditions required to reach this objective. Climact developed the model used in the study. The technological assumptions are based on input from industrial actors, focusing on the most CO₂-intensive sectors : steel, chemicals and refinery. It should be noted that refinery is usually not considered in the industrial sector, the BBL-scenario is in fact the only scenario considered in this work that includes refineries in the industrial sector. Cement is usually included in the CO₂-intensive industries, but there is no clinker production, which is the most CO₂-intensive step of cement production, in Flanders, so it doesn't need to be considered in this study. Other industrial sectors, like food, paper, non-ferrous, glass and ceramic are considered to a lesser extent in the study.

Bond Beter Leefmilieu (BBL), the network of sustainable organisations in Flanders, made its own study, based on the study from VLAIO, once again with the help of Climact for the modeling. BBL considered that VLAIO's study lacked some possible scenarios, particularly a scenario with higher ambitions in terms of circularity and thus lower production volumes. The study used the same model as VLAIO's study, but considering BBL's own assumptions. The study is called "Hoe creëren we een klimaatneutrale Vlaamse industrie?" (How to create a *climate neutral* Flemish industry) [10]. This section is strongly inspired by the report.

In comparison to other scenarios, this one thus only considers the industrial sector, and only considers the Flemish industry. It does however model the Flemish industry in greater detail than other scenarios, taking into account some existing and future projects that are already announced.

BBL's scenario is based on the central "MIX" scenario from the VLAIO study, making some adjustments on the assumptions. Part of the new assumptions are based on the Material Economics report : "Industrial Transformation 2050" [59]. The main adjustments are :

- Higher production volumes decreases thanks to circular economy and material efficiency
- Higher electrification and circular technologies
- Less use of carbon capture and biomass
- Phase-out of the refineries by 2040, as their products wouldn't be used anymore

The BBL-scenario allows for an emissions reduction of 95%, whereas the MIX-scenario only allowed for a 86% reduction. Remaining emissions thus need to be compensated in other sectors, like land use. The BBL-scenario depends on carbon capture, but to a much lesser extent than the MIX-scenario. 2.8 Mt are captured in the BBL-scenario, while 12.4 Mt are captured in the MIX-scenario. Most of this carbon capture takes place in the chemical sector. 60% of the captured carbon in the BBL scenario is used for the production of methanol (CCU), while the remaining carbon is stored in empty gas fields (CCS). By relying less on carbon capture, the BBL-scenario aims at avoiding that society keeps investing in so-called "fossil lock-ins", technologies that are not compatible with our ambitions in the long term, and would make our industry lag behind concerning new future-proof technologies.

Low temperature heat is completely electrified, allowing for zero emissions in sectors like food and paper. Other sectors are more difficult to decarbonise. For the primary steel production, all blast furnaces are replaced by H2-DRI. Emissions in the chemical sector stay more significant, as a large share of chemical recycling is considered, which still causes some emissions.

Figure 2.9 shows the evolution of the final energy consumption (FEC) in the BBL scenario, and a snapshot of the FEC in 2050 in the MIX-scenario. While the consumption barely drops in the MIX-scenario, a drop of 51% is observed in the BBL-scenario. BBL's mix is also much more electrified (orange on the graph), with a lower share of fossil fuels (black and gray on the graph). There is less energy demand for carbon capture.

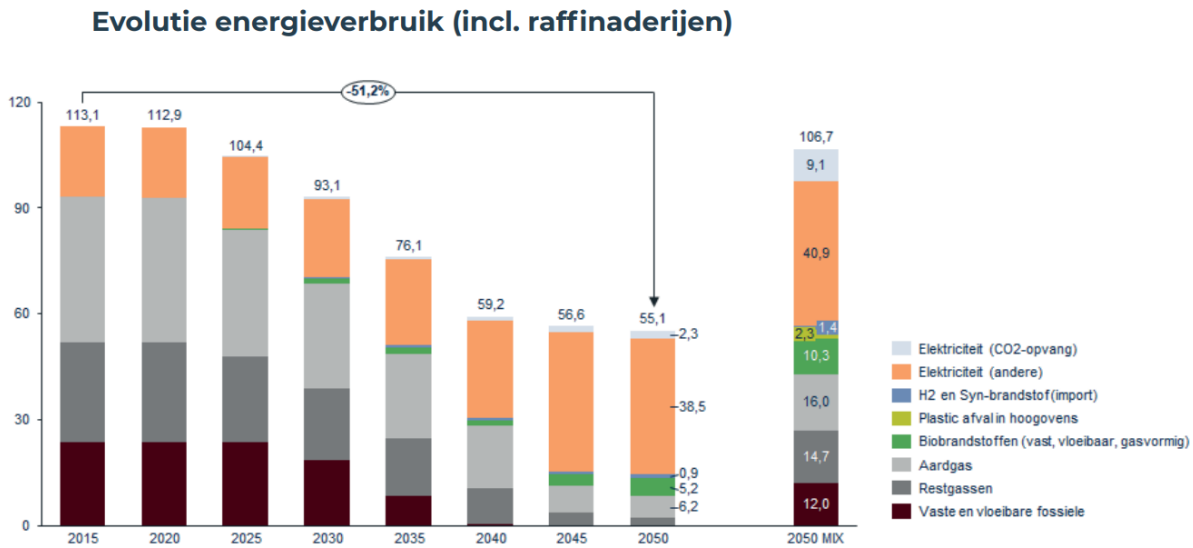


Figure 2.9: Evolution of FEC in the BBL scenario (left) and 2050 FEC in the MIX-scenario (right) (including refineries). Black/gray : fossil fuels, green : bio-fuels, light green: waste, blue: e-fuels, orange: electricity, light blue: electricity for CC. From BBL study [10]

Figure 2.10 shows the demand for non-energy inputs (excluding crude oil input in refineries). The BBL-study also shows a higher reduction of this non-energy (feedstock) demand than the MIX-scenario. Furthermore, the energy mix of the BBL-scenario is less fossil-based and relies more heavily on chemical recycling. These feedstocks are used in the chemical sector, except for the hydrogen, which is used for the H2-DRI process in the steel sector.

In the chemical sector, the goal is to close the carbon circle. The demand for their products (mainly plastics) is expected to decrease thanks to material efficiency, material substitution and circular models. The remaining demand should be met maximally by recycling, which at the same time avoids incineration of waste, and production of fossil feedstock for the production. The main challenge to achieve this is the collecting of the plastic waste. Currently, only a fraction of the produced plastics ends up available for recycling. On top of the recycling routes, other production methods for HVC will thus still be needed. The planned propane dehydrogenation (PDH) plant of Borealis is expected to produce 22% of the HVC. Carbon capture is applied to this plant. Other technologies used in the model are electric cracking, methanol-to-olefin (MTO), and biomass-based. Finally, 35% of the production is expected to use plastic waste through chemical recycling. Mechanical recycling is not modeled, but it could definitely increase the share of recycling in the HVC production further. The ethylene cracker "Ineos Project One"⁵ is not included in the model, as it is considered a fossil lock-in not compatible with long term climate neutrality ambitions.

In the steel industry, all of the blast furnaces (BF-BOF) are expected to disappear, and be replaced by the H2-DRI-EAF route, between 2030 and 2040. A temporary solution for limiting the costs is to first replace only the BF by H2-DRI, keeping the BOF until their end of life,

⁵"Project ONE aims to build an ethane cracker in the Port of Antwerp with a nameplate capacity of 1450kt of ethylene per year." [66]

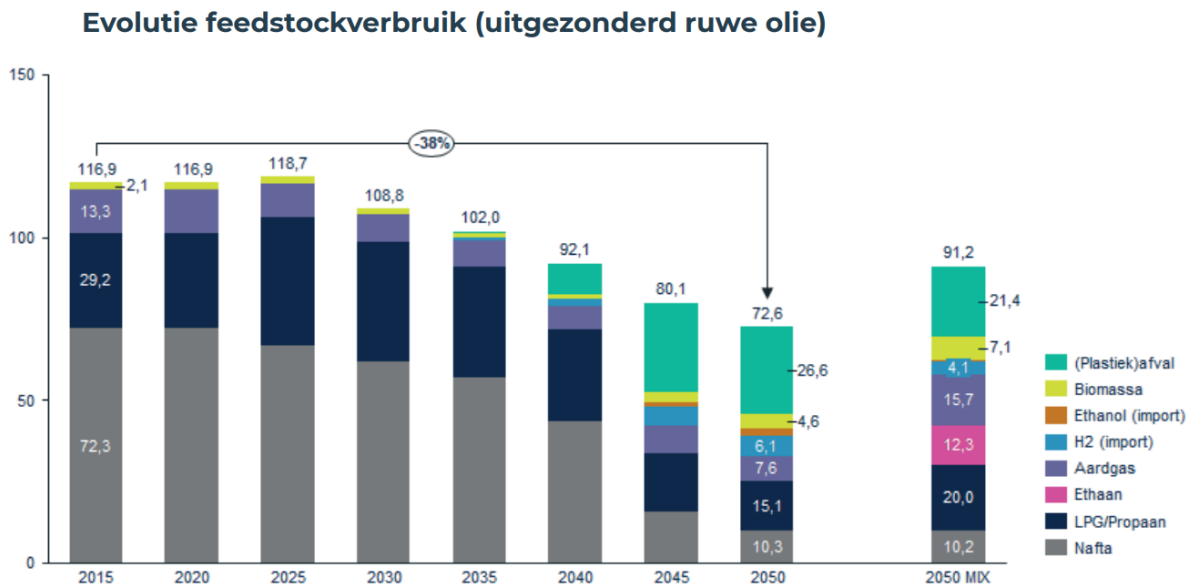


Figure 2.10: Evolution of feedstock consumption in the BBL scenario (left) and 2050 feedstock consumption in the MIX-scenario (right) (excluding refineries). From BBL study [10]

before replacing it with an EAF. Also, green hydrogen availability towards 2030 to 2040 is quite uncertain, so there is a possibility of temporarily using natural gas for the reduction of iron. This is not a carbon neutral solution, but the related emissions are much lower than with the BF route, and it allows to switch to green hydrogen as soon as it becomes available. This is however not the strategy that ArcelorMittal is following in Ghent, where the two Belgian blast furnaces are located. One of these furnaces was recently replaced, locking the production method for another 20 years at least. The EAF furnaces using scrap steel are supposed to keep operating without change. As the BF route is abandoned by 2050, it won't produce any rest gases anymore (CO) that could have been used for the production of ethanol in the chemical sector in the Steelanol [69] project, which is thus not possible in this scenario.

For the other sectors, like food, paper, glass, non-ferrous and ceramics, the MIX scenario assumes production levels based on current trends. The BBL scenario sets production volumes inspired by the FPS scenarios (section —). This implies lower production volumes, except for the glass industry, which is important for the renovation of buildings.

The cost of investments for the transition towards the BBL-scenario mainly originate from the changes in the chemical and steel sector. The MIX-scenario is projected to have significantly higher investments cost, mainly due to the more important use of CCS. The cost of CCS is however still extremely uncertain.

Chapter 3

Methodology

3.1 Adjusted Low Demand scenario

A detailed overview of the methodology and the assumptions made in the adjusted Low Demand scenario can be found in appendix A, and the final EUD matrix in appendix B. This section presents the motivation for adjusting the Low Demand scenario, and the main characteristics of the scenario.

Hugo Baudson's Low Demand scenario [7] gives an interesting view on what the Belgian energy system could look like if we used no more energy than required to live "decently". Its bottom-up approach allows to make ambitious assumptions on sufficiency, counting only the energy uses that are necessary for decent living. Hugo Baudson mentions two limitations to the "Decent living with minimum energy" [63] article, on which his Low Demand scenario is based :

1. The global methodology for the "Decent Living" article consists in the definition of energy needs for every country in the world, taking into account some parameters that are different for every country. Hugo Baudson further specified some of the parameters or methodologies in his scenario, to better correspond to the Belgian reality, for example the population density and the climate. But other important particularities, especially in the Belgian industrial sector, are still not taken into account.
2. The methodology follows a bottom-up approach, which inherently means that certain consumption (sub)sectors are omitted. Once again, the industry is probably the sector where most omissions were made.

Other limitations of Hugo Baudson's Low Demand scenario regarding the industrial sector were identified :

3. The approach to define the industrial energy consumption consists in the definition of the embodied energy of all the services (housing, transport, infrastructure, ...) that were estimated necessary for decent living in the other sectors. This thus means that the assumption is made that all of our material needs are met by local production from industry within Belgium, and that the Belgian industry produces no more, no less than what is needed for the Belgian population. This does obviously not correspond with reality, especially in a small country like Belgium which exports a large share of its

produced goods, and imports a large share of its demand in goods. Even though effort is being made to relocalise industry in Europe [16], relocalisation is rather considered at an European scale, and even 100% European production does not seem realistic. Still, this approach is interesting as it allows to calculate the "energy footprint" of the Belgian population, which represents our share in responsibility in the use of energy and resources needed to produce it, in the same way as a "carbon footprint" allows to calculate someone's responsibility in anthropogenic emissions and their consequences. However, international conventions require calculation of territorial emissions, i.e. emissions that are physically released in the country. Furthermore, in the framework of the modeling of a national energy system, it is the territorial consumption that is required.

4. As the approach consists of calculating the embodied energy of each "Decent Living" service, based on various sources, it is not obvious what these changes would mean for the different industrial sectors.

The aim of the variant of the Low Demand scenario developed below is thus to **redefine the energy demand for the industrial sector**, with a territorial approach rather than a footprint approach, and taking into account Belgian specificities in the industrial sector. A simple adjustment is also made for the **freight sector**.

Instead of starting from each "Decent Living" service requiring industrial production and then calculating its embodied energy, we start from the current industrial production and energy consumption in each individual industrial sector. We then make assumptions on the Belgian materials demand evolution, based on the sufficiency assumptions from Hugo Baudson's Low Demand scenario in the other sectors, but we also make assumptions on the demand out of Belgium, and the evolution of international trade with other countries. This allows to estimate the evolution of material production levels in Belgium. Finally, making assumptions on the technologies used in the industry and the evolution of their energy efficiencies allows to estimate the final energy consumption (FEC) and the end-use demand (EUD) of the industry, which is the input needed to analyse the scenario with EnergyScope TD.

It is thus necessary to estimate how the local demand of products from a certain industrial sector relates to its local production. Different approaches are used in other studies :

- The EnergyVille scenario [22] simply considers the industrial production volumes stay constant, at the same level as in 2020.
- The EU reference scenario [29] makes projections on industrial production volumes based on economical reasoning, rather than behaviour within the country.
- CLEVER [5], Climact [41] and many others suppose a constant P/C^1 ratio. This means that even if production and consumption are very different, if the consumption (demand) is halved, the production is halved, and the net import or export is also halved. The evolution of the production is defined by the demand, but it is *not* equal to the demand.
- The négaWatt French scenario [6] uses a more complex methodology, that differs if the country is a net importer or exporter in the sector. If the demand decreases and the coun-

¹Production / Consumption

try is a net importer, local production will stay constant and only import will decrease, but if it is a net exporter, it will produce less while still exporting constant volumes.

The methodology that will be used in our scenario is keeping a **constant P/C ratio** in most sectors. While the négaWatt approach is interesting because it favours relocalisation of industry, if all countries follow this approach, they will all import less while still exporting constant volumes, which is not possible globally. For our scenario it is supposed that other countries, especially the neighbouring European countries to which and from which Belgium exports and imports most materials, will go through similar changes. It is thus needed to have a global approach. If each country keeps constant P/C ratios, and has similar material demand reductions, a global equilibrium will be maintained. That is why this approach was chosen in this work.

In terms of sufficiency, one of the most ambitious sectors in the Low Demand scenario is the **transportation**. The yearly passenger distance is divided by 3, the share of public mobility goes from 20% [14] to 80%, and the occupancy of cars from 1.5 to 3. This leads to a 96% reduction of the distance traveled by cars ! The total reduction in material demand for both cars and vehicles for public mobility (bus, train) is estimated at 89%. The most impacted industry is steel, but other industries, like the chemical and non-ferrous metals industries, are also impacted.

Another important sector is the **construction**. The Low Demand scenario assumes an important decrease in floor area per capita, which is almost half the current floor area. A more modest decrease in floor area is also considered in the tertiary sector. Then, we make the strong assumption that the transition from the current situation to the projected situation is complete by 2050, and that the rate of construction and renovation will be the same as currently. This allows important reductions, especially in the steel and cement industries, where we consider materials substitution by wood.

In the chemical industry, on top of the assumptions in construction and transportation, reduction of plastic packaging, which is the main HVC consumer, is considered. High recycling rates also allow an important reduction of the feedstock demand. The ammonia demand drops significantly thanks to a drastic change in agricultural practices.

The reductions considered in the food industry are less ambitious, as less reductions in sufficiency are possible, for the obvious reason that access to food is considered essential. No sufficiency reductions are assumed in the glass and wood industries, as their use is expected to increase in the construction sector. In the paper industry, sufficiency is limited. No reduction is assumed in the consumption of graphic paper (used in books, ...), as its use, for example in education, is considered essential, especially considering other assumptions made in the Low Demand scenario, for example the reduction of the number of laptops to one per household.

Finally, the demand evolution for freight transport was estimated to be proportional to the evolution of production volumes, weighted by their share of FEC in the industry.

3.2 Simulations with EnergyScope TD

Six Belgian scenarios for 2050 were simulated with EnergyScope TD. For his master thesis, Hugo Baudson already simulated his original Low Demand Scenario and the High Demand Scenario (the EU reference scenario). Four additional scenarios are simulated in this work : the Low Demand Scenario with adjusted industrial and freight sector, presented in the previous section, the FPS and Climact Behaviour scenario, the CLEVER Belgian scenario and the EnergyVille central scenario. The energy and transportation demand from these scenarios is used as input for the EnergyScope simulation, which will generate an appropriate energy system, which may be different than the original energy systems considered in the scenarios, but satisfies the same EUD. As the data provided by the scenario reports varies from one to another, and does not always correspond to an adequate input for the EnergyScope, a methodology had to be defined to translate the data from the reports into an EnergyScope input. This methodology is presented in section 3.2.1. General assumptions and parameters used in EnergyScope are presented in section 3.2.2, and the methodology for the interpretation of the EnergyScope outputs in order to compare them to the original scenarios is presented in section 3.2.3.

3.2.1 Obtaining the EUD matrix

The methodology explained hereunder was used for generating the EnergyScope input for the **FPS-Climact Behaviour**, **CLEVER Belgian**, and **EnergyVille central** scenarios. A similar methodology was also applied for the adjusted Low Demand scenario, which is detailed in Appendix A. The methodology used by Hugo Baudson for his original Low Demand scenario and the EU reference scenario is not exactly the same, with main differences in the industrial sector, but in order to stay consistent with his work, his EUD matrices were used for those two scenarios.

Transportation

All three scenarios provide transportation demand expressed in pkm and tkm. It is thus already expressed in EUD and doesn't need to be translated. However, three adjustments need to be made :

- The soft mobility should be excluded, as it is not considered in EnergyScope.
- Aviation is not included in EnergyScope. Extra-EU aviation is excluded, while intra-EU aviation is considered to be provided by other public transportation, like bus or train.

These adjustments are in line with what was made in Hugo Baudson's thesis [7].

Residential and services sector

All three scenarios provide electricity demand separately from the heat demand. Their heating demand also refer to end-use demand (i.e. excluding technology-related losses and including ambient heat for heat pumps). Some scenarios do however present buildings and services consumption as a single one, or don't differentiate the constant (hot water for heating) from the variable (space heating or lighting) shares. Whenever this is the case, the ratios from the EU reference scenario, based on Gauthier Limpens' calculations [55], are used.

Industrial demand (excluding NED)

A significant shift towards electrification is considered in most scenarios. This means that the low and high temperature heat demands are increasingly provided by electricity instead of fossil fuels, and that the share of electricity in the FEC increases drastically. This does however not affect the EUD. The shares of high temperature heat, low temperature heat (constant and variable) and electricity (constant and variable) in 2050 are thus assumed to be the same as in the EU reference scenario, as obtained by Gauthier Limpens [55].

Except for direct electrical heating, the technologies used to provide high temperature heat do however have an efficiency lower than 100%. The technologies used in each scenario were assumed based on their FEC energy mix. The data regarding their efficiency are mainly based on EnergyScope's data on technologies [55]. In some cases, when the mix was presented as categories of fuels, assumptions had to be made on the specific fuel used : for example, biomass was assumed to be wood used in boilers, and synthetic fuels to be SNG, also for boilers. Multiplying each fuel consumption by its efficiency, we obtain a total (provisional) EUD.

This provisional EUD does however not take into account the COP of heat pumps. According to EnergyScope's ratios, low temperature heat accounts for about 13% of industrial EUD. Although all scenarios mention heat pumps are used for low temperature industrial heat demand to lower the FEC, none of them provide exact numbers concerning these heat pumps. It will be seen later that all EnergyScope simulations model the low temperature demand to be 100% provided by heat pumps. For the three original scenarios, the assumption was made that 50% of the low temperature demand is met by heat pumps, and 50% by direct electricity. Using EnergyScope's ratios, this has the effect of increasing the total industrial EUD (excl. NED) with 7.75%.

At this stage we have calculated the total industrial EUD. This EUD is however not yet the input that should be used in EnergyScope.

Indeed, the production of primary HVC, ammonia and methanol are modeled separately in EnergyScope. The non-energy demand, discussed hereunder, defines the demand for these molecules. This means that EnergyScope will find the best way to produce (or import) these molecules, using extra energy, that is thus not used by the specific industrial demand. The industrial energy demand for the production of these molecules thus needs to be subtracted from the EUD obtained above. As the scenarios don't provide information regarding the energy consumption for methanol production, and it only represents a fraction of the total NED, only the energy consumption for primary HVC and ammonia production are subtracted. It is assumed that the technologies for their production are all high temperature and electrified, so their FEC is equal to their EUD.

The first step, i.e. taking into account technology efficiencies, does generally not make an important difference as losses partly compensate the ambient heat from heat pumps. The obtained EUD is generally only slightly higher than the FEC. It should be noted that, at this point, estimating the EUD as the FEC is thus not necessarily a conservative approach. The second step, i.e. removing HVC and ammonia energy consumption, does however have an important impact, bringing the EUD (excluding HVC and NH₃) well below the FEC (including

HVC and NH3). This is mainly due to the high energy consumption of the HVC production.

Non-energy demand

The non-energy EUD is not defined by FEC, but by the material demand for primary HVC, ammonia and methanol. As the information regarding non-energy demand was inconsistent from one scenario to another, the NED for each of these molecules was defined using the relative reduction of their demand in each scenario, assuming the same current demand for all scenarios. For HVC, the secondary production also needs to be subtracted. The assumed current demand is defined by Rixhon et al. [67], expressed as their energy equivalent, based on their LHV : 39.8 TWh HVC, 9.8 TWh ammonia and 1.5 TWh methanol.

The EUD matrix obtained for each scenario can be found in appendix B.

3.2.2 EnergyScope simulation

The methodology described hereunder was used for the simulation of all six scenarios, including the original LD scenario and the EU reference scenario, for which the EUD matrix obtained by Hugo Baudson is used.

One of the most important parameter that has to be fixed is the limit on GHG emissions in 2050. The global warming potential of operation (GWP_{op}) of resources in EnergyScope is defined by the emissions related to their production, transport and combustion. Some renewable resources, like wood and wet biomass, have a non-zero GWP_{op} , because some emissions are considered for their transportation. Setting the emissions limit at zero would thus exclude these resources, which is not desirable. A first solution is to allow a small quantity of emissions. Around 3 Mt CO₂e for example could be considered to be compensated by land use [14]. It was however observed that this led to the (limited) use of cheap but dirty resources like coal. The emissions limit was thus set to zero, and the GWP_{op} value for wood and wet biomass was set to zero. The emissions related to these resources can still be calculated from the results of the EnergyScope simulation.

Another parameter that was adjusted for each scenario is the share of public mobility in the total passenger mobility demand (in pkm). Indeed, the scenarios have different levels of ambition regarding its share, ranging from 20% to 80%.

Finally, as the reduction of non-energy demand is considered separately for each product, their shares have to be adjusted for each scenario.

3.2.3 Defining Final Energy Consumption from EnergyScope results

From the EnergyScope results, it is not as obvious as it may seem to obtain the FEC mix for each sector.

First, the FEC is defined by the energy "which reaches the final consumer's door" [30]. But EnergyScope doesn't define where this "consumer's door" is. Combined heat and power (CHP)

plants, for example, providing high temperature heat to the industry, could be considered as part of the industry ("inside the consumer's door") and as part of the energy sector ("out of the consumer's door"). It is thus necessary to make conventions. The conventions made for this work are stated below.

- Regarding **CHP** plants, they are considered to be part of the energy sector. The related FEC in the consuming sectors is thus heat or electricity and not gas.
- The **electricity** generation is also obviously considered to be entirely part of the energy sector.
- **Biomethanation** of wet biomass is considered to be part of the energy sector as well. Its gas production will be considered as a biofuel.
- **Boilers**, on the other hand, are considered to be part of the industrial sector. The considered FEC is thus for example gas or wood, but not heat.
- All the **heat pumps** (including in district heating networks) are considered to be part of the residential, tertiary and industrial sector. Ambient heat is thus not included in their FEC.
- All the **hydrogen** production is considered to be part of the energy sector, and none part of the industrial sector.
- Processes related to the conversion of feedstock in order to produce the non-energy products, like the production of HVC with methanol using the MTO technology, are considered to be part of the industry, even though the energy used for these processes was not included in the industrial EUD matrix input.

Second, EnergyScope doesn't specify which energy is used for which sector. When different sectors use the same resource, which can be considered as different types of resource (for example natural gas, synthetic natural gas (SNG), and bio-gas), it is considered that all sectors use the same share of each type of fuel, in order that the total consumptions add up for each type of the resource. As a simple example, if gas is obtained for 70% from imported SNG and for 30% from biomethanation, and is used for 50% in the industrial and 50% in the transport sector, it is considered that half of the SNG (35%) goes to each sector, and half of the bio-fuel (15%) goes to each sector.

Chapter 4

Results

The five main scenarios analysed in this work are the following :

1. The adjusted **Low Demand** (LD) scenario, for which the data from Hugo Baudson's thesis [7] is used for the residential, tertiary and passenger mobility sectors, and our own data for the industrial and freight sectors (see section 3.1).
2. The **Behaviour** scenario from **Climact**'s study for the FPS Public Health [41].
3. The Belgian scenario of the **CLEVER** project [5, 68].
4. The **EnergyVille** "PATHS2050" central scenario [22].
5. The **EU reference** scenario [29, 31]

These scenarios are cited in order of growing global energy demand, even though some irregularities of this trend are observed in specific sectors, as will be seen later.

In this and following chapters, the "Low Demand (LD)" scenario designates the new adjusted version of this scenario, using the territorial energy consumption calculated in this work. When referring to the original scenario obtained by Hugo Baudson, it will be explicitly called "*Original Low Demand*" scenario.

In section 4.1, the five original scenarios are analysed based on their reports and additional available data. Only for the LD scenario, which is built directly with EnergyScope, the results from EnergyScope are used.

For section 4.2, the four other scenarios were also simulated with EnergyScope, and the obtained energy systems are compared with the four original scenarios.

In the following sections, all the energy systems obtained with EnergyScope are analysed and compared with each other.

The sankey diagrams for the five scenarios simulated in EnergyScope, which show the energy fluxes of the energy system over a year, can be found in appendix C.

4.1 Comparison of the original scenarios

4.1.1 Sufficiency and efficiency assumptions

We start by analysing the sufficiency and efficiency assumptions made in the main scenarios. The EnergyVille scenario assumes constant production. The EU reference scenario assumes slight production increases, but no precise numbers are presented. None of these two scenarios provide numbers for the efficiency improvements in each industrial sector. This section thus focuses on the other three scenarios : the LD, Climact BEH and CLEVER scenarios. Additionally, BBL's assumptions are shown for comparison [10]. Two other common references are also added to the comparison : the Material Economics "Industrial Transformation 2050" report [59], and the Fraunhofer ISI and ICF "Industrial Innovation - Pathways to deep decarbonisation of the industry" report [43]. These scenarios and reports don't present values for sufficiency and efficiency for all the industrial sectors. The following graphs thus only show the data available in the reports. When the assumption of a constant production or efficiency is made, this is explicitly indicated by a "0%" mention on the graphs, in order to differentiate it from the scenarios making no explicit assumptions.

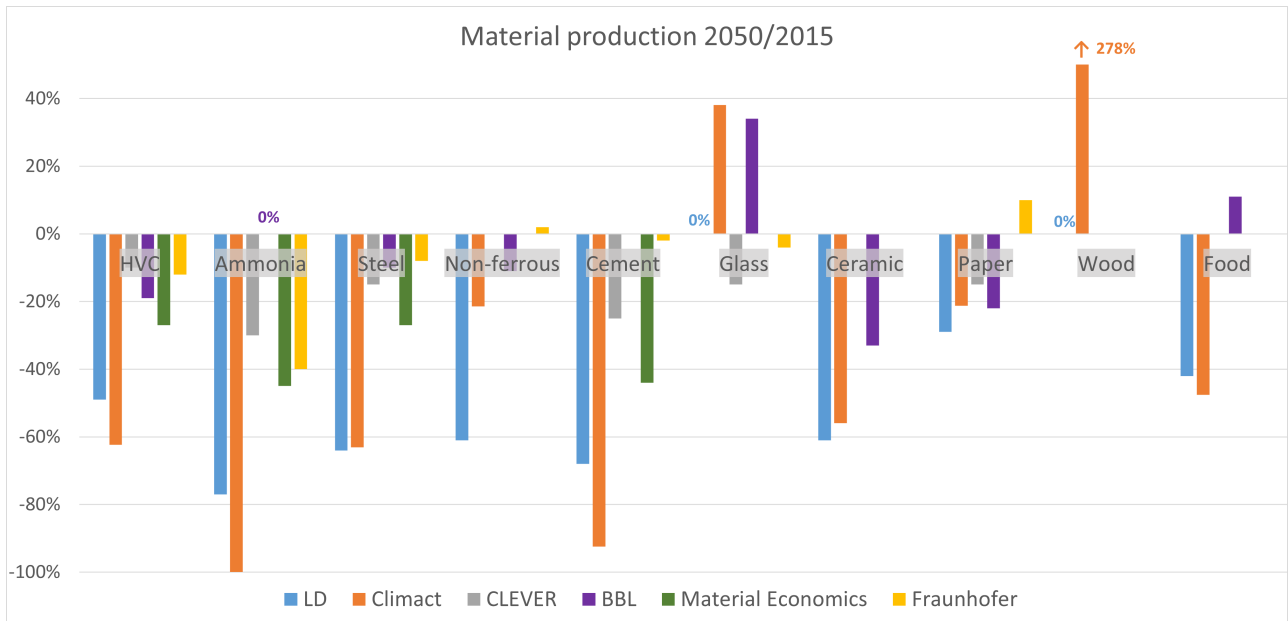


Figure 4.1: Reductions in material production for different industrial sectors between 2015 and 2050

Figure 4.1 shows the evolution between 2015 and 2050 of the material production assumed in each scenario for each industrial sector. Reductions are achieved thanks to sufficiency, circularity, material efficiency, material substitution, etc. Depending on the sector, the Climact BEH or the LD scenario is the most ambitious one regarding reduction of production. They achieve these high reductions thanks to more important sufficiency measures in various sectors, including construction, transport, agriculture, packaging, etc, for which less materials and products are needed. The Climact and BBL scenarios assume an increase of around 35% in glass production, due to its increased use for buildings renovation. The Climact scenario also

assumes a drastic increase of 278% in the wood industry, because of the highly increased use of wood in construction.

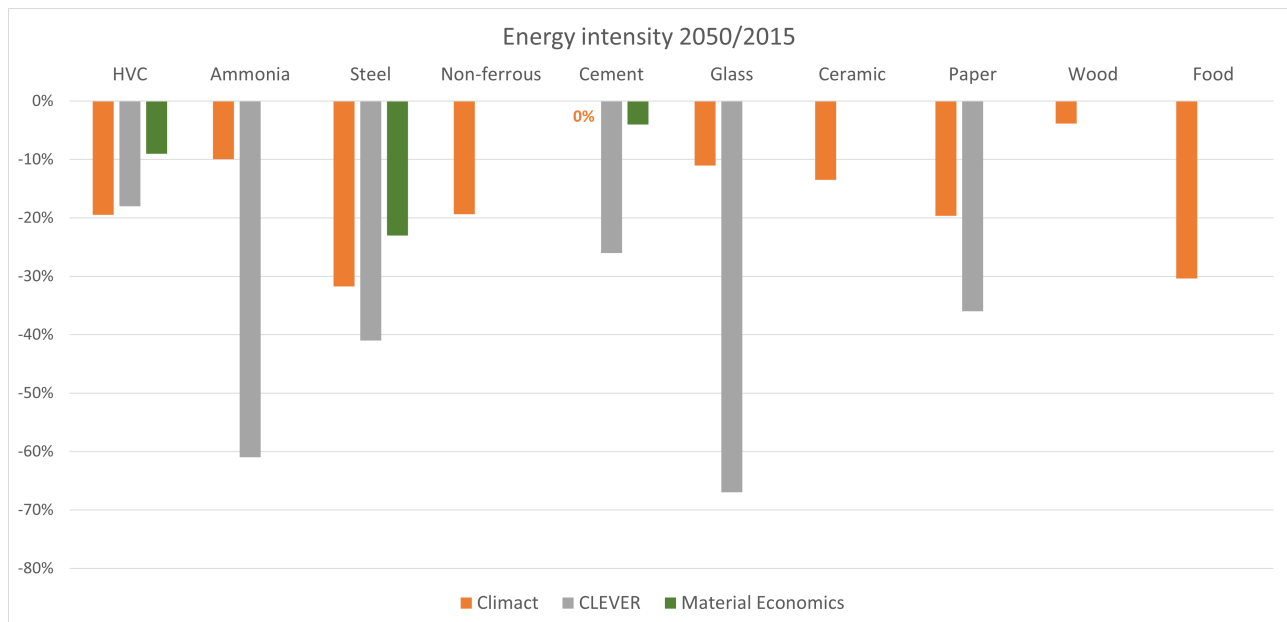


Figure 4.2: Reductions in energy intensity for different industrial sectors between 2015 and 2050

Figure 4.2 shows the improvements in energy efficiency, expressed as the decrease of the energy intensity for each industrial sector, for the Climact BEH, CLEVER and Material Economics scenarios. The assumptions in the LD scenario are mainly based on the Climact scenario, so they are not shown in the graph. We can observe that regarding efficiency, the CLEVER scenario is generally the most ambitious scenario, with very high reductions in energy intensity for ammonia production and glass production.

4.1.2 Industrial final energy consumption

We then analyse the final energy consumption (FEC) of the industrial sector in the original scenarios. Only for the original and the adjusted Low Demand (LD) scenarios, the FEC was obtained with EnergyScope, as it is the model originally used to build the corresponding energy systems for these scenarios. For all other scenarios, the FEC was directly provided in the reports.

Figure 4.3 shows the 2050 energy mix of the **FEC excluding feedstock** of the industry for the five scenarios. The FEC mix for the year 2015 is shown for reference. Both the original LD and the adjusted LD scenarios are shown. The mix for the BBL scenario is also added, but it must be noted that this one does only concern Flanders and not Belgium, so total FEC cannot be compared.

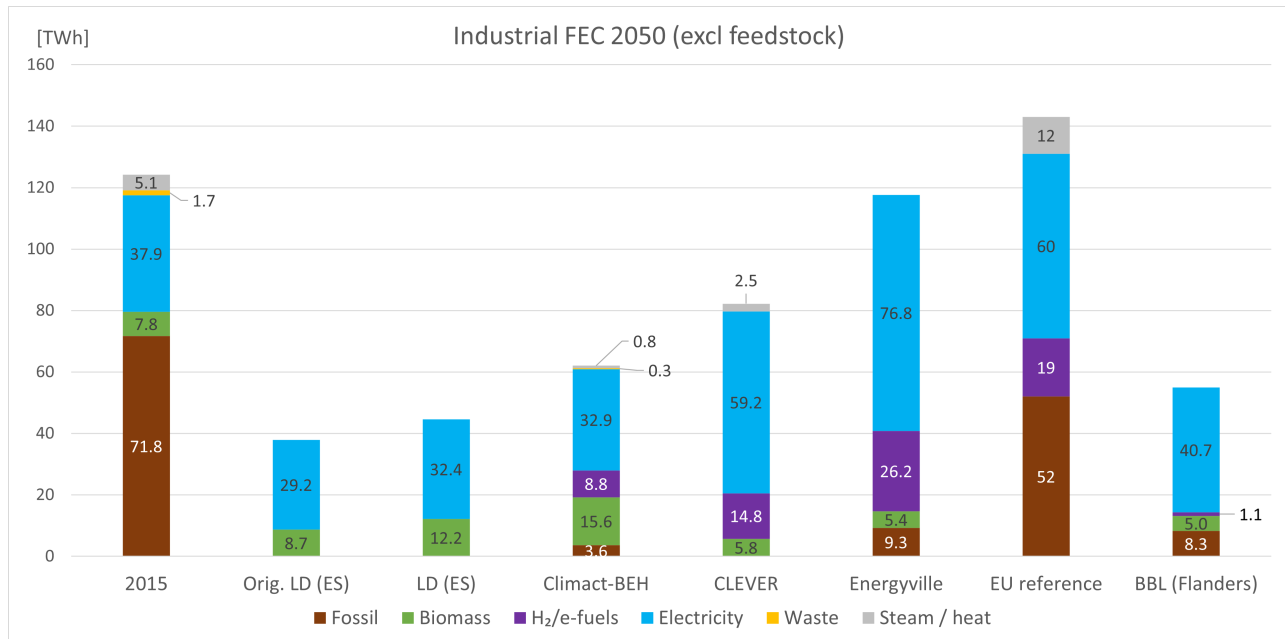


Figure 4.3: Industrial final energy consumption in 2050 excluding feedstock. From original scenarios.

The total FEC (excluding feedstock) decreases compared to 2015 in all scenarios, except for the EU reference scenario, where economic growth and increasing production volumes, combined with limited energy efficiency improvements, lead to an increase of energy consumption of 15%. With constant production volumes, the EnergyVille scenario only achieves a 5% reduction of FEC. The CLEVER and Climact Behaviour scenarios, which consider significant sufficiency measures and decreases in production volumes, achieve a 34% and a 50% reduction respectively. Finally, the adjusted Low Demand scenario, which is the most ambitious regarding sufficiency measures, achieves a reduction of 64%.

In 2015, the industrial FEC mix was still dominated by fossil fuels (58%). The share of electricity was 31%, and the remaining 11% were provided by biomass, distributed heat and waste. Only the Low Demand scenario and the CLEVER scenario are completely fossil-free by 2050. In the Climact BEH scenario, fossil fuels provide 5% of the energy, in the BBL scenario 15%, in the EnergyVille scenario 8%, and in the EU reference scenario 36%. While the EU reference scenario doesn't reach carbon neutrality, the Climact BEH, EnergyVille and BBL scenarios rely on carbon capture and compensation in other sectors in order to reach net carbon neutrality.

Electrification is observed in all scenarios. In the EU reference scenario, it is limited, going from 36% in 2015 to 42% in 2050. Electrification is however much more important in all other scenarios providing from 53% of the FEC for the Climact BEH scenario, to 65%, 72%, 73% and 74% in the EnergyVille, CLEVER, Low Demand and BBL scenarios respectively.

The remaining consumption, which is often not electrified because specific industrial processes are considered harder to electrify, is provided by bio-fuels and e-fuels. EnergyScope does not take these specific processes into account, so the reason why biomass is used in the LD scenario is different, as will be seen later.

Finally, the amounts of distributed heat and non-renewable waste are limited in all scenarios.

The primary **non-energy** or feedstock consumption, used in the chemical industry, mainly for the production of HVC, is shown at figure 4.4 for the different scenarios. As no specific assumptions regarding feedstock were made for Belgium in the CLEVER scenario, it is not represented in this graph. Secondary feedstock (plastics used for mechanical or chemical recycling) is not shown in the graph, as it does not correspond to our definition of non-energy demand : it is not a fuel that could have directly been used for other energy purposes. It represents significant shares of the total feedstock consumption for the adjusted Low Demand and BBL scenarios, respectively 62% and 35%.

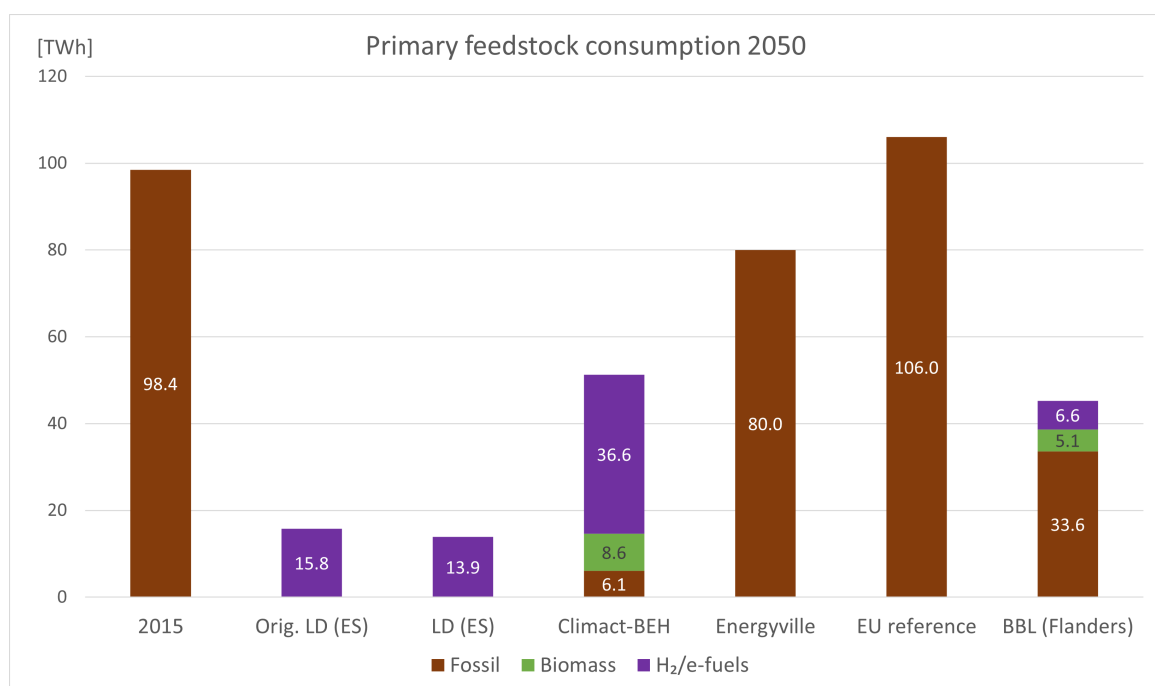


Figure 4.4: 2050 primary feedstock consumption (excluding secondary/recycled feedstock)

The total primary feedstock consumption decreases from the 2015 consumption in all scenarios, except in the EU reference scenario, due to increasing production volumes. Despite constant production volumes, efficiency improvements allow for a decrease in the EnergyVille central scenario. The decrease is more significant in the Climact BEH scenario thanks to sufficiency measures. In the adjusted LD scenario, the decrease in primary feedstock is drastic, thanks to even more sufficiency measures, and the large share of recycling.

In 2015 (and still today), the feedstock consumption was based only on fossil fuels. This is still the case in 2050 in the EU reference scenario and in the EnergyVille scenario. In the BBL scenario, fossil fuels still represent 74% of the primary feedstock consumption. In the BEH scenario, it only represents 12% of the feedstock consumption. The remaining feedstock is delivered by bio-fuels and e-fuels in these two scenarios. No fossil fuels are used in the LD scenario, as no emissions are allowed, and EnergyScope accounts for emissions embedded in products from the moment they are produced (see section 2.2.1). The primary feedstock is then entirely provided by imported e-fuels.

4.1.3 Global final energy consumption by sector

We then take a step back to see where this industrial energy consumption fits in the total energy consumption of the residential, tertiary, transportation and industry sectors. Figure 4.5b shows the FEC by sector, and their share in the total FEC for each scenario. The "buildings" category includes both households and services.

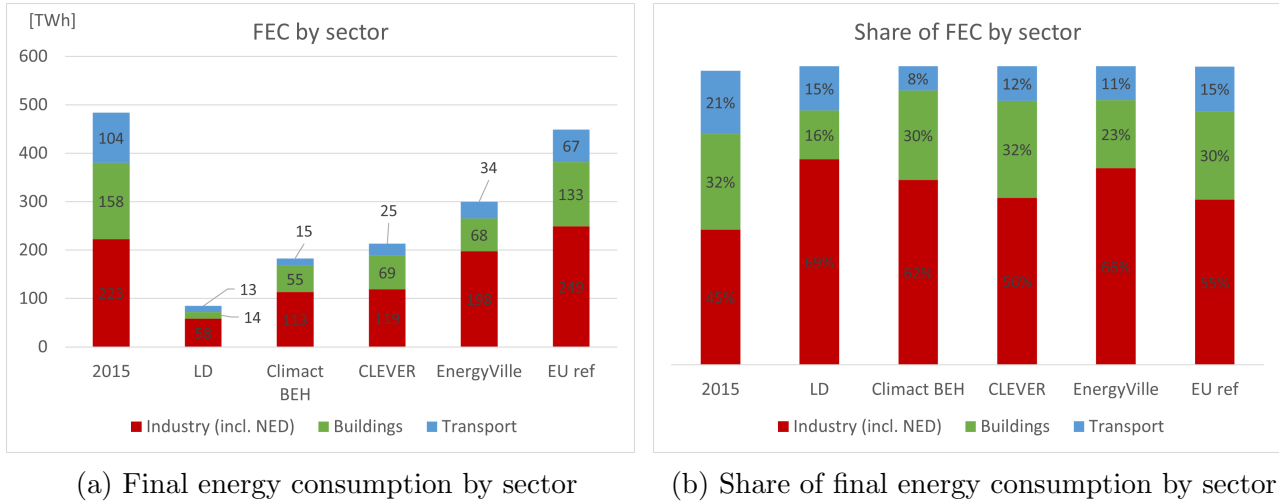


Figure 4.5: Comparison of FEC by sector for the various scenarios

All scenarios project an increase of the share of industry in the FEC, because of a drastic decrease in buildings consumption thanks to insulation, and in transportation thanks to the switch to electric vehicles and public mobility. Efficiency improvements in the industrial sector are less marked. The increase of industrial share is the most important in the LD scenario, because there are also very drastic decreases in demand (sufficiency) in the buildings and transportation sectors. The sufficiency assumptions for the industrial sector do not reduce its consumption as much as in the other sectors.

4.1.4 End-use demand

In this section, the EUD for all the sectors (residential, tertiary, industrial and transportation), are compared for the five main scenarios of this thesis. The calculation of the EUD of the Low Demand Scenario, which was updated to correspond to territorial consumption, is detailed in appendix A. For the Climact BEH, CLEVER and EnergyVille scenarios, the methodology explained in section 3.2.1 was used to obtain the EUD from the available data. The EUD of the EU reference scenario was determined in Hugo Baudson's master thesis [7].

Figure 4.6 shows the EUD of the five scenarios for the sectors where it can be expressed as energy (TWh), i.e. the residential (households), tertiary (services) and industrial sectors. The NED is shown separately from the rest of the industrial EUD. Globally, the increasing trend from the LD scenario to the EU reference scenario is observed, but there are some irregularities.

In the **residential** sector, the EnergyVille projects a slightly higher EUD than the reference scenario, but the trend is otherwise coherent with the global trend. The EUD in the LD sce-

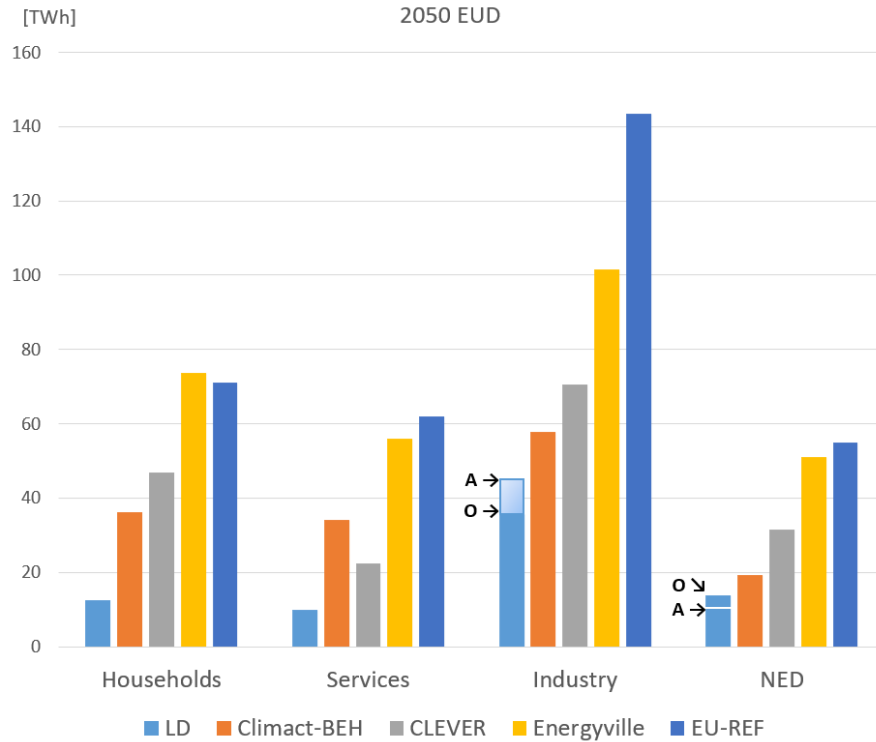


Figure 4.6: 2050 EUD of the different scenarios in households, services and industry, and NED (O = original LD scenario, A = adjusted LD scenario)

nario is about 82% lower than in the EU reference scenario. In the Climact BEH scenario and the CLEVER scenario, the EUD is respectively 49% and 34% lower.

In the **tertiary** sector, the global trend is maintained, except that the CLEVER scenario has a significantly lower demand than the Climact BEH scenario. The EUD in the LD scenario is 84% lower than in the EU reference scenario. In the Climact BEH, CLEVER, and EnergyVille scenarios, the EUD is respectively 45%, 64% and 9% lower.

In the **industrial** sector (excluding NED), the global trend is maintained. The territorial calculation of the industrial consumption in the adjusted LD scenario leads to a 25% increase of its EUD compared to the original scenario. The EUD in the adjusted LD scenario is 69% lower than in the EU reference scenario. In the Climact BEH, CLEVER and EnergyVille scenarios, the EUD is respectively 60%, 51% and 29% lower.

Finally, the **NED** demand also follows the global trend. Here, the adjusted LD scenario has a lower demand than the original one. In the adjusted LD scenario, ambitious reductions are possible thanks to recycling. The EUD in the adjusted LD scenario is 78% lower than in the EU reference scenario. In the Climact BEH, CLEVER and EnergyVille scenarios, the EUD is respectively 65%, 43% and 7% lower.

Figure 4.7 shows the EUD for the transportation, which is not expressed in TWh, but in passenger-kilometer for the passenger transportation, and in tonne-kilometer for freight.

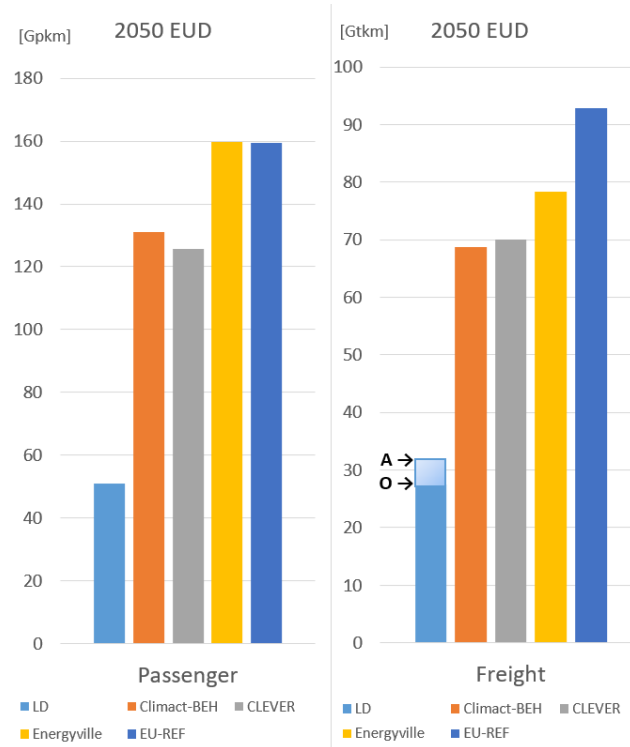


Figure 4.7: 2050 EUD for passenger transportation and freight (O = original LD scenario, A = adjusted LD scenario)

For **passenger transportation**, the demand is about the same in the Climact BEH and the CLEVER scenarios (10700 km/cap/y). The demand in the EnergyVille and EU reference scenario are also similar to each other (13300 km/cap/y). The LD scenario (4300 km/cap/y) has a demand 68% lower than the EU reference scenario. The Climact BEH and CLEVER scenarios have a demand about 20% lower. The scenarios also consider very different shares of this mobility met by public mobility : 80% in the LD scenario, 60% in the Climact BEH scenario, 50% in the CLEVER scenario, and only 21% in the EnergyVille scenario.

The demand for **freight mobility** is about 25% higher in the adjusted LD scenario than in the original scenario. In the adjusted LD scenario, the freight mobility is about 63% lower than in the EU reference scenario. Here again, the mobility is similar in the Climact BEH and CLEVER scenarios, about 26% lower than the EU reference scenario. In the EnergyVille scenario, the freight mobility is 15% lower than in the EU reference scenario.

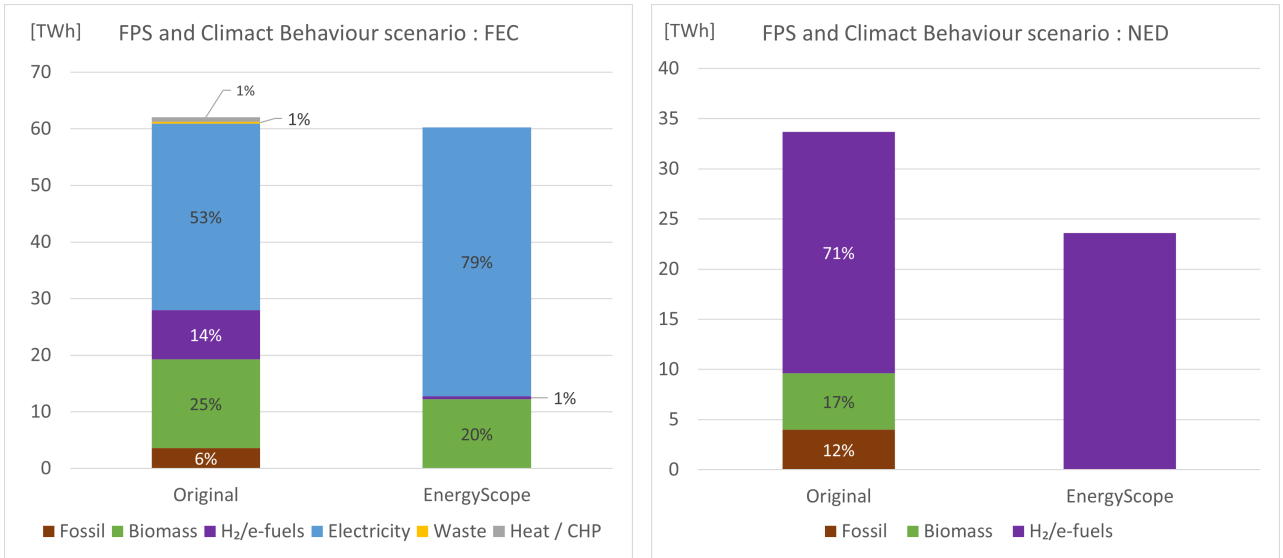
4.2 Comparison of the industrial sector in the existing scenarios with EnergyScope simulations

The results in this and following sections are based on the simulation of the scenarios with EnergyScope TD, using the methodology described in section 3.2.

In this section, the original scenarios are compared to their EnergyScope (ES) simulation. No comparison is made for the LD scenario, as its EnergyScope simulation is the original scenario.

For each scenario, the FEC (excluding feedstock consumption) of the industrial sector, and its energy mix, are compared. The feedstock consumption is compared separately. In this section, only the feedstock consumption related to the production of HVC, ammonia and methanol is considered, as these are the only products considered in EnergyScope for non-energy consumption. Other non-energy consumptions are subtracted in the original scenarios in order to make coherent comparisons.

4.2.1 FPS and Climact Behaviour scenario



(a) Final energy consumption excluding feedstock (b) Feedstock consumption for HVC, ammonia and methanol production

Figure 4.8: Comparison of FEC and feedstock consumption in the original FPS and Climact Behaviour scenario, and in the EnergyScope simulation

Figure 4.8 shows that in the original FPS-Climact BEH scenario, the industrial FEC mix is moderately electrified, with relatively large shares of biomass and e-fuels, and still some fossil fuels for specific processes. The mix is significantly more electrified in the EnergyScope simulation, with a share of biomass that is also relatively large, but no use of fossil fuels and almost no e-fuels. The total FEC is also slightly lower, thanks to the use of heat pumps. The original scenario provides feedstock mainly with e-fuels, but also with some bio-fuels and fossil fuels. EnergyScope uses only imported e-fuels. The total demand is lower in the

ES simulation, because of the importation of methanol and the MTO process which is very efficient, compared to other technologies used in the original scenario.

In the original scenario, limited amounts of fossil fuels can be used both for FEC and NED, while reaching net carbon neutrality, because of the use of CCS, BECCS, and because emissions embedded in plastics are not accounted for.

4.2.2 CLEVER Belgian scenario

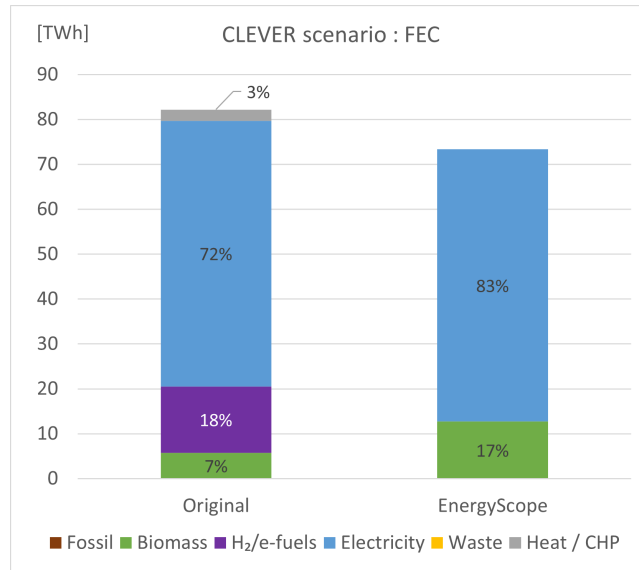


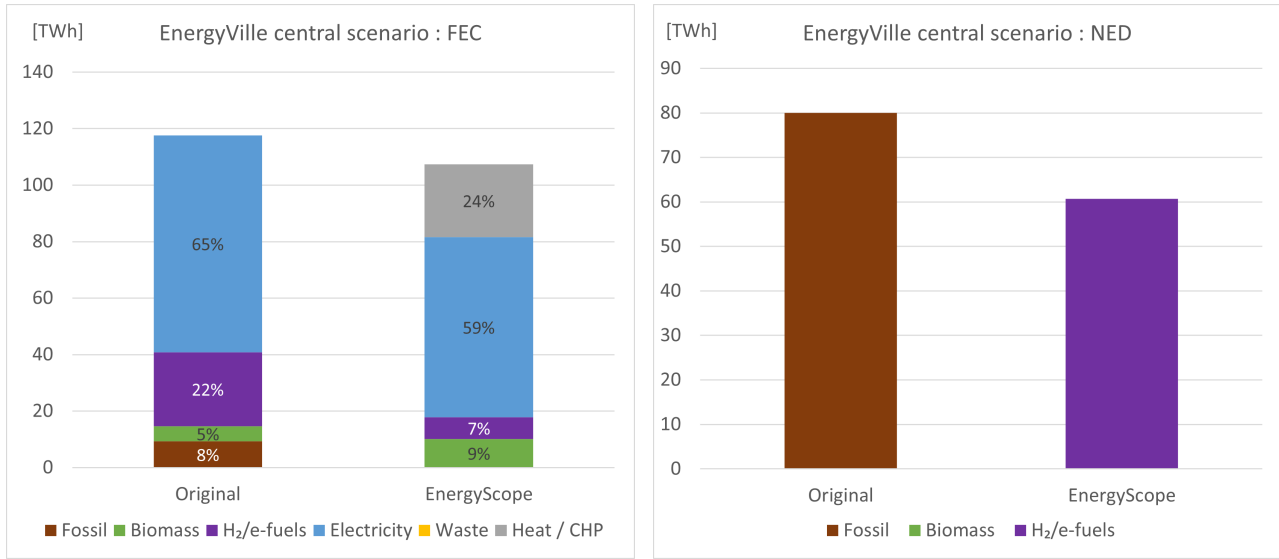
Figure 4.9: Comparison of FEC in the original Belgian CLEVER scenario, and in the EnergyScope simulation

As shown in figure 4.9, the FEC mix in the CLEVER scenario is quite ambitious regarding electrification (72%). The EnergyScope simulation is even more ambitious, with 83% of energy provided by electricity. The original scenario also relies on a significant amount of e-fuels, and a smaller share of bio-fuels. The only other resource considered in the EnergyScope simulation is wood. The total FEC is significantly lower in the EnergyScope simulation (-11%), thanks to the use of heat pumps and lower consumptions in the chemical sector, where imported e-fuels are used.

The NED is not compared, as no specific data regarding NED was assumed for the Belgian CLEVER scenario.

4.2.3 EnergyVille scenario

Figure 4.10 shows the comparison of the original and EnergyScope simulated EnergyVille scenario. The original scenario assumes significant electrification. Electrification in the EnergyVille scenario is lower, as the local renewable resources have reached their full capacity, electricity is needed in other sectors, and CHP plants powered by imported SNG are used to produce electricity and provide high temperature heat to the industry. The original scenario relies heavily on e-fuels (22%) and more moderately on biomass. Taking into account the energy for CHP, powered by e-fuels, the ES simulation also relies heavily on e-fuels. The original scenarios also keeps 8% of fossil fuels, mostly covered by CCS. As in the previous scenarios, the



(a) Final energy consumption excluding feedstock (b) Feedstock consumption for HVC, ammonia and methanol production

Figure 4.10: Comparison of FEC and feedstock consumption in the original EnergyVille central scenario, and in the EnergyScope simulation

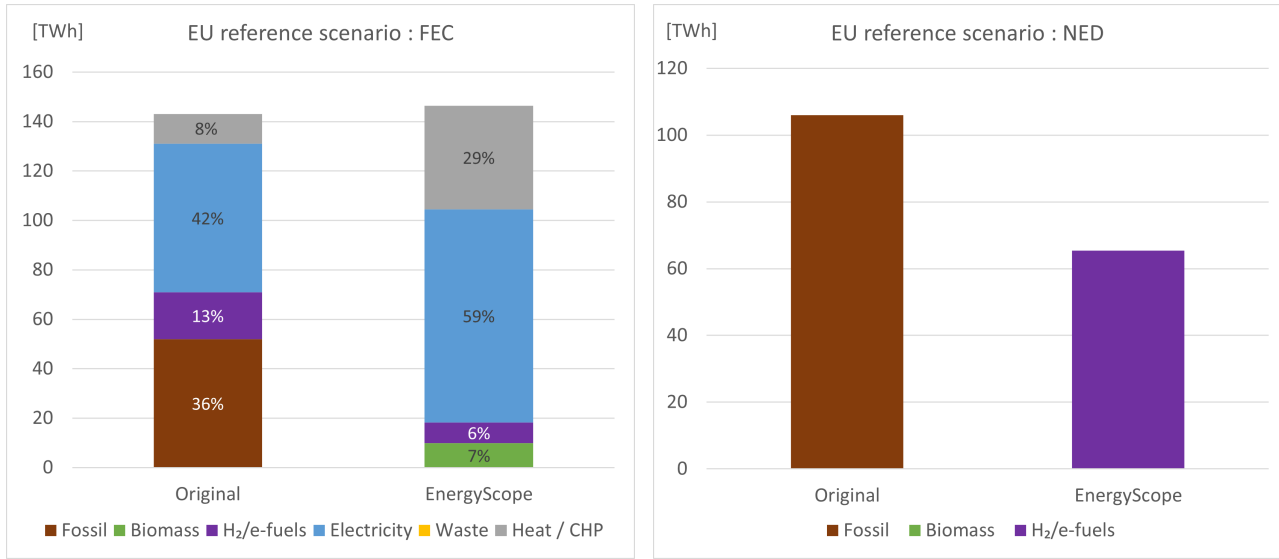
total FEC is lower in the EnergyScope simulation, thanks to the greater use of heat pumps, and a lower consumption in the chemical sector for HVC and ammonia production.

Regarding NED, the EnergyVille scenario still relies for 100% on fossil fuels, while the ES simulation relies only on imported e-fuels. As in the Climact BEH scenario, this is explained by the difference of carbon accounting mechanisms. The total demand is lower in the ES simulation, because of the import of e-fuels and the efficient MTO process.

4.2.4 EU reference scenario

As shown on figure 4.11, electrification is limited in the EU reference scenario. It is more important in the ES simulation. The use of heat is also more important in the ES simulation, where CHP plants are used. A large share of fossil fuels (36%) is still used in the original scenario, it is far from reaching carbon neutrality. The ES simulation, on the other hand, reaches carbon neutrality, using only renewable resources. Unlike the other scenarios, the total FEC of the ES simulation is higher than the original scenario. This may seem particularly astonishing, as the EU reference scenario is the least ambitious one, with lower efficiencies, less use of heat pumps, ... It can be explained by the methodology used to obtain the EUD used for the ES simulation, which is not the same as for the previous scenarios. Indeed, the EUD matrix used is the original one, using a simpler methodology, also used by Hugo Baudson. The main imprecision, compared to the methodology developed in this work, is the double counting of the chemical sector, which explains the higher than expected FEC.

Regarding NED, once again, the ES simulation uses only imported e-fuels and a more efficient process (MTO), leading to a lower total demand.



(a) Final energy consumption excluding feedstock (b) Feedstock consumption for HVC, ammonia and methanol production

Figure 4.11: Comparison of FEC and feedstock consumption in the original EU reference scenario, and in the EnergyScope simulation

4.3 Comparison of EnergyScope simulations for the global energy system

In this section, only the results from the EnergyScope simulations are analysed, leaving the original scenarios aside.

In his master's thesis [7], Hugo Baudson already analysed his original Low Demand scenario, and the EU reference scenario (called "High Demand"). He then used these two scenarios as a lower bound and upper bound, and simulated intermediate scenarios, varying the EUD linearly between the two scenarios. In this work, the scenario with the lowest global demand is the adjusted LD scenario, with an EUD slightly higher than the original LD scenario. The scenario with the largest global demand is the EU reference, like in Hugo Baudson's thesis. The range of considered EUD is thus similar in both cases, and the main trends in the modification of the energy system with the EUD are the same. One of the main interests of this work, is that real scenarios, with concrete assumptions, are behind the intermediate EUD values, instead of a linear construction between a lower and an upper bound.

For a better understanding of this section, it may be useful to consult the sankey diagrams of the different simulated scenarios, available in appendix C.

We will briefly analyse the changes in the global energy system with the increasing EUD in the different scenarios. For a more complete analysis, see [7]. This work focuses on a more in-depth analysis of the industrial sector, which is addressed in the next section.

Figure 4.12 shows the primary energy consumed in the different scenarios. The main observa-

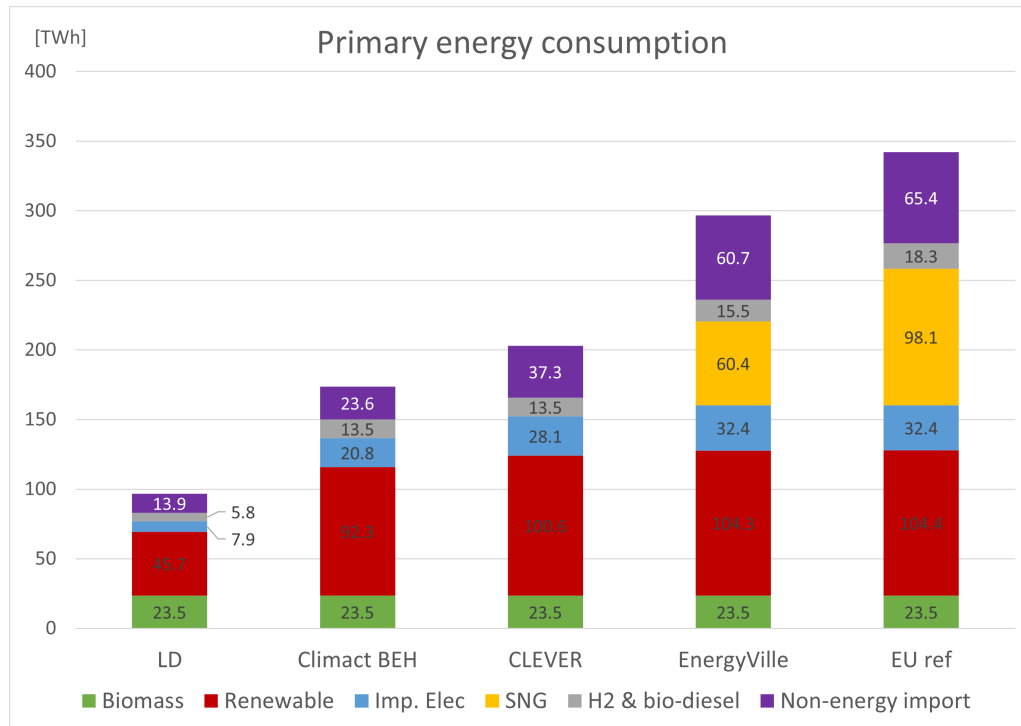


Figure 4.12: Total primary energy consumption in the EnergyScope simulations.
 "Renewable" includes electricity generation from PV, wind and hydro.

tions regarding the evolution between the LD and EU reference scenarios are in line with Hugo Baudson's observations :

- The local biomass resources (wood and wet biomass) are used at their full availability in all scenarios. Wood is used in industrial boilers, while wet biomass is used to produce bio-gas, used in industrial boilers, public mobility and freight.
- In all scenarios, the ammonia NED is imported, and HVC are produced using the MTO process with imported green methanol.
- The endogenous electricity production ("Renewable" on the graph, mainly from wind and solar PV) increases up to the CLEVER scenario, after which the maximum capacities are reached, and there is almost no more increase.
- The import of electricity increases with the production of endogenous electricity, up to the CLEVER scenario, where the assumed maximal availability (32.4 TWh) is almost reached.
- In the EnergyVille and EU reference scenario, the endogenous electricity production and electricity import are at their maximum and don't suffice to meet the demand. SNG is then imported for use in CHP plants, to meet both the industrial high temperature heat and the electricity demand.
- In the freight sector, in all scenarios, imported hydrogen is used for the trucks, and electricity for the trains. In the LD scenario, bio-gas (from biomethanation) is used for

the boats. As its demand in other sector increases in the other scenarios, it is replaced by imported bio-diesel.

- The entire low temperature heat demand is met by heat pumps in all scenarios.

[GW]	LD	Climact BEH	CLEVER	EnergyVille	EU ref	Max
PV	20.8	49.3	57.1	59.2	59.2	59.2
Wind onshore	10	10	10	10	10	10
Wind offshore	0.9	6	6	6	6	6
CHP gas	0	0	0	3.9	6.1	∞
Heat pumps	4.3	11.7	12.1	23.6	26.2	∞
MTO	0.94	0	2.66	4.54	4.89	∞

Table 4.1: Installed energy conversion capacities for some of the main technologies

Table 4.1 summarises some of the main installed capacities for endogenous electricity generation (PV and wind), CHP plants powered by gas, heat pumps, and MTO technologies. The capacities for CHP correspond to their thermal capacities.

In all scenarios, onshore wind reaches its full potential. In all but the LD scenario, this is also the case for offshore wind. PV (almost) reaches its full potential for the CLEVER scenario. This confirms that maximum endogenous electricity generation capacity is reached at this point.

The CHP and heat pump capacities installed are also coherent with the observations made above.

No flexibility is assumed regarding the production of HVC, which is thus constant throughout the year. The MTO capacity is thus directly proportional to the HVC demand.

The capacities installed for high temperature heat supply are discussed in greater detail in the next section.

[GWh]	LD	Climact BEH	CLEVER	EnergyVille	EU ref
Batteries	0	0	0	12.3	7.0
Gas storage	427	1686	1134	14961	23635
LT heat daily	8.8	22.4	24.8	54.0	59.5
LT heat seasonal	135	472	470	857	941
HT heat daily	18.4	44.7	55.3	74.6	69.0

Table 4.2: Installed storage capacities

Table 4.2 summarises the storage capacities installed in the different scenarios.

Electric batteries are only used in the EnergyVille and EU reference scenarios, except for the vehicle-to-grid system which is used in all scenarios, allowing electric vehicles to help regulate the energy system.

The need for gas storage increases drastically in the EnergyVille and EU reference scenario,

because of its use in dispatchable CHP plants.

Low temperature heat storage, both daily and seasonal, as well as daily high temperature heat storage, globally increase with higher demand scenarios.

Curtailment	LD	Climact BEH	CLEVER	EnergyVille	EU ref
Absolute [TWh]	4.4	9.8	10.9	1.7	1.2
Relative	8.1%	8.6%	8.4%	1.0%	0.7%

Table 4.3: Curtailment over a year by scenario. Relative = (Curtailment) / (Total electricity generation over a year)

Curtailment occurs when the electricity demand is low and the electricity generation from renewable resources (wind, PV) is high. There is too much power on the grid, and there is no other choice than to reduce the production. Storage technologies, as well as flexibility in the HT heat generation, as will be seen later, allow to reduce curtailment, but there is still some curtailment in all scenarios, occurring when storage technologies are already at full capacity. Free energy from the wind or the sun is then wasted. Table 4.3 shows the amount of energy that is lost in this way every year in all scenarios, as well the share of the total electricity generation over a year that it represents. The relative amount of curtailment is stable for the first three scenarios, and then decreases drastically in the EnergyVille and EU reference scenarios, thanks to the use of dispatchable CHP plants, which help regulate the energy system.

4.4 Industrial sector in EnergyScope simulations

In this section, the industrial sector, simulated with EnergyScope for each scenario, is analysed in greater detail.

4.4.1 Final Energy Consumption

The FEC of the industrial sector, excluding feedstock, is shown in figure 4.13. The share of specific electricity end-use demand and LT heating EUD was assumed to be the same in all scenarios. The LT heating demand is entirely met by electric heat pumps in all scenarios. For those two end-use types, the energy mix is thus 100% electrical in all scenarios. The high temperature heat demand is then the only one responsible for variation in the industrial energy mix from one scenario to the other.

All available wood is used in industrial wood boilers in all scenarios. Gas boilers, using bio-gas from biomethanation or imported SNG, are also used in all scenarios. In the EnergyVille and EU reference scenario, gas powered CHP plants, considered to be part of the energy sector, provide heat directly to the industrial sector. In the next section, the high heat supply is discussed in greater detail.

The consumption of primary feedstock for the production of HVC, ammonia and methanol is shown in figure 4.14. In all scenarios, imported methanol is used directly or used to produce

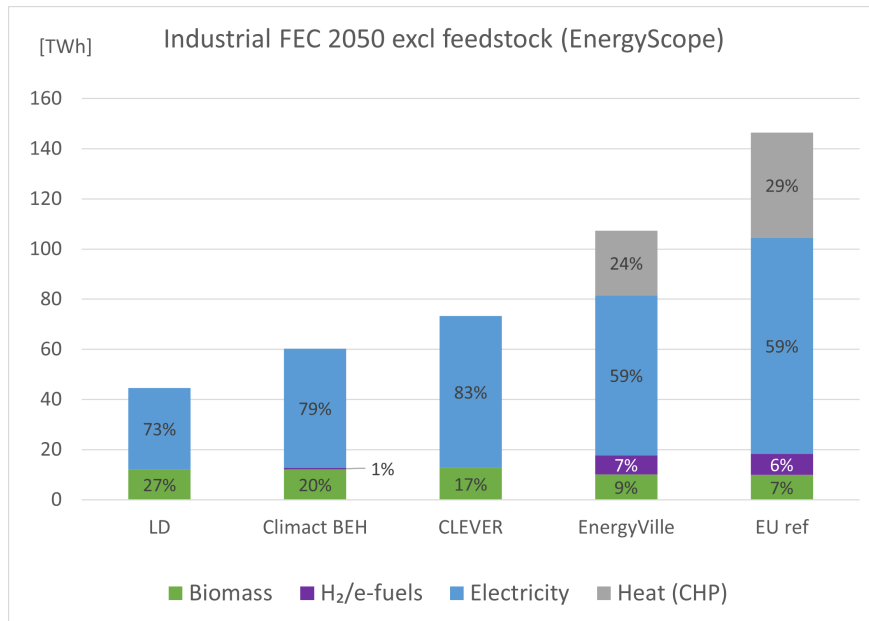


Figure 4.13: Industrial final energy consumption in 2050 excluding feedstock in EnergyScope simulations

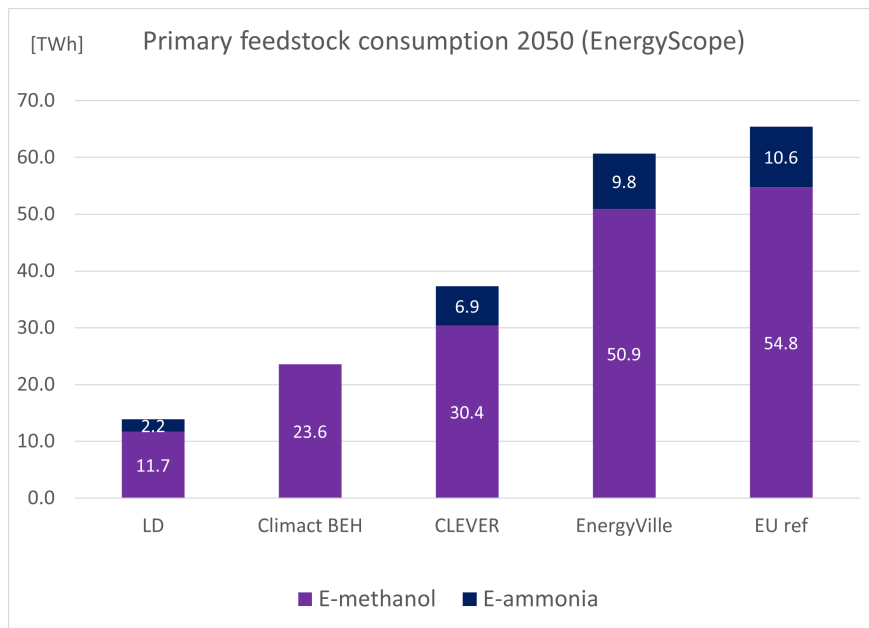


Figure 4.14: Primary feedstock consumption in 2050 (excluding secondary / recycled feedstock) in EnergyScope simulations

HVC through the MTO process. Ammonia is also directly imported, except for the Climact BEH scenario, where the demand for ammonia is assumed to be completely phased out by 2050. The other option would be to import green hydrogen and use it to produce ammonia locally. This is assumed in most original scenarios. But ammonia is much easier to transport over long distances than hydrogen, and is thus cheaper to import, making it the obvious choice for EnergyScope.

4.4.2 A focus on high temperature heat

Energy mix and installed capacities

The high temperature heat is used to provide the high temperature EUD input of the model, as well as the heat needed for the MTO process to produce HVC. In some cases, a limited amount is also used for electrolyzers to produce green hydrogen. The HVC EUD and the HT heat EUD are considered to be constant in EnergyScope, and no flexibility is considered for the demand. The total HT heat demand is thus also constant all year round.

Figure 4.15 shows the energy mix over one year for the high temperature heat supply. It should be noted that this mix is however not constant hour by hour, day by day throughout the year. EnergyScope allows for flexibility in the heat supply. The most suited technologies, depending on weather conditions and demand, can be chosen for every hour of every day.

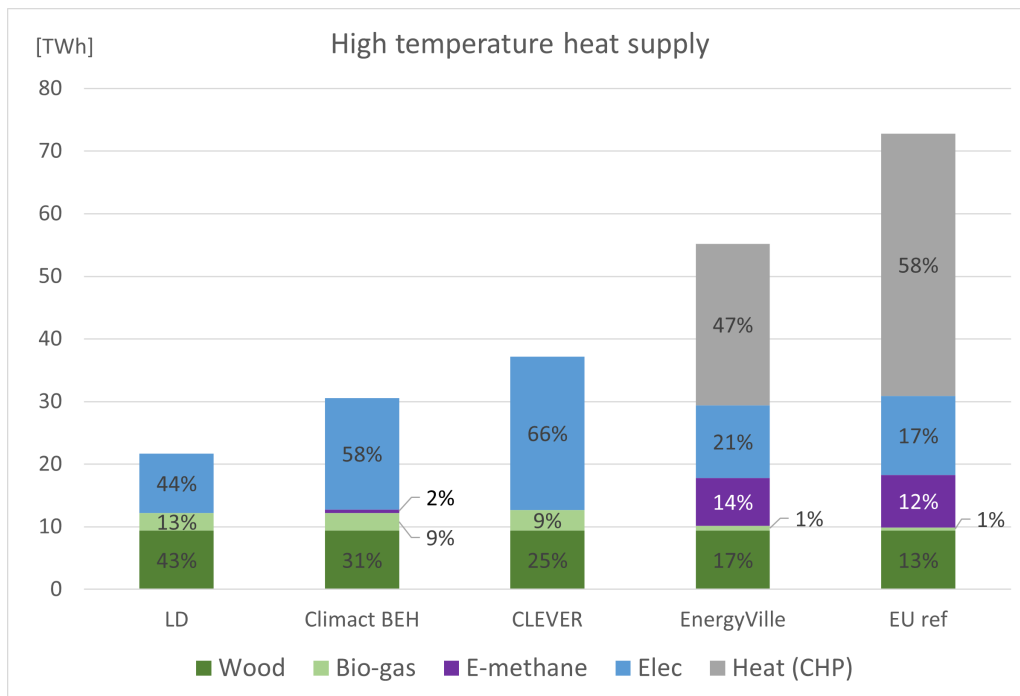


Figure 4.15: Energy mix over one year for the high temperature heat supply of the different scenarios in EnergyScope simulations

All available wood is used in all scenarios. Gas boilers are also used in all scenarios. In the LD, Climact BEH and CLEVER scenarios, they are fueled almost exclusively by bio-gas, obtained through biomethanation of wet biomass.

In the EnergyVille and EU reference scenario, gas powered CHP plants are installed, both to provide high temperature heat, and to supply the increasing global electricity demand. Extra SNG thus needs to be imported, which is used both in the CHP plants and the gas boilers (as well as buses for public mobility). This explains why the direct use (in boilers) of bio-gas decreases in these two scenarios, and is replaced by imported SNG (e-methane). The difference in bio-gas (as well as more imported SNG) is in fact embedded in the heat from CHP. As we chose to consider CHP to be part of the energy sector, this is however not shown in the graph.

Finally, direct electricity is used in all scenarios (as we will see later, only at certain moments under certain conditions). Its use decreases in the EnergyVille and EU reference scenarios, as available electricity is used in priority to meet the electricity demand, and it is partially replaced by CHP for the HT heat demand.

Figure 4.16 shows the installed capacities of technologies that can provide high temperature heat, i.e. wood boilers, gas boilers, direct electricity and CHP. The total constant demand is also shown.

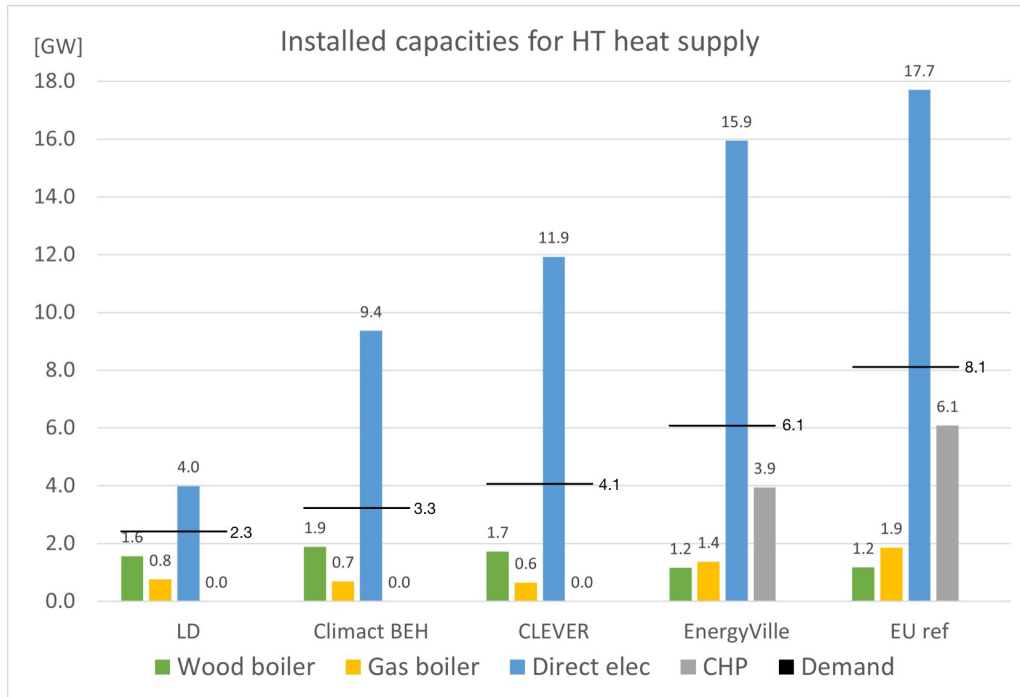


Figure 4.16: Installed capacities of various technologies for the supply of high temperature heat in EnergyScope simulations. The black line indicates the constant demand for high temperature heat.

A first observation is that the direct electric capacities are always much higher than the demand. This is explained by the fact that, when important quantities of renewable electricity are available, it does not only provide 100% of the HT heat demand, but it is also used to recharge the HT storage capacities. On the other hand, when no green electricity is available, the HT heat needs to be fully supplied by the other technologies (including HT heat storage, not shown on this graph).

Even though the same amount of wood is used in all scenarios over the year, the installed capacities of wood boilers are higher in the scenarios with lower demand. As no CHP plants can be used to stabilise the energy system, wood boilers are used for that purpose in these scenarios, requiring higher capacities.

The gas boiler capacity increases in higher demand scenarios, simply because more gas is used to provide heat.

Figure 4.17 shows the storage capacities installed for high temperature heat. At the left (4.17a), the absolute capacities are shown. At the right (4.17b), they are expressed as function of the high temperature demand : the number of hours that they could meet the demand on their own, starting at a 100% charge.

We can observe that the relative capacities increase from the LD scenario to the Climact BEH and CLEVER scenarios. While a majority of the HT demand is met by dispatchable wood and gas boilers in the LD scenario, the extra demand in the Climact BEH and CLEVER scenarios are met by direct electricity, which requires more storage capacities.

Then, in the EnergyVille and EU reference scenarios, the capacities decrease again, because of the use of dispatchable CHP, increasing again the share of demand met by dispatchable technologies.

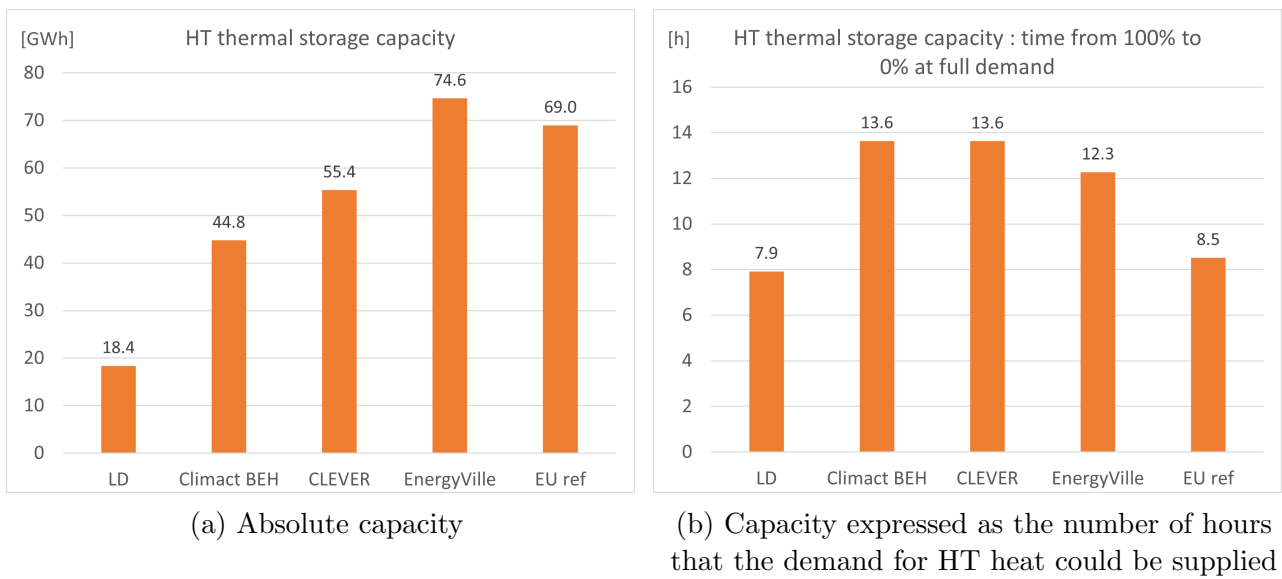


Figure 4.17: High temperature thermal storage capacities in the different scenarios in the EnergyScope simulations

Hourly operation

To better illustrate and fully understand the operation of high temperature heat supply in EnergyScope's simulations, let's take a closer look at some examples of hourly operation during the 24 hours of a day.

As seen in section 2.2.1, EnergyScope simulates weather and demand conditions over a year using a set of typical days (TDs). In this work, 12 TDs were used. To each of the 365 days of the year, one of those TDs is assigned.

In this section, we will only compare the LD scenario and the EnergyVille scenario. From the 12 TDs, we selected 4, which represent very different conditions. They are also some of the most frequent typical days over the year, representing together 60% of the days of the year. The selection of typical days is performed independently for each simulation. This means that the TDs from the LD scenario are not exactly the same than for the EnergyVille scenario. We can however verify that the 4 considered typical days are very similar, justifying the comparison.

Figure 4.18 shows an overview of the characteristics of the 4 selected typical days (1, 4, 6 and 9). The season column shows the seasons in which most of these typical days occur. The demand conditions are characterised by the space heating demand, and the variable electricity demand over the day. Finally, weather conditions are represented by the PV and wind capacity.

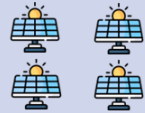
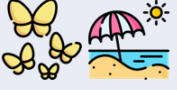
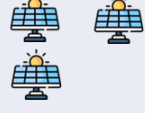
Typical day	Season	Heating demand	Variable electricity demand	PV capacity factor	Wind capacity factor
1					
4					
6					
9					

Figure 4.18: Overview of the characteristics of the 4 selected typical days. Icons from [44].

In the following figures, the hourly operation for HT heat production is compared for the LD scenario and the EnergyVille scenario. It should be noted that the graphs are not at the same scale for the two scenarios, as the total demand is very different.

Figure 4.19 shows the hourly operation of high temperature heat supply for TD 1. It corresponds to a cold autumn or winter day, with high heating demand. Days are short so the PV capacity factor is low, but it is relatively windy, mostly in the evening, leading to a quite high wind capacity factor.

In the LD scenario, most of the demand is met by wood boilers. Gas boilers and stored HT heat are also used for to a lesser extent. During a relatively short period (11AM - 14 PM), more electricity is available thanks to PV panels, and the thermal storage is recharged. The wood and gas boilers remain mostly unaffected. In the evening, as wind power increases, electricity is used to recharge the storage capacities once again.

In the EnergyVille scenario, wood boilers are also used, but as the demand is much higher, it only represents a small share of the supply. CHP provides most of the heat. Gas boilers are also used, while recharging the thermal storage, in order to fill the storage for the next day.

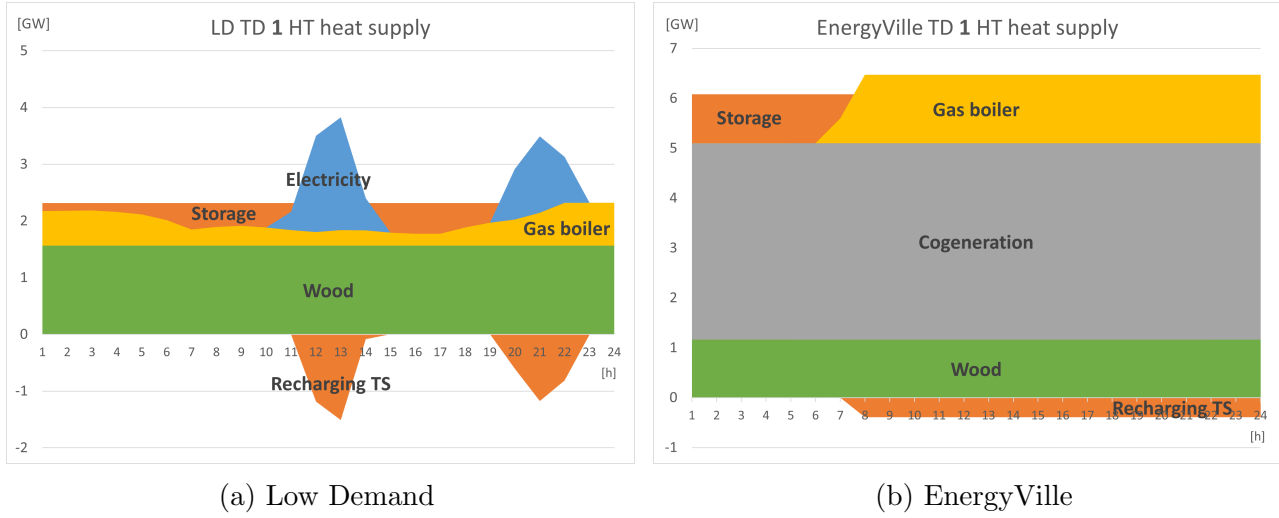


Figure 4.19: Comparison of the HT heat supply over 24 hours : TD 1

In figure 4.20, the hourly operation for another typical winter day, TD 4, is shown. In this case, the heating demand is slightly lower, but it is also less windy, leading to lower renewable electricity production.

In the LD scenario, no electricity is available for the HT heat demand. The demand is then entirely met by wood and bio-gas boilers.

In the EnergyVille, the operation is the same as for TD 1 : mainly CHP, as well as some wood and gas boilers.

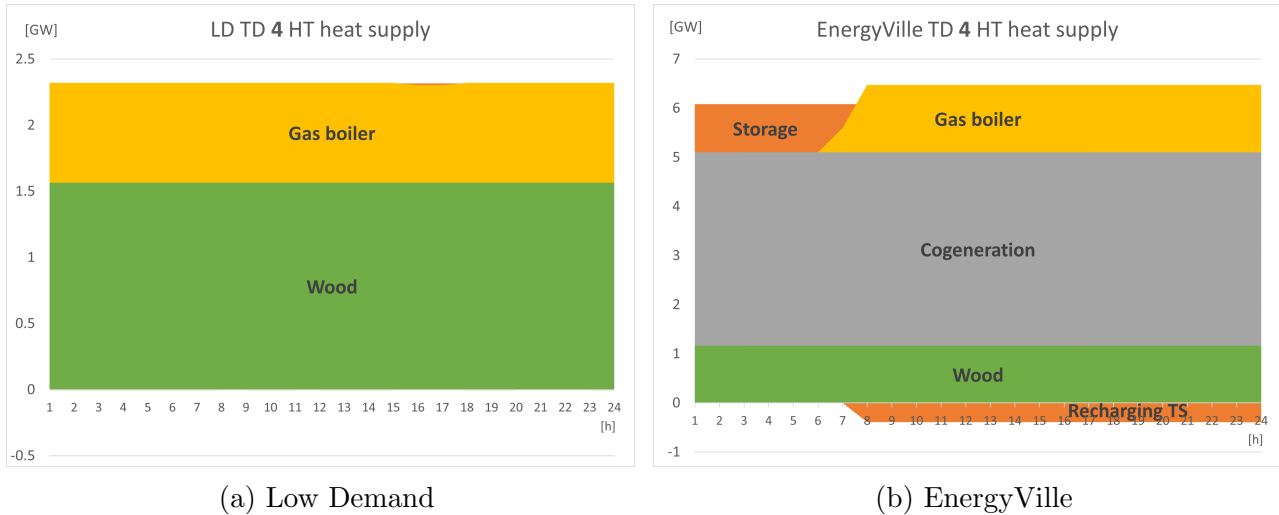


Figure 4.20: Comparison of the HT heat supply over 24 hours : TD 4

TD 6, shown in figure 4.21, is a typical spring or summer day, with relatively low heating and lighting demand, and sunny, windy conditions, leading to both very high PV and wind capacity factors.

In the LD scenario, during the day, electricity can then provide 100% of the HT heat demand, and on top of that, recharge the thermal storage. The full electrical HT heat generation capacity is used. During the night, this thermal storage is then used to provide up to 100% of

demand. For such days, the energy mix for HT heat is thus 100% electrical.

In the EnergyVille scenario, the situation is relatively similar. But as the total demand is higher, electricity is not available for the HT heat supply in the early morning and in the evening, when the sun is low. The period of recharge of the thermal storage is thus shorter, and it provides heat for a longer time. The electric HT heat generation capacity and storage capacity are much larger, but the HT heat consumption is also much larger, and the stored heat doesn't suffice to provide the heat until the next day. Some cogeneration thus needs to be used in the early morning before electricity takes over again.

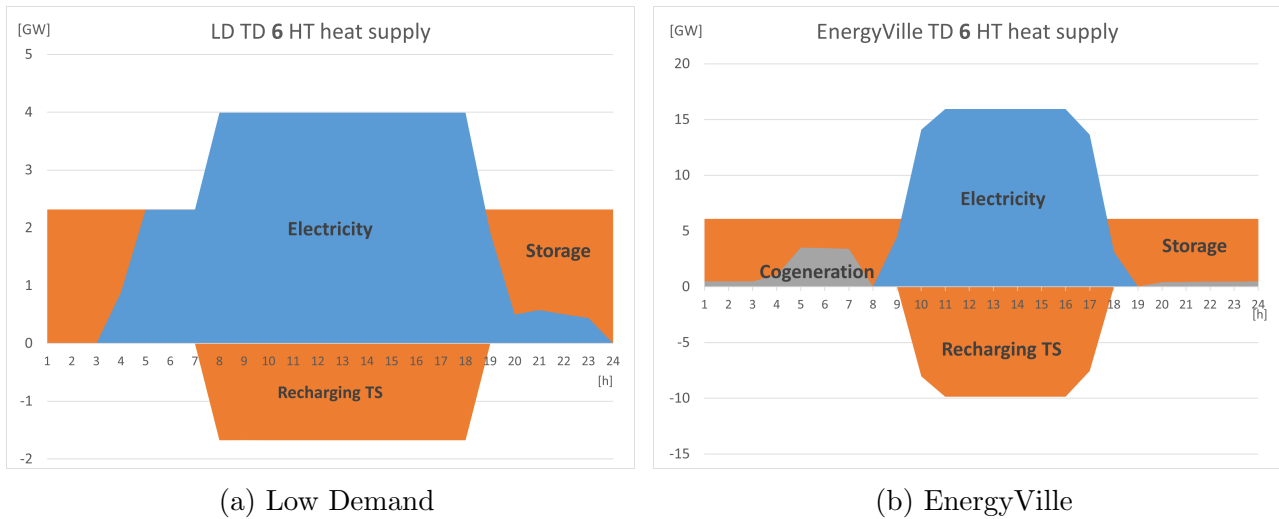


Figure 4.21: Comparison of the HT heat supply over 24 hours : TD 6

In figure 4.22, the hourly operation for another spring or summer day, TD 9, is shown. The heating and lighting demand is slightly lower than for TD 6, but the PV and wind capacity factors are also significantly lower (more cloudy, less windy day).

In the LD scenario, although electricity once again provides all the HT heat during the day and, on top of that, recharges thermal storage, the thermal storage does not suffice to provide the HT heat in the evening, night and early morning. Wood and gas boilers are then used.

In the EnergyVille scenario, wood and gas boilers are operated at almost full capacity during the whole day. Electricity is used during the day, but can only recharge the thermal storage slightly. As the demand is higher, less electricity is available for HT heat production. Storage, on top of the wood and gas boilers, does then not suffice during the night, and a substantial capacity of CHP is required, providing electricity to the global system at the same time.

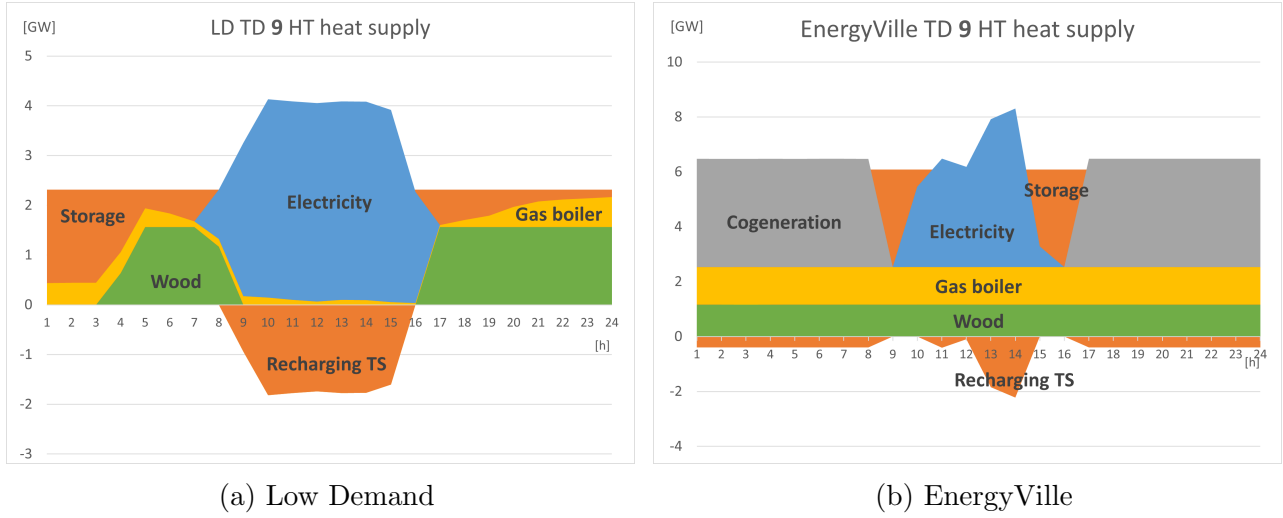


Figure 4.22: Comparison of the HT heat supply over 24 hours : TD 9

These (theoretical) hourly operation strategies would have important implications for the industrial processes. This is discussed in section 5.1.

4.5 Emissions in EnergyScope simulations

All resources used in the different scenarios are considered to be carbon-neutral, except for wood and wet biomass. While their production theoretically compensates the combustion emissions, EnergyScope considers their transportation to be responsible for some emissions. As all scenarios use these resources at their maximal availability, the emissions related to these resources are identical, i.e. **111 kt CO₂e/year for wood**, and **166 kt CO₂e/year for wet biomass**. This is about 0.25% of the 2015 emissions.

EnergyScope allows to calculate the emissions related to the construction of technologies, based on their life cycle assessment. As the topic is very complex, the values obtained should be considered with a critical eye. In all scenarios, PV manufacture is the main emitter, representing between 84% and 91% of the emissions. We thus observe (table 4.4) a significant increase from the LD scenario to the CLEVER scenario, but almost no more increase in the EnergyVille and EU reference scenarios, as the maximum PV potential has been reached.

Unit	LD	Climact BEH	CLEVER	EnergyVille	EU ref
[kt CO ₂ e/y]	1599	4543	5195	5682	5770

Table 4.4: Emissions related to the construction of technologies in the EnergyScope simulations

These obtained emissions could however be criticised in the context of a carbon-neutral society. Indeed, in all scenarios, freight transport is considered to be completely carbon-neutral, so it could be justified to consider the transportation of endogenous biomass to be carbon-neutral as well. The industry is also considered to be carbon-neutral, so one could argue that if the technologies are constructed in Belgium, their construction would also be carbon neutral. This is a very complex subject and we will not go into further detail in this work.

Finally, it is important to remind that only the emissions related to the energy system are considered in EnergyScope. The industrial process emissions (for example for cement production) are not accounted for, and could increase the total emissions significantly.

4.6 Costs in EnergyScope simulations

EnergyScope calculates the total cost of the energy system as the sum of the investment cost of the technologies (distributed over their lifetime), the yearly maintenance of the technologies, and the cost of their operation (i.e. the cost of the resources used). All technologies are included, including in the transportation sector (electric vehicles, trains, ...).

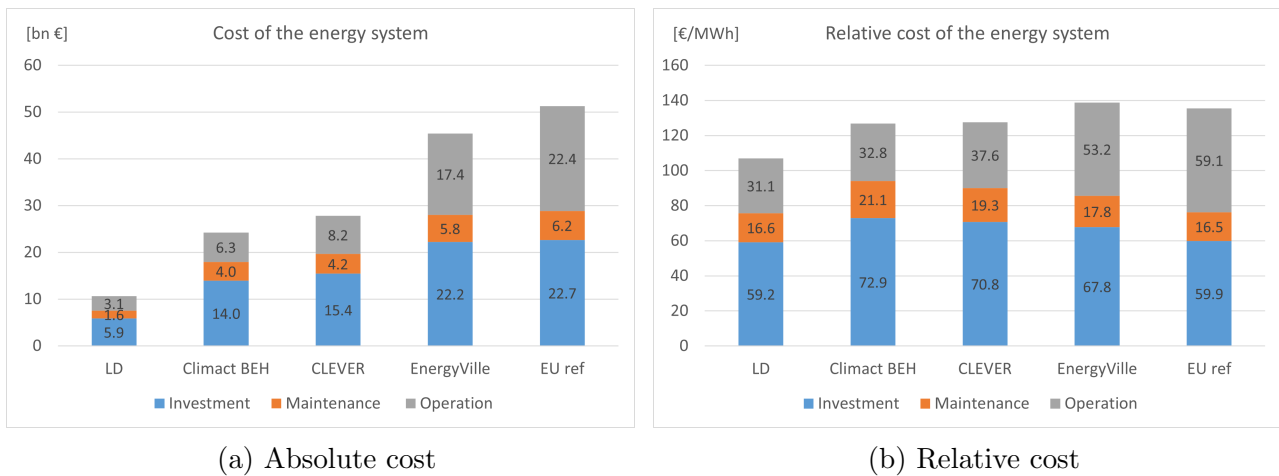


Figure 4.23: Cost of the energy system simulated with EnergyScope for the five scenarios

Figure 4.23a shows the cost of the system for each scenario. As the demand increases, the cost obviously increases. Figure 4.23b is more interesting. It shows the cost of the energy system, relative to the total EUD. In order to include the transportation EUD in a single metric (in TWh), it was expressed as the FEC of the transportation sector in each scenario. Globally, the relative cost of the energy system increases as the demand increases. This is mainly linked to the increase of operational cost of the imported resources, which have a larger share in the energy system in the higher demand scenarios. In the LD scenario, the relative important share of biomass, which is a cheap resource, and doesn't require expensive technologies, brings the relative cost down even further. Regarding the investment cost, two main factors have an opposite effect : the relative increase of electric vehicles (on top of the increasing global mobility, the private mobility share increases as well) and the relative decrease of the cost of

renewable technologies.

Although the relative cost of the energy system is expressed as a unit of cost of energy, and it has the same order of magnitude as electricity prices, it can not be considered an 'energy price', nor compared with the price of electricity for example. First, because the cost encompasses all technologies, including vehicles for example, which is not the case for the price of energy. Second, EnergyScope calculates the total cost of the system, without taking into account any economic or political considerations. It does not answer the question "Who will pay?". As the total cost includes infrastructure, resources, energy conversion technologies, and technologies on the user-side (HP, vehicles, ..), the cost will probably be shared between individuals, industries, energy suppliers, public services, etc. These considerations are beyond the scope of this work.

Chapter 5

Discussion

5.1 Main findings

5.1.1 General findings

One of the main findings from the analysis of the original scenarios is that they all agree that the share of industry in the total final energy consumption will increase significantly, as less efficiency improvements are possible than in other sectors.

We further observed that the five main scenarios show a global trend of decreasing final energy consumption reductions, from the ambitious LD scenario, through the Climact BEH, CLEVER, and EnergyVille scenarios, to the EU reference scenarios, which projects an increase of final energy consumption. The main drivers for this trend are the sufficiency assumptions, which show a wide range of ambitions, while the efficiency assumptions have a more limited impact, as they generally have a more limited range of ambitions.

Recycling is a factor that can have an important impact, especially in the chemical sector, as it allows to reduce both the energy consumption and the feedstock consumption, on top of avoiding landfill or incineration.

Some scenarios don't achieve a fossil-free industry. These scenarios rely on carbon capture or compensation in other sectors to reach net neutrality, or do not reach carbon neutrality at all (EU reference scenario). Electrification of the final energy consumption, on the other hand, is a common characteristic of all scenarios. Regarding feedstock consumption, the scenarios show very different assumptions, some still assuming a 100% fossil mix, and others switching for a small or larger part, or even completely, to e-fuels and bio-fuels. As the current carbon accounting rules don't account for the carbon locked in products like plastics, a scenario with a fossil feedstock mix can be called carbon neutral. Extra ambition is required to decarbonise the feedstock mix and compensate for future end-of-life emissions from the products.

Comparing the original scenarios with their simulation in EnergyScope, we have observed that the mix from the EnergyScope simulation is generally even more electrified than in the original scenarios. No fossil fuels are used (so no CCS is needed), and the use of bio-fuels and e-fuels is generally lower (except for the higher demand scenarios).

The zero-emissions objective doesn't allow for any fossil fuels in the EnergyScope simulations, even for feedstock consumptions, as EnergyScope accounts for the emissions from fossil fuels from the moment they are used, whether it is for combustion or for non-energy demand. For all scenarios, EnergyScope then relies on a feedstock of imported e-fuels. As the products are

imported directly (ammonia and methanol), or are transformed in the efficient methanol-to-olefins process, it allows for a significant reduction of the NED. Indeed, a significant amount of the energetic content of fossils fuels is lost during the transformation into final products. This does however imply that some industries, like ammonia production, are delocalised, which would have economic implications, that are beyond the scope of this work. From a technical point of view, it does make sense, as ammonia is easier to transport than the hydrogen that would be needed to produce green ammonia locally.

Comparing the EnergyScope simulations, we observed that in the LD, Climact BEH and CLEVER scenarios, most of the demand could still be met by endogenous resources, mainly biomass and electricity generation from solar and wind energy, except for the non-energy demand and part of the freight and public mobility sectors. In the EnergyVille and EU reference scenario, import of synthetic natural gas (SNG) is needed to power CHP plants, providing high temperature heat to the industry and electricity to the grid. The increasing demand is accompanied by increasing conversion technology capacities, as well as energy storage capacities. Finally, while the low demand scenarios offer the advantage of relying less on imported resources, they dispose of a lesser share of dispatchable energy generation, leading to higher levels of curtailment.

Even in these scenarios with high levels of curtailment and the maximum endogenous potential that is not reached, we observe (almost) no local production of hydrogen. We also modeled the availability of concentrated CO₂ from industries like cement (not accounted for as emissions), in order to allow local production of e-fuels, but the model always preferred importing e-fuels than capturing the CO₂, producing hydrogen, and using them for local e-fuels production.

Finally, we have shown that for lower demand scenarios, despite these higher levels of curtailment, the relative cost of the energy system, defined as the total cost divided by the total end-use demand (with transport expressed as the FEC), is generally lower in lower-demand scenarios, mainly due to the relative reduction of the import of expensive e-fuels.

5.1.2 Operating of the energy system in the industrial sector

In the industrial sector, EnergyScope simulations show that the only demand type that is not fully electrified is the high temperature heat demand. On top of electricity, it relies on wood boilers and gas boilers, as well as combined heat and power plants in the higher demand scenarios. We have observed that the installed capacities for electric high temperature heat generation are up to 3 times higher than what is strictly needed to satisfy the assumed constant demand. When solar and wind electricity generation is high, it is used to recharge high temperature thermal storage units, requiring extra capacity.

By observing the operation of the high temperature heat supply over a day for some of the typical days of the year, we can better understand the required installed capacities. Both in low demand and high demand scenarios, depending on weather and demand conditions, on some days, no electricity is available and wood boilers, gas boilers, or CHP plants (in the higher demand scenarios) need to be used. On other days, electricity generation can provide 100% of the HT heat demand during the day, and during the night, the heat stored during the day can be used. Finally, on intermediate days, a mix of electricity, wood boilers, gas boilers, CHP plants and stored heat are used.

Simplified, the HT heat generation technologies are installed in the following order, adding the next technology once the previous uses all available resources : (i) wood and gas boilers (using bio-gas), (ii) electricity (mainly from wind, solar and imports), and (iii) gas-powered CHP plants. Storage capacities are needed to manage the use of resources through non-dispatchable technologies. As (i) and (iii) are dispatchable, this means the relative storage capacities need to be the highest when the share of electricity is largest, which is observed in the Climact BEH and CLEVER scenarios.

It is important to realise what this mode of operation would practically imply for industries. First, some industrial processes need specific fuels, like H₂-DRI steel for example. But even putting this issue aside, some challenges remain, both for low demand and high demand scenarios.

When no electricity is available, all the demand is met by wood boilers, gas boilers, or CHP plants. All the industries would thus need to be equipped with one of these technologies. At other moments, the demand is entirely met by electricity. All the industries would thus also need to have the possibility to operate using electricity only. Finally, during the night, when storage capacities have been recharged all day, industrial processes need to be able to operate using only the stored energy. Three types of technologies are thus needed for every industrial process requiring HT heat :

1. They need to be equipped with wood or gas boilers, or to get heat from CHP plants.
2. All processes need to be able to be operated 100% electrically, and recharge storage capacities at the same time.
3. All industries need to be equipped with storage capacities allowing to keep the processes running for a whole night.

This is obviously a major challenge and it may not seem realistic, but it is what the model, accounting for investment cost in all the heat generation and storage technologies, found to be the cheapest in order to attain a carbon neutral system.

Depending on the industrial process, it may not be simple to use the same infrastructure when operating with boilers, heat from CHP plants, electricity, or stored heat. Then, separate infrastructure would be needed, and the process would need to switch from one to the other. These costs were not accounted for in EnergyScope. Instead of relying on thermal storage, it may for example be cheaper to allow for overproduction when electricity is available, and underproduction when it is not. Flexibility of the demand is however not modeled in EnergyScope, which is one of the limitations of this work, discussed in the next section.

5.2 Limitations

A first limitation of this work is thus that **flexibility** of the demand is not fully accounted for. Elia's study "Powering Industry Towards Net Zero" [21] projects that industrial flexibility will become an inherent part of future business cases. They identify four forms of industrial flexibility :

1. Switching between energy carriers. For some processes, it is possible to switch between typically gas boilers and electric boilers. This is what was analysed in the EnergyScope simulations.

2. Energy can be stored using batteries, green molecules or heat storage, which was also analysed in the EnergyScope simulations.
3. Additional production capacity allows to operate the processes flexibly, at the moments where a lot of electricity is available, and thus cheap, creating so-called 'virtual batteries'.
4. Geographical location shifting allows to shift the load to regions where green electricity is available. This mainly concerns data centres, which are not considered in this work.

While the first two forms are included in the EnergyScope model in some way, the second two are not. The lack of consideration of flexibility thanks to additional production capacity is one of the main limitations of this work.

In late May 2023, a new record has been set on the production of renewable electricity in Belgium. On Whit Monday, the electricity demand was relatively low, lower than the production from renewables. The measures taken to mitigate this issue included curtailment and export to other countries, but also paying industries to increase their consumption, through negative electricity prices [74]. Already today, flexibility on the industrial demand is thus used to regulate the energy system, and its importance is expected to increase significantly in the future.

Then, while EnergyScope has the advantage of modeling the whole energy system and the interactions between the sectors, it does not model the industrial sector in great **detail**, and does thus not take into account the specificities of the different industrial processes :

1. All sectors are not necessarily as easily electrifiable
2. All sectors don't allow flexibility by switching energy carriers at an hourly time-scale, or it is not economically viable due to ramping up costs
3. The use of thermal storage is more difficult for certain processes

While the assumed operation for HT heat will probably not be feasible in all sectors, the simulations show the advantage of such an operation, for the sectors where it is possible.

Non energy-related CO₂ emissions like **process emissions** are currently at about the same level as industrial energy-related CO₂ emissions [29]. The EU reference scenario doesn't project a significant decrease of these emissions. In this work, only energy-related emissions and those related to the feedstock demand ('locked' in products) were considered. An important part of the emissions thus remained out of the picture. While in some sectors, like steel, a switch of technologies (towards H₂-DRI in this case) can reduce these emissions, it is more challenging in other sectors, like the cement industry.

Carbon Capture and Storage could be applied to these sectors in order to reduce their emissions. The cost and energy consumption of these technologies were not considered in this work.

As the EnergyScope model is **deterministic**, it often relies on a single technology for each different function in the system. For example, HVC are produced exclusively through MTO. Most existing scenarios have a more cautious approach, assuming a mix of different technologies. In this way, the uncertainties related to any particular technology don't affect the global scenario as much as if a single technology is considered.

Some studies regarding the transition of the industrial sector include **refineries**. Others, like this work, don't consider refineries to be part of the industrial sector, but part of the energy sector. Refineries were thus not analysed in this work. This sector is however very energy- and carbon-intensive. In the more ambitious scenarios, fossil fuels are however (almost) completely phased out (except for the NED in some scenarios), reducing the demand for the products from refineries, and their energy consumption and emissions.

While this work presents possible scenarios for the energy system of 2050, and own assumptions have been made in the industrial and freight sector for the Low Demand scenario, only their **technical** implications have been analysed, leaving aside any economical, political or sociological considerations, regarding both the consequences of the changes considered in the scenarios, and the feasibility of the scenarios. Specific policies needed to reach the ambitions of the scenarios are out of the scope of this work.

Taking a look back at the "Doughnut of social and planetary boundaries" presented in the introduction (figure 1.1), it should be reminded that only the planetary boundary related to climate change, due to emissions from the energy system, was considered. It is thus **only one part** of one of the boundaries constituting the ecological ceiling.

The simulations were made using the "**snapshot**" version of EnergyScope TD. It does only optimise the energy system for a given year, 2050 in this case, without considering the current energy system, nor the evolution from the current system to the 2050 system.

5.3 Further work

Using the "**pathways**" version of EnergyScope, which simulates not only a specific year (2050), but the complete transition from the current energy system to that year, would allow to make a more complete analysis of the transition towards these 2050 scenarios. Except for the LD scenario, all the original scenarios are "pathway" scenarios, providing intermediate assumptions on the demand, at least for the years 2030 and 2040.

It would be interesting to compare the advantages of **flexibility** through the switching of energy carriers and through additional production capacities. The practical feasibility and the related costs of these two strategies for each industrial sector would need to be investigated. Integrating flexibility on the demand side, through additional production capacity, in EnergyScope would then allow to measure its potential. In the chemical sector, for the HVC production, explicitly modeled in EnergyScope, flexibility could be implemented relatively easily. Currently, the HVC demand is constant throughout the year and it cannot be stored. By simply adding a storage technology for HVC to the model, it would allow the MTO technology to operate flexibly and help manage the intermittency of wind and solar power.

Currently, while the HT heat demand is considered constant, time series are considered for the electricity demand and LT heat demand. These time series are common to the residential, tertiary and industrial sectors. Instead of implementing flexibility in the model, another approach could thus be to make specific time series for the industrial sector.

A more **detailed** modelling of the industrial sectors would make the simulations more pre-

cise and in phase with reality. For example, if H₂-DRI is assumed in the steel sector, a part of the HT heat demand could be replaced by a final hydrogen demand (comparable to the final demand for HVC, ammonia and methanol). More synergies between the sectors could also be implemented, like the recuperation of residual heat from high temperature processes in district heating networks for example.

In order to account for all the emissions of the industrial sector, it would be necessary to estimate the process emissions in the different scenarios. The cost and energy consumption of carbon capture technologies that could be applied to reduce these emissions could then also be studied.

Analysing each industrial sector in more detail would also be needed to verify the feasibility of EnergyScope's current operation strategy of the HT heat supply : Can electricity be used for all processes ? Can wood/gas boilers be used for all processes ? Can CHP plants be used for all processes ? Can stored HT heat be used in all sectors ?

A more in-depth analysis of the **sufficiency measures** assumed in the LD scenario could make it more robust. Simplified assumptions were for example made for the renovation of buildings. A study focusing specifically on the material needs for the renovation of buildings would be interesting.

Finally, this thesis was performed from an engineering student's perspective. The assumptions made in the considered scenarios, especially the assumptions regarding sufficiency, do however not only have technical implications. They also have very important **economical, political and sociological** implications. It would thus be interesting to complement this work, criticise its assumptions and observations, with an economical, political and/or sociological approach.

Chapter 6

Conclusion

In this work, we have first analysed and compared different scenarios of the Belgian energy system in 2050, which made very different assumptions regarding the energy demand, due to varying levels of sufficiency ambition. We have then made our own assumptions for the industrial and freight sectors, in order to build an ambitious "Low Demand" scenario, based on a previous scenario from Hugo Baudson for the residential, tertiary, and passenger transportation sectors. We have simulated the assumptions on energy demand of the existing scenarios, as well as the Low Demand scenario, in EnergyScope TD. In order to do so, we developed a new, more precise, methodology to compute the End Use Demand, which is one of the main input data for EnergyScope TD, from the data provided by the existing scenario's reports. We have then analysed and compared the results from these simulations. One main advantage of this work compared to previous work, is that behind the simulations of scenarios with an intermediate energy demand, lie real scenarios, with specific assumptions leading to this energy demand. Finally, we have analysed in deeper detail the energy mix, installed capacities and hourly operation of the energy system in the industrial sector, especially for high temperature heat demand.

In comparison with the residential, tertiary and transportation sectors, the industrial sector is more complex in two main ways. First, the demand in the industrial sector depends on the demand in all other sectors. These sectors define the number of cars that need to be manufactured, the buildings construction and renovation, the demand for ammonia-based fertilisers, etc. Their transition towards 2050 also affects the industrial sector, for example the buildings renovation, the switch to public transportation, or the material substitution of reinforced concrete by wood. In order to make an industrial scenario, it is thus necessary to have a global view. Second, as the Belgian economy is tightly connected to its European neighbours, and even to the whole world, the Belgian industry is not only defined by local parameters. How the rest of the world insulates their homes doesn't affect the Belgian residential sector, but it could affect the Belgian industrial sector. Therefore, assumptions need to be made regarding the links between local production, consumption, import and export.

Comparing various scenarios, we have identified some common findings, on which all scenarios agree, and some important differences in the scenarios.

While the scenarios differ greatly regarding sufficiency assumptions, their efficiency assumptions are more similar.

In all scenarios, electrification of the energy mix takes place, increasing from the current 36% to up to 74% of the final energy consumption in the original scenarios, and even more in some

EnergyScope simulations.

As less efficiency improvements are expected in the industrial sector than in the other ones, all scenarios also agree that the share of the energy consumption from the industry will increase significantly towards 2050, reaching 55% to 69% of the total demand, while it currently only represents 45% of the demand. Improvements in this often overlooked sector could thus make the biggest difference for the transition towards 2050.

We have observed that with a greater demand, the energy system is not simply scaled up, but fundamental changes occur in the system. The lower the demand, the less expensive e-fuels, like synthetic natural gas, need to be imported. This is a main advantage of the lower demand scenarios, leading to lower costs and more autonomy. But with these scenarios also comes a major challenge : as they have a larger share of variable renewable energy resources, and a smaller share of dispatchable generation, the energy system is harder to regulate, leading to more curtailment and the need for more storage capacity.

We have focused on the industrial high temperature heating demand, where the complex operation of different technologies is used to optimise and regulate the whole energy system. While its feasibility is not always verified, this mode of operation shows the role that industry could play to help regulate the whole energy system. While main principles remain the same in all scenarios, a different specific strategy is used in each scenario, using different shares of dispatchable technologies, storage capacities, and electricity, with its fluctuating availability.

It has become clear that the industry will have a crucial role in a sufficiency-based energy system of 2050, as it will be the major sector impacting the total energy demand, but also because of the role it could play to regulate the energy system, which will be a major challenge in a low demand scenario with large shares of variable energy sources.

Appendix A

Industry adjustments for the Low Demand scenario

This appendix provides the methodology used to obtain the projected Belgian territorial industrial demand, that is used in the "Adjusted Low Demand" scenario. A simple adjustment is also made for the freight sector. The reasoning is mainly based on the assumptions made in other sectors in the original "Low Demand" scenario, defined in Hugo Baudson's master thesis [7]. Various other studies are also used when the required information isn't determined by Hugo Baudson.

The methodology consists of starting with the current final energy consumption (FEC) for each sector, applying assumptions on sufficiency to reduce the material demand, and then assumptions on efficiency to reduce the FEC of the sector. The initial FEC used are those from 2015, defined in the JRC database [35].

Before considering each sector individually, some general assumptions are made regarding import/export and the construction sector.

A.0.1 Import/export

As explained in section 3.1, a constant production/consumption is assumed in most sectors. This approach makes sense at a global scale, assuming other countries will go through similar change, which is the idea from the "Decent Living" article [63]. Then, evolutions in production, consumption, import and export will be proportional to each other. The approach used hereunder is based on the estimation of the relative demand reduction to estimate the relative production reduction. It is important to remember that this does not mean that the production is equal to the consumption, like in the original Low Demand scenario. Imports and exports still happen in this scenario.

A.0.2 Construction

The construction sector is modeled by the residential and tertiary buildings. In the Low Demand scenario, the residential floor area per person is expected to decrease from 55 m² to 28 m² (-46%). A slight increase of the average household size from 2.3 to 2.5 persons per household is considered (against the current trend). In the tertiary sector, the floor surface is defined by

the Climact CORE-95 scenario [14], which projects a slight decrease of 7%.

Globally, it is supposed that the material demand for the construction sector in 2050 is directly proportional to the floor area of buildings and the construction rates. The Low Demand scenario makes the strong assumption that the entire residential and tertiary buildings stock consists of only "advanced new" buildings. This means that by 2050, all buildings are replaced by new ones. More realistically, but still a strong assumption, we can consider that all buildings are replaced or renovated to meet the high energetic performances considered by Hugo Baudson in the residential and tertiary sectors. In Climact's Pathways Explorer, the highest level of ambition that can be set for building renovation is a 4% annual rate, which means that all buildings would be renovated before 2050. Then, construction and renovation rates in 2050 can be supposed to go back to the current rates, material demand reduction for the construction sector is assumed to be equal to the floor area reduction. Sector-specific assumptions on material substitution are also made. In reality, a lot of other parameters affect the material demand, like the share of single-family homes versus apartments and material efficiency in the buildings, but these were not modeled in this work.

The relative reductions from these two sectors (residential and tertiary) are assumed to define the global reduction in construction, including also construction in industry, infrastructure, etc. The global reduction then amounts to **35%**. An overview of the reduction of floor surface in buildings is showed in table A.1.

	2015 surface [Mm ²]	2050 surface [Mm ²]	Reduction
Residential	616	334	-46%
Tertiary	227	210	-7%
Total	843	544	-35%

Table A.1: Reduction in floor area in the residential and tertiary sectors

A.1 Steel

A.1.1 Construction

The construction sector is the main steel consumer. As seen previously, a 35% decrease in material demand is assumed in the construction sector. In addition, it is assumed that 20% of steel is substituted by wood in the construction sector [14]. This means that **48% less steel** is needed for construction.

A.1.2 Passenger transportation

The transportation sector is another main steel consumer. The Low Demand scenario assumes an important decrease in passenger mobility : from the current 12910 pkm/cap to 4300 pkm/cap, a 67% decrease. According to data from Fraunhofer ISI and ICF [42], the current

share of steel used in the passenger transportation sector for cars (at European scale) is around 95%, while the other 5% is currently used for public mobility vehicles. At the same time, 80% of traveled passenger-kilometers (excluding aviation and soft mobility) are traveled by car in 2015 [14]. The Low Demand scenario assumes the share of passenger-kilometers traveled by cars to decrease to only 20%. The scenario also assumes a doubling of the mean car occupancy from 1.5 to 3. Taking into account the global mobility decrease, the decrease of the car share, the increase in occupancy and the assumed slight population increase, the distance traveled by cars every year decreases 96%. On the other hand, we assume a constant occupancy in public transport. Then, the global decrease in mobility and the increase in the public mobility share compensate each other, and the distance traveled by public mobility increases, but less drastically than the car distance decrease (+42%). Vehicles (both cars and public mobility vehicles) are assumed to have a lifetime limited by traveled kilometers, which is assumed to be similar in 2015 and 2050. The use of steel in the vehicles is also assumed similar in 2015 and 2050.

Then, distance traveled by cars can be defined as :

$$\text{Distance} = \text{Population} * \text{Mobility} [\text{pkm/cap}] * \text{Car share} / \text{Occupancy} [\text{cap/car}]$$

And the distance traveled by public mobility (in pkm) :

$$\text{Passenger-kilometers} = \text{Population} * \text{Mobility} [\text{pkm/cap}] * \text{Public mobility share}$$

Tables A.2 and A.3 show the data for private and public mobility.

Year	Population [Mcap]	Mobility [pkm/cap]	Car share [%]	Occupancy [cap/car]	Car distance [M car-km]
2015	11.2	12910	80%	1.5	77116
2050	11.9	4300	20%	3	3411

Table A.2: Private mobility

Year	Population [Mcap]	Mobility [pkm/cap]	Public mobility share [%]	Public mobility [Mpkm]
2015	11.2	12910	20%	28918
2050	11.9	4300	80%	40936

Table A.3: Public mobility

The 96 % decrease in steel demand for cars, and the 42 % increase in demand for public mobility add up to a **global 89% decrease** in demand for the passenger transportation sector.

A.1.3 Global reduction

According to Material Economics [59], at an European scale, 42% of steel is used for construction and 31% for transportation. In this work, the total steel demand is modeled by these two

sectors. One can note that from the remaining 27%, the majority (16%) is used for machinery, used mainly in industry. As the industrial activity will decrease due to sufficiency, mainly in construction and transportation, it is reasonable to assume the demand for machinery will follow the trend from construction and transportation. By adding up the reductions in these two sectors, we thus obtain a global **64% demand reduction for steel**.

Then, a 41% energy efficiency improvement is considered [68], bringing a total reduction in FEC of 80%, see table A.4.

2015 FEC [TWh]	Sufficiency and material substitution	Efficiency	2050 FEC [TWh]
25.79	-64%	-41%	5.24

Table A.4: Reduction of steel FEC

A.2 Cement

The cement demand is completely defined by the construction sector. Most of the cement is used for construction of buildings, while a smaller share is used for construction of infrastructure [59]. In this work the cement demand evolution is defined by the evolution of the demand for buildings construction. We have already defined a 35% decrease in material demand in buildings. We then also assume 40% of concrete substitution by wood, adding up to a 61% decrease of the demand. We then assume a 19% decrease of the clinker-to-cement ratio. As clinker production is the main energy consuming step, this is considered as a 19% efficiency improvement. Further 26% process efficiency improvements are considered, bringing the final energy consumption of the cement sector down **77%**, see table A.5.

2015 FEC [TWh]	Sufficiency	Material substitution	Clinker-to-cement ratio	Efficiency	2050 FEC [TWh]
4.38	-35%	-40%	-19%	-26%	1.02

Table A.5: Reduction of cement FEC

A.3 Ammonia

The vast majority of ammonia produced in the EU is used for producing nitrogen fertilisers, 90% according to Material Economics [59]. The reduction of ammonia consumption is a complex topic, as the whole current agricultural system is based on synthetic nitrogen fertilisers. Assumptions on the demand are made using Climact's 2050 Pathways Explorer [14]. The Behaviour scenario assumes that nitrogen fertilisers will not be used anymore at all in 2050. It is the only scenario studied in this work that makes such a strong assumption. For the adjusted Low Demand scenario, we will decrease the level of ambition slightly, and suppose a 60% decrease in synthetic fertiliser use. As a consequence, the loss of 13% crop yields is assumed [14]. Other assumptions from the BEH scenario are left unchanged : improved livestock

management practices, a decrease of meat consumption and global calories consumption. All together, this adds up to a **77% decrease in ammonia demand**. The assumption from the BEH scenario of a **10% decrease in energy intensity** is also used. We thus obtain a 79% decrease in FEC, see table A.6.

2015 FEC [TWh]	Sufficiency	Efficiency	2050 FEC [TWh]
3.67	-77%	-10%	0.76

Table A.6: Reduction of ammonia FEC

A.4 High Value Chemicals

High Value Chemicals (HVC) are used for the production of plastics. The three main consumers are packaging (40%), construction (20%) and transportation (10%), which make up 70% of the demand [59].

A.4.1 Packaging

We consider, as is the case in the Behaviour scenario, a 25% decrease in the use of packaging. This goes against the current upwards trend. Then, according to Material Economics [59], material efficiency could allow for a 20% decrease of material use, without compromising functionality. This brings the total reduction of plastics use in packaging to 40%.

A.4.2 Construction

In construction, we assume like in the other sectors, that the use of plastics will decrease proportionally to the floor area decrease, i.e. 35%. We then assume 20% of material substitution by wood, in line with Climact's assumptions in the Behaviour scenario [14]. The total material demand reduction is 48%.

A.4.3 Transportation

For the transportation, we make the same assumption as in the steel sector : a 89% decrease in material demand, due to the drastic decrease of the use of cars. We make no further assumptions.

A.4.4 Global FEC reduction

This brings the global reduction in material demand from these three sectors to 49%. An 18% efficiency improvement is assumed. The FEC decreases 59%, see table A.7.

2015 FEC [TWh]	Sufficiency and material substitution	Efficiency	2050 FEC [TWh]
20.8	-49%	-18%	8.61

Table A.7: Reduction of HVC FEC

A.4.5 Non-energy demand

For the non-energy demand, the 49% sufficiency assumption is kept. Then, Material Economics considers a 62% recycling rate (mechanical and chemical recycling) is feasible [59]. The current recycling rate is around 7%. This would bring the demand for primary feedstock down 59% further. The need for primary feedstock would thus drop **79%**.

A.5 Transport equipment

The reduction of demand in the transport equipment industry is proportional to the decrease of steel and HVC demand for the transportation sector that was already obtained previously, i.e. -89%. A 15% efficiency improvement is considered [14]. The projected decrease of FEC of the sector is **90%**, see table A.8.

2015 FEC [TWh]	Sufficiency	Efficiency	2050 FEC [TWh]
3.10	-89%	-15%	0.30

Table A.8: Reduction of transport equipment FEC

A.6 Non-ferrous metals, other chemicals, ceramics and machinery equipment

No specific sufficiency assumptions were made for these four sectors. It is assumed they will follow the trend from steel, cement, ammonia and HVC. Adding up all these sectors, we obtain a global **61%** reduction of material demand thanks to sufficiency measures. This is clearly an approximation, but it is justified by the fact that the products from these industries are mainly used in similar consuming sectors as the previously considered industries. Machinery equipment is mainly used in industry, so its use will follow the global trend. The efficiencies considered are those from Climact's Behaviour scenario [14]. An overview of the FEC from these industries is shown on table A.9.

Sector	2015 FEC [TWh]	Sufficiency	Efficiency	2050 FEC [TWh]
Non-ferrous metals	3.33	-61%	-19%	1.04
Other chemicals	9.80	-61%	-22%	2.95
Ceramics	7.25	-61%	-13%	2.44
Machinery equipment	2.18	-61%	-15%	0.72

Table A.9: Reduction of NFM, other chemicals, ceramics and machinery FEC

A.7 Wood, glass and textile

No sufficiency assumptions are made for these three industries. Their production levels in 2050 are assumed to be the same as in 2015.

- **Wood** : Although global material demand in construction will decrease, material substitution by wood will increase its share of the global material demand. The Behaviour scenario considers an important increase of wood products consumption [14], but as biomass is a limited resource in Belgium, and competition between different types of consumers is expected to be important, no extra production is considered in this work.
- **Glass** : Glass is mainly used in construction, transportation and packaging. Reductions thanks to sufficiency in these sectors are compensated by the higher use of glass for construction in low energy-intensity buildings (double and triple glazing).
- **Textile** : The majority of the Belgian demand is currently met by import. As the demand decreases, it is assumed only the import will decrease. It is the only sector for which relocalisation is considered.

The efficiency improvements that are considered are those from Climact's Behaviour scenario [14]. An overview of the FEC from these three sectors is shown on table A.10.

Sector	2015 FEC [TWh]	Sufficiency	Efficiency	2050 FEC [TWh]
Wood	2.63	0%	-4%	2.53
Glass	4.30	0%	-11%	3.83
Textile	2.27	0%	-15%	1.93

Table A.10: Reduction of wood, glass and textile FEC

A.8 Food

The demand for food is calculated using Climact's 2050 Pathways Explorer [14]. The assumed calories consumption from the Low Demand scenario, 2000 kcal/person, is used (the BEH scenario considers only 1800 kcal). Other assumptions from the Behaviour scenario are left

unchanged, like food waste reduction and the reduction of meat consumption. A 42% reduction of the demand can be obtained. Then, a 30% efficiency improvement is considered, bringing the total reduction in FEC to 60%, see table A.11.

2015 FEC [TWh]	Sufficiency	Efficiency	2050 FEC [TWh]
16.90	-42%	-30%	6.75

Table A.11: Reduction of food FEC

A.9 Pulp and paper

Production of paper and paperboard has been steadily increasing at a global scale, at 2% per year according to Fraunhofer ISI [42], mainly due to the increase of its use in packaging for e-commerce. 50% of the demand is indeed for packaging. Graphic papers (books, printing paper, ...) makes up 37% of the demand, sanitary and household papers make up 8% and other special papers, used among others in industry make up 5% of the demand [34]. For this work, no reductions are considered for graphic papers and sanitary and household papers. The current trend is a decrease of use of graphic papers, due to digitisation. The Low Demand scenario however assumes a limited use of electronic devices (only one laptop per household). The use of graphic paper, among others for education, will thus remain essential. On the other hand, the trend for paper use in packaging is a steady increase. As the Low Demand scenario assumes significant decreases in the global production and consumption of goods, it is supposed that the demand for paper for packaging will decrease proportionally to the global industrial activity from all previously considered sectors, i.e. a 53% decrease. The demand for special papers is also assumed to follow this trend. The global demand for pulp and paper then decreases 29%. We assume, as in Climact's Behaviour scenario, a 20% efficiency improvement. We obtain a reduction of FEC of 43%, as shown in table A.12.

2015 FEC [TWh]	Sufficiency	Efficiency	2050 FEC [TWh]
8.31	-29%	-20%	5.02

Table A.12: Reduction of paper FEC

A.10 Other industrial sectors

The demand of materials from the industries classified under "Other industrial sectors" in the JRC database [35], are supposed to follow the trends from all previously considered sectors, i.e. a 51% decrease. The efficiency improvements proposed in Climact's Behaviour scenario allow for a 15% reduction of energy intensity. We then obtain a 59% FEC reduction, see table A.13.

2015 FEC [TWh]	Sufficiency	Efficiency	2050 FEC [TWh]
9.55	-51%	-15%	3.95

Table A.13: Reduction of other industrial sectors FEC

A.11 Total reduction

Adding up all the sectors, we obtain a total FEC in 2050 of **46.77 TWh**, a 62% reduction compared to the FEC of the industry in 2015 (124.26 TWh). The breakdown of total reductions thanks to sufficiency and efficiency is shown in table A.14

2015 FEC [TWh]	Sufficiency	Efficiency	2050 FEC [TWh]
124.26	-51%	-23%	46.77

Table A.14: Total reduction of FEC in the adjusted Low Demand scenario

A.12 End-Use-Demand for EnergyScope

EnergyScope doesn't take the FEC as input, but the end-use-demand (EUD). Also, the energy used for the production of primary HVC and ammonia should not be included in this EUD, as EnergyScope models the processes for the production (or import) of these materials using energy on top of the industrial consumption input, in order to meet the non-energy demand input. The share of primary HVC, 38%, was obtained in section A.4. To obtain the EUD from the FEC (excluding primary HVC and ammonia), it is necessary to make assumptions on the efficiency of the used technologies. As our efficiency assumptions for this scenario are mainly based on Climact's Behaviour scenario [41], we will use the ratio between FEC and EUD calculated for this scenario with the methodology developed in section 3.2.1, i.e.

$$\left(\frac{EUD}{FEC}\right)_{LD-mod} = \left(\frac{EUD}{FEC}\right)_{BEH} = 1.042$$

This high value is possible thanks to the high level of electrification, and the use of heat pumps, that allow a ratio higher than 1.

We can then obtain the EUD that can be used as input in EnergyScope, see table A.15.

2050 FEC [TWh]	2050 FEC excluding prim- ary HVC & NH ₃ [TWh]	EUD/FEC ratio	2050 EUD [TWh]
46.77	42.74	1.042	44.52

Table A.15: Calculation of Adjusted Low Demand EUD

A.13 Non-energy demand

Using data from Xavier Rixhon et al. [67], the 2015 non-energy demand is estimated at 51.09 TWh. It is expressed as the energy content of the material, defined by its lower heating value. The current distribution is a 77.9% share for HVC, a 19.2% share for ammonia, and a 2.9% share for methanol. We have estimated the reduction in primary HVC production to be 79%, and the reduction in ammonia production 77%. We then assume a constant methanol production. We obtain a global feedstock end-use demand reduction of 77%, see table A.16.

Material	2015 EUD [TWh]	2015 share	EUD reduction	2050 EUD [TWh]	2050 share
Primary HVC	39.80	77.9%	-79.4%	8.20	68.7%
Ammonia	9.81	19.2%	-77.1%	2.25	18.8%
Methanol	1.48	2.9%	-0.0%	1.48	12.4%
Total	51.09	-	-76.6%	11.93	-

Table A.16: Reduction of non-energy demand

A.14 Freight

The freight demand is assumed to follow the global trend of material production reduction in the industry, i.e. -51%. As the EUD is defined in tkm and not energy consumption, no efficiency assumptions are made. EnergyScope TD will itself try to meet the freight demand most efficiently using the different available technologies. The 2050 demand is shown on table A.17

2015 EUD [tkm]	Sufficiency	2050 EUD [tkm]
70195	-51%	34396

Table A.17: Reduction of the freight mobility in the adjusted Low Demand scenario

The final EUD matrix for the adjusted Low Demand scenario can be found in appendix B.

Appendix B

EnergyScope input for the different scenarios

B.1 EUD matrices

	Households	Services	Industry	Transport	Units
Electricity constant	2271	2109	15893	0	[GWh]
Electricity variable	1223	1645	5253	0	[GWh]
High temperature heat	0	0	17584	0	[GWh]
Low T heat variable	4816	4936	4585	0	[GWh]
Low T heat constant	4243	1181	1202	0	[GWh]
Passenger mobility	0	0	0	51152	[Mpkm]
Freight mobility	0	0	0	34396	[Mtkm]
Non-energy demand	0	0	11927	0	[GWh]

Table B.1: EUD matrix of the adjusted Low Demand scenario

	Households	Services	Industry	Transport	Units
Electricity constant	6593	9171	20670	0	[GWh]
Electricity variable	3550	7155	6832	0	[GWh]
High temperature heat	0	0	22870	0	[GWh]
Low T heat variable	20592	14538	5964	0	[GWh]
Low T heat constant	5373	3327	1563	0	[GWh]
Passenger mobility	0	0	0	131130	[Mpkm]
Freight mobility	0	0	0	68630	[Mtkm]
Non-energy demand	0	0	19313	0	[GWh]

Table B.2: EUD matrix of the FPS and Climact Behaviour scenario

	Households	Services	Industry	Transport	Units
Electricity constant	6175	4662	25162	0	[GWh]
Electricity variable	3325	3552	8317	0	[GWh]
High temperature heat	0	0	27840	0	[GWh]
Low T heat variable	32900	11544	7260	0	[GWh]
Low T heat constant	4600	2664	1903	0	[GWh]
Passenger mobility	0	0	0	125700	[Mpkkm]
Freight mobility	0	0	0	70000	[Mtkm]
Non-energy demand	0	0	31633	0	[GWh]

Table B.3: EUD matrix of the CLEVER Belgian scenario

	Households	Services	Industry	Transport	Units
Electricity constant	12831	12800	36287	0	[GWh]
Electricity variable	6909	10060	11994	0	[GWh]
High temperature heat	0	0	40149	0	[GWh]
Low T heat variable	45030	29030	10469	0	[GWh]
Low T heat constant	8860	3980	2744	0	[GWh]
Passenger mobility	0	0	0	159690	[Mpkkm]
Freight mobility	0	0	0	78380	[Mtkm]
Non-energy demand	0	0	51093	0	[GWh]

Table B.4: EUD matrix of the EnergyVille PATHS2050 central scenario

	Households	Services	Industry	Transport	Units
Electricity constant	9213	12815	51288	0	[GWh]
Electricity variable	4961	9997	16893	0	[GWh]
High temperature heat	0	0	56713	0	[GWh]
Low T heat variable	45360	32023	14753	0	[GWh]
Low T heat constant	11595	7179	3822	0	[GWh]
Passenger mobility	0	0	0	159271	[Mpkkm]
Freight mobility	0	0	0	92766	[Mtkm]
Non-energy demand	0	0	55012	0	[GWh]

Table B.5: EUD matrix of the EU reference scenario

B.2 Shares of the NED

The EUD matrix only contains the total NED, but the demand was estimated separately for HVC, methanol and ammonia for each scenario. It is thus necessary to adjust the shares of each product in the NED.

	LD	Climact BEH	CLEVER	EnergyVille	EU ref
HVC	0.688	0.923	0.736	0.779	0.779
Methanol	0.124	0.077	0.047	0.029	0.029
Ammonia	0.188	0.0	0.217	0.192	0.192

Table B.6: Shares of the NED for the different scenarios

B.3 Shares of public mobility

	LD	Climact BEH	CLEVER	EnergyVille	EU ref
Public mob. share	0.8	0.6	0.5	0.21	0.205

Table B.7: Shares of public mobility for the different scenarios

Appendix C

Sankey diagrams

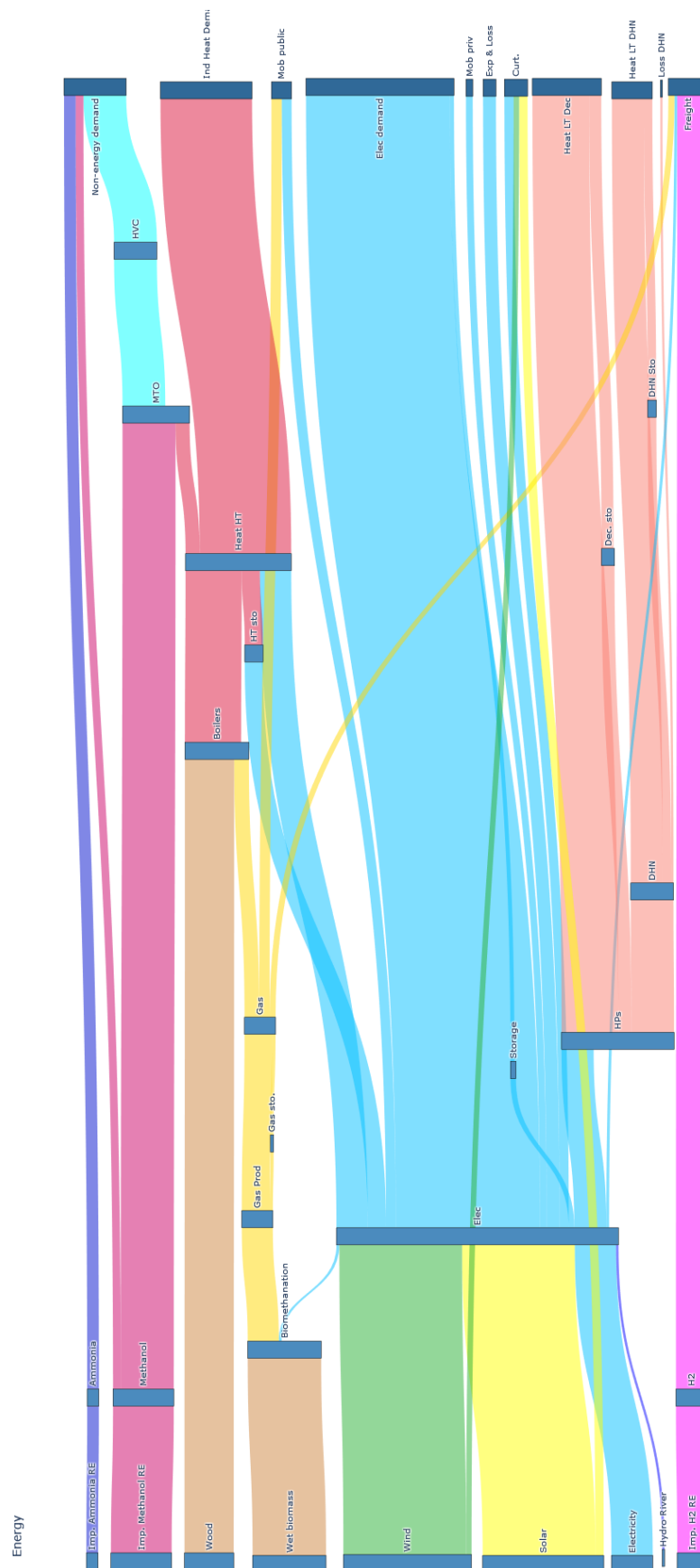


Figure C.1: Sankey diagram of the adjusted Low Demand scenario

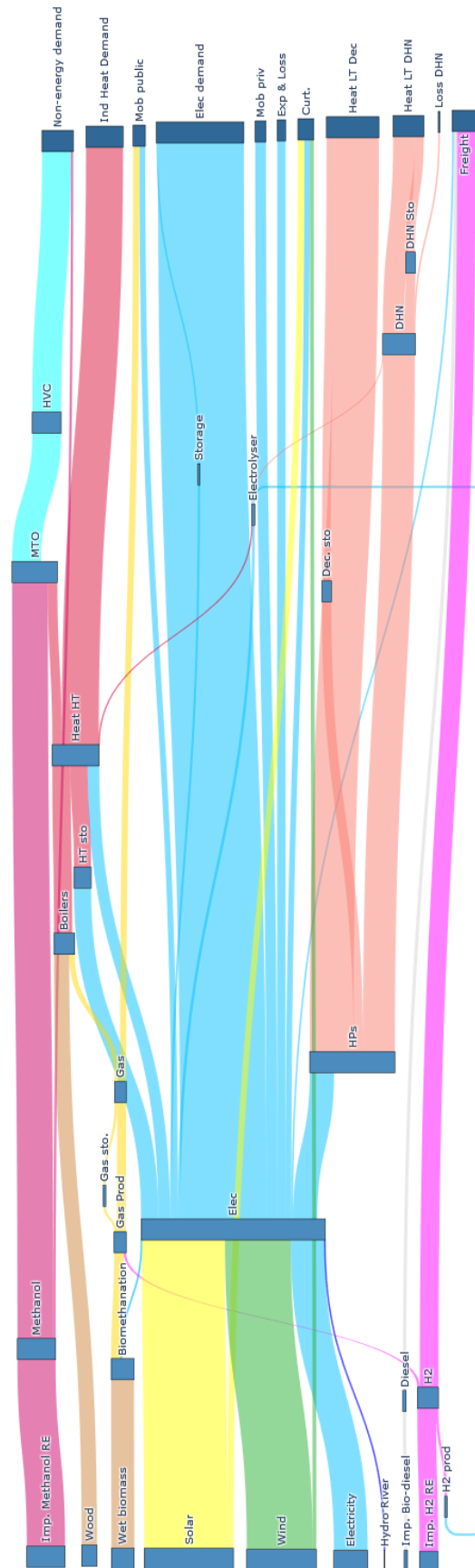


Figure C.2: Sankey diagram of the FPS and Climact Behaviour scenario

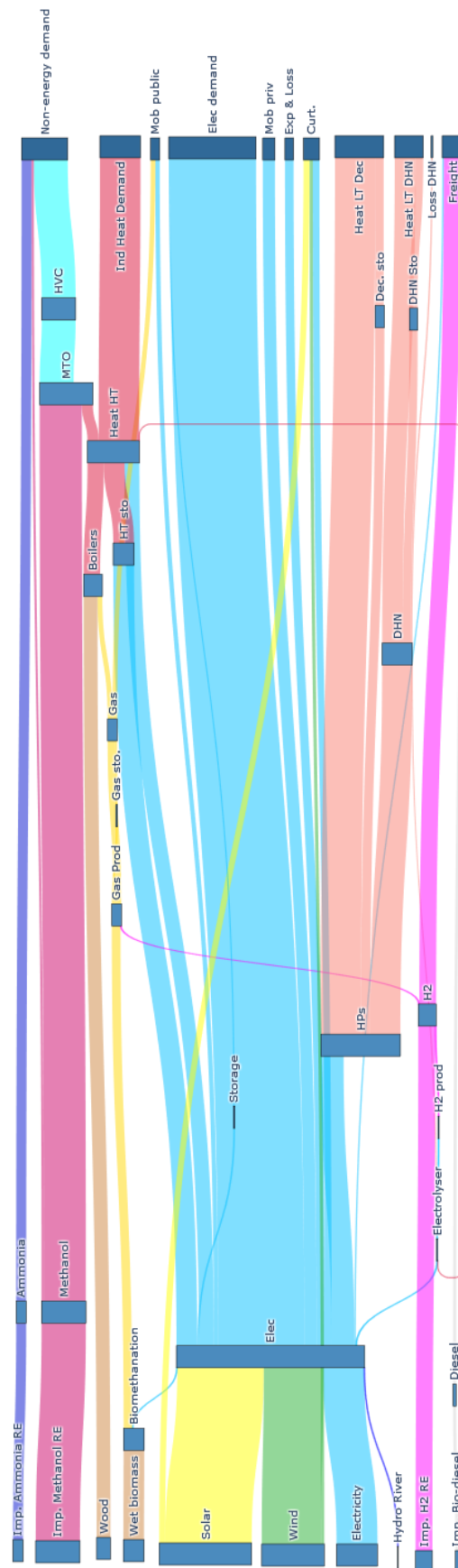


Figure C.3: Sankey diagram of the CLEVER Belgian scenario

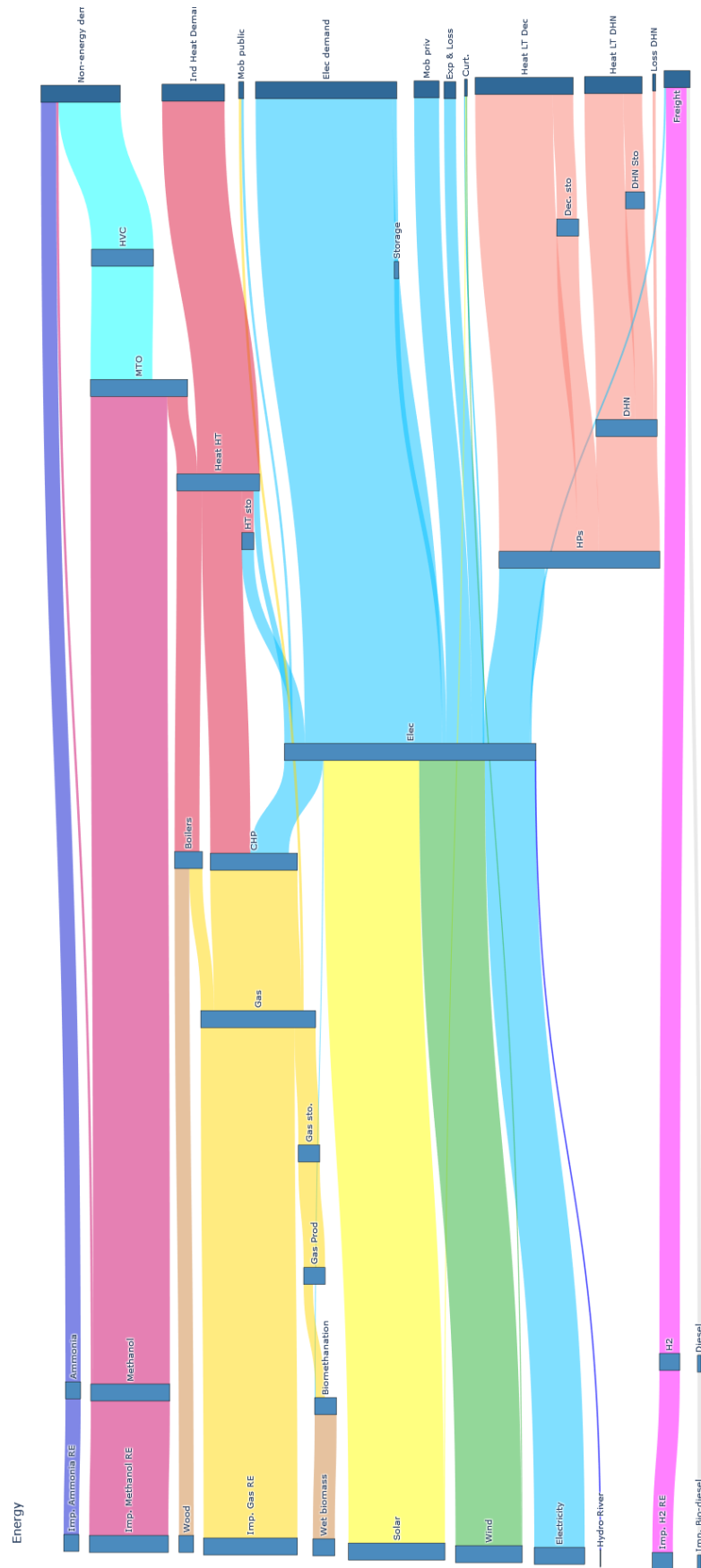


Figure C.4: Sankey diagram of the EnergyVille PATHS2050 central scenario

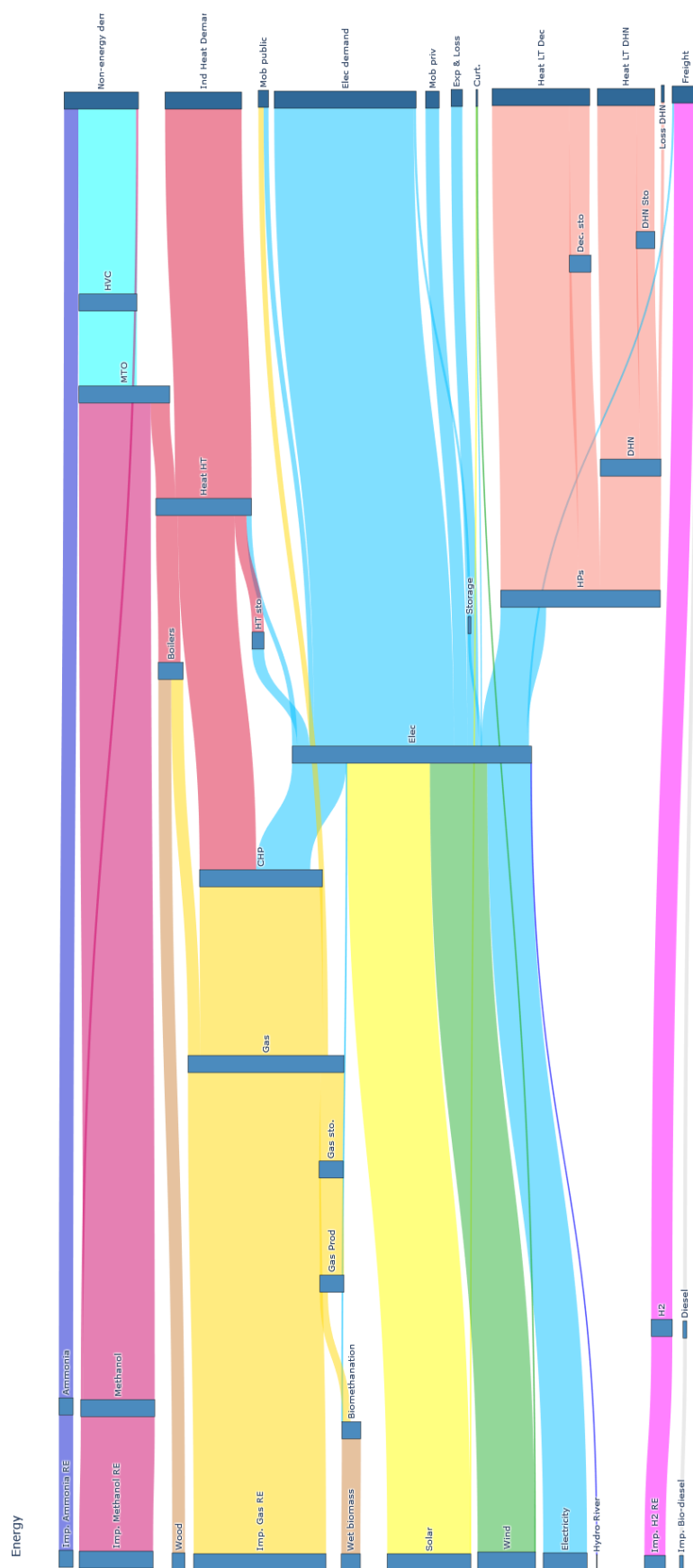


Figure C.5: Sankey diagram of the EU reference scenario 2020 (NED 2016)

Bibliography

- [1] Adrien Toledano et al. *Establishment of energy consumption convergence corridors to 2050 - Industrial sector*. June 2022. URL: <https://clever-energy-scenario.eu/wp-content/uploads/2023/02/2206-Convergence-corridors-Industry.pdf>.
- [2] Agentschap Innoveren en Ondernemen. *Naar een koolstofcirculaire en CO₂-arme Vlaamse industrie*. URL: <https://www.vlaio.be/nl/publicaties/naar-een-koolstofcirculaire-en-co2-arme-vlaamse-industrie> (visited on 05/16/2023).
- [3] Artur Wyrwa et al. “Energy scenarios for Poland—a comparison of PRIMES and TIMES–PL modeling results”. In: (2015).
- [4] Association négaWatt. *Association négaWatt*. Association négaWatt. URL: <https://negawatt.org/> (visited on 05/16/2023).
- [5] Association négaWatt. *CLEVER energy scenario*. URL: <https://clever-energy-scenario.eu/> (visited on 05/16/2023).
- [6] Association négaWatt. *Scenario negaWatt for France 2022-2050*. 2022.
- [7] Hugo Baudson. “Impact of demand reduction on the Belgian energy system in 2050”. In: (2022).
- [8] Belgian Federal Government. *The functionality economy*. URL: https://www.belgium.be/en/economy/sustainable_development/sustainable_economy/innovative_economic_models/functionality_economy.
- [9] Bellona. *Case Study: Hydrogen use in Steel: Tata Steel, the Netherlands*. URL: <https://www.frompollutiontosolution.org/casestudy-h2insteel>.
- [10] Bond Beter Leefmilieu. *Hoe creëren we een klimaatneutrale Vlaamse industrie ?* Bond Beter Leefmilieu, Oct. 2021. URL: <https://www.bondbeterleefmilieu.be/artikel/bbl-berekent-zo-wordt-vlaamse-industrie-sneller-klimaatneutraal>.
- [11] Carbon Market Watch. *THE CLIMATE FRIENDLY TRANSITION OF EUROPE’S ENERGY INTENSIVE INDUSTRIES*. 2016.
- [12] Cembureau. *Cembureau Activity Report 2020*. 2021.
- [13] Climact and European Climate Foundation. *Net Zero by 2050: From Whether to How*. 2018.
- [14] Climact and FPS Public Health. *2050 Pathways Explorer - Belgium*. URL: <https://becalc.netzero2050.be/> (visited on 05/15/2023).
- [15] Danielle Devogelaer et al. *Towards 100% renewable energy in Belgium by 2050*. 2013.

- [16] Direction de l'information légale et administrative. *La relocalisation : une vraie bonne idée ?* vie-publique.fr. May 2, 2023. URL: <http://www.vie-publique.fr/parole-dexpert/289178-la-relocalisation-une-vraie-bonne-idee-par-jean-marc-figuet> (visited on 05/18/2023).
- [17] Clarion Energy Content Directors. *Boilers running on hydrogen: What you need to know*. Power Engineering. Aug. 16, 2022. URL: <https://www.power-eng.com/hydrogen/boilers-running-on-hydrogen-what-you-need-to-know/> (visited on 05/26/2023).
- [18] Doughnut Economics Action Lab. *About Doughnut Economics — DEAL*. 2023. URL: <https://doughnuteconomics.org/about-doughnut-economics> (visited on 06/03/2023).
- [19] Dr Moncef Hadhri. *Cefic Facts and Figures 2023*.
- [20] E3 Modelling. *PRIMES – E3 Modelling*. URL: <https://e3modelling.com/modelling-tools/primes/> (visited on 05/23/2023).
- [21] Elia. *Powering Industry Towards Net Zero*. 2022. URL: https://www.elia.be/en/news/press-releases/2022/11/20221118_visionpaper.
- [22] EnergyVille. *PATHS2050 — Energy outlook*. URL: <https://perspective2050.energyville.be/> (visited on 05/16/2023).
- [23] EnergyVille. *Research into sustainable energy and intelligent energy systems — EnergyVille*. Apr. 28, 2023. URL: <https://www.energyville.be/en> (visited on 05/16/2023).
- [24] EUROFER. *European Steel in Figures 2017*. 2017.
- [25] Eurofer. *Map of EU steel production sites*. 2019.
- [26] European Commission. *Circular economy action plan*. URL: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (visited on 05/23/2023).
- [27] European Commission. *Communication COM/2020/102: A New Industrial Strategy for Europe — Knowledge for policy*. URL: https://knowledge4policy.ec.europa.eu/publication/communication-com2020102-new-industrial-strategy-europe_en (visited on 05/23/2023).
- [28] European Commission. *EU Emissions Trading System (EU ETS)*. URL: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en (visited on 05/23/2023).
- [29] European Commission. *EU Reference Scenario 2020*. OCLC: 1337459147. Luxembourg: Publications Office of the European Union, 2021. ISBN: 978-92-76-39356-6.
- [30] European Commission. *Glossary: Final energy consumption*. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Final_energy_consumption (visited on 05/24/2023).
- [31] European Commission. Directorate General for Energy., European Commission. Directorate General for Climate Action., and European Commission. Directorate General for Mobility and Transport. *EU reference scenario 2016*. LU: Publications Office, 2016. URL: <https://data.europa.eu/doi/10.2833/9127> (visited on 12/20/2022).
- [32] European Commission. Directorate General for Mobility and Transport. *EU transport in figures :statistical pocketbook 2017*. LU: Publications Office, 2017. URL: <https://data.europa.eu/doi/10.2832/147440> (visited on 05/25/2023).

- [33] European Commission. Statistical Office of the European Union. *Energy balance sheets: 2016 data : 2018 edition*. LU: Publications Office, 2018. URL: <https://data.europa.eu/doi/10.2785/02631> (visited on 12/20/2022).
- [34] EUROPEAN SCENARIO INDUSTRY AND MATERIALS WORKING GROUP. *Prospective stories for key basic materials and industry sectors*. June 15, 2021.
- [35] European Union. *JRC-IDEES - Integrated Database of the European Energy System (2000-2015)*. July 2018.
- [36] Eurostat. *Energy statistics - an overview*. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview (visited on 06/03/2023).
- [37] Eurostat. *Energy, transport and environment statistics: 2019 edition*. 2019 edition. OCLC: 1127382058. Luxembourg: Publications Office of the European Union, 2019. ISBN: 978-92-76-10971-6.
- [38] *Federale regering steunt productie groen staal in België*. URL: https://www.tinnevanderstraeten.be/federale_regering_steunt_productie_groen_staal_in_belgi.
- [39] Fushan Feng et al. “Recent progress on the traditional and emerging catalysts for propane dehydrogenation”. In: *Journal of Industrial and Engineering Chemistry* 118 (Feb. 25, 2023), pp. 1–18. ISSN: 1226-086X. DOI: [10.1016/j.jiec.2022.11.001](https://doi.org/10.1016/j.jiec.2022.11.001). URL: <https://www.sciencedirect.com/science/article/pii/S1226086X22006153> (visited on 05/25/2023).
- [40] Fertilizers Europe. *Paving the way to green ammonia and low-carbon fertilizers*.
- [41] FPS Public Health - DG Environment. *Scenarios for a climate neutral Belgium by 2050*. May 2021. URL: <https://climat.be/doc/climate-neutral-belgium-by-2050-report.pdf>.
- [42] Fraunhofer ISI, ICF. *Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis*. 2019.
- [43] Fraunhofer ISI, ICF. *Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation*. 2019.
- [44] Freepik. *Icon made by Freepik from www.flaticon.com*. URL: <https://www.flaticon.com/authors/freepik>.
- [45] Gauthier Limpens. *Application of EnergyScope TD to the Belgium Case - Supplementary Material*.
- [46] Gauthier Limpens. *Overview — EnergyScope_documentation 2.2 documentation*. URL: <https://energyscope.readthedocs.io/en/master/sections/Overview.html> (visited on 05/24/2023).
- [47] GBPN. *GBPN - Input Data*. URL: <https://tools.gbpn.org/databases-tools/mrv-tool/%20model-input-data>. (visited on 05/19/2023).
- [48] Heat Roadmap Europe. “2015 Final Heating & Cooling Demand in Belgium”. 2017.
- [49] IEA. *Ammonia Technology Roadmap*. 2021.
- [50] IEA. *IEA – International Energy Agency*. IEA. URL: <https://www.iea.org> (visited on 06/02/2023).

- [51] Joel Millward-Hopkins et al. *Providing decent living with minimum energy: A global scenario - Supplementary Material*.
- [52] Joint Research Centre. *Deep decarbonisation of industry: The cement sector*. 2020.
- [53] Juan Correa Laguna et al. *Description of the EnergyVille TIMES Be model*. 2022.
- [54] Julian M Allwood and Jonathan M Cullen. *Sustainable materials with both eyes open*. 2012.
- [55] Gauthier Limpens. “Generating energy transition pathways : application to Belgium”. PhD thesis. UCLouvain, 2021. URL: <http://hdl.handle.net/2078.1/249196>.
- [56] Gauthier Limpens, Hervé Jeanmart, and Francois Maréchal. “Belgian Energy Transition: What Are the Options?” In: *Energies* 13.1 (Jan. 4, 2020), p. 261. ISSN: 1996-1073. DOI: [10.3390/en13010261](https://www.mdpi.com/1996-1073/13/1/261). URL: <https://www.mdpi.com/1996-1073/13/1/261> (visited on 10/02/2022).
- [57] Gauthier Limpens et al. “EnergyScope TD: A novel open-source model for regional energy systems”. In: *Applied Energy* 255 (Dec. 2019), p. 113729. ISSN: 03062619. DOI: [10.1016/j.apenergy.2019.113729](https://linkinghub.elsevier.com/retrieve/pii/S0306261919314163). URL: <https://linkinghub.elsevier.com/retrieve/pii/S0306261919314163> (visited on 10/02/2022).
- [58] Gabriel Lopez et al. “Towards defossilised steel: Supply chain options for a green European steel industry”. In: *Energy* (Mar. 2023), p. 127236. ISSN: 03605442. DOI: [10.1016/j.energy.2023.127236](https://linkinghub.elsevier.com/retrieve/pii/S0360544223006308). URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360544223006308> (visited on 03/27/2023).
- [59] Material Economics. *Industrial Transformation 2050*. 2019. URL: <https://materialeconomics.com/publications/industrial-transformation-2050>.
- [60] ME. *Energy efficiency in steam generation — Maintenance and Engineering*. Apr. 9, 2021. URL: <https://www.maintenanceandengineering.com/2021/04/09/energy-efficiency-in-steam-generation/> (visited on 05/26/2023).
- [61] Donella H. Meadows and Club of Rome, eds. *The Limits to growth: a report for the Club of Rome’s project on the predicament of mankind*. New York: Universe Books, 1972. 205 pp. ISBN: 978-0-87663-165-2.
- [62] Michel Cornet et al. *Scenarios for a Low Carbon Belgium by 2050*. Climact and VITO.
- [63] Joel Millward-Hopkins et al. “Providing decent living with minimum energy: A global scenario”. In: *Global Environmental Change* 65 (Nov. 2020), p. 102168. ISSN: 09593780. DOI: [10.1016/j.gloenvcha.2020.102168](https://linkinghub.elsevier.com/retrieve/pii/S0959378020307512). URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959378020307512> (visited on 10/02/2022).
- [64] N. Gudde, JF Larivé, and M. Yugo. *Refinery 2050: Conceptual Assessment*. 2019.
- [65] negaWatt Belgium. *negawatt Belgium — For a Belgian energy transition based on sufficiency!* URL: <https://www.negawatt.be/> (visited on 05/16/2023).
- [66] *Project ONE by INEOS*. Ineos Project One. URL: <https://project-one.ineos.com/en/> (visited on 05/16/2023).

- [67] Xavier Rixhon et al. “Comprehensive integration of the non-energy demand within a whole-energy system: Towards a defossilisation of the chemical industry in Belgium”. In: *34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2021)*. 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environment Impact of Energy Systems. Taormina, Italy: ECOS 2021 Program Organizers, 2022, pp. 152–163. ISBN: 978-1-71384-398-6 978-1-71384-393-1. DOI: [10.52202/062738-0014](https://doi.org/10.52202/062738-0014). URL: <http://www.proceedings.com/062738-0014.html> (visited on 04/02/2023).
- [68] Sébastien Meyer. *Dashboard_BE_v5.15*. 2023.
- [69] Steelanol. *Steelanol*. URL: <http://www.steeanol.eu/en> (visited on 05/16/2023).
- [70] Stefano Moret. “Devising Energy Transition Pathways under Uncertainty”. 2023.
- [71] The Investopedia Team. *Sharing Economy: Model Defined, Criticisms, and How It’s Evolving*. URL: <https://www.investopedia.com/terms/s/sharing-economy.asp>.
- [72] The Shift Project. *Décarboner l’industrie sans la saborder*. 2022.
- [73] Umwelt Bundesamt. *Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE - Summary Report*. 2019.
- [74] Vincent Legraive. *Cette semaine, la Belgique a produit trop d’électricité: il a fallu PAYER certains grosses industries pour qu’elles consomment plus !* RTL Info. Section: Economie, Belgique, Actu, Info. June 2, 2023. URL: <http://www.rtl.be/actu/belgique/economie/cette-semaine-la-belgique-produit-trop-deelectricite-il-fallu-payer-certains/2023-06-02/article/554463> (visited on 06/03/2023).
- [75] Xavier RIXHON. “Analysis of EUD”. Apr. 2022.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain

Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | www.uclouvain.be/epl