École polytechnique de Louvain

Impact of demand reduction on the Belgian energy system in 2050

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Abstract

Fifty years ago, the Meadows report “The limits to growth” was published. The authors already warned the world about the limits to growth and called for an anticipation of these limits. In addition, efforts to reduce our GHG emissions are increasing drastically these past few years, following the publication of the “European Green Deal”.

One way of reducing these emissions attracts a growing attention: the reduction of the demand. Indeed, if we reduce our energy consumption, we emit less $CO_{2,eq}$ in the atmosphere. The present work results from a partnership between UCLouvain and negaWatt Belgium. It aims to highlight the impacts of the reduction of the demand in the Belgian energy system in 2050, the year at which the carbon neutrality must be achieved in the European Union.

In this master thesis, a range of energy demand is defined. Its lower limit is defined with the help of the article “Providing a decent living with minimum energy: a global scenario”, while the higher limit is defined with the projections of the European Commission in the “EU Reference Scenario 2050”. The low demand scenario needs around 4 times less primary energy than the high demand one.

Afterwards, intermediate scenarios are constructed and simulated with EnergyScope TD, which models the whole energy system. These simulations show two main tipping points in the energy system. One above which (at higher energy demand) the energy system imports an increasing share of primary energy resources and below which the Belgian maximum endogenous potential is not reached. The other one is determined by the use of cogeneration of heat and power units in higher demand scenarios, to meet the high demand in electricity and in high temperature heat.

The reduction of the demand would lead to a lower energy dependency on importations and a lower cost of the energy system.

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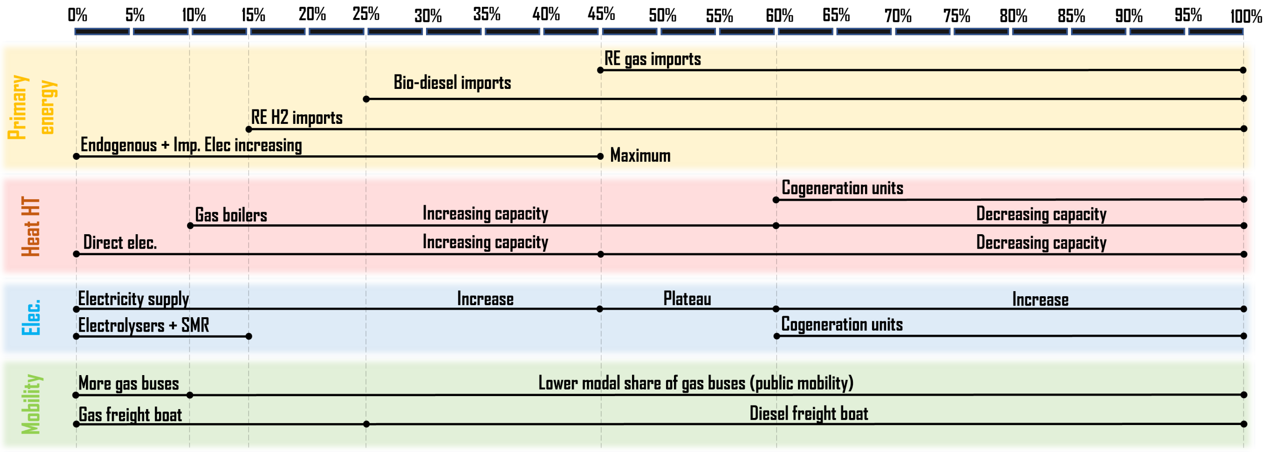
Il y a cinquante ans, le rapport Meadows ”The limits to growth” était publié. Les auteurs mettaient déjà en garde le monde contre les limites de la croissance et appelaient à anticiper ces limites. De plus, les efforts visant à réduire nos émissions de gaz à effet de serre ont augmenté de façon spectaculaire ces dernières années, suite à la publication du ”European Green Deal”.

Un moyen de réduire ces émissions suscite une attention croissante : la réduction de la demande. En effet, si nous réduisons notre consommation d’énergie, nous émettons moins de $CO_{2,eq}$ dans l’atmosphère. Le présent travail résulte d’un partenariat entre l’UCLouvain et negaWatt Belgium. Il vise à mettre en évidence les impacts de la réduction de la demande dans le système énergétique belge en 2050, année à laquelle la neutralité carbone doit être atteinte dans l’Union Européenne.

Dans ce mémoire, un intervalle de demande énergétique est défini. Sa limite inférieure est définie à l’aide de l’article ”Providing a decent living with minimum energy : a global scenario”, tandis que la limite supérieure est définie à l’aide des projections de la Commission Européenne dans leur rapport ”EU Reference Scenario 2050”. Le scénario de faible demande nécessite environ 4 fois moins d’énergie primaire que le scénario de forte demande.

Ensuite, des scénarios intermédiaires sont construits et simulés avec EnergyScope TD, qui modélise l'ensemble du système énergétique. Ces simulations montrent deux points de basculement principaux dans le système énergétique. L'un au-dessus duquel (pour une demande énergétique plus élevée) le système énergétique importe une part croissante des ressources énergétiques primaires et en dessous duquel le potentiel endogène maximal belge n'est pas atteint. L'autre est déterminé par l'utilisation d'unités de cogénération de chaleur et d'électricité dans des scénarios de demande plus élevée, pour répondre à la demande élevée en électricité et en chaleur à haute température.

La réduction de la demande entraînerait une moindre dépendance énergétique vis-à-vis des importations et un coût plus faible du système énergétique.



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List of Acronyms

BEV Battery Electric Vehicle

c_p Yearly capacity factor

CHP Cogeneration of Heat and Power

CO_2 Carbon dioxyde

COP Coefficient of Performance

DHN District Heating Network

DLS Decent Living Standard

EC European Commission

EnergyScope TD EnergyScope Typical Days

EU European Union

EUD End-Use Demand

EUI End-Uses Inputs, lines of the demand matrix of `EnergyScope TD`

FEC Final Energy Consumption

GDP Gross Domestic Product

GHG GreenHouse Gas

GWh Giga Watt hour

GWP Global Warming Potential

H2 Hydrogen

HD High Demand

HT heat High Temperature Heat

HVC High-Value Chemicals

HW Hot Water

Imp. Imported

IPCC Intergovernmental Panel on Climate Change

IRM Institut Royal Météorologique

ktoe kilo ton oil equivalent

LD	Low Demand
LHV	Lower Heating Value
LT heat	Low Temperature Heat
NED	Non-Energy Demand
pkm	passenger kilometer
PV	Photovoltaic
RE	Renewable Energy
SH	Space Heating
SNG	Synthetic Natural Gas which is an imported RE fuel
TD	Typical Days
tkm	ton kilometer
TWh	Tera Watt hour

Chapter 1

Introduction

Fifty years ago, the Meadows report "The limits to growth" was published [1]. In 1972, scientists already warned the world about the limits to the world population, industrialisation, pollution, food production, and resource depletion growths. They stated that *"the most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity"* (Meadows, 1972).

They promoted the idea that *"the state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied, and each person has an equal opportunity to realize his individual human potential"* (Meadows, 1972). Recently, Millward-Hopkins et al. studied the minimum energy required to satisfy the basic needs of each person on earth, without consideration of culture or wealth, in their article "Providing a decent living with minimum energy: a global scenario" [2].

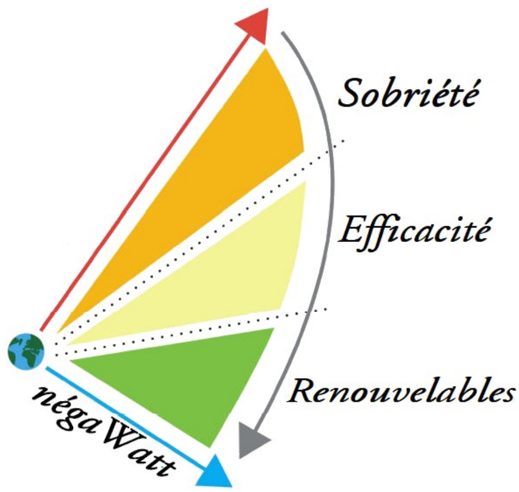
Jean-Marc Jancovici said about the energy: *"There is a unit of account for the transformation of the world: it is the energy. [...] The energy is indeed, by definition in physics, the mark of the change of state of a system, and thus the transformation of the environment"* (Jancovici, 2013) [3]. The GDP (gross domestic product) is also a measure of the transformation, but economic. The consumption of energy and the GDP are highly correlated. The rapid increase of fossil fuels consumption allowed us to live in societies with growing economies and growing basic needs met for the majority of people. The economic growth present in our societies has always been based on the consumption of energy, almost exclusively from fossil fuels.

The high level of consumption of fossil fuels emit large amount of greenhouse gases (GHG) in the atmosphere. These GHG are responsible for the increase of the world mean temperature and the climate change. In their sixth assessment report, the Working Group 1 of the IPCC, the Intergovernmental Panel on Climate Change, estimates that *"emissions of greenhouse gases from human activities are responsible for approximately 1.1°C of warming since 1850-1900"* [4]. To limit the increase of the world mean temperature and the climate change, we must reduce drastically our emissions of CO_2, which is the biggest contributor to the greenhouse effect, through human activities. To do so, several parameters can be influenced. They are included in the Kaya equation that follows:

$$CO_2 = \frac{CO_2}{Energy} \cdot \frac{Energy}{GDP} \cdot \frac{GDP}{Population} \cdot Population$$

This equation is rather simple, if we want to decrease the left term of the equation, the right term must be reduced. First, the population is projected to increase in the next years, and it is hard to induce a variation in this parameter. The parameter "$\frac{CO_2}{Energy}$" corresponds to the CO_2 content of the energy that is consumed. To emit less GHG, we must switch to energy sources emitting less GHG, such as the renewable energies. As the evolution of the GDP is out of the scope of this work, we will consider the last two terms together, leading to the parameter "$\frac{Energy}{Population}$", which is the energy consumed per capita. This thesis investigates scenarios with decreasing energy consumption, and the impacts of this reduction of demand on the energy system. The evolution of the GDP is not investigated, but with the reduction of the energy demand, the services needed by each of us will decrease, as well as the industrial products.

The aim fixed by the European Commission is to reach a carbon neutrality in 2050. This objective is part of the European Green Deal [5] and is in line with the objectives of the Paris Agreement to stay well below an increase of the world mean temperature of 2°C and pursuing efforts to limit it to 1.5°C. The year studied in this thesis is the one of the carbon neutrality, 2050. Then, no operational GHG emission will be allowed in the energy system modelling. In addition to this objective to reach carbon neutrality, the reduction of the energy consumption and the deployment of renewable energies in the European Union (EU) help to reduce our dependence on the importation of fossil fuels, such as gas or oil.



In general, the energy system models consider the demand as a fixed input, but négaWatt constructs their scenarios on the concept of sufficiency, and consequently on a reduction of the demand. The approach proposed by négaWatt can be summarised in three ideas: sufficiency, efficiency and renewable. "Association négaWatt"[1] is a French organisation that provides carbon-neutral scenarios for France, based firstly on sufficiency, then on efficiency, and lastly on renewable production. In terms of energy production, the négaWatt scenarios exclude nuclear and fossil fuelled power plants, aiming for a 100% renewable energy system in 2050. Before defining how to produce energy, négaWatt focuses on the services that will consume this energy, and prioritise the essential needs. The sufficiency is the idea that not every service of our daily life are essential. Sufficiency actions can be individual or collective. Then, we should decrease as much as possible the energy needed to satisfy the services, through efficiency actions, like deep renovation of buildings. Finally, the remaining energy that must be produced should be produced from renewable energy, such as wind, solar, biomass, etc.

Sébastien Meyer founded the Belgian organisation "negaWatt Belgium" whose goal is to produce similar scenarios for Belgium, as for France, to open a public debate around energetic choices. This thesis is realised in the framework of a partnership between negaWatt Belgium and UCLouvain to investigate the impacts of the reduction of the demand on the Belgian energy system in 2050.

[1] https://negawatt.org/

The reduction of the demand is a large concept and includes sufficiency, as well as efficiency. The energy system model used in this work is `EnergyScope Typical Days`, which was adapted to Belgium by Gauthier Limpens [6]. It is based on the PhD thesis of Stefano Moret [7], who worked on the Switzerland version of `EnergyScope TD`, that is an open-source energy system model, that optimises the whole energy system. It is used to simulate the whole energy systems, depending on a varying demand, for a snapshot of 2050, the year at which the carbon-neutrality must be achieved. `EnergyScope TD` is presented in Chapter 2.

The first step of this thesis is to define a range for the energy demand. The high demand (HD) scenario is defined by the projections of the European Commission (EC) in their report “EU Reference Scenario 2050” [8]. Further explanations are provided in Chapter 3. The low demand (LD) scenario is defined with the help of the article “Providing a decent living with minimum energy: a global scenario” [2]. Millward-Hopkins et al. define Decent Living Standards (DLS), which are the minimum services needed by each individual to have a decent living. The LD scenario is defined in Chapter 4.

After defining the range of possible energy consumptions, we simulate both HD and LD scenarios with `EnergyScope TD`. Afterwards, intermediate scenarios are defined to observe the impacts of the reduction of the demand on the Belgian energy system in 2050. The results are presented in Chapter 5.

Chapter 2

EnergyScope TD

EnergyScope Typical Days (TD) is an open-source energy system model, which optimises the energy system of a defined region (here Belgium) by minimising its cost under limited Global Warming Potential (GWP), considering parameters and constraints. It was adapted to Belgium in the thesis of Gauthier Limpens [6]. The version used in this thesis is `EnergyScope TD` snapshot, which models the energy system for one specific year, which is 2050 in this work, to account for carbon neutrality. This snapshot version does not give the details of the transition pathway. The three categories of parameters are : the resources, the technologies and the end-use demand (EUD). An overview of `EnergyScope TD` operation is shown in Figure 2.1. Both resources and EUD are further developed in following sections.

- **The resources** are defined by their cost of operation, their emissions of $CO_{2,eq}$, their yearly availability and their hourly time series (for intermittent resources). Details are given in Section 2.2.
- **The technologies** are defined by their investment and maintenance costs, their efficiencies, and their lifetimes. The data related to technologies weren't further reviewed, and the one established by Gauthier Limpens in its thesis were considered.
- **The end-use demand (EUD)** is the demand expressed in terms of service provided. It doesn't take into account the technology used to provide this service. For example, the passenger mobility EUD is expressed in terms of passenger kilometre (pkm), rather than energetic content of the fuel powering the vehicle, as the service linked to the passenger mobility is the displacement of people. The EUD is different from the Final Energy Consumption (FEC), which is the energy required to provide the services, and includes the efficiency of the technologies. Except for heat pumps, the FEC is always greater than the EUD, due to efficiencies lower than 100%.

In this thesis, we consider the Belgian energy system in the year 2050 when the carbon neutrality should be achieved, following the European Green Deal [5]. The limitation on the GWP is then 0 $tCO_{2,eq}$/year. The model has an hourly resolution and includes the need of storage technologies to counter the intermittency of certain renewable resources.

2.1 End-use demand

The end-use demand (EUD) is the demand that symbolises the needs in services without taking into account the efficiency of the technologies providing these services. Table 2.1 shows the empty demand

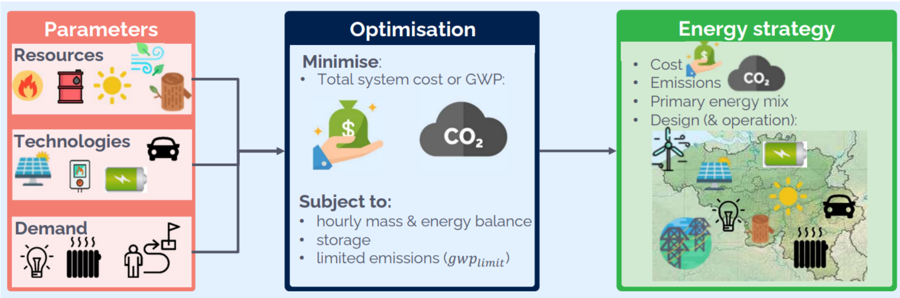


Figure 2.1: Overview of `EnergyScope TD` operation. Source: Gauthier Limpens thesis [6].

matrix, as defined in `EnergyScope TD`. The demand is divided in four sectors: households, services, industry, and transportation; and eight end-uses inputs (EUI): electricity, lighting, heating high temperature, space heating, hot water, passenger mobility, freight mobility and non-energy demand. The demand is defined on an annual basis. The units of the EUD are the GWh, except for passenger and freight mobilities, which are the passenger kilometre (pkm) and the ton kilometre (tkm), respectively.

	HOUSEHOLDS	SERVICES	INDUSTRY	TRANSPORT.	Units
ELECTRICITY	-	-	-	0	[GWh]
LIGHTING	-	-	-	0	[GWh]
HEAT_HIGH_T	0	0	-	0	[GWh]
HEAT_LOW_T_SH	-	-	-	0	[GWh]
HEAT_LOW_T_HW	-	-	-	0	[GWh]
MOB._PASSENGER	0	0	0	-	[Mpkm]
MOB._FREIGHT	0	0	0	-	[Mtkm]
NON_ENERGY	0	0	-	0	[GWh]

Table 2.1: Energy demand matrix as defined in `EnergyScope TD`. Abbreviations: *T = Temperature, SH = Space Heating, HW = Hot Water, MOB. = Mobility.*

Each sector has its own needs and doesn't necessarily have needs for all EUI. Therefore, not every cell of the matrix can be filled in. This is why some cells are filled in with "0", as their sectors and EUI are not compatible.

The demand is defined on an annual basis, but the optimisation is performed on an hourly resolution. Therefore, the demand is converted to be usable by `EnergyScope TD`. This conversion is shown in Figure 2.2 and is explained hereafter:

- **The electricity EUD** is composed of a constant and a variable shares (named "electricity" and "lighting", respectively). The varying demand of electricity is shared over the year according to a time series, which is based on the real 2015 Belgian electricity demand. In addition, the power grid has losses that are added to the hourly EUD, named "$\mathbf{Net}_{loss}$" in Figure 2.2.
- **The low temperature (LT) heat EUD** is also composed of a constant and a variable shares (named "heat low T HW" and "heat low T SH", respectively). They refer to "hot water" and "space heating", respectively. The varying demand of heat is shared over the year according to a time series, which is based on calculations made by Gauthier Limpens [6]. Two categories of heat low temperature suppliers are considered in `EnergyScope TD`: District Heating Network (DHN) and decentralised heating. The maximum share of DHN is fixed in `EnergyScope TD` at 37% for the

year 2050 and is based on the heat roadmap study [9]. The DHN has losses that are added to the hourly EUD.

- **The high temperature (HT) heat EUD** is only present in the industrial sector. It is considered to be required continuously throughout the year.
- **The passenger mobility EUD** is shared over the day according to a time series. A constant demand in passenger mobility for every day of the year is assumed. This EUD is divided in a public mobility and a private mobility shares, which are considered to vary in our demand reduction scenarios. For the public mobility, the maximum modal shares are 30% for the tramway, 50% for the train and 100% for the bus. These modal shares weren't investigated further in this work.
- **The freight mobility EUD** is shared continuously over the year. This EUD is divided in a boat freight mobility, a train freight mobility and a road freight mobility shares. Their maximum modal shares are respectively 30%, 25% and 100%.
- **The non-energy demand (NED)** is shared continuously over the year. The non-energy demand is defined by Rixhon et al. as *"energy products used as raw materials in the different sectors; that is not consumed as a fuel or transformed into another fuel"* [10], inspired by the Eurostat definition [11]. It is used in the production of plastics and fertilizers, for example.

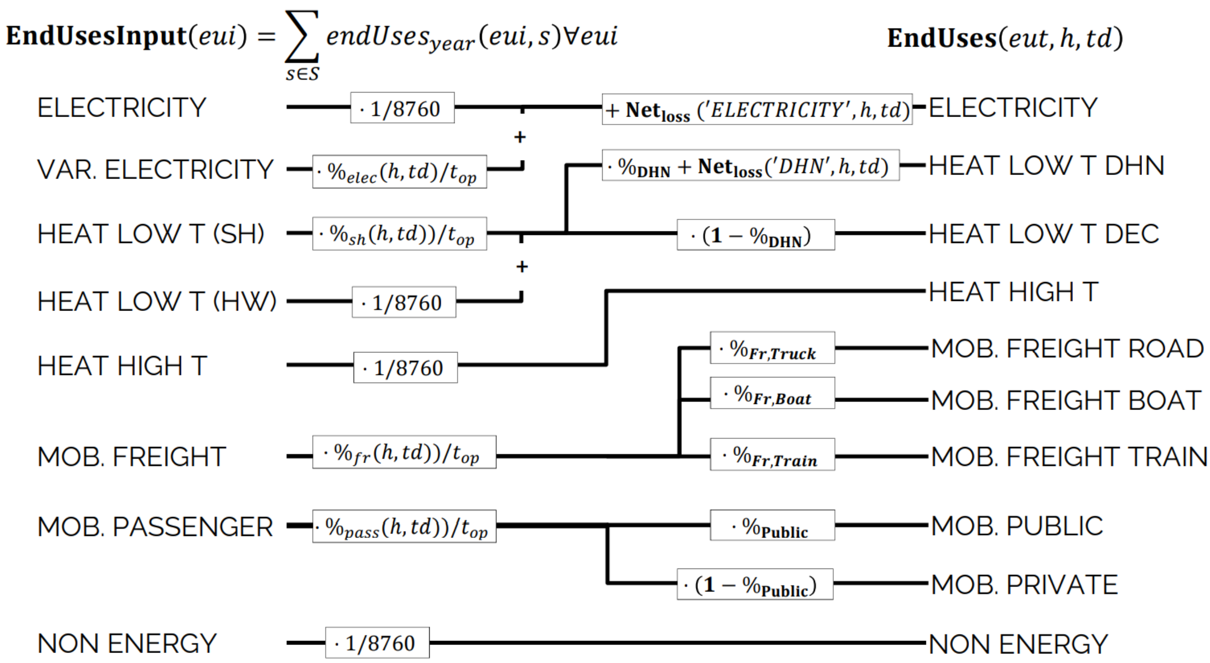


Figure 2.2: Conversion of the yearly EUI into the hourly end-uses. Abbreviations: space heating (SH), district heating network (DHN), hot water (HW), passenger (pass) and freight (fr). Source: Gauthier Limpens PhD thesis [6].

2.2 Resources

To simulate the Belgian energy system, it is important to define what primary energy is available and in what quantity. Resources can be grouped in two categories: endogenous and exogenous. These terms refer to resources that are produced within Belgium and imported from abroad, respectively. This distinction is important, as it defines the energy dependence of Belgium on importations. Belgium's endogenous resources are solar, wind, hydro, and biomass. The first three resources depend on the installed capacity of their conversion technologies. The three of them are converted to produce electricity with photovoltaic panels (PV) for solar, onshore and offshore wind turbines for wind, and river dams for hydro. The biomass is composed of wood and wet biomass, and they are limited by their availability. Biomass can be burned to produce heat or electricity and can also be used to produce Synthetic Natural Gas (SNG), which is considered to be a renewable energy (RE) fuel when produced from biomass. The exogenous resources are the one that are imported in Belgium from abroad. They are the hydrocarbons, imported electricity, or other fuels, such as the e-fuels, produced via power to gas technologies.

The modelling results of the energy system depend largely on the maximum capacity of the conversion technologies, or on the availability of the resources. As the considered year is 2050, the energy sector must reach carbon neutrality. Consequently, the only resources taken into account are renewable ones: solar, wind, hydro, biomass, imported electricity, bio-fuels and e-fuels.

The maximum potentials of the resources are the one presented in Gauthier Limpens PhD thesis, if not explicitly expressed.

- **Solar:** The solar energy is converted into electricity with PV panels, and into LT heat with thermal solar panels. The latter is usually not used in `EnergyScope TD`. Indeed, it has a negative correlation with heat demand, which is generally lower when the irradiation is high, because of higher ambient temperature. The installed capacity of PV panels is limited by its surface requirement. The constraint is that the maximum surface covered with PV panels is 250 km^2 (a little less than 1% of Belgium area). This results in a maximum of 59.2 GW.
- **Wind:** The wind is converted into electricity with onshore and offshore wind turbines. Their maximum potentials are 10 GW and 5 GW, respectively[1].
- **Hydro:** The hydro energy is converted in electricity with river dams and its maximum potential is 0.115 GW.
- **Biomass:** The term biomass designates wood and wet biomass. Their availabilities are updated for this work: 9.45 TWh for wood, and 14.1 TWh for wet biomass. Their prices are also updated: 21.3€/MWh for wood and 9.6€/MWh for wet biomass [12].
- **Bio-fuels and e-fuels:** The bio-fuels are the RE fuels produced from biomass, while the e-fuels are those produced from hydrogen electrolysis combined with carbon dioxide (CO_2). They are considered to be entirely imported from abroad. Their importation is not limited.
- **Imported electricity:** The imported electricity depends on the interconnections with neighbouring countries. In its PhD thesis, Gauthier Limpens projects the transfer capacity until 2050, as shown in Figure 2.3. In 2050, Belgian interconnections are estimated to be 18080 MW. The full capacity cannot be reached simultaneously, so the simultaneous import capacity decreases to 11894 MW. In order to limit Belgium electrical dependence from neighbouring countries, the electricity importation is limited to 10% of its capacity[2], which is 32.4 TWh/y [6]. The imported electricity related $CO_{2,eq}$ emissions depend on the electricity mix of neighbouring countries. As the carbon neutrality should be achieved in the EU in 2050, the electricity imported from these countries is considered to be carbon-neutral.

[1]Should be updated with recent agreements of Belgium on offshore turbines in the North Sea

[2]This limitation could be discussed, as the simulations of the energy system will show that the dependence on energy importations are higher in every scenario.

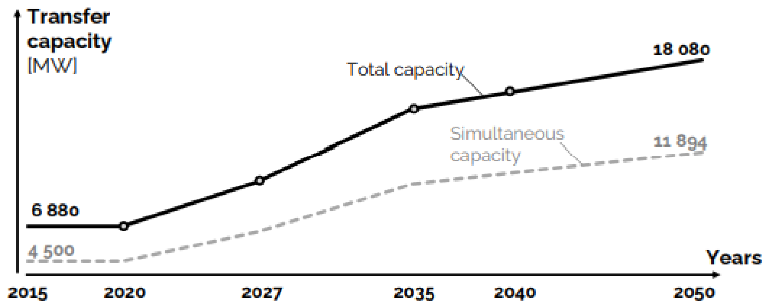


Figure 2.3: Total and available transfer capacities from neighbouring countries. Source: Gauthier Limpens thesis [6].

2.3 Limits of EnergyScope TD

In this thesis, we model the energy system of different energy demand scenarios, but we are limited by the framework of `EnergyScope TD`. First, `EnergyScope TD` doesn't include every aspect of the energy system. The agricultural and the international aviation sectors are not modelled in `EnergyScope TD`. Some assumptions are made in this thesis to either not take some energy demand into account, or to attribute some energy demand to other sectors, like the aviation that is attributed to Belgian people by making the assumption that these travels can be performed by cars, trains, or buses (for the intra-EU aviation). Moreover, the soft mobility (walk, bike, e-bike, two-wheelers, etc.) is not taken into account, even though it represents a non-negligible share of our displacements.

Then, the different prices and technology efficiencies in such a long term are hard to predict, and aren't precise. The current energy crisis shows us how the energy market can be fluctuating and how projections are always wrong. The prices and technology efficiencies should often be updated in `EnergyScope TD`, in order to stay precise and accurate.

In addition, the main limitation of `EnergyScope TD` is its sensitivity to the prices, and other parameters. Indeed, the results can vary a lot when varying a little the price of the technologies and resources. Gauthier Limpens analyses the Sobol index of 122 groups of parameters, for a carbon-neutral scenario in 2050 [6]. The Sobol index indicates the sensitivity of a system to a certain parameter. The higher the Sobol index, the more sensitive the model is to this parameter. The parameters having the highest Sobol indices are the light renewable energy (RE) fuels price (Sobol index = 53.2%), the nuclear capacity (Sobol index = 12.8%), the fuel-cell price (Sobol index = 8.5%), the fuel-cell efficiency (Sobol index = 4.4%) and the car price (Sobol index = 4.2%). The main parameter leading to a high sensitivity of the model is encountered in the scenarios of this thesis. The light RE fuels are RE hydrogen, RE gas and RE methanol. These imported light RE fuels represent the majority of the primary energy in the high demand scenario. A little change in the estimation of their prices could change largely the results of the scenarios. Moreover, these RE fuels do not have limitations on their importations. We then consider the capacity of production of the other countries to be great enough to provide Belgium with its needs.

Chapter 3

High demand scenario: European Commission projections

The purpose of this chapter is to define the demand considered in the HD scenario. To do so, we consider the European Commission (EC) projections of the consumption in Belgium. In its **"EU Reference Scenario 2020"** report [8], the European Commission projects the annual energy consumption by steps of five years until 2050, both at the European Union (EU) and at Member States levels. This report updates the previous versions published in 2013 [13] and 2016 [14]. The demand considered by `EnergyScope TD` was previously based on the latter. It has been actualised with the latest version for this thesis.

The "Reference Scenario" projects the evolution of the EU energy system, in terms of supply and consumption, as well as the GHG emissions, based on the impact of macroeconomic factors, fuel prices, technology trends and policies. The energy system is divided in four sectors: residential, tertiary, industrial, and transports. The energy consumption projections are made for the EU energy system, but also for each of the Member States. The interest for this thesis lays in the projections of the EUD needed by `EnergyScope TD` to complete the demand matrix. They are the specific electricity demand, the HT and LT heat demands, the passenger, and freight mobilities, and the non-energy demand, for Belgium in 2050. The EC projects an increase of the Belgian population to 11 926 987 inhabitants in 2050.

The "Reference Scenario" is not a forecast, it does not predict the future energy system and GHG emissions, but it gives a model-based simulation of a possible future outlook, taking assumptions and historical trends as entries. This is simulated considering the policy context at the cut-off date (December 2019), and the policies planned until 2030, both at EU and Member States levels. Between 2030 and 2050, it is considered that no additional policy is applied. The previous policies are still considered, but at a slower pace. The years from 2020 and beyond are projections, while past years (2005 – 2015) are based on historical data. Calibration ensures continuity between historical data and projections[1].

This report comes along with consumption data [15] that helped construct the `EnergyScope TD` demand matrix. The methodology used to convert this data into the demand matrix is explained in Appendix A.

[1] This paragraph was inspired by the EC report [8]

This chapter presents the modelling suite used to simulate the “Reference Scenario”. This scenario considers different policies at EU and Member States levels, which are briefly discussed. Afterwards, the demand matrix will be completed after a discussion about the different energy sectors and a comparison with the 2015 historical consumption. Finally, the limits of the European Commission projections will be presented.

3.1 Modelling suite

The “Reference Scenario” is based on interconnected models, each of them doing specific simulations in their domain, and sharing it to the other models.

Figure 3.1 shows the different interconnections between the models, constituting the modelling suite that simulates the “Reference Scenario”. The models and their interconnections are explained hereafter. Both `PRIMES` and `PRIMES-TREMOVE` will be more detailed, since they simulate the energy and transport sectors, from which the information will be taken.

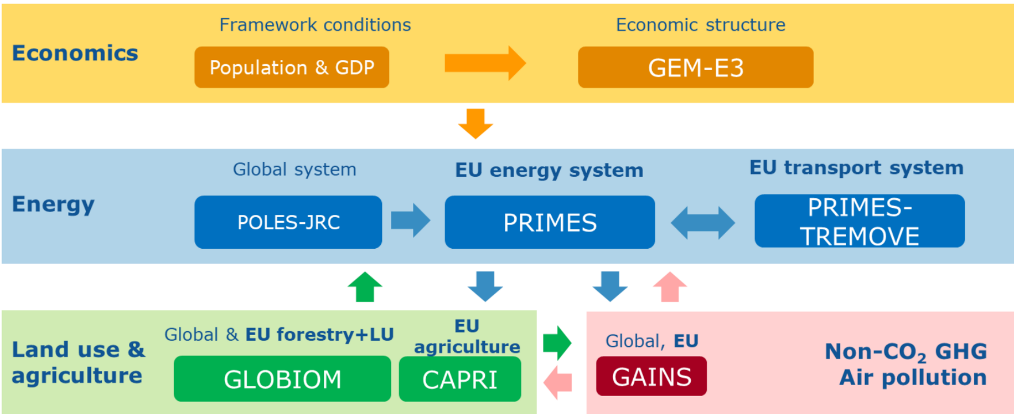


Figure 3.1: Illustration of the “EU Reference Scenario 2020” modelling suite. Source: European Commission [8].

- **Economics:** `GEM-E3` macroeconomic model provides macroeconomic projections to the other models and uses their results to perform macroeconomic and social impact analyses. The projections match the Gross Domestic Product (GDP) and population projections by country, provided by the “2021 Ageing Report” [16] assumptions.
- **Energy:** The energy system model `PRIMES` is central to the modelling suite. It delivers energy, transport and CO_2 emission projections, while the `PRIMES-TREMOVE` model delivers the transport system projections and is part of `PRIMES`, but includes the open source `TREMOVE` model. `POLES-JRC` model is used for international fossil fuel price trajectories.
- **Land use and agriculture:** `GLOBIOM` model delivers projections of LULUCF (Land Use, Land Use Change, and Forestry) emissions and removals of $CO_{2,eq}$ from the atmosphere and `CAPRI` model delivers agricultural activity projections.
- **Non-CO_2 GHG and air pollution:** `GAINS` model provides non-CO_2 emissions projections and air pollution impact assessments.

All models can be used independently in their specific domains, or coupled together to deliver a full situation of the energy, transport, GHG emissions and economic systems, each one using the results of the other models.

The aim of this thesis is to define the energy demand for the following sectors: industrial, residential, tertiary and transport. Then, only PRIMES and PRIMES-TREMOVE are to be further developed.

PRIMES PRIMES energy system model provides detailed projections of energy demand, energy supply, prices and investments, covering the entire energy system. This model covers the whole energy system by sectors. Moreover, PRIMES handles multiple policy objectives, such as reduction of GHG emissions, energy efficiency, and renewable targets.

In addition, PRIMES takes the results on macroeconomic and multi-sectorial projections from GEM-E3, and projections of the energy prices from POLES-JRC as inputs. The projections made by PRIMES are then transmitted to GAINS, GEM-E3, CAPRI and GLOBIOM models.

PRIMES-TREMOVE PRIMES-TREMOVE transport model projects the evolution of the demand for passengers and freight transport by transport modes, and transport vehicles/technologies. PRIMES-TREMOVE is based on the open source TREMOVE model [17] that estimates the transport demand, modal shifts, vehicle stock renewal and destruction decisions and emissions of air pollutants; for policies such as road pricing, public transport pricing, emission standards, subsidies for cleaner cars, etc. The model is part of PRIMES and deals with the transport system.

3.2 Key policies

The "Reference Scenario" is based on policies at EU and Member States levels and considers the policies taken until December 2019 (cut-off date) in the fields of transport, energy, and climate. These policies are considered to be implemented until 2030 and continue afterwards, assuming no additional measures applied between 2030 and 2050. The energy trends of the period 2020-2030 are extended until 2050, but at a slower pace.

The EU level policies considered in the "Reference Scenario" include the directives and regulations included in the "Clean Energy for All Europeans" package, the revised EU ETS Directive, and key transport policies such as the CO_2 standards for vehicles, the directive on alternative fuels infrastructure, the Clean Vehicles Directive, etc.

The Member States policies considered in the "Reference Scenario" are the ones constituting the National Energy and Climate Plans (NECPs). They include in particular the coal phase-out and nuclear related policies.

3.3 Projections of the demand

This section is inspired from the "EU Reference Scenario 2050" report [8]. Its aim is to define the EUD of the HD scenario. The graphs presented are our own, based on the EC data [15].

Historically, the energy consumption increased until a peak in 2006, right before the financial crisis of 2007-2009. From that moment on, the energy consumption decoupled from the economic growth. Then, the rebound in energy consumption due to the post COVID-19 pandemic is projected to last until 2025, before resuming its downward trend. The energy efficiency and renewable energy sources targets policies should sustain the decoupling after 2030, according to the European Commission. Figure 3.2 shows the decoupling between the GDP which is projected to increase, and the FEC which is projected to decrease slightly.

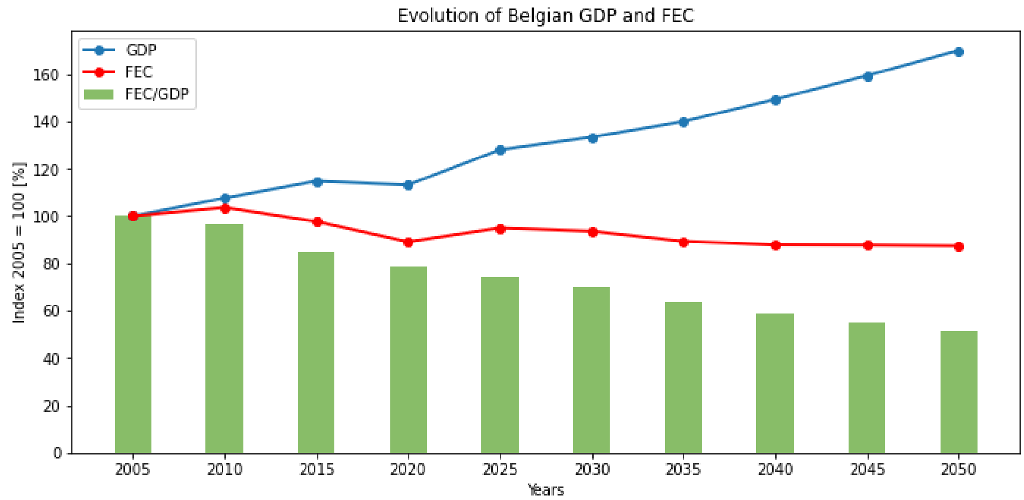


Figure 3.2: Belgian GDP and FEC trends, showing their decoupling over time. Data used: EC [15].

The energy consumption trends by sector are shown in Figure 3.3. The main trend is towards a general decrease of the energy demand, after a post COVID-19 rebound. This projected decrease is a consequence of the existing policies in December 2019, both at EU and Member States levels, including a general improvement in the efficiency. In Belgium, the energy consumption trend is different depending on the sectors. Demands from the transportation and residential sectors are projected to decrease slightly, while demand from the tertiary sector is stabilizing and demand from the industrial sector is projected to increase. This graph does not include the non-energy demand (NED) which is projected to be 55 TWh in 2050.

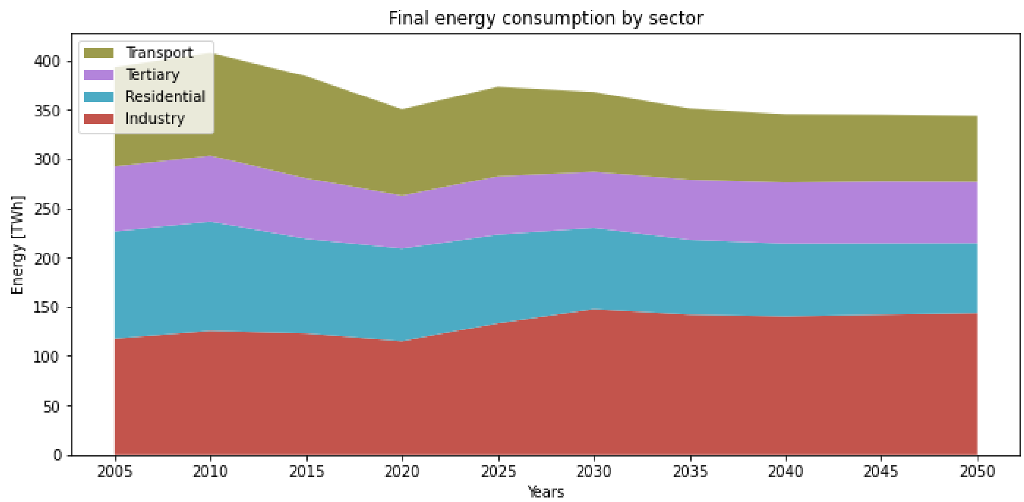


Figure 3.3: Belgian final energy consumption by sector. Data used: EC [15].

The demand matrix completed for the HD scenario is presented in Table 3.1. The methodology used to complete it is explained in Appendix A. In his PhD thesis, Gauthier Limpens approximates the EUD with the FEC projections to complete this demand matrix, which is a conservative assumption [6].

	HOUSEHOLDS	SERVICES	INDUSTRY	TRANSPORT.	Units
ELECTRICITY	9212.6	12814.7	51287.5	0	[GWh]
LIGHTING	4960.6	9997.2	16892.9	0	[GWh]
HEAT_HIGH_T	0	0	56713.3	0	[GWh]
HEAT_LOW_T_SH	45360.0	32023.1	14753.0	0	[GWh]
HEAT_LOW_T_HW	11595.0	7178.5	3822.4	0	[GWh]
MOB._PASSENGER	0	0	0	159270.5	[Mpkm]
MOB._FREIGHT	0	0	0	92766.4	[Mtkm]
NON_ENERGY	0	0	55012.1	0	[GWh]

Table 3.1: Energy demand matrix of the HD scenario.

Residential sector The residential sector is modelled in `PRIMES`, which considers 270 building categories, depending on the building type, geographic location, age of construction, income classes and service sub-sectors. The major share of energy demand is for space heating, even though this demand is reduced due to efficiency improvements (renovation and more efficient space heating equipment). The cooling demand increases with time, due to a more affordable market, and the increase of the cooling degree days (CDD), due to climate change. Cooking and water heating are considered to stabilise, while the efficiency of lighting continues at the same pace and the electric appliances demand increases.

In Belgium, the projection of energy demand of the residential sector in 2050 is **71.1 TWh**.

Tertiary sector The tertiary sector includes the services and the agriculture. As the agriculture is not taken into account in `EnergyScope TD`, this sector won't be further developed. Concerning the services sector, its energy efficiency improvements are significant, following the residential sector. Space heating continues to be the largest energy use. However, it drops thanks to efficiency improvements. The renovation rate is lower in services sector than in residential sector, but its demolition-reconstruction rate is higher, leading to deeper energy savings. The specific electricity use has the highest increase, due to a higher technology use and the increase use of electric appliances.

In Belgium, the projection of energy demand of the tertiary sector in 2050 is **62.0 TWh**.

Industrial sector The model assumes a gradual shift towards high value-added industrial products over time in an international competition context. Different policies are taken into account for the industrial sector, including the Circular Economy Action Plan (2015) [18]. The recycling of materials is considered to progress over time, leading to a reduction in the energy demand, as recycled materials are less energy intensive than non-recycled ones [8]. The modelling suite includes 10 categories of industries, like iron and steel, building materials or non-energy sectors.

In Belgium, the projection of energy demand of the industrial sector in 2050 is **198.5 TWh**.

Transport sector For the transport sector, the demand is directly given in terms of EUD. Hence, the unit used to define the transport of passengers and the transport of goods are respectively the pkm (passenger kilometre) and the tkm (ton kilometre), since the service required is to go from a point A to a point B, no matter the transport mode. The transport sector is the most impacted sector following the COVID-19 pandemic, since the population was not allowed to move around. However, the "Reference Scenario" projects that this sector will return to a pre-pandemic level in 2030. It even projects an increase of the mobility EUD, with a faster increase for the freight mobility.

Figures 3.4 and 3.5 show the evolution of the mobility EUD and its projected modal distribution for passenger and freight mobilities, respectively. This modal share is only informative, as `EnergyScope TD` only considers the total EUD, and will distribute it between the different transport modes. The projection of passenger mobility for Belgium in 2050 is **159.3 Gpkm**, including the intra-EU aviation. We make here the assumption that the travels realised historically by plane within Europe (short-haul flights) will be realised in 2050 by other transport modes. This represents 11.6% of the passenger mobility EUD. The modal share of intra-EU aviation is shifted to car, train, and bus. The share of public transport is an interesting parameter. In this scenario, it is 20.5%. Moreover, the projection of freight mobility is **92.8 Gtkm**. Consequently, the passenger mobility per capita is 13354 pkm/cap and for the freight mobility, 7778 tkm/cap.

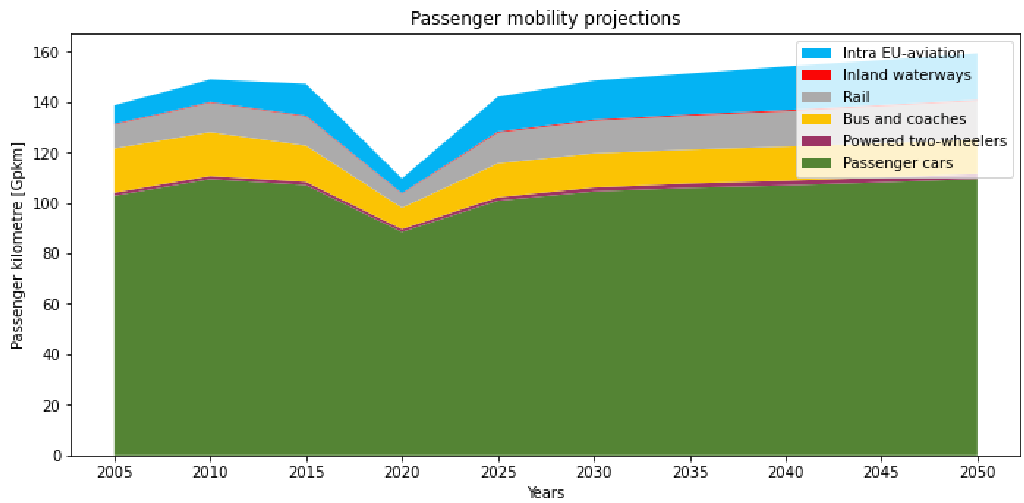


Figure 3.4: Passenger mobility EUD by transport mode. Data used: EC [15].

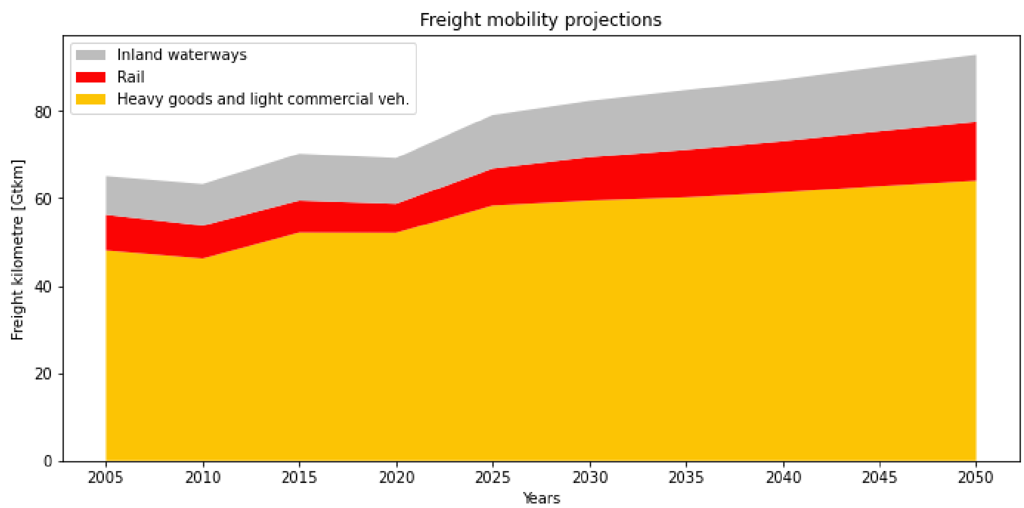


Figure 3.5: Freight mobility EUD by transport mode. Data used: EC [15].

3.4 High demand matrix analysis

The total yearly EUD in the HD scenario (based on the European Commission projections) is **374.1 TWh** for Belgium in 2050.

Figure 3.6 shows the distribution of the EUD by sector. The sector with the greatest EUD is the industry, which represents alone more than half of the total EUD, including the NED.

Figure 3.6: EUD by sector for the HD scenario.

The energy needed to provide the passenger and freight mobilities EUD, approximated by their FEC (see Chapter 2 for an explanation of the difference between EUD and FEC), are taken from the `EnergyScope TD` simulation of the HD scenario (see Section 5.1), to stay coherent with future analyses. This includes 3.1 TWh of public mobility, 19.7 TWh of private mobility and 19.7 TWh of freight mobility.

The distribution of total EUD between the EUI is shown in Figure 3.7. The electricity bar includes the EUI "electricity" and "lighting" which are the constant and variable shares of the electricity demand, as explained in Section 2.1. The LT heat bar includes the EUI "heat low T SH" and "heat low T HW", the variable and constant shares of the LT heat demand. The main EUI are the electricity and the LT heat.

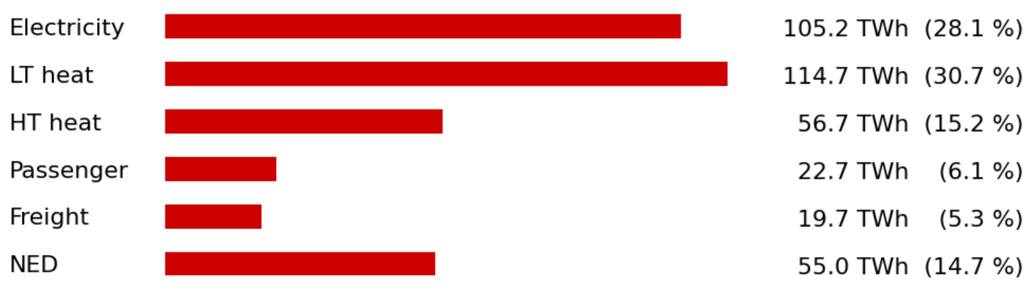


Figure 3.7: Energy consumption by EUI for the HD scenario.

3.5 Comparison to the 2015 demand

The energy consumption in 2020 was largely impacted by the COVID-19 pandemic, and then cannot be used as a reference for comparison. This is why the year 2015 was chosen for comparison. The demand matrix of 2015 is presented in Table 3.2.

	HOUSEHOLDS	SERVICES	INDUSTRY	TRANSPORT.	Units
ELECTRICITY	12464.4	12678.9	29888.2	0	[GWh]
LIGHTING	6711.6	9891.3	9844.5	0	[GWh]
HEAT_HIGH_T	0	0	62559.6	0	[GWh]
HEAT_LOW_T_SH	61371.0	31683.8	16273.8	0	[GWh]
HEAT_LOW_T_HW	15687.7	7102.4	4216.5	0	[GWh]
MOB._PASSENGER	0	0	0	147161.8	[Mpkm]
MOB._FREIGHT	0	0	0	70194.7	[Mtkm]
NON_ENERGY	0	0	46171.6	0	[GWh]

Table 3.2: 2015 EUD matrix.

The comparison of the EUD by sector between 2015 and 2050 is shown in Table 3.3 and illustrated in Figure 3.8. The total EUD for 2015 is 391.9 TWh. The EUD projections of the EC for 2050 are 4.5% lower, leading to a reduction of the energy that must be supplied.

We notice a large increase of the energy consumption in the industrial sector (+17.5%), a stabilisation in the tertiary sector (+1.1%), and a large decrease in both the residential (-26.1%) and the transport sectors (-35.0%). In addition, the share of public mobility in 2015 was 17.9% and is projected to increase to 20.5% in 2050. This increase is due to the consideration of public mobility policies.

	2015 EUD [TWh]	2050 EUD [TWh]	Change [%]
Households	96.2	71.1	-26.1
Services	61.4	62	+1.1
Industry	169.0	198.5	+17.5
Transport	65.4	42.5	-35.0
Total	**391.9**	**374.1**	**-4.5**

Table 3.3: Comparison between the HD scenario and the 2015 EUD by sectors.

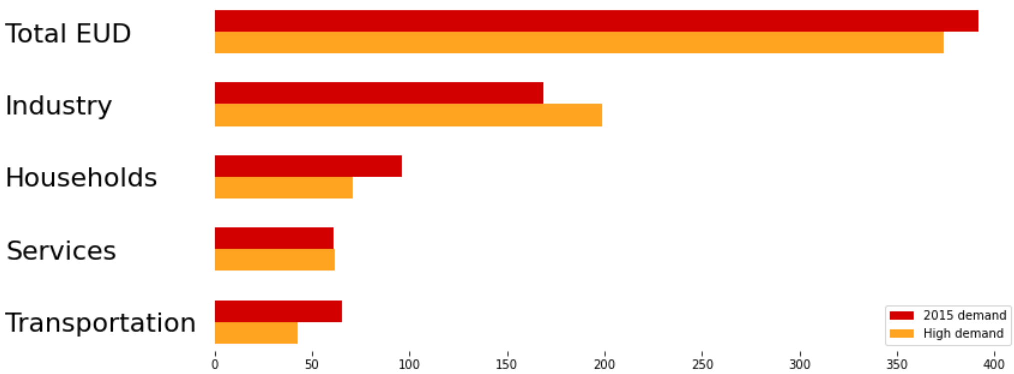


Figure 3.8: Comparison between the HD scenario and the 2015 EUD by sectors.

3.6 Limits of the European Commission projections

The projections of the European Commission about the energy consumption in 2050 show some limitations. Firstly, these projections are based on the policy framework at the cut-off date of December 2019.

However, the report was published in July 2021, which is more than one year and a half after the cut-off date. In the meantime, some important new policies appeared at the EU level. The most influencing policy is the "Delivering the European Green Deal" [5] one, including "Fit for 55", that constraints the Member States to reduce their GHG emissions by at least 55% compared to 1990 levels. Therefore, the projections are not up-to-date. Hence, the approach is conservative, as new policies adopted since December 2019 would rather decrease the projections of consumption than increase them.

Moreover, the EC considers the policy framework on December 2019 to last only until 2030. Consequently, the projections cannot be precise, since no additional policy is considered between 2030 and 2050, and the only change in the consumption is the remaining effects of these policies. The "Reference Scenario" is not a forecast, but it is a projection based on a policy framework, that will evolve with time and the actual consumption in 2050 will certainly not be the same as their projections.

Chapter 4

Low demand scenario: Decent living with minimum energy

This chapter deals with the low demand (LD) scenario. It represents the minimum energy that each individual would need to have a decent living. This is the lower bound of the energy demand considered in this thesis.

This chapter aims to complete the demand matrix used by `EnergyScope TD` for the LD scenario. To do so, the article "Providing Decent Living with Minimum Energy: A Global Scenario" [2] and its "Supplementary material" [19] are used. This article will be named the "Decent Living" article throughout the chapter, for ease of reading. The article follows a bottom-up approach.

The idea of this approach is to build a consumption scenario by compiling consumption services and goods. It starts with no consumption and adds the consumption considered needed for a decent living. This approach tends to underestimate the energy demand, because services or goods are more likely to be omitted than double counted. Climact and négaWatt use this approach. They estimate consumption services such as the floor space, or the volume of hot water consumption per capita, for example. On the other hand, the top-down approach starts with a reference consumption and subtracts the energy associated to services that can be avoided, or the impact of new policies, it is the case of the European Commission approach (in its report "EU Reference Scenario 2050").

Millward-Hopkins et al.[2] consider each individual on earth equal in their needs, without consideration of wealth or cultural influence of consumption, this is a global approach. The only differences between countries taken into account in the establishment of the energy needs are outdoor temperature, age structure, climate, degree of urbanisation, population density and water scarcity.

The majority of the parameter values used to define the EUD are taken directly from the supplementary material [19]. In some cases, they are refined by a more detailed search in the sources of the "Decent Living" article [2]. In other cases, they are adapted for Belgium to take into account a more accurate reality. For example, for services, they only considered education, health, and retail. Offices, hotels, and restaurants are added in this scenario.

The chapter starts with a discussion on two major demographic parameters: the population and the degree of urbanisation projections for Belgium in 2050. Afterwards, the Decent Living Standards (DLS), which are the minimum services required for a decent living, are presented. And then, the EUD will be presented by sectors: households, services, transports, and industry; and an adjustment of the demand matrix will be done to equalise the levels of demand reduction across sectors. The major parameters and assumptions will be developed. The detailed explanation of the methodology is presented in Appendix B. The demand matrix is then analysed and compared to the HD scenario and to the demand of 2015. Finally, the limitations of the methodology are presented.

4.1 Population and degree of urbanisation projections

The projection of the population is a key parameter in the estimations of the EUD because the high and low demand scenarios EUD will be compared. They must be based on the same population. In addition, the parameters set by Millward-Hopkins et al. [2] are given per capita. Indeed, the minimum of energy consumption for a decent living is set for each individual.

On the 1st of January 2021, Statbel (the Belgian statistical office) counted 11 521 238 inhabitants in Belgium [20]. The European Commission (via EUROSTAT) projects a population of **11 926 987 inhabitants** in 2050 [21], which is an increase of about 3.5%. As the HD scenario is based on this projection, this is the one that is chosen for the further calculations. For the record, Statbel predicts 12 499 666 inhabitants in Belgium in 2050 [22]. Actually, it is not important to have the most accurate projection of the Belgian population in 2050. What is important is rather to compare what is comparable. So, it is important to use the same population projection in both scenarios (high and low demand).

The degree of urbanisation is an important parameter for the passenger mobility, which is different for urban and rural inhabitants. The definition considered in this thesis is the one of Eurostat [23] and is developed in Appendix B.1. It leads to a degree of urbanisation of 82% in Belgium [24]. This value is considered constant until 2050.

4.2 Decent Living Standards

Hereafter, the minimum standards defining a decent living, called the Decent Living Standards (DLS), are presented. They are either taken directly from the "Decent Living" article, or adapted to correspond to the Belgian reality. Direct and indirect energy consumptions are related to each of these services. The direct consumptions are categorised in residential, tertiary and transport sectors. The indirect energy consumptions (energy embodied in the manufactured goods, in the infrastructures etc.) are attributed to the industrial sector.

- Households:
  - **Household size:** 2.5 persons/household
  - **Floor space:** 28 m^2/cap
  - **Illumination:** 6h/day, 33% of the house
- Nutrition:
  - **Food:** 2000 kcal/cap/day
  - **Cooking appliances:** 1 cooker/household
  - **Cold storage:** 1 fridge-freezer/household
- Clothing:
  - **New clothes:** 4 kg/year
  - **Washing facilities:** 1 washer/household (78 kg of washing/cap/year)
- mobility:
  - **Passenger:** 3910-6014 pkm/cap/year
  - **Freight:** 2309 tkm/cap/year
  - **Vehicle production:** consistent with pkm
  - **Infrastructure:** consistent with pkm
- Water:
  - **Water supply:** 50L/cap/day
  - **Water heating:** 20L/cap/day
- Communication and information:
  - **Phones:** 1 phone/person (over 10 yo)
  - **Computers:** 1 laptop/household

In addition, the services sector is composed of education, health, retail, offices and other services (including hotels and restaurants).

4.3 Definition of the demand

As the "Decent Living" article follows a bottom-up approach, the energy consumption calculations have a high level of details, starting from assumptions of DLS. In this section, the methodology used to compute the EUD is summarised for each of the four sectors independently. Its aim is to provide the data required to complete the demand matrix, shown in Table 4.1. The demand matrix is analysed in Section 4.4.

	HOUSEHOLDS	SERVICES	INDUSTRY	TRANSPORT.	Units
ELECTRICITY	2270.6	1054.5	12776.9	0	[GWh]
LIGHTING	1222.7	822.7	4208.4	0	[GWh]
HEAT_HIGH_T	0	0	14128.5	0	[GWh]
HEAT_LOW_T_SH	4815.6	2467.9	3675.3	0	[GWh]
HEAT_LOW_T_HW	4243.4	590.7	952.3	0	[GWh]
MOB._PASSENGER	0	0	0	51152.1	[Mpkm]
MOB._FREIGHT	0	0	0	27539.4	[Mtkm]
NON_ENERGY	0	0	13704.7	0	[GWh]

Table 4.1: Energy demand matrix of the LD scenario.

4.3.1 Households

The surface of the households is a predominant parameter for the heating demand, as well as the average household size (persons/household). The decision was made to fix the household size to 2.5 persons/household in 2050. This is an ambitious goal, since the current mean size of the households is 2.3 and the trend is rather towards a decrease in the EU [25]. The floor area that we consider is 28 m^2/cap, which follows the "high demand" scenario of the "Decent Living" article (still an ambitious scenario) [2]. The average floor area estimated by négaWatt Belgium [26] in 2020 was 55 m^2/cap, which is almost twice the space considered in this thesis. The average household floor area is then 70 m^2 ($=2.5 \cdot 28$).

The residential sector EUD is composed of electricity and LT heat EUD (including constant and variable shares).

Electricity In the households sector, the specific electric EUD is computed based on the direct consumption of the electric appliances considered as DLS. Their consumptions are summarised in Table 4.2. Cooking is considered to be fully electrified in 2050 and represents the main electricity consumption in the households (45.7%).

	EUD [GWh]
Cooking	1596.2
Cold storage	572.5
Clothes washing	773.9
Phones	51.7
Computers	295.8
Illumination	203.2
Total	**3493.3**

Table 4.2: Households electricity EUD.

The electricity EUD is divided in a constant and a variable shares, as explained in Section 2.1. Their ratio in the residential sector are the same considered for the HD scenario and are 65% and 35%, respectively [27]. The constant share of electricity EUD is 2270.6 GWh (the "electricity" EUI) and the variable share is 1222.7 GWh (the "lighting" EUI).

Heat The heat EUD is also divided in a constant and a variable shares. They are water heating and space heating EUD, respectively. The volume of water consumed by each individual is 48 L/day, of which 20 L are heated. This represents 4243.4 GWh of water heating EUD, for the residential sector.

For space heating, we consider the heating intensities given by the Global Building Performance Network (GBPN) [28]. For a new building, with state-of-the-art energetic standards, they estimate that the heating intensity of the residential buildings is 14.4 kWh/m^2, for a region like Belgium (Western EU, with high heating demand, and low cooling demand). The heating intensity of a building is the energy required to heat 1 m^2 during one year. Low energy intensities consider high degree of insulation, low temperature needed, high efficiency of the heat provider, etc. The space heating EUD for households is 4815.6 GWh.

4.3.2 Services

The tertiary sector is composed of different service categories. We consider here the education, health, retail, offices and other services (including restaurants, hotels, etc.). Their surfaces for Belgium are estimated by Climact until 2050 in their Pathways Explorer [29]. Although agriculture is sometimes considered by energy models, `EnergyScope TD` does not include it. It is then not treated in this work. Table 4.3 summarises the surfaces by service categories and includes their heating intensities to define the total space heating EUD of the tertiary sector. The heating intensities are once again taken from the GBPN data [28].

	Surface [Mm^2]	Heating intensity [kWh/m^2]	**EUD 2050 [GWh]**
Education	30.9	13.0	**400.6**
Health	9.9	11.7	**115.8**
Retail	39.6	11.5	**456.7**
Offices	97.5	10.5	**1024.6**
Others	32.6	14.4	**470.2**
Total	**210.4**	**11.7**	**2467.9**

Table 4.3: Services space heating EUD.

Millward-Hopkins et al. [2] make a strong assumption on the electricity, lighting and hot water EUD for the tertiary sector. They estimate the energy consumption of these three EUD together to be equal to the EUD of space heating. The heating intensities correspond to the best norms for new buildings, and are highly ambitious. Consequently, the other EUD are also highly ambitious, as they are defined proportionally to the space heating EUD. The ratios between electricity, lighting and hot water EUD are the one of the HD scenario. The assumption that space heating accounts for the half of the tertiary sector energy consumptions is coherent, since it accounts for 51.6% in the HD scenario.

4.3.3 Transportation

The EUD of the transportation sector is not an energy based unit, but is based on the kilometres travelled by passengers (pkm) or tons of goods (tkm).

Passenger mobility The passenger mobility depends on the degree of urbanisation. Indeed, the inhabitants of urban areas need to travel less than the rural inhabitants, thanks to the higher proximity in cities. The passenger mobility EUD is 4909 pkm/cap for urban inhabitants and 7014 pkm/cap for rural inhabitants. This is adapted to fit the transport modes that are considered by `EnergyScope TD`. The soft mobility (1000 pkm/cap) is subtracted from the total EUD. The same assumption as in Section 3.3, concerning the aviation is made. Its modal share is shifted to train, bus and car. The total passenger EUD is shown in Table 4.4. The passenger mobility EUD is distributed in three transport modes: train (40%), bus (40%) and car (20%). Therefore, the share of public mobility is 80%.

	Urban	Rural
Distance [pkm/cap]	3910	6014
Percentage of living population [%]	82	18
Total mobility demand [Mpkm]	**51152.1**	

Table 4.4: Passenger mobility EUD.

Freight mobility The freight mobility is estimated to be 2309 tkm/cap [30]. This distance is shared between road and rail mobilities, at 1495 tkm/cap (65%) and 814 tkm/cap (35%), respectively. The total EUD is 27539.4 Mtkm.

4.3.4 Industry

As the “Decent Living” article uses a bottom-up approach, the industry sector will not reflect the current reality of the industries in Belgium. The EUD consumed by the industry sector therefore comes from the production of goods, such as electrical appliances, but also from the construction, the infrastructure dedicated to mobility, the food industry and the operation and embodied energy of collective infrastructures. In this approach, all the industrial productions consumed in Belgium are needed by Belgium, and it is assumed that no imports or exports of goods are made.

The energy required for these different categories of the industry are summarised in Table 4.5.

Category	**EUD [GWh]**
Mobility	4579.2
Household buildings	4341.4
Service buildings	9211.2
Information and communication	1896.6
Manufacturing goods	1747.7
Food industry	7266.9
Collective services	6698.2
Total	**35741.3**

Table 4.5: Industrial sector EUD.

The NED is added proportionally to the HD scenario: 13704.7 GWh.

4.3.5 Homogenisation of the demand matrix

The aim of this section is to adapt the demand matrix of the LD scenario so that the difference between high and low demand scenarios EUD is in the same range for each of the sectors. Table 4.6 compares each cell of the demand matrix by showing the ratio of the HD scenario EUD divided by the LD scenario EUD. If we found 4 for example, it means that the LD scenario has an EUD that is 4 times lower than the one of the HD scenario. This table helps to understand how ambitious a demand is compared to the HD scenario.

	HOUSEHOLDS	SERVICES	INDUSTRY	TRANSPORT.
ELECTRICITY	4.1	12.2	4.0	-
LIGHTING	4.1	12.2	4.0	-
HEAT_HIGH_T	-	-	4.0	-
HEAT_LOW_T_SH	9.4	13.0	4.0	-
HEAT_LOW_T_HW	2.7	12.2	4.0	-
MOBILITY_PASSENGER	-	-	-	**3.1**
MOBILITY_FREIGHT	-	-	-	**3.4**
NON_ENERGY	-	-	4.0	-
Total	**5.7**	**12.6**	**4.0**	**-**

Table 4.6: Ambition of the LD scenario matrix.

The residential sector is the less homogeneous sector, with ratios ranging from 2.7 for water heating to 9.4 for space heating. For the former, only the volume of water to heat and the increase in temperature can be modified, with low possible changes. For the latter, the high ratio is due to the consideration of ultra efficient buildings and a low surface to heat per capita. The averaged ratio is 5.7. As the same ratio of consumption has been considered for the tertiary sector in both scenarios, the ratios are almost homogeneous, at 12.6. The same reasoning leads to a global ratio of 4.0 for the industrial sector. The transportation sector shows a similar demand reduction between the passenger and the freight mobilities, around 3 times lower EUD.

When considering the ratios at the level of the sectors, the services sector seems really ambitious (12.6) compared to the other ones [3.1 - 5.7]. This difference is due to the methodologies that are different for each sector in the "Decent Living" article [2]. For the tertiary sector, the consideration of the energy consumption does not go deep in the details specific to each service, as the main assumption was to consider the space heating EUD to be half of the tertiary sector EUD. No specific detail was considered for restaurants, or hospitals, for which the consumption is not the same as for offices, for example.

To have ratios ranging at the same scale and homogenise the demand matrix, we make the assumption that the EUD of the tertiary sector is twice the one found in Section 4.3.2, leading to a factor of 6.3. The final demand matrix for the LD scenario is shown in Table 4.7.

	HOUSEHOLDS	SERVICES	INDUSTRY	TRANSPORT.
ELECTRICITY	2270.6	2109.0	12776.9	0
LIGHTING	1222.7	1645.4	4208.4	0
HEAT_HIGH_T	0	0	14128.5	0
HEAT_LOW_T_SH	4815.6	4935.8	3675.3	0
HEAT_LOW_T_HW	4243.4	1181.4	952.3	0
MOBILITY_PASSENGER	0	0	0	51152.1
MOBILITY_FREIGHT	0	0	0	27539.4
NON_ENERGY	0	0	13704.7	0

Table 4.7: Final LD scenario matrix.

This increase of the services EUD represents an increase in the total electricity EUD of 8.4%. For the heat EUD, the increase is 18.3%. The impact on the energy system is not consequent. As explained later, the only low temperature heat provider consists of heat pumps. When considering the increase in electricity EUD and the one required by the heat pumps, at the electricity layer, this leads to an increase of the electricity production of 6.3% for the LD scenario.

4.4 Low demand matrix analysis

The total EUD in the LD scenario is **85.4 TWh** for one year, in Belgium. This demand is 4.38 times lower than the projections of the European Commission (374.1 TWh). It represents a decrease of 77.2% of the total EUD.

Figure 4.1 shows the EUD of the LD scenario by sectors. The industrial sector has the highest EUD, it represents more than half of the total EUD.

Figure 4.1: Energy consumption by sector for the LD scenario.

Figure 4.2 shows the EUD distribution by EUI. The electricity bar includes the EUI "electricity" and "lighting" which are the constant and variable shares of the electricity demand, as explained in Section 2.1. The heat LT bar includes the EUI "heat low T SH" and "heat low T HW", the variable and constant shares of the low temperature heat demand. The main EUD are the electricity and the LT heat.

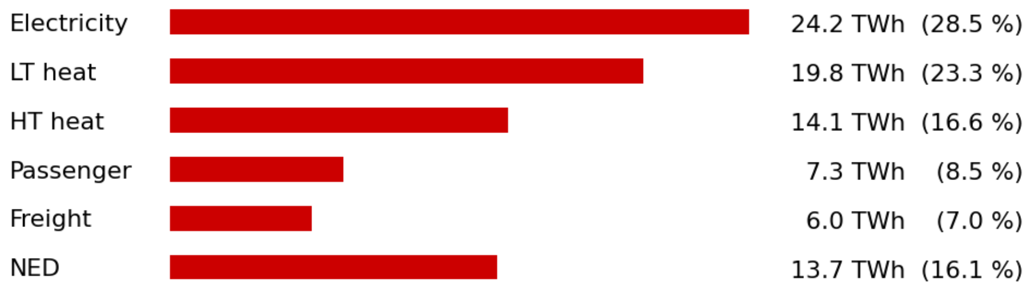


Figure 4.2: Energy consumption by EUI for the LD scenario.

4.5 Comparison to the high demand scenario and the 2015 demand

Table 4.8 compares both high and low demand scenarios to the actual demand of 2015. As mentioned previously, 2015 is chosen as it is the most recent year for which the European Commission gives data in their database [15], excluding 2020 as it was impacted by the COVID-19 pandemic and then cannot be the reference.

At the total EUD level, the HD scenario consumes 5% less EUD and the LD one requires 78.2% less EUD than in 2015. Figure 4.3 illustrates the changes for each sector and for the total EUD.

	2015 EUD [TWh]	High 2050 EUD [TWh]	Change [%]	Low 2050 EUD [TWh]	Change [%]
Households	96.2	71.1	-26.1	12.6	-86.9
Services	61.4	62	+1.1	9.9	-83.9
Industry	169.0	198.5	+17.5	49.4	-70.8
Transport	65.4	42.5	-35.0	13.2	-79.8
Total	**391.9**	**374.1**	**-4.5**	**85.4**	**-78.2**

Table 4.8: Comparison of both high and low demand scenarios with 2015 demand.

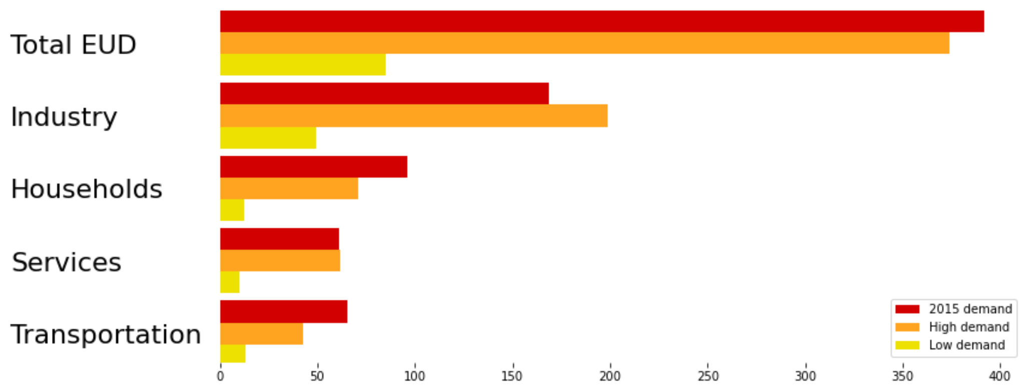


Figure 4.3: Comparison of both high and low demand scenarios with 2015 demand.

4.6 Limits of the methodology

The "Decent Living" article [2], on which the LD scenario is based, shows some limitations. The main one is the fact that this is a global methodology. The ambition of the article is to define the minimum energy needs to have a decent living, for every country in the world, taking into account their geographic and demographic differences, as well as their climate. Then, the quantification of the parameters was not always precise. In order to reduce this limitation, we have specified certain parameters or methodologies.

Another limitation is the main one when using a bottom-up approach, which is the omission of certain consumptions. Indeed, the methodology consists in defining the consumption considered essential. When doing this inventory, some sectors could have been forgotten. This is the case with the services sector. They only considered education, health and retail, while we added the offices and other services (hotel, restaurant etc.).

Chapter 5

Results

This chapter presents the simulation and the results related to the demand scenarios defined in the range of total EUD established by both high and low demand scenarios. The demand matrix and the public transport share are used as varying parameters between the scenarios.

The energy systems of the boundary demand scenarios are analysed in this chapter, with a focus on the primary energy required to meet the EUD[1]. The Sankey diagrams representing the energy system are shown to visualise the energy fluxes between the primary resources, the conversion technologies and the EUD. Sankey diagrams are *"a type of flow diagram in which the width of the arrows is proportional to the flow rate"*, according to Wikipedia[2]. The Sankey diagram is used as a tool that represents the energy conversions inside the energy system.

When the energy system of the scenarios at the extremities of the EUD range are presented, intermediate scenarios are constructed in the EUD interval. These intermediate scenarios are defined by their demand matrix and by their share of public mobility. The objective of this chapter is to identify changes in the energy system, depending on the EUD reached in 2050. The scenarios at which these changes occur are called tipping points.

5.1 High demand energy system analysis

The energy system of the HD scenario is modelled by `EnergyScope TD` by minimising its cost. The resulting energy system is the one that considers the European Commission's projections of the energy consumption, for Belgium in 2050. This is one of the possible carbon-neutral energy systems. It considers a 4.5% reduction of the EUD compared to 2015. Moreover, this is the scenario with the highest total EUD considered in this work.

5.1.1 Primary resources

The total EUD of the HD scenario was computed in Chapter 3 and is 374.1 TWh. It is an input to the model. Next, the primary energy resources is 349.7, resulting from the simulation of the energy system. The total EUD is met by converting primary resources into this EUD, with the help of conversion technologies.

[1] `EnergyScope TD` takes into account the maximum energy potentials presented in Section 2.2.
[2] https://en.wikipedia.org/wiki/Sankey_diagram

Logic would tell that the quantity of primary resources should be greater than total EUD, because of global efficiencies below 100%. However, low temperature heat is supplied exclusively by heat pumps which efficiencies are above 100%. The DHN (District Heating Network) heat pumps have a Coefficient of Performance (COP) of 4.2, while the decentralised heat pumps have a COP of 3.2. It means that for 1 kWh of electricity provided to DHN heat pumps, 4.2 kWh of heat low temperature is provided to the energy system. The heat is absorbed from the ambient air and is not considered as a resource. Consequently, the output energy of heat pumps is greater than the input. Moreover, the difference in energy between the output and input of heat pumps (84.9 TWh) is higher than the losses (60.5 TWh). The losses are due to the use of the grid and DHN, but they are also due to the efficiencies of the conversion technologies. Thus, the primary energy is lower than the EUD in this scenario.

The Belgian endogenous RE is composed of wind, solar, hydro, wood and wet biomass. They are all used at their maximum potential. For wind, solar and hydro energy, they are converted into electricity, with conversion technologies: onshore and offshore wind turbines, photovoltaic panels (PV) and hydroelectric plants. Their installed power, yearly production and yearly capacity factor are presented hereafter. The yearly capacity factors are post-processed by `EnergyScope TD` to take into account for the share of energy produced during the year compared to its installed capacity.

- **Wind onshore** Installed power: 10 GW, Yearly production: 21.3 TWh, c_p: 24.3%
- **Wind offshore** Installed power: 5 GW, Yearly production: 18.0 TWh, c_p: 41.2%
- **PV** Installed power: 59.2 GW, Yearly production: 61.5 TWh, c_p: 11.2%
- **Hydro** Installed power: 0.115 GW, Yearly production: 0.5 TWh, c_p: 48.0%

In addition, wood and wet biomass are also used to their maximum availability in the HD scenario. The sum of all these endogenous RE resources is 125.0 TWh representing 35.6% of the primary energy consumed in the energy system.

Moreover, the imported electricity also has limitations due to the limited power connections with other countries. This limitation is 32.4 TWh every year, and is also entirely used in this scenario.

Primary resources	**Energy [TWh]**	**Share**
Wind	39.4	(11.2%)
Solar	61.5	(17.6%)
Hydro	0.5	(0.1%)
Wood	9.5	(2.7%)
Wet biomass	14.1	(4.0%)
Imp. electricity	32.4	(9.3%)
Imp. RE H2	15.6	(4.5%)
Imp. RE ammonia	10.6	(3.0%)
Imp. RE methanol	54.8	(15.7%)
Imp. RE diesel	2.7	(0.8%)
Imp. RE gas	108.6	(31.1%)
Total	**349.7**	**(100%)**

Table 5.1: Primary resources for the HD scenario.

Table 5.1 shows the energetic content of the primary energy used in the energy system, and Figure 5.1 illustrates the distribution. Endogenous resources account for only 35.7%, about a third of the primary energy. The importation of RE fuels and imported electricity account for 55.0% (192.3 TWh) and 9.3% (32.4 TWh), respectively. Consequently, the share of imported resources is **64.3%**.

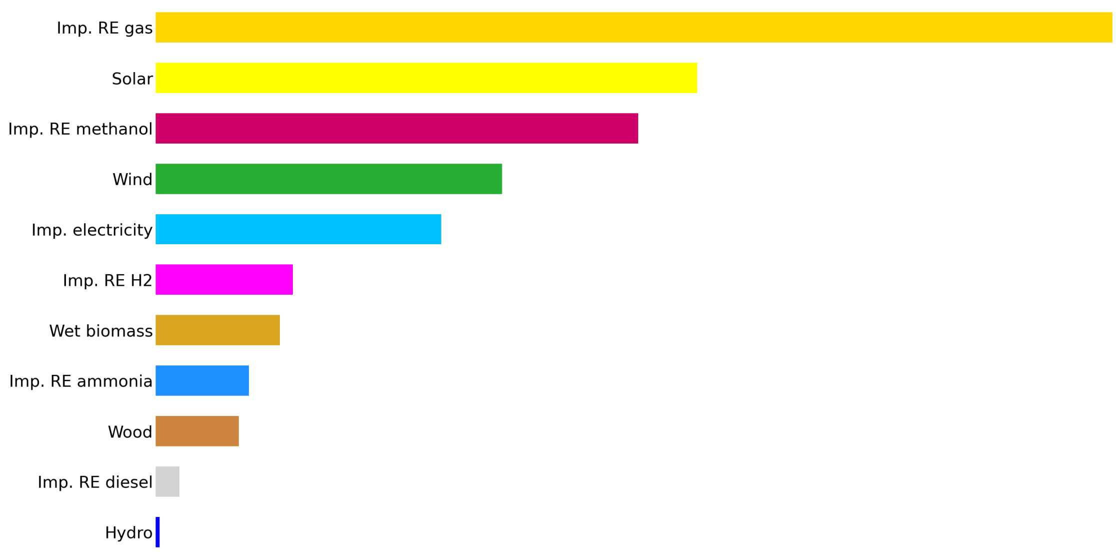


Figure 5.1: Primary resources for the HD scenario.

5.1.2 Sankey diagram

Figure 5.2 shows the Sankey diagram illustrating the energy system that meets the European Commission projections of the demand. Its analysis is based on the EUD hereafter:

- **The specific electric EUD** is 105.2 TWh, as seen previously. This is directly supplied by the electricity mix. Specific electricity represents 57.5% of the whole electricity produced.
- **The HT heat EUD** is 56.7 TWh. The majority of its production comes from the Cogeneration of Heat and Power (CHP) units, transforming SNG (Synthetic Natural Gas, it is a RE gas)) into electricity and HT heat. The other conversion technologies that produce HT heat are direct electricity, wood boilers and gas boilers. Beside the EUD, some HT heat produced is consumed by methanol-to-HVC technology, which converts the imported methanol into the HVC (High Value Chemicals) EUD.
- **The LT heat EUD** is 114.7 TWh. This is distributed between DHN and decentralised heat production. The share of LT heat dedicated to DHN is 37%. The maximum share is fixed in `EnergyScope TD` at 37% on the basis of the heat roadmap projections [9]. The fact that the maximum of authorized DHN is reached is due to its higher COP compared to decentralised LT heat production. The whole LT heat is supplied by heat pumps and consumes 33.9 TWh of electricity.
- **The passenger mobility EUD** is 159.3 Gpkm. This is provided by different transport modes. The modal share of the public mobility is 20.5%, and is supplied by train (50%), tramway (30%) that are powered by electricity, and by buses (20%) that are powered by RE gas. Their consumption is 3.1 TWh (1.5 TWh of electricity and 1.6 TWh of gas). The private mobility is supplied by Battery Electric Vehicles (BEV), consuming 19.7 TWh of electricity. The energy intensity of the passenger mobility is then 142.8 GWh/Gpkm.

- **The freight mobility EUD** is 92.8 Gtkm. This is provided by the freight train (25%), that consumes 1.4 TWh of electricity, the freight boat powered by a bio-diesel engine (30%), that consumes 2.7 TWh of bio-diesel, and the fuel-cell truck powered by hydrogen (45%), that consumes 15.6 TWh of RE hydrogen (H_2). The bio-diesel and the RE H_2 are entirely imported in this scenario.
- **The non-energy demand (NED)** is 55.0 TWh, including 42.9 TWh of HVC, 10.6 TWh of ammonia and 1.6 TWh of methanol. The HVC need is produced exclusively by the conversion of methanol into HVC. This conversion requires a consumption of HT heat of 14.1 TWh. The required methanol and ammonia are imported.

The SNG is imported at 94.8%. The rest of it is produced by bio-hydrolysis, converting wet biomass into SNG and electricity. The CHP units convert 110.8 TWh of RE gas into 51.0 TWh of HT heat and 48.8 TWh of electricity.

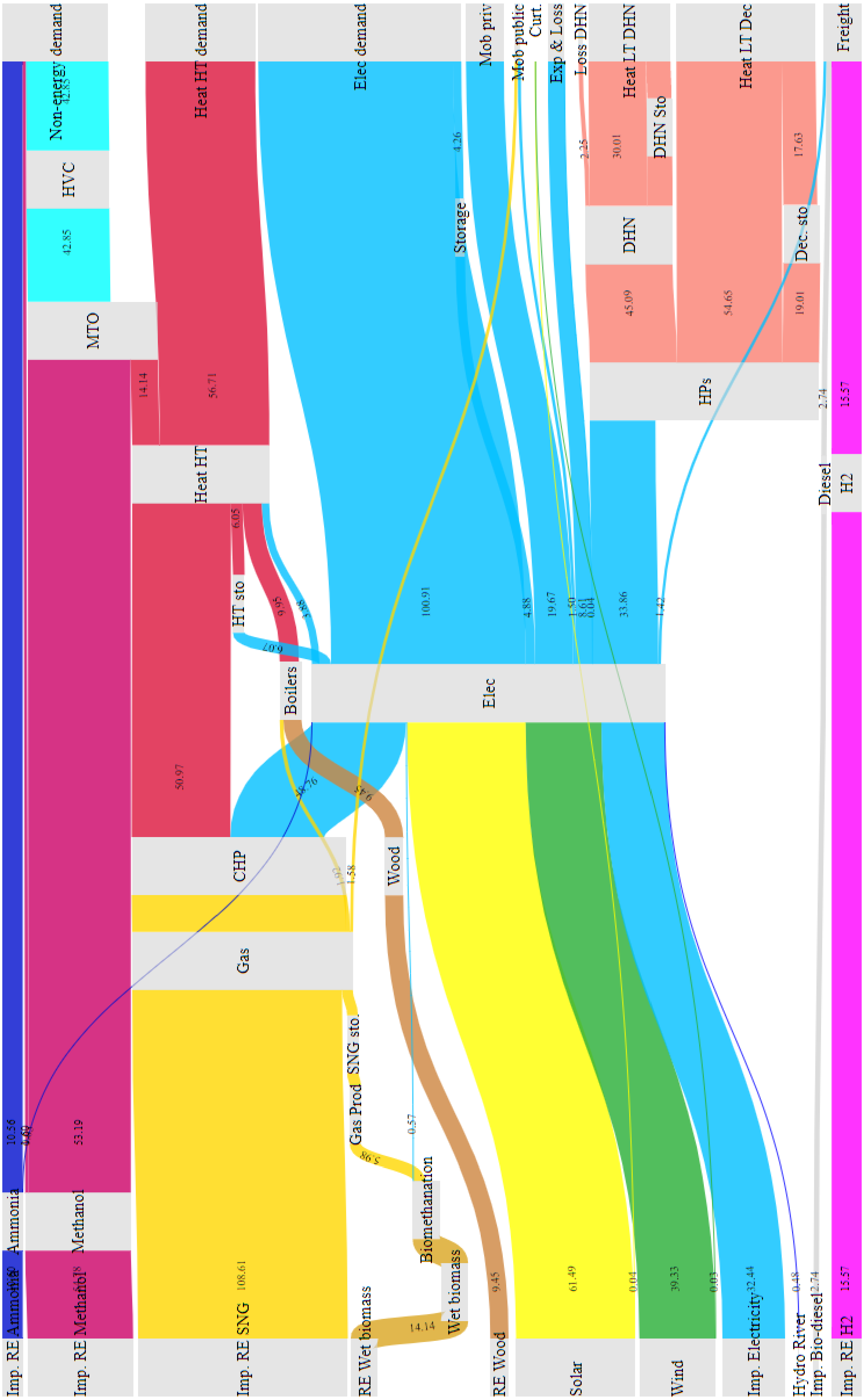


Figure 5.2: Sankey diagram of the HD scenario.

5.2 Low demand energy system analysis

The results of the LD scenario energy system are presented the same way as for the HD scenario.

The resulting energy system is the one that considers the minimum energy for a decent living after the definition of DLS for Belgium in 2050. This is one of the possible carbon-neutral energy systems. It considers a 78.2% reduction of the EUD compared to 2015. Moreover, this is the scenario with the lowest total EUD considered in this thesis, having a total EUD that is 4.38 times lower than in the high demand scenario.

5.2.1 Primary resources

The total EUD of the LD scenario was computed in Chapter 4 and is 85.4 TWh. It is an input to the model. Next, the primary energy resources is 91.0 TWh, resulting from the simulation of the energy system. The total EUD is met by converting primary resources into this EUD, with the help of conversion technologies

Like in the high demand scenario, the LT heat is exclusively supplied by heat pumps but the difference in energy between the output and input of heat pumps (14.4 TWh) is lower than the losses (20.0 TWh). Then, the primary energy resources are higher than the total EUD in this scenario.

The Belgian endogenous RE is composed of wind, solar, hydro, wood and wet biomass. It is interesting to see that their installed power is not at the maximum for each of them. For wind, solar and hydro energy, they are converted into electricity, with conversion technologies: onshore and offshore wind turbines, photovoltaic panels (PV) and hydroelectric plants. Their installed power (and share of maximum capacity), yearly production and yearly capacity factor are presented hereafter.

- **Wind onshore** Installed power: 10 GW (max), Yearly production: 21.0 TWh, c_p: 24.0%
- **Wind offshore** Installed power: 2.9 GW (57.8% of total capacity), Yearly production: 10.2 TWh, c_p: 40.5%
- **PV** Installed power: 16.2 GW (27.4% of total capacity), Yearly production: 16.7 TWh, c_p: 11.7%
- **Hydro** Installed power: 0.115 GW (max), Yearly production: 0.5 TWh, c_p: 46.7%

The wind onshore and the hydroelectricity plants are at full capacity, while wind offshore and PV are not. In addition to these electricity supply technologies, wood and wet biomass are consumed at their full potentials: 9.5 TWh and 14.1 TWh, respectively. The sum of all these endogenous RE resources is 72.0 TWh representing 79.1% of the total primary energy consumed by the energy system.

The imported electricity has a limitation, which is 32.4 TWh. This energy system imports only 3.2 TWh of electricity, which is 1% of the maximum potential (as we assume that only 10% of the capacity should be used). The remaining importations are RE ammonia and RE methanol, which are exclusively used for the NED.

Table 5.2 shows the energetic content of the primary energy used in the energy system, and Figure 5.3 illustrates the distribution. Endogenous resources account for 79% of the primary energy. The importation of RE fuels and imported electricity account for 17.4% (15.8 TWh) and 3.6% (3.2 TWh), respectively. Consequently, the share of imported resources is **21%**.

Primary resources	**Energy [TWh]**	**Share**
Wind	31.2	(34.3%)
Solar	16.7	(18.3%)
Hydro	0.5	(0.5%)
Wood	9.5	(10.4%)
Wet biomass	14.1	(15.5%)
Imp. electricity	3.2	(3.6%)
Imp. RE ammonia	2.6	(2.9%)
Imp. RE methanol	13.2	(14.5%)
Total	**91.0**	**(100%)**

Table 5.2: Primary resources for the HD scenario.

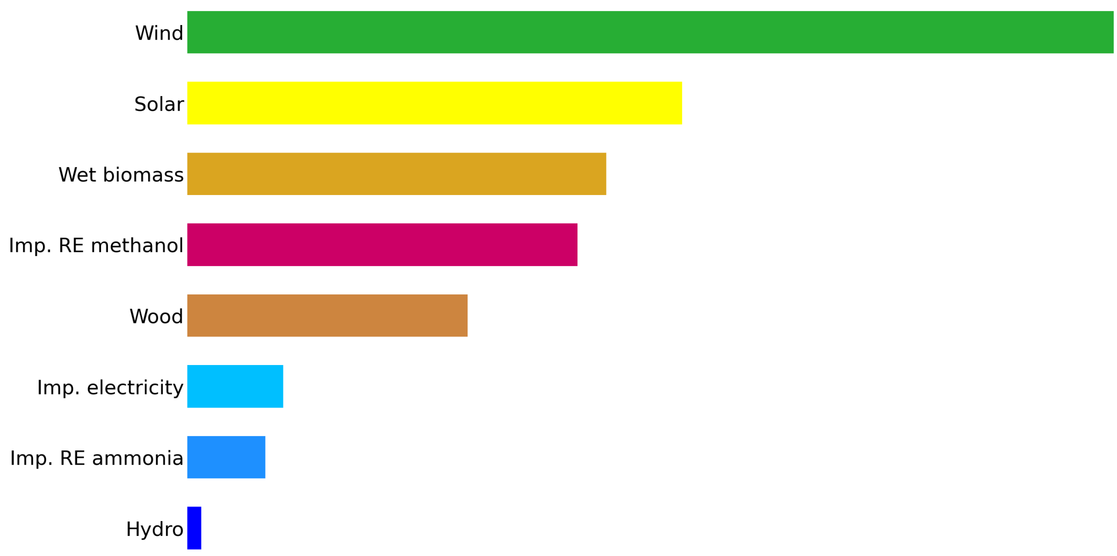


Figure 5.3: Primary resources for the HD scenario.

5.2.2 Sankey diagram

Figure 5.4 is the Sankey diagram illustrating the energy system that meets the demand of the low demand scenario. Its analysis is based on the EUD, hereafter:

- **The specific electric EUD** is 24.2 TWh, as seen previously. It is supplied by the electricity mix. Specific electricity represents 46.4% of the whole electricity produced. This is less than in the high demand scenario, due to a higher share of electrified services (HT heat and RE hydrogen via direct electricity and electrolysers, respectively).
- **The HT heat EUD** is 14.1 TWh. Its production comes from electricity and wood boilers. In addition to specific HT heat, it supplies methanol-to-HVC and electrolyser technologies.
- **The LT heat EUD** is 19.8 TWh. It is almost entirely supplied by heat pumps, with only 0.3 TWh supplied by the electrolyser and biomass to methanol, via heat recovery. The heat pumps consume 5.8 TWh of electricity.
- **The passenger mobility EUD** is 51.2 Gpkm. The modal share of public mobility is 80% and is powered by electricity for trains (26%) and tramways (30%), and by SNG for buses (44%). The

SNG is produced via biomethanation from wet biomass. Their energy consumption are 1.3 TWh of electricity and 4.3 TWh of SNG. Then, the private mobility is supplied by BEV, consuming 1.6 TWh. The energy intensity of the passenger mobility is then 141.8 GWh/Gpkm. This shows no significant difference with the high demand scenario. This is due to the fact that the same mobility technologies are used in both scenarios. The increase of the public mobility modal share should have lowered this intensity, but it is compensated by the higher use of SNG in gas powered buses that are less efficient than private BEV cars.

- **The freight mobility EUD** is 27.5 Gtkm. This is provided by the freight train (25%), that consumes 0.4 TWh of electricity, the freight boat powered by a gas engine (30%), that consumes 0.9 TWh of SNG and the fuel-cell truck powered by hydrogen (45%), that consumes 4.6 TWh of RE H2. The SNG is produced by biomethanation of wet biomass and RE H2 is produced by electrolysers consuming electricity and a little of heat HT. The energy intensity of the freight mobility is 216.6 GWh/Gtkm. This shows no significant difference with the high demand scenario. This is logic, since the freight technologies didn't change between both scenarios, except for the boat mobility, that changes from bio-diesel engine to RE gas engine.
- **The non-energy demand (NED)** is 13.7 TWh, including 10.7 TWh of HVC, 2.6 TWh of ammonia and 0.4 TWh of methanol. The HVC need is produced exclusively by the conversion of methanol into HVC. This conversion requires a consumption of heat HT of 3.5 TWh. The required RE methanol and RE ammonia are imported.

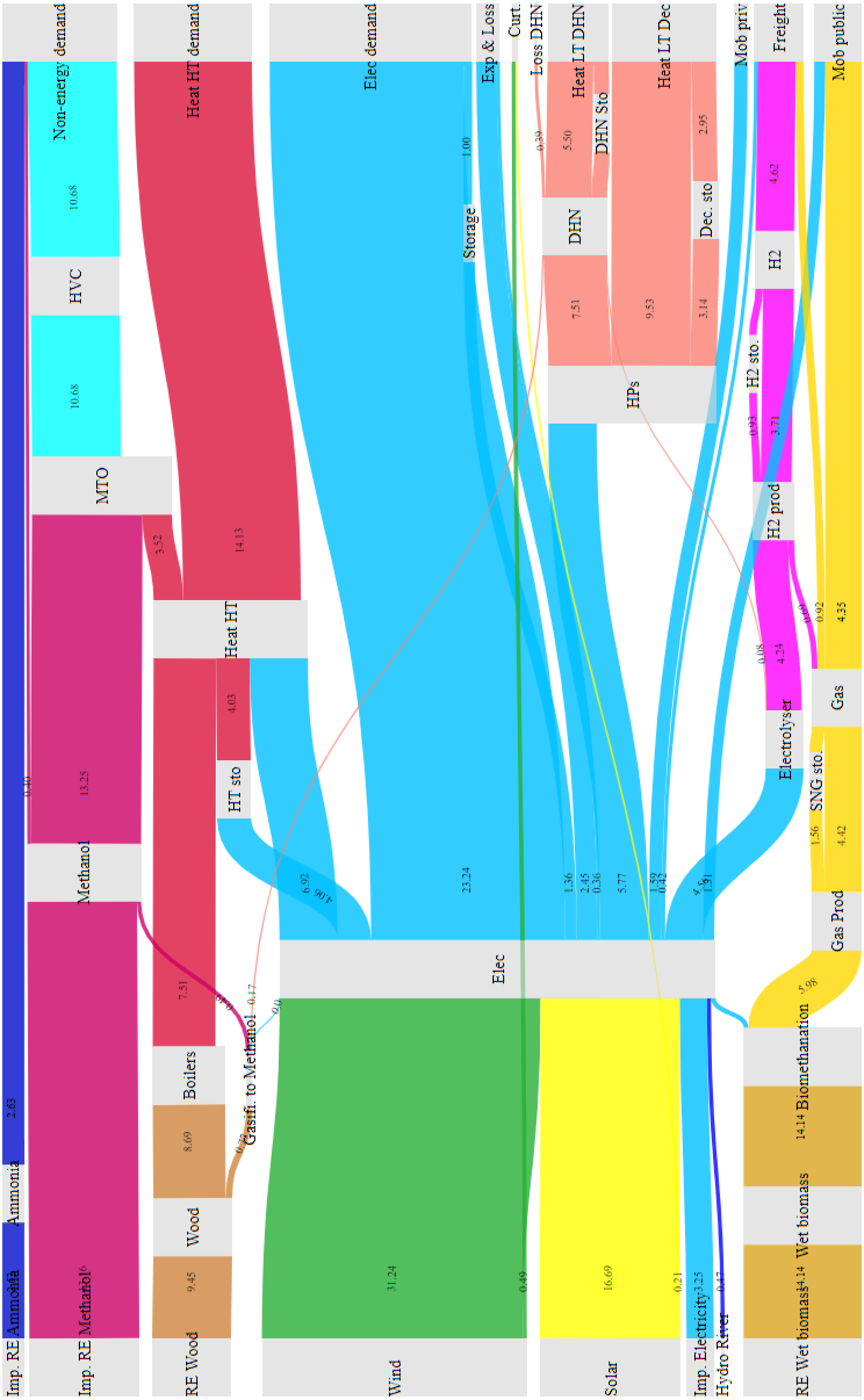


Figure 5.4: Sankey diagram of the LD scenario.

5.3 Intermediate scenarios

In this section, intermediate scenarios with different EUD levels are analysed. They are defined by their demand matrix and share of public mobility. The intermediate scenarios are constructed linearly between the LD scenario (assimilated to the 0% scenario) and the HD scenario (assimilated to the 100% scenario) by steps of 5%. Therefore, the demand matrix of the 50% scenario is the mean of the low and high demand matrices, for example. `EnergyScope TD` treats the demand matrix by considering the sum of the EUD of each EUI (the lines of the matrix). Thus, the evolution of the total EUD is defined by the ranges of the EUI, shown in Table 5.3.

EUI	**Ranges [LD - HD]**			
Electricity:	[17.2	-	73.3]	TWh
Lighting:	[7.1	-	31.9]	TWh
HT heat:	[14.1	-	56.7]	TWh
LT heat SH:	[13.4	-	92.1]	TWh
LT heat HW:	[6.4	-	22.6]	TWh
Passenger mobility:	[51.2	-	159.3]	Gpkm
Freight mobility:	[27.5	-	92.8]	Gtkm
Non-energy demand:	[13.7	-	55.0]	TWh
Public mobility share:	[80	-	20.5]	%

Table 5.3: Ranges of EUD.

5.3.1 Instructions for reading the graphs

The graphs shown in this chapter are constructed as follows. The scenarios will be compared all at once with bar charts. The “Decent living” scenario (the 0% one) is placed on the left, while the “European Commission” scenario (the 100% one) is placed on the right of the graphs. In between, the scenarios are placed on an EUD increasing order. It is important to notice that the graphs do not represent any temporality. Each scenario represents a possible future outlook of the energy system in 2050, achieving carbon neutrality. The actual level of EUD in 2050 will be determined by the policies and the actions taken at both collective and individual levels. The total EUD will probably lay in the range considered in this work.

Moreover, the scenarios are shown in an EUD increasing order from the left side to the right side of the graphs, but the opposite order could have been chosen, as the graphs do not show any temporality or pathway. Some dynamic terms inducing an evolution are used (such as “decreases”, “increases”, “appears”) but they do not reflect any temporality and are only used to define differences in the total EUD. Consequently, a “change” in the energy system refers to a difference in the technologies or resources used between proximate EUD scenarios.

Figure 5.5 shows the evolution of the EUD by sectors in all scenarios. The evolution is linear and increases from the 0% scenario to the 100% one. The sector that consumes the most energy is the industry one in every scenario.

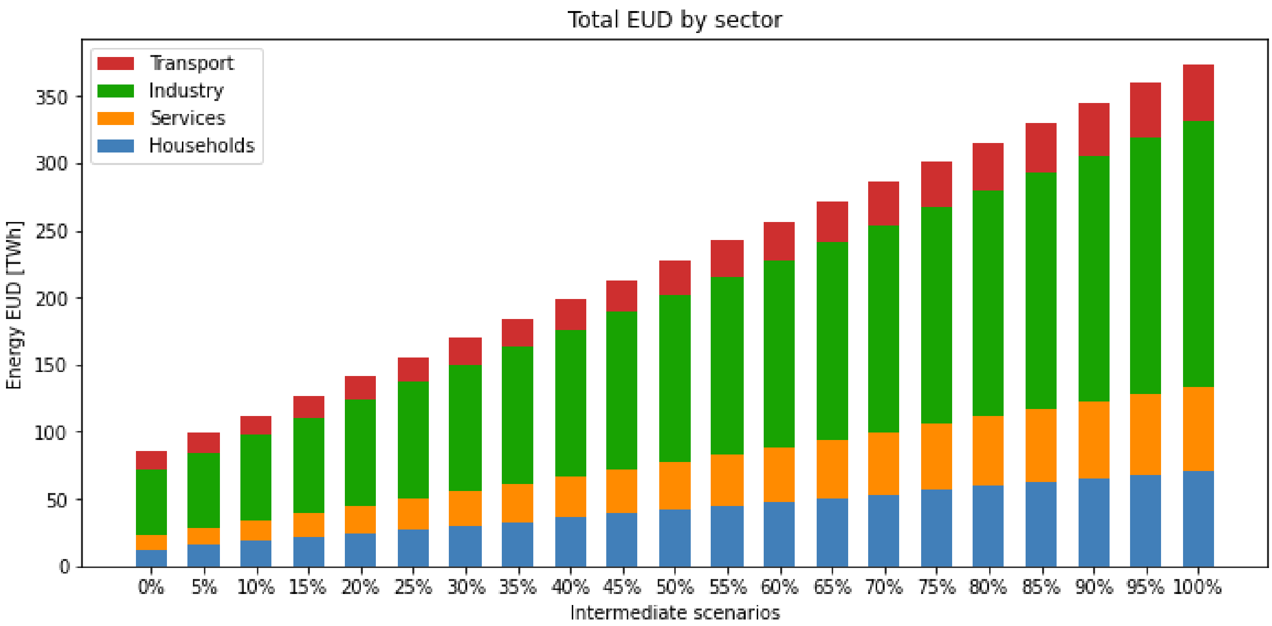


Figure 5.5: Total EUD by sectors over intermediate scenarios. LD = 0%, HD = 100%.

Figure 5.6 shows the evolution of the EUD by EUI. The main energy consumption layers are the specific electricity and the specific LT heat.

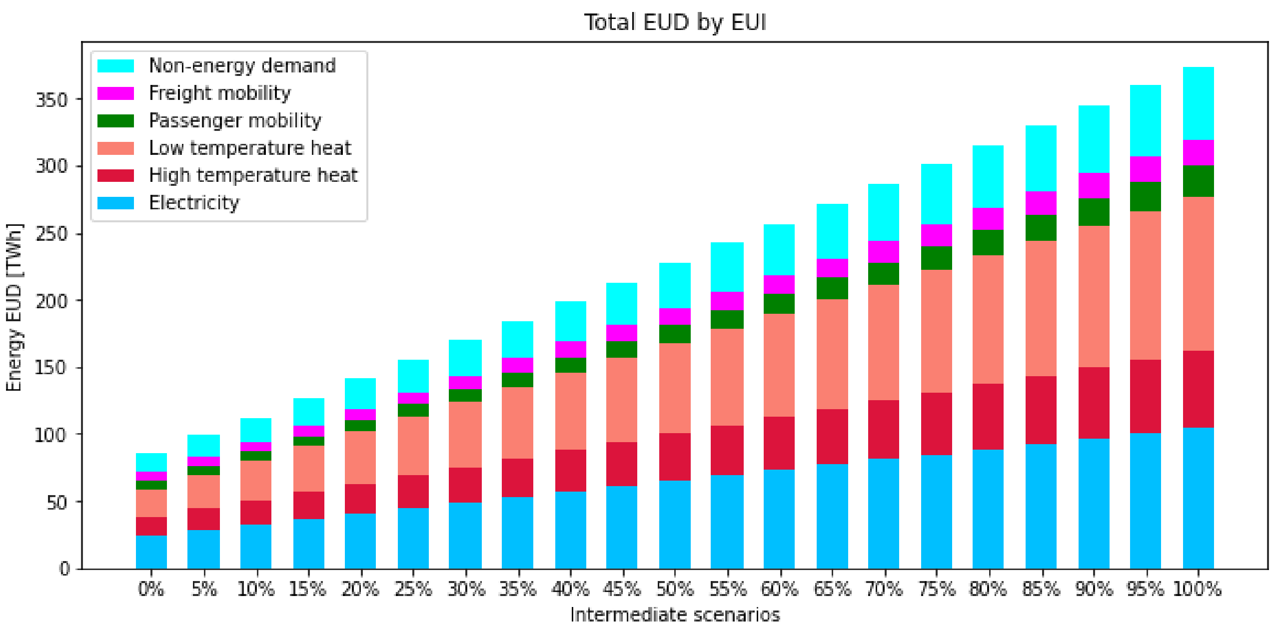


Figure 5.6: Total EUD by EUI over intermediate scenarios. LD = 0%, HD = 100%.

Different aspects of the energy system are investigated, and the aim is to observe tipping points between the scenarios. These tipping points are levels of demand around which a major change occurs. It can be a change in technologies used, in primary energy resources, etc.

5.3.2 Primary energy

The evolution of the primary energy is shown in Figure 5.7. It is almost linear, but does not evolve at the same rate as the total EUD. Indeed, the LT heat is supplied by heat pumps in every scenario and the share of the LT heat EUD in the total EUD increases with higher consumption, ranging from 23.2% in the LD scenario to 30.7% in the HD scenario. For this reason, the primary energy consumption increases less rapidly than the total EUD, for higher demand scenarios.

In all scenarios, the NED primary resources increase (imported RE methanol and RE ammonia) is constant and does not have any tipping point. This sector acts independently of the other sectors inside the energy system. Indeed, in all scenarios the resources are imported and transformed independently of the rest of the energy system, excepted that it consumes a share of the HT heat.

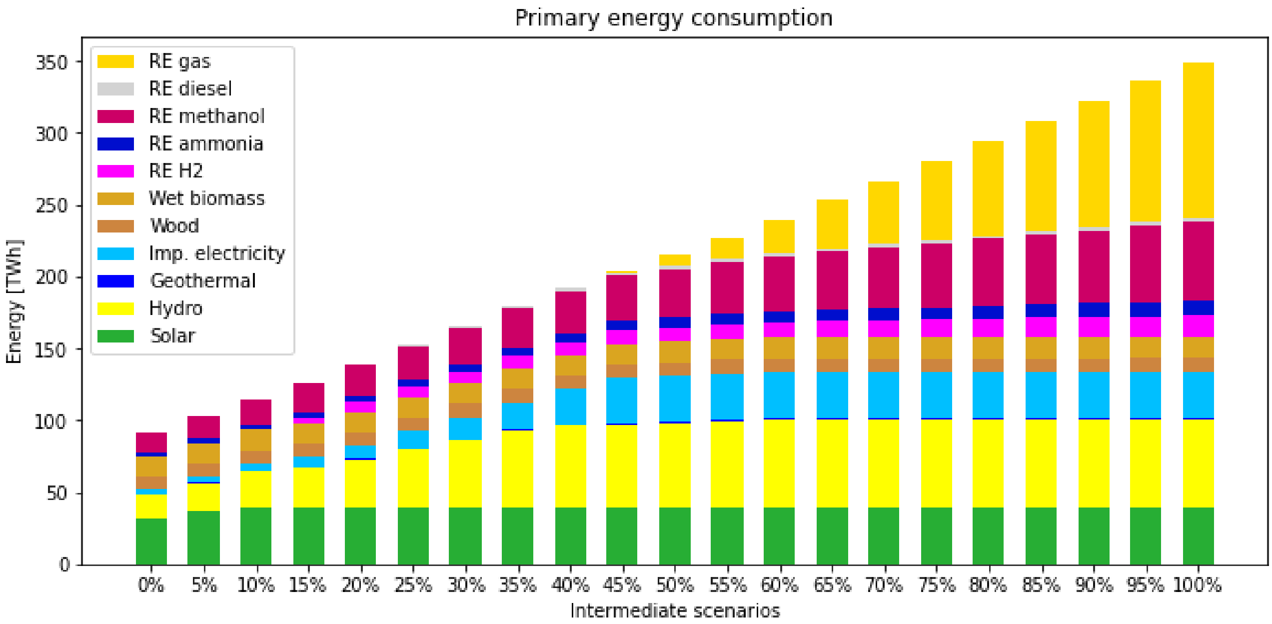


Figure 5.7: Primary energy consumption over intermediate scenarios. LD = 0%, HD = 100%.

In the scenarios ranging from 0% to 45%, the endogenous energy production and the imported electricity increase until reaching their maximum installed capacity/available resources on the 45% scenario. This maximum is reached for wind onshore, hydro, wood, and wet biomass in all scenarios but offshore wind and PV do not, their maximum reached on the 10% and 45% scenarios respectively. Besides, the imported electricity also reaches its maximum on the 45% scenario.

In the scenarios ranging from 45% to 100%, as the endogenous energy production and imported electricity reached their maximum, the need of primary energy to meet the increasing EUD is compensated by SNG imports. This SNG is used to produce HT heat and electricity, as will be explained later.

In addition, the importations of renewable hydrogen start in the 15% scenario. In lower demand scenarios, the required RE hydrogen is produced by electrolysers. Additionally, the importations of bio-diesel start in the 25% scenario. Both of these imported RE fuels are used exclusively to meet the freight mobility EUD, as seen in Section 5.3.6. These importations are the consequences of the scarcity of the SNG. Indeed, on the scenarios ranging from 0% to 40%, no SNG is imported, and then the only available SNG is the one produced via biomethanation, and is 6 TWh in all these scenarios. Hence, with the growing needs in SNG for the sectors that use it, it becomes more and more precious. This leads to progressive changes in technologies to priorise the use of SNG to the sectors that need it, like for the passenger mobility.

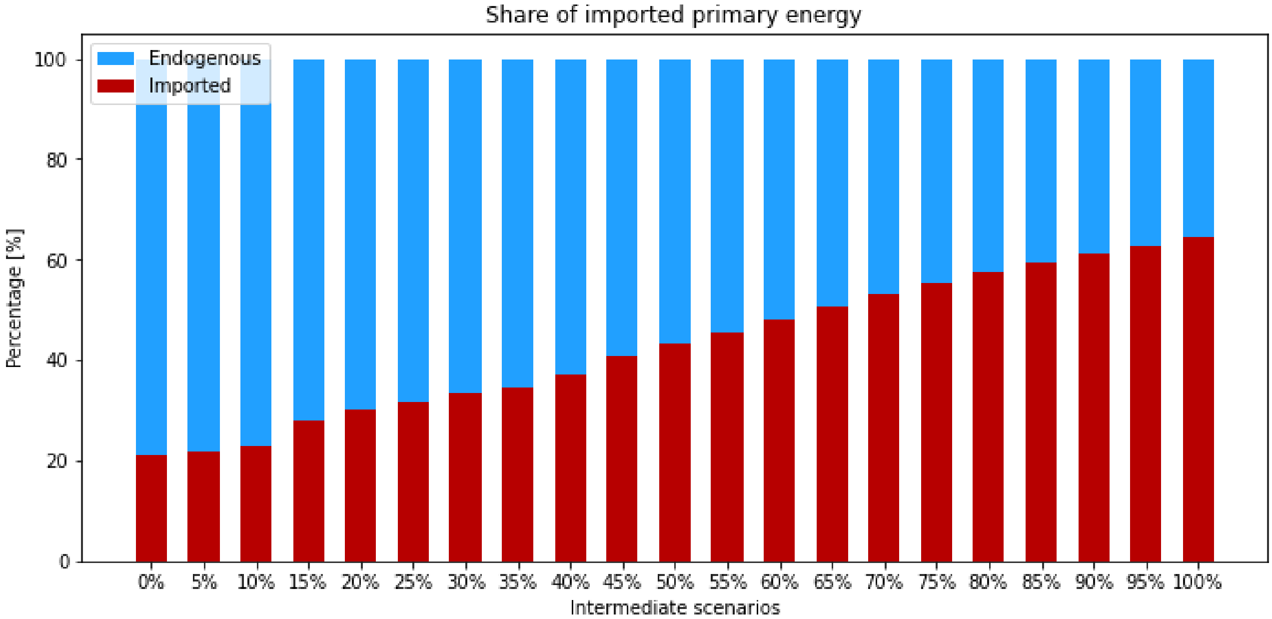


Figure 5.8: Share of imported primary energy over intermediate scenarios. LD = 0%, HD = 100%.

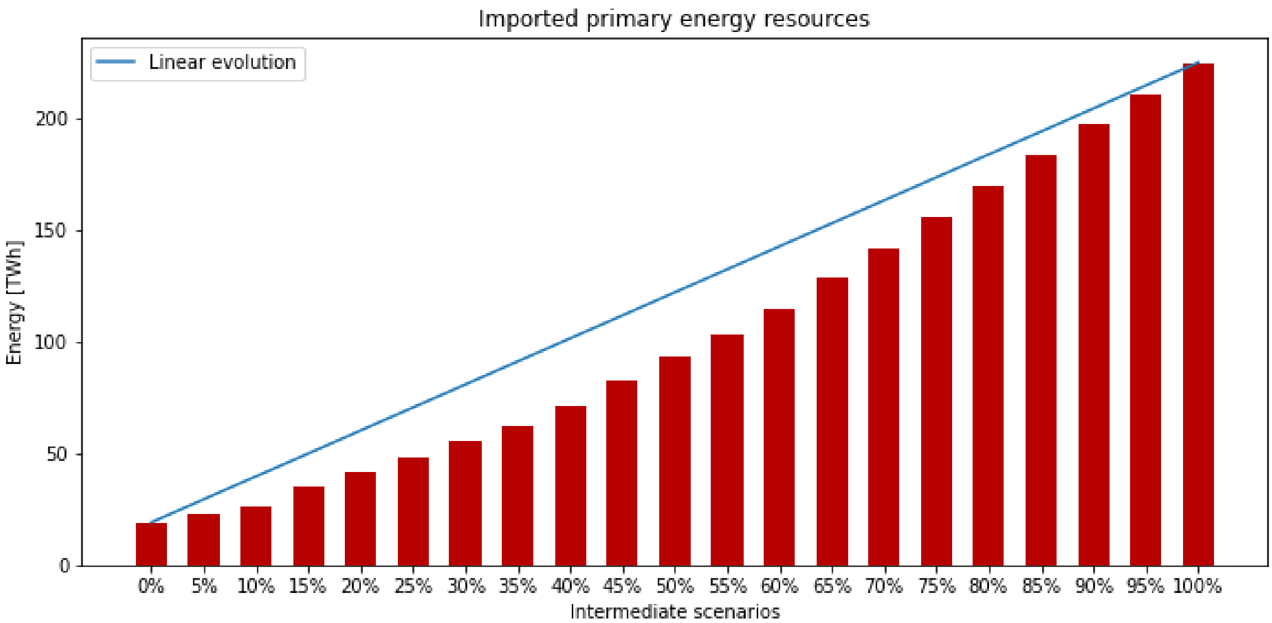


Figure 5.9: Imported primary energy over intermediate scenarios. LD = 0%, HD = 100%.

Figure 5.8 shows the share of imports in the primary energy mix. The share of imports increases with the increase of EUD. A sudden increase of this share is noticeable between the scenarios 10%-15% and corresponds to a change in the supply of hydrogen. On lower demand scenarios, hydrogen is produced by electrolysers in Belgium while in higher demand scenarios, it is imported.

Both the share of imported primary resources and the total primary resources increase linearly. As a consequence, the imported primary energy resources evolve quadratically. It means that a decrease in the EUD induces a stronger decrease in the quantity of imported resources for high demand scenarios compared to low ones. This is shown in Figure 5.9 in which the straight line shows a linear evolution (to highlight the quadratic evolution).

5.3.3 High temperature heat

The high temperature heat layer drives the major changes in the energy system. Figure 5.10 shows the HT heat supply in all scenarios. At low demand scenarios, direct electricity produces the majority of the HT heat and at high demand scenarios, it is mainly produced by the CHP units. In between, the gas boilers play a key role in this production.

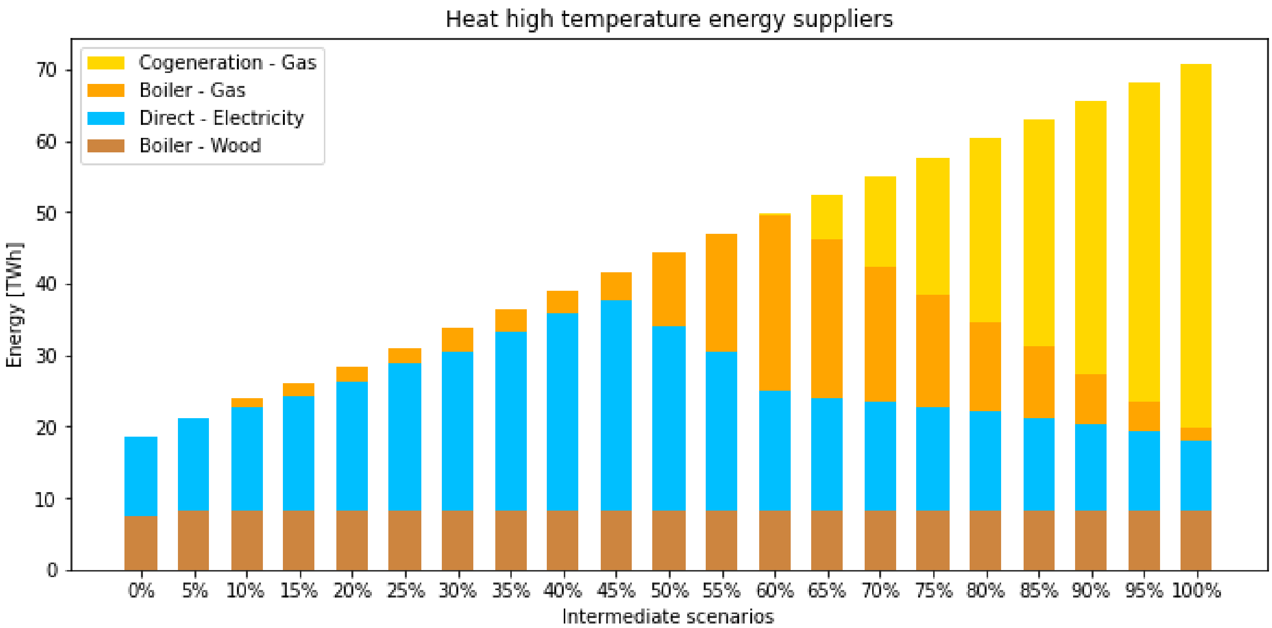


Figure 5.10: HT heat supply over intermediate scenarios. LD = 0%, HD = 100%.

In the scenarios ranging from 0% to 10%, the HT heat is produced by wood boilers and direct electricity. In the 0% scenario, the wood is not entirely consumed in boilers, but some of it is consumed to produce methanol. In the 5% scenario, the wood is entirely consumed in boilers, and this consumption is constant through all higher demand scenarios. Since the maximum endogenous electricity production is not reached (nor the maximum imported electricity), the electrification of different sectors can be achieved, including the production of HT heat. Then, direct electricity (via resistances) produces the rest of the HT heat in these two scenarios.

In the scenarios ranging from 10% to 45%, another industrial heat technology appears, the gas boiler. RE gas is not imported until the 45% scenario, and is entirely produced by wood gasification on lower demand scenarios. The direct electricity HT heat production reaches its maximum in the 45% scenario.

In the scenarios ranging from 45% to 60%, the gas boilers produce a growing share of the HT heat, compensating the decrease of direct electricity use. The importation of SNG starts at the 45% scenario and is almost entirely used in gas boilers to provide HT heat. A little share of SNG is used for the public mobility EUD. As seen in the previous section, the electricity production from endogenous resources and imported electricity is reaching a maximum around the 45% scenario. In parallel, the specific electric EUD is still growing linearly, as well as the HT heat EUD. Then, electricity supply is dedicated to sectors whose electrification is important and optimal for the energy system, such as private mobility, or LT heat sectors. The share of electricity dedicated to the production of HT heat decreases and is replaced by a growing use of gas boilers.

In the scenarios ranging from 60% to 100%, the specific electric can no longer be supplied by only endogenous resources and imported electricity. Another technology must then produce electricity. This is the role of the CHP units, which produce electricity and HT heat with the combustion of gas. As they combine both electricity and HT heat productions, the use of CHP units increases drastically in higher demand scenarios and replaces the gas boilers.

5.3.4 Electricity

The electricity layer is a major one, as some sectors are projected to electrify deeply in the future, like the passenger mobility sector. Figure 5.11 shows the evolution of the production of electricity for the different intermediate scenarios. The electricity production is mainly achieved by endogenous resources, which are PV panels, wind turbines (onshore and offshore) and hydro in Belgium. The onshore wind turbines and the hydro are at their maximum in every demand scenario, while PV and offshore wind turbines are not. In addition, in every scenario, electricity is imported from neighbouring countries. On the other side, Figure 5.12 shows the electricity consumption. In every scenario, total electricity supply must meet electricity consumption. They are analysed separately, since they don't have the same tipping points, but they follow the same trend in their total electricity consumption/production.

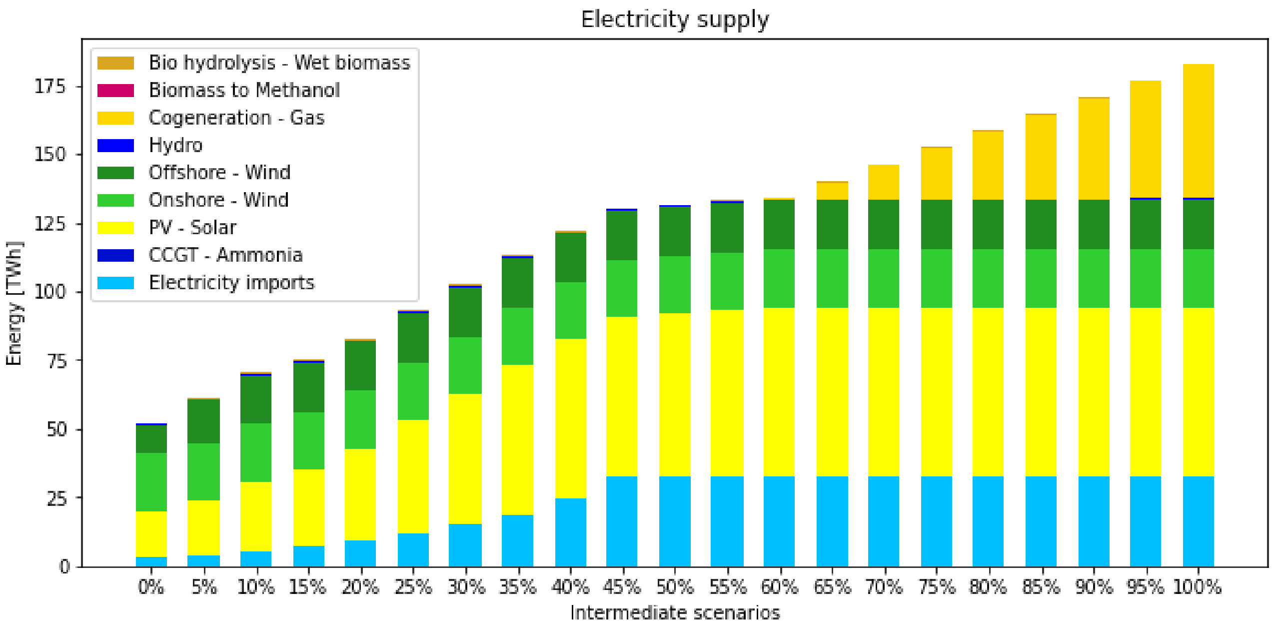


Figure 5.11: Electricity supply over intermediate scenarios. LD = 0%, HD = 100%.

In the scenarios ranging from 0% to 45%, the endogenous electricity production capacity and the imported electricity are increasing with higher demand, until each of the technologies reach their maximum installed capacity. Hydro and wind onshore maximum installed capacities are achieved in every scenario. Wind offshore achieves its maximum capacity in the 10% scenario. PV panels achieve almost their maximum capacity in the 45% scenario (95% of its maximum capacity), and the imported electricity achieves its maximum of importation on the 45% scenario.

In the scenarios ranging from 45% to 60%, the electricity production reaches a plateau (130-134 TWh of electricity produced), as endogenous resources and electricity imports are at their maximum capacity. No additional electricity supply technology is added in the energy systems of these scenarios. This plateau is due to a change in the electricity consumption and will be explained afterwards.

In the scenarios ranging from 60% to 100%, the increase in the electricity production is entirely due to the use of CHP units, which consume SNG to produce electricity and HT heat.

The specific electric EUD increases linearly between both extreme scenarios. The LT heat is exclusively supplied by electricity through heat pumps in all the scenarios.

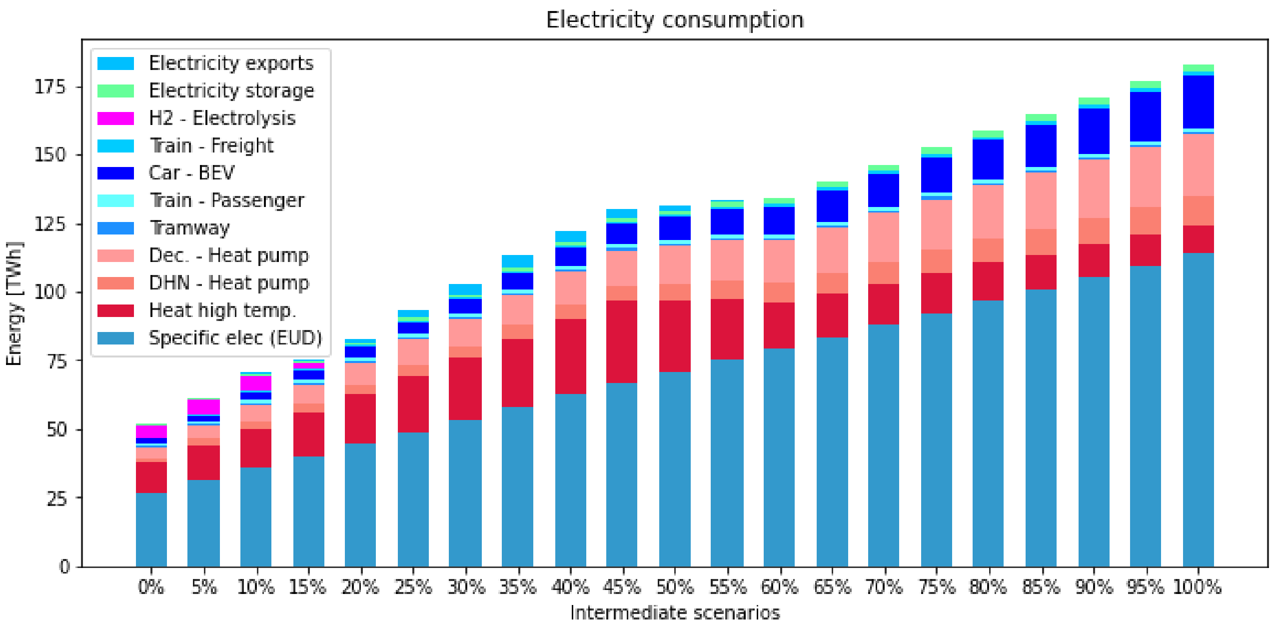


Figure 5.12: Electricity consumption over intermediate scenarios. LD = 0%, HD = 100%.

In the scenarios ranging from 0% to 15%, the endogenous resources and the imported electricity are not at their maximum capacity, so there is electricity available to be consumed in addition to the specific electricity EUD. The LT heat is entirely electrified in every scenario, as well as the private mobility via BEV cars. In addition, in these scenarios, the extra electricity produces HT heat and RE hydrogen via direct electricity and electrolysers, respectively.

In the scenarios ranging from 15% to 45%, the electricity is consumed by the same sectors, except for hydrogen. Indeed, the need of hydrogen becoming too high, it starts being imported from the 15% scenario, and is entirely imported from the 20% scenario, leading to no use of electrolysers.

In the scenarios ranging from 45% to 60%, the electricity consumption reaches a plateau, as seen in the electricity supply explanations. The 45% scenario sees the beginning of the importation of SNG, and the 60% scenario sees the appearance of the CHP units in the energy system. In between, the electricity consumption (and supply) is stable, due to a switch in the HT heat production technologies from direct electricity to gas boilers, as explained previously. The increasing need for electricity forces the HT heat production to dis-electrify. As these phenomena occur equally, the electricity supply shows a plateau.

In the scenarios ranging from 60% to 100%, the increase of electricity consumption is due to the increase of the specific electricity, LT heat and private mobility EUD which are electrified in every scenario. The electricity used to produce HT heat still decreases, but at a slower pace.

5.3.5 Passenger mobility

The passenger mobility is divided in two categories: private and public mobilities. As the total passenger mobility EUD increases linearly and the public mobility share [%] decreases also linearly, the public mobility EUD evolution is quadratic.

Figure 5.13 shows the passenger mobility EUD by transport mode, and Figure 5.14 shows the energy used by these transport modes. The total EUD evolves linearly (by definition of the scenarios) while the total energy consumption does not.

The evolution of total public mobility is quadratic and smooth, even though a change operates on its modal share. Around the 10% scenario, the modal share of the gas powered bus decreases and is compensated by an increase in the train modal share. In the two first scenarios (0% and 5%) the modal share of the gas powered buses is higher than in higher demand scenarios. This corresponds to the tipping point of the gas boiler technology. Indeed, in the first scenarios, the energy system produces high levels of SNG compared to the needs, from the wet biomass (biomethanation) and uses it for the passenger mobility. In higher demand scenarios, the gas boilers will consume the exceeding gas produced and fewer SNG remains for the passenger mobility. Therefore, the total energy consumed is lower in the 10% scenario than in lower demand scenarios, because the train is more efficient than the gas powered bus.

The private mobility doesn't have any change in its technology used, which is the BEV car in every scenario. The private mobility sector is entirely electrified in the range of consumption considered.

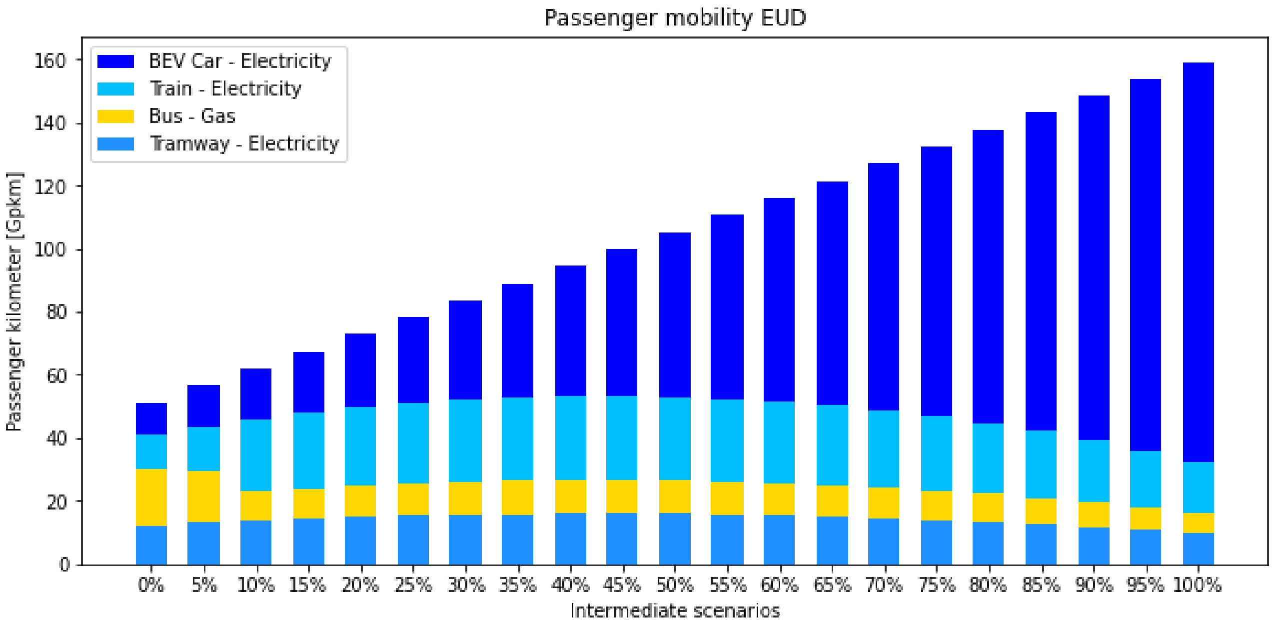


Figure 5.13: Passenger mobility EUD over intermediate scenarios. LD = 0%, HD = 100%.

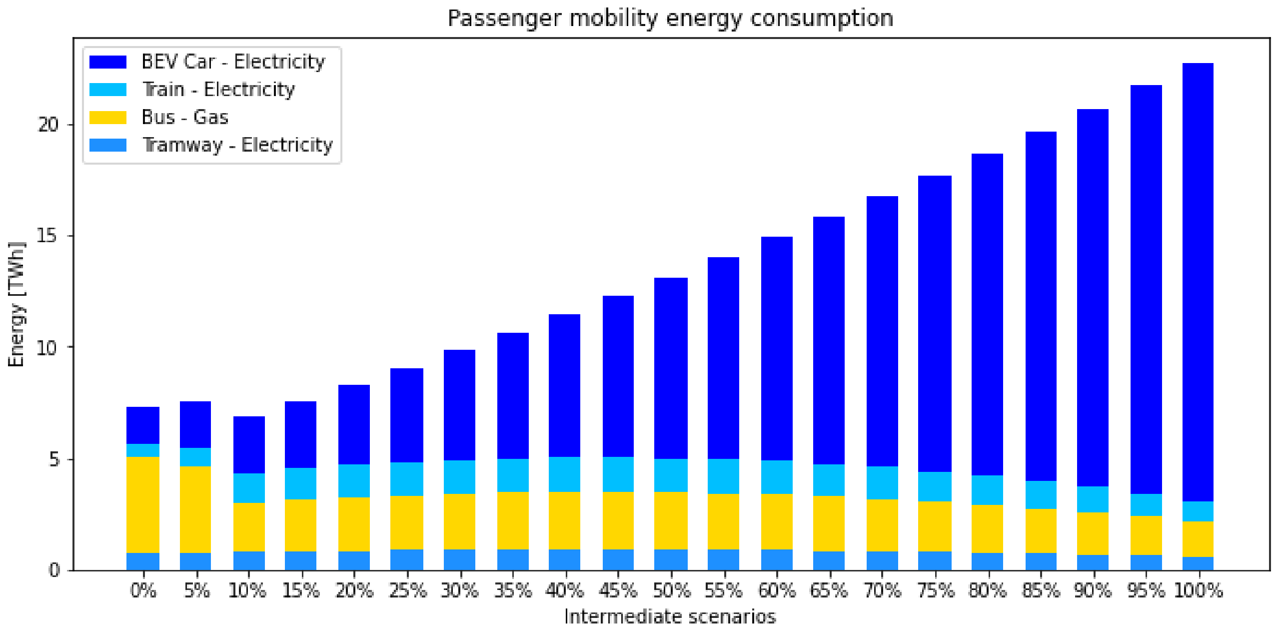


Figure 5.14: Passenger mobility energy consumption over intermediate scenarios. LD = 0%, HD = 100%.

5.3.6 Freight mobility

The freight mobility is divided in three transport modes: road, boat, and train transports. They have a constant modal share over the scenarios that are 45% of road transport, 30% of boat transport and 25% of train transport[3]. These modal shares are defined in `EnergyScope TD`. Figure 5.15 shows the freight mobility EUD evolution with varying demand scenarios, distributed by transport modes. Figure 5.16 shows the evolution of the energy consumption related to freight mobility. The difference between these two figures is due to a lower efficiency for fuel-cell trucks compared to boats and trains.

As expressed earlier, the freight mobility technologies used for road and rail transport are the same in every scenario. The road freight mobility is accomplished by fuel cell trucks (powered with hydrogen) and the train is powered with electricity. For boat mobility, there is a tipping point at the 25% scenario. In lower demand scenarios, the boats are powered with SNG, produced from biomethanation (wet biomass). In higher demand scenarios, the boats are powered by bio-diesel, which is entirely imported from the 25% scenario until the 100% one. This change is explained by the growing need in SNG in public mobility and HT heat sectors. The reason of the boat freight mobility change to biodiesel while other transport modes do not is because of their energy intensities (GWh/Gtkm). Indeed, the energy intensity of the diesel powered boat is 0.098 GWh/Gtkm, while it is 0.471 for diesel powered trucks. In addition, the change is due to a better energy intensity of the diesel boat compared to the gas boat, of which its energy intensity is 0.111 GWh/Gtkm.

Figure 5.17 shows the hydrogen layer. The positive side of the graph represents the supply part while the negative side of the graph represents the consumption part of the hydrogen layer and shows that the only hydrogen consumption in every scenario is the fuel cell trucks, and a marginal loss occurs in hydrogen storage. In the scenarios lower than 15%, the RE hydrogen is produced by electrolysis, and

[3]The 25% modal share for the freight train is consistent with the objectives of "Vision rail 2040" to increase it from 12% to 20% of the freight mobility in 2040. URL: `https://news.belgium.be/fr/vision-rail-2040`

a bit of steam methane reforming, which converts SNG into RE hydrogen and CO_2. This CO_2 is not considered to be emitted, as it was previously captured in the RE wet biomass. In scenarios higher than 15%, the RE hydrogen is entirely imported. The tipping point associated to hydrogen is then the 15% scenario.

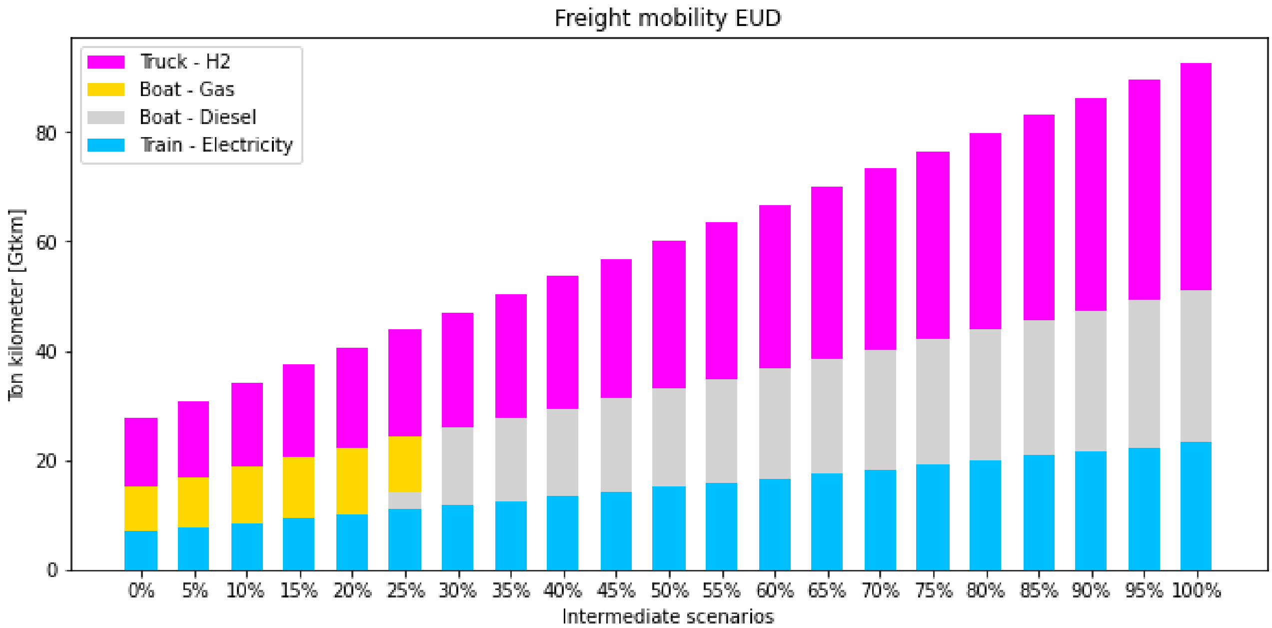


Figure 5.15: Freight mobility EUD by transport mode over intermediate scenarios. LD = 0%, HD = 100%.

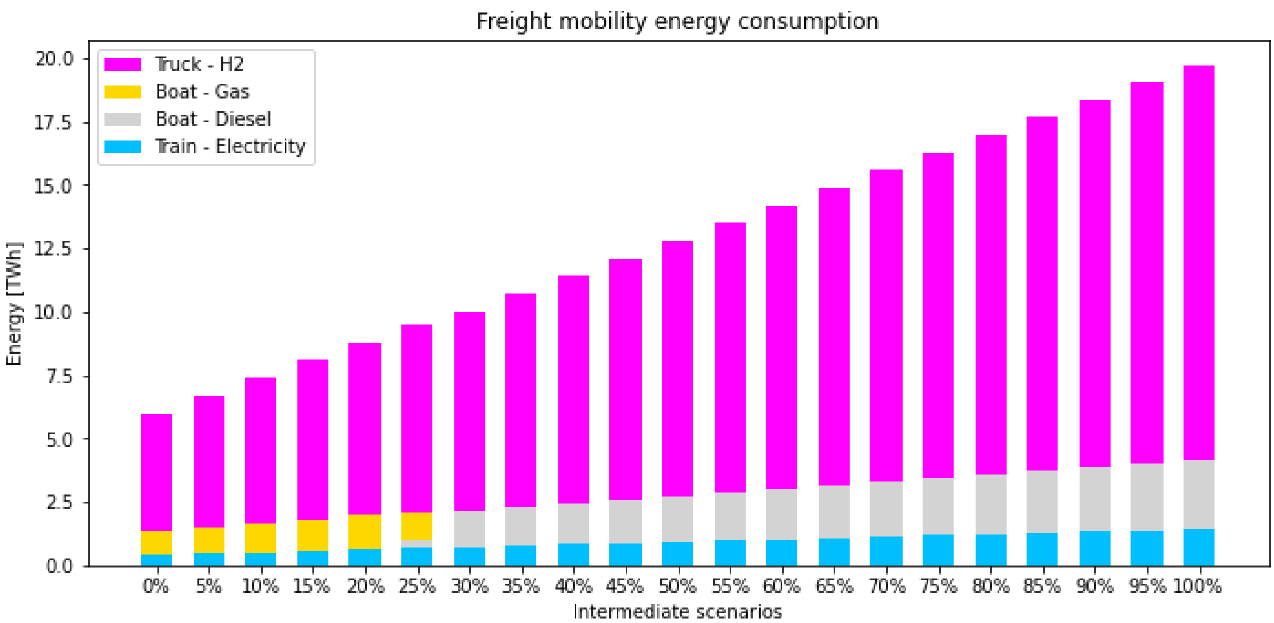


Figure 5.16: Freight mobility energy consumption by transport mode over intermediate scenarios. LD = 0%, HD = 100%.

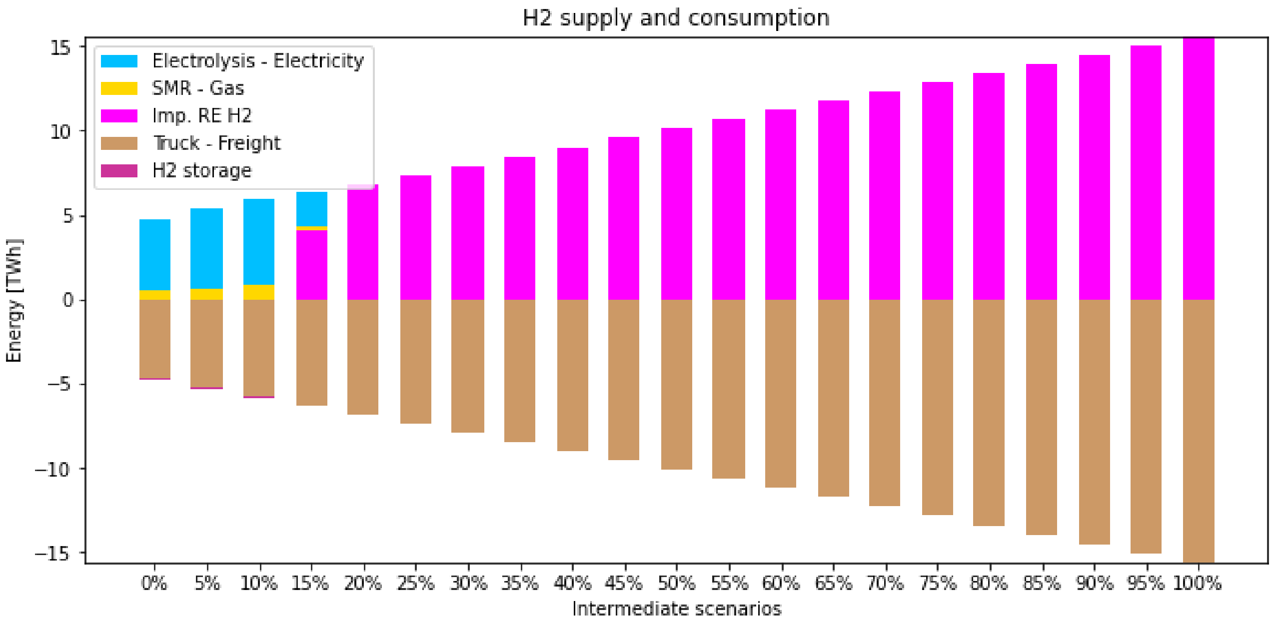


Figure 5.17: Hydrogen supply and consumption over intermediate scenarios. LD = 0%, HD = 100%.

5.3.7 Energy system yearly cost

Figure 5.18 shows the cost of the energy system distributed in investment, maintenance, and operation. Investment refers to the yearly cost of the construction of the conversion technologies, the vehicles, etc. Maintenance refers to the yearly cost of the maintenance of these conversion technologies. Operation refers to the cost of the resources (imported resources and endogenous wood and wet biomass). We can see that the more the consumption is reduced, the more the annual cost is reduced, quadratically, due to the operation cost. Indeed, the share of imported resources is higher for higher demand scenarios, yielding to a quadratic increase of the operational cost. The investment and maintenance costs follow a linear evolution with the demand.

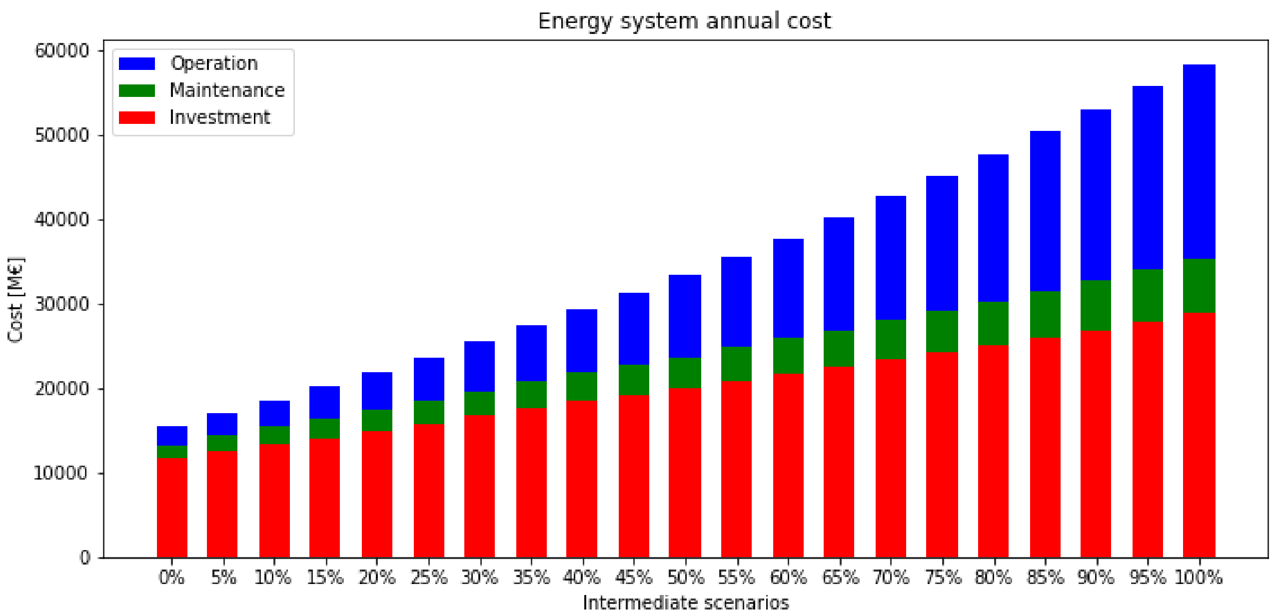


Figure 5.18: Energy system annual cost over intermediate scenarios. LD = 0%, HD = 100%.

5.3.8 GHG emissions

Even though no operational emissions are considered (carbon-neutrality in 2050), the construction of the conversion technologies emits some $CO_{2,eq}$ in the atmosphere. This is computed in `EnergyScope TD` with the life cycle assessment of the technologies. The energy system then still emits carbon. Figure 5.19 shows the evolution of these emissions with the demand. There is a tipping point around the 40% scenario, corresponding to the scenario at which the maximum PV capacity is installed. Indeed, the GWP of the construction phase is mainly due to the installation of PV panels, accounting for 81% to 90% of the emissions in all scenarios. Besides, the following important emissions are made by the wind turbines, which reach their maximum capacity at the 10% scenario and is constant in higher demand scenarios. This accounts for around 0.3 $MtCO_{2,eq}$ in all scenarios.

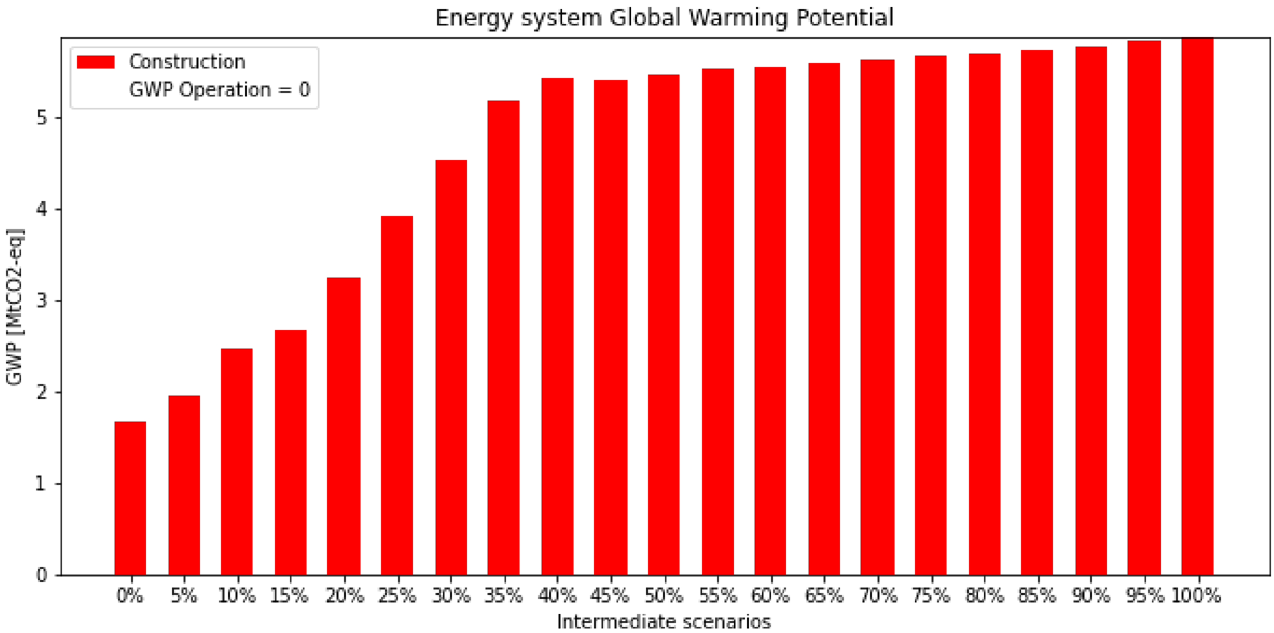


Figure 5.19: Energy system annual global warming potential over intermediate scenarios. LD = 0%, HD = 100%.

5.3.9 Tipping points summary

The results of the simulations of the intermediate scenarios show some changes in the energy system, depending on the level of EUD. Five tipping points are counted, including two major ones (45% and 60%) and three with less impact (10%, 15% and 25%). They are summarised hereafter:

- **The 45% scenario tipping point** is due to the maximum endogenous primary energy produced reached, as well as the maximum imported electricity. On higher demand scenarios, the energy system imports SNG in addition to other RE fuels already imported in lower demand scenarios. The importation of SNG represents 95% of the primary energy increase to replace the increase of endogenous energy production and imported electricity (without consideration of the other imported fuels, as they are already imported before the 45% scenario). The remaining 5% of the increase are due to a marginal increase in the solar capacity. This involves a more important share of HT heat produced from SNG in higher demand scenarios, leading to a lower installed capacity of HT heat produced from direct electricity. Consequently, the production of electricity stabilises due to two parallel phenomena: a higher specific electricity EUD and a lower share of electricity supply dedicated to HT heat.

- **The 60% scenario tipping point** is due to a saturation in the electricity and HT heat productions. Indeed, the higher need of specific electricity and HT heat requires the installation of CHP units, producing both EUD from imported SNG. The installed capacity of CHP is increasing linearly with higher EUD. Between 60% and 100%, the EUD increase is 115.5 TWh and the increase in CHP installed capacity is 7.18 GW. Therefore, for each TWh of EUD difference, the difference in CHP capacity installed is 62.2 MW.
- **The 10% scenario tipping point** occurs in the public mobility sector. The modal share of gas powered buses is reduced in higher demand scenarios and is compensated by an increase of the train modal share.
- **The 15% scenario tipping point** occurs in the hydrogen layer. The only technology that uses hydrogen is the fuel-cell truck (freight mobility). The hydrogen is produced via electrolysis and a little share of SMR in lower demand scenarios, while it is entirely imported in higher demand scenarios.
- **The 25% scenario tipping point** occurs in the freight mobility. In lower demand scenarios, the freight boat is powered with SNG but around the 25% demand scenario, a higher need for HT heat induce a relocation of the use of SNG towards gas boilers. Consequently, the freight boat switches to a diesel powered technology, inducing the importations of bio-diesel in higher demand scenarios.

Figure 5.20 illustrates these tipping points.

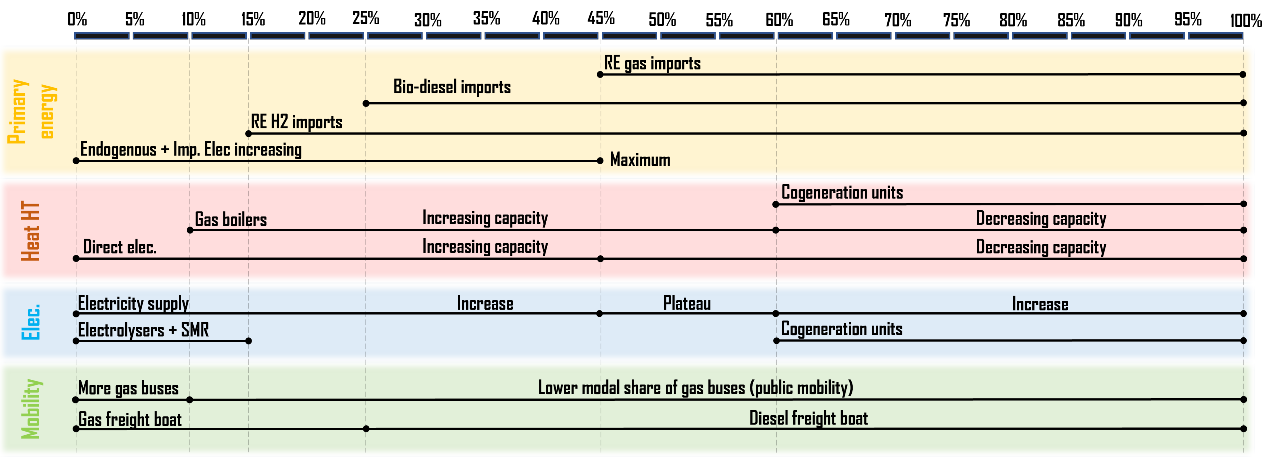


Figure 5.20: Summary of the tipping points.

In addition, there are sectors that do not have a tipping point, the same technologies are used in all scenarios to provide their EUD.

- The LT heat EUD is always satisfied by heat pumps
- The private mobility EUD is always entirely satisfied by BEV cars
- The NED primary resources are always imported, via RE methanol and RE ammonia.

Chapter 6

Conclusion

The reduction of our emissions of GHG represents a high interest in the scientific community. However, the reduction of the demand is still not enough investigated. The energy demand is often a fixed parameter of the energy models, but what better way to decrease our emissions than to decrease the demand ? We often hear that "the best CO_2 is the one that is not emitted", and it could be extended to "the best energy is the one that is not consumed". This master thesis results from a partnership between UCLouvain and negaWatt Belgium, and its aim is to explore the impacts of a reduced demand by defining a range of possible EUD for Belgium in 2050. The lower limit of this EUD range is defined with the help of the article "Providing Decent Living with Minimum Energy: A Global Scenario" [2] and its total EUD is 85.4 TWh. To compare, in Belgium in 2015, the total EUD was 391.9 TWh. Hence, the low demand scenario requires 4.6 times less EUD than in 2015. Additionally, the higher limit of this EUD range is defined based on the "EU Reference Scenario 2050" [8] report, published by the European Commission. The total EUD required in this scenario is 374.1 TWh, which represents a decrease of 4.5% compared to the 2015 EUD. As the European Commission projects a GDP growth until 2050, they also project in parallel a decoupling of the EUD with the GDP due to efficiency policies.

To compare the scenarios, their energy systems are simulated by EnergyScope TD. The main difference is their primary energy resources. Indeed, the high demand scenario relies on 64.3% of imported renewable energy resources, while the low demand scenario relies mainly on endogenous energy production (79%), and imports limited resources (21%). Afterwards, intermediate scenarios with varying levels of EUD are simulated to identify the tipping points of the energy system. These tipping points are levels of EUD around which a major change occurs in the energy system. The main one occurs around the 45% scenario and is the EUD level at which the maximum endogenous energy production is reached for Belgium. Its total EUD is 215.3 TWh. From this scenario and in higher levels of EUD, the energy system imports a growing quantity of SNG, a renewable energy fuel produced via power-to-gas or biomethanation technologies. In lower demand scenarios, the endogenous energy production, as well as the importations, decrease with lower levels of EUD. The other main tipping point occurs around the 60% scenario. Its total EUD is 258.6 TWh. In higher demand scenarios, the SNG is used to power cogeneration of heat and power units, as the specific electric EUD and the high temperature heat increase. The other three tipping points induce minor changes in the system. They represent switches in the technologies used for the public and freight mobilities and result from the scarcity of SNG with higher levels of EUD.

The results show that Belgium's endogenous energy production is used at its maximum potential only at certain levels of EUD. Thus, even if Belgium's endogenous potential is not high enough for the current level of EUD, there are scenarios in which it provides the majority of the energy supply, assuming that a reduction in the demand is considered. With another point of view, the more we decrease the demand, the less the energy system will be dependent on importations of RE fuels. In addition, it is economically interesting to decrease the demand and more precisely the required importations of resources, as their price follow a quadratic trend with the decrease of the total EUD.

In this thesis, the demand was considered as a varying input to the energy system model `EnergyScope TD`, while it was often considered as a fixed parameter in the energy system models. In addition, the projected availability of wood and biomass in Belgium in 2050 has been updated. The update of the potentials of each resource should be done for the whole energy system. Indeed, their estimations do not take into account the new deals signed to shift towards more endogenous energy production. For example, Belgium signed, together with Denmark, Germany, and the Netherlands, an agreement to increase the installed capacity of offshore wind farms up to 150 GW. Also, Belgium and Denmark signed an agreement on sale of Danish renewable energy-shares to Belgium via the connection of Belgium to the Danish energy island in 2033 [1]. These new agreements should be taken into account into the estimation of the potentials.

This thesis contributes to the increasing interest given to the reduction of the demand. It leaves room for improvements and researches. Firstly, a more precise definition of the EUD related to the industrial sector should be accomplished. Indeed, in the low demand scenario, the actual possible EUD reductions could be interesting to define, with the pathway to actually reduce this EUD. By the way, it would be interesting to define the pathway to achieve the resulting scenarios considered here, as only the snapshot of the situation in 2050 was considered.

To conclude, the reduction of the demand will not only decrease our needs in primary energy resources, but will also make us less dependent on energy importations.

[1] https://stateofgreen.com/en/news/historic-declaration-can-provide-230-million-european-households-with-green-electricity/

Appendices

Appendix A

Methodology defining the demand matrix of the high demand scenario

The high demand matrix is defined by the data associated to the “EU Reference Scenario 2050” [8] for Belgium, in the year 2050. The same methodology can be used to define the demand of each time step (every 5 years). The data used in `EnergyScope TD` for this thesis is adapted to the latest report of the European Commission published. The methodology consists in using the ratios defined by Gauthier Limpens in its PhD thesis “Generating energy transition pathways : application to Belgium” [6], as well as the ones defined in [27], to construct the demand matrix in [ktoe] and then converting it in [GWh]. The construction of the non-energy demand is defined by [10] on the basis of the same data. The ratios are adapted to the updated data, and to the latest publications.

A.1 First step: finding the information

The end-use demands (EUD) for heating, electricity and mobility in 2050 are calculated from the projection done by the European Commission in their “EU Reference Scenario 2050”. Their projections for the mobility are already given in EUD, as they are expressed in Gpkm for the passenger mobility and in Gtkm for the freight mobility. However, the heating and electricity EUD are not given as such. The final energy consumption (FEC) of the different sectors (industry, residential, tertiary) are given. The difference between the EUD and the FEC is detailed in Section 2 and can be summarised as follows: the FEC is the amount of input energy needed to satisfy the EUD in energy services. Except for heat pumps, the FEC is greater than the EUD. A conservative approach is then applied by considering that the EUD is equal to the FEC for electricity and heating demands.

The information taken from the European Commission data is presented in Table A.1. The information is taken from the 2020 report, except for the non-energy demand, which is taken from the previous report (2016). Indeed, the value given in the 2020 report seemed unreasonable. The 2016 projection estimated a non-energy demand of 9113.5 ktoe in 2050 [14], coherent with the trend of the previous years projections. In the 2020 data, this value is 16373.0 ktoe for 2050, which is an increase of 121%. In order to stay coherent with the previous projections, the value of the 2016 report is considered here.

Concerning the mobility of passengers, the European Commission considers the intra-EU aviation mobility. As EnergyScope TD doesn't deal with aviation (for Belgium), this passenger distance travelled is proportionally attributed to the other transport modes that can replace aviation (car, train and bus). Indeed, we assume that the intra-EU aviation will be replaced by other transport modes in 2050. The passenger mobility considered by EnergyScope TD is then 159.3 Gpkm.

Sector	**Value**	**Units**
Industry	12336.1	ktoe
Residential	6115.9	ktoe
Tertiary	5332.2	ktoe
Electricity	9042.6	ktoe
Passenger total	159.3	Gpkm
Passenger aviation	18.5	Gpkm
Freight	92.8	Gtkm
Non-energy	9113.5	ktoe

Table A.1: Information used from the "EU Reference Scenario 2050" report [8].

A.2 Second step: differentiate electricity and heat

Then, the electricity and heating demands are distributed in the three sectors: households, services and industry. Gauthier Limpens [6] considers the ratio of electricity to heat to be constant between 2015 and 2035. We assume that this is also true until 2050. This ratio is calculated from European Commission – Eurostat [31]. They are 24.9% and 58.2% for residential and services, respectively. In terms of the share of electricity in total consumption, the percentages become **19.9%** and **36.8%**, respectively. Thus, electricity represents about one fifth of residential consumption, and a little over one third for services. Then, the electricity demand for the industry sector is calculated from the subtraction of the residential and services electricity consumption from the total electricity EUD. Table A.2 summarises the electricity and heat consumptions by sectors.

EUD [ktoe]	Households	Services	Industry
Electricity	1218.7	1961.5	5862.5
Heat	4897.2	3370.7	6473.7

Table A.2: Separation between electricity and heat EUD by sectors.

A.3 Third step: variable and constant electricity demand

As explained in Section 2.1, the electricity is divided in a constant and a variable shares. These shares are to be found in Gauthier Limpens's thesis [6] and were updated in the `EnergyScope TD` documentation [27]. The share of variable electricity in the total electricity consumption is 32.5%, and the constant share is 67.5%. For the residential sector, the variable share is 35%, for the services one 43.8%, and for the industry one 24.8%. Table A.3 summarises the variable and constant electricity EUD of electricity by sector.

EUD [ktoe]	Households	Services	Industry
Constant (ELECTRICITY)	792.1	1101.9	4409.9
Variable (LIGHTING)	426.5	859.6	1452.5

Table A.3: Separation between variable and constant electricity EUD by sectors.

A.4 Fourth step: space heating, hot water and industrial processes

The heating EUD is also divided in a variable (space heating) and a constant (hot water) shares, for residential and services sectors. For the industry one, the heat demand also includes a share devoted to industrial processes (heat high temperature). The heat used by industrial processes cannot be provided by technologies such as heat pumps or thermal solar. The division between these shares are the one from Gauthier Limpens's thesis [6], updated in the `EnergyScope TD` documentation [27]. Table A.4 summarises the heating EUD by sectors.

EUD [ktoe]	Households	Services	Industry
Industrial process	0	0	4876.5
Space heating	3900.3	2753.5	1268.5
Hot water	997.0	617.2	328.7

Table A.4: Separation of the heat EUD by sectors.

A.5 Fifth step: non-energy demand

The methodology used to define the non-energy demand is the one explained in [10]. The idea is that the required molecules of the end-use demand are ammonia, methanol and High-Value Chemicals (HVC). The study estimates the demand of these three molecules in 2020 to be 3069 kt of HVC, 1895 kt of ammonia and 269 kt of methanol. The European Commission projects an increase of 7% between 2020 and 2050 in Belgium, in their 2016 report [14]. In order to express the demand in TWh, the study uses the Lower Heating Value (LHV) of the three molecules: 47 MJ/kg for HVC, 18.8 MJ/kg for ammonia and 19.9 MJ/kg for methanol. The demand projection for 2050 is shown in Table A.5. The total NED is **55012.1 GWh**.

Demand in 2050	Mass [kt]	Energy equivalent [TWh]
HVC	3281	42.8
Ammonia	2026	10.6
Methanol	288	1.6

Table A.5: Non-energy demand of the HD scenario.

A.6 Sixth step: conversion of the demand

Finally, the demand matrix can be completed in [ktoe] unit. This one is converted to be expressed in [GWh], as shown in Table A.6.

	HOUSEHOLDS	SERVICES	INDUSTRY	TRANSPORT.	Units
ELECTRICITY	9212.6	12814.7	51287.5	0	[GWh]
LIGHTING	4960.6	9997.2	16892.9	0	[GWh]
HEAT_HIGH_T	0.0	0.0	56713.3	0	[GWh]
HEAT_LOW_T_SH	45360.0	32023.1	14753.0	0	[GWh]
HEAT_LOW_T_HW	11595.0	7178.5	3822.4	0	[GWh]
MOBILITY_PASSENGER	0	0	0	159270.5	[Mpkm]
MOBILITY_FREIGHT	0	0	0	92766.4	[Mtkm]
NON_ENERGY	0	0	55012.1	0	[GWh]

Table A.6: Energy demand matrix for the HD scenario.

Appendix B

Methodology defining the demand matrix of the low demand scenario

The aim of this appendix is to show the methodologies used to define the different end-use demands (EUD). They will be explained by sectors: transportation, households, services, and industry. The majority of the figures are from the article "Providing Decent Living with Minimum Energy: A Global Scenario" [2], referenced as "Decent Living" in the following, and its supplementary material. This article uses a bottom-up approach, which means that they establish detailed consumption parameters to define the demand. As their aim is to define the minimum energy required for a decent living, they define the demand by making an inventory of the needed services. The opposite approach is the top-down one, where they start with a reference situation, and they reduce the consumption. The article also uses a global approach, as they consider decent living standards for everyone, without consideration of the wealth or the cultural influences. Everyone around the world is considered equal in its energy requirements. The only differences between countries are the outdoor temperature, the climate, the degree of urbanisation, the age distribution, the density of population and water scarcity.

Some complementary figures adapted to Belgium are also considered. The article has three scenarios: the central, the low-energy and the high-energy. The three scenarios are still really ambitious. The central one will be considered for all parameters, except for the floor space, and the average household size (number of people), as explained in Section B.3.

For some parameters, the value used in "Decent Living" is approximated from its references. The values found in these references will be used in this appendix. We start by developing the estimation of the degree of urbanisation in Belgium in 2050. We consider a population in 2050 of 11 926 987 inhabitants.

B.1 Urbanisation projection

The urbanisation of Belgium plays a key role in defining the passenger mobility (EUD for the transportation sector, and embodied energy for the industry sector). Indeed, the mobility will be considered more important for people living in rural areas, as there is less proximity between the different destinations than in urban areas.

The World Bank estimates that Belgium is composed of 98.08 % of urban population in 2020 [32]. This percentage is high because the definition of the urbanisation is general for every country and doesn't represent accurately the reality of the Belgian demography. Climact's percentage of urbanisation in 2020 was 78.76%, and it predicts a stabilisation of this value in 2050. In its "CORE95" and "BEHAVIOUR" scenarios, they consider 79% of urbanisation in Belgium in 2050 [29].

Eurostat has a clearer definition of the degree of urbanisation [24]. It defines three territorial typologies to define the degree of urbanisation:

- Cities: at least 50 % of the population lives in one or more urban centres
- Towns and suburbs: less than 50 % of the population lives in an urban centre, but at least 50 % of the population lives in an urban cluster
- Rural areas: more than 50 % of the population lives in rural grid cells

where the surface is divided in grid cells of 1 km^2. Each grid cell is categorised in three different types: urban centre, urban cluster or rural grid cell.

- Urban centres: a cluster of non-diagonal contiguous grid cells (in other words, excluding those cells with only touching corners) with a population density of at least 1 500 inhabitants per km^2 and collectively at least 50 000 inhabitants after gap-filling
- Urban clusters: a cluster of contiguous grid cells of 1 km^2 (in other words, grid cells that share a common border including grid cells that only touch diagonally at corners) with a population density of at least 300 inhabitants per km^2 and a minimum population of at least 5 000 inhabitants
- Rural grid cells: all grid cells outside urban clusters/centres

This methodology leads to the establishment of the degree of urbanisation in Belgium, where 27.4% of the population lives in cities, 54.6% in towns and suburbs and 18% in rural areas [23]. Cities and towns and suburbs are considered as urban, which lead to a **degree of urbanization of 82 %**. As Climact estimates a stabilisation over time until 2050, this is the percentage of urbanisation that is considered.

B.2 Transportation

The EUD in the transportation sector is the passenger kilometre (pkm) for the passenger mobility and the ton kilometre (tkm) for the freight mobility. It is the sum of kilometres travelled by each one of the passengers, or by each ton of goods. `EnergyScope TD` doesn't take into account the aviation, except for the internal aviation, which doesn't exist in Belgium. Even though, "Decent Living" still considers that some aviation can persist in their scenario, at a level of 1000 km/cap. This distance represents a short distance return flight (about 3000 km return trip), every 3 years. Like in Section 3.3, we assume that these travels will be achieved by other transport modes in 2050 (car, train or bus). The distances travelled by plane are transferred proportionally to these three transport modes.

Moreover, `EnergyScope TD` only considers motorised means of mobility. The soft mobility, including walking and cycling, are not considered in the total passenger mobility EUD.

B.2.1 Passenger mobility

The baseline estimates of the distance travelled each year by each person (MOB_{base}) are 7000 km/capita and 10000 km/capita for urban and rural areas, respectively [2]. This distance is modified to reflect the population dispersion in the country. As seen in Section B.1, the urbanization in Belgium is considered to be 82% in 2050.

Equation B.1 shows the modification of the distance travelled by Belgians (MOB_n), as used in the "Decent Living" article:

$$MOB_n = MOB_{base} * (f_{fixed} + f_{var} * \frac{LD_{base}}{LD_n}) \tag{B.1}$$

where the distance travelled is a function of a fixed distance ($f_{fixed} = 0.5$) and a variable one ($f_{var} = 0.5$), which is multiplied by a factor taking into account the lived density (LD). The base lived density (LD_{base}) is the median of the density of population, around the world, and its value is 189 [pers/km^2]. The lived density is defined in Equation B.2:

$$LD = \text{Population density} * \frac{\text{Total land area}}{\text{Inhabited land area}} = 469.2\,[\text{pers/km}^2] \tag{B.2}$$

The total land area of Belgium is 30689.2 km^2 [33]. Then, considering the projection of population in 2050, the population density is $Density = \frac{11926987 \text{ inhabitants}}{30689.2km^2} = 388.6$ [inhabitants/km^2]. The inhabited area (25422.6 km^2) is defined as the sum of the agricultural (13073.6 km^2) and urban land areas (12349 km^2) [34][35].

Table B.1 summarises the passenger mobility EUD, excluding the soft mobility travels. As `EnergyScope TD` doesn't consider soft mobility, it will be deducted from this total. Millward-Hopkins et al. estimate that 1000 km/cap can be accomplished every year with soft mobility (by walk or cycling for example) [2]. This represents 2.74 km/day, which is at a feasible level. They estimate that the air transport can still be part of their scenarios, with a return every 3 years in a distance of approximately 1000 miles ($\simeq$ 1609 km), to reach 1000 km/cap ($\simeq 2*1000*1.6/3$). `EnergyScope TD` doesn't take into account the aviation, except for the internal aviation, which doesn't exist in Belgium. Like in Section 3.3, we assume that these travels will be achieved by other transport modes in 2050 (car, train or bus). The distances travelled by plane are transferred proportionally to these three transport modes.

	Urban	Rural
Distance [pkm/cap]	3910	6014
Percentage of living population [%]	82	18
Total mobility demand [Mpkm]	**51152.1**	

Table B.1: Passenger mobility EUD.

Even though `EnergyScope TD` defines itself the transport modes that are used by the energy system, it is interesting to know what is considered in the "Decent Living" article for two reasons. First, it is used in the industrial sector to size the manufacturing of vehicles, as well as the infrastructure. Secondly, it will define the percentage of public transport, which is used as a parameter by `EnergyScope TD`.

The remaining passenger kilometres are distributed between trains, buses, and cars. They assume that 40% of the remaining mobility is attributed to trains, 40% to buses and the last 20% to cars. The distribution is shown in Table B.2. This leads to a public transport modal share of 80%.

	Urban	Rural	Units
Trains 40%	1564	2406	[pkm/cap]
Buses 40%	1564	2406	[pkm/cap]
Cars 20%	782	1202	[pkm/cap]
Total	**3910**	**6014**	**[pkm/cap]**

Table B.2: Modal share of passenger mobility.

B.2.2 Freight mobility

The freight mobility is also expressed per capita. The value used in the "Decent Living" article is 2309 tkm/cap, considering 1495 tkm/cap of road freight and 814 tkm/cap of rail freight [30]. This gives **27372.4 Mtkm**.

B.3 Households

The surface of the households is a predominant parameter for the heating demand. On its "central scenario", the "Decent Living" article considers a household size of four people on average, for a floor-area of 10 m^2/cap plus 20 m^2 in the household for the kitchen and the bathroom facilities, leading to a household floor area of 60 m^2 for 4 people, or 15 m^2/cap. The average household size and the floor area per capita must be discussed and compared with the current data. First, the average household size considered is way higher than the current value. In 2020 in Belgium, Eurostat estimated that the average household size was 2.3 people/household [25]. Then, it is important to size it in order to consider a value that is still feasible. In its "high energy" scenario (that is still really ambitious in general), they consider a household average size of 2 people/household, which is below the current value. The assumption made here is a trade-off between ambitiousness and feasibility, we consider a household average size of 2.5 people/household. Then, the floor area per capita in the central scenario is way below the current values. In 2020, négaWatt Belgium estimated that the average floor area in households was about 55 m^2/cap [26]. The floor area considered by [2] is then increased to its "high energy" scenario value, that is 20 m^2/cap plus 20 m^2 for the kitchen and the bathroom facilities. Considering these two parameters, the floor area becomes 28 m^2/cap.

B.3.1 Electricity and lighting

The electrical appliances decent living standards for each household are a cooker, a fridge-freezer, washing facilities, a computer, and lighting. In addition, each person over 10 years old should have a phone. The following paragraphs develop the electric demand of the direct use of the appliances.

Cooking Food is considered to be exclusively cooked with electric appliances (oven and cooking plates). The energy needed to cook food is 5-7 MJ/kg of cooked food [36], with an improvement of 67% [37] and half of the food eaten is cooked [2]. As presented in [38], the recommended daily consumption of food is on average 2000 kcal/day for each person. The mean caloric value of food is 1500 kcal/kg [2]. After computation, it leads to 1.32 MJ/day/cap, or **1596.2 GWh** for the whole population during one year, for food cooking.

Cold storage It is considered that the minimum cold storage need is one fridge-freezer for each household [39]. The consumption of the best practice freezer is currently 120 kWh/freezer [37] . It leads to a consumption of **572.5 GWh** of cold storage for one year.

Washing clothes Considering the weight of the different clothes worn and the frequency of the required wash, the total weight of clothes to wash per person is 78 kg/year [2]. This must be multiplied by the energy required to wash and dry 1 kg of clothes, that is 2.5 MJ/kg [37][40]. When adding 20% to account for non-clothing items (towels and beddings), it gives 65 kWh/cap, or **773.9 GWh** of clothes washing for one year.

Communication and information Rao et Min advance that each adult should have a phone for a decent living [39]. In the "Decent Living" article, Millward-Hopkins et al. consider then that this applies to every person aged above 10 years old. As there is no precision concerning the age distribution in the population in the EUROSTAT population projection, the same percentage of people above 10 years old as Statbel projection is considered: 88.5% of the Belgian population will be older than 10 years old in 2050 [22]. It means that 10 552 833 people are older, and that in Belgium, there would be 10 552 833 phones in 2050. The phone considered is the Fairphone, whose consumption is 4.9 kWh for one year [41]. Moreover, [39] considers that each household should have one computer for decent living. Its consumption is 62 kWh/year [42], considering a 10 years lifetime. This sums up to **347.5 GWh** of electricity consumption for one year.

Lighting The lighting energy use is computed as follows :

$$E_{lighting} = t_{illum} * A * E/\eta \tag{B.3}$$

where t_{illum} is the time of illumination each day [s/year], E is the illuminance [lm/m^2], A is the area illuminated [m^2] and η is the efficacy of the lights [lm/W].

- $t_{illum} = 6\,h/day = 7884000s/day$ [2]
- The low practical limit for the illuminance is $E = 125\,lm/m^2$ [37]
- 33% of the house is constantly illuminated [2], which means $A = 0.33 * 60 = 20\,m^2$
- $\eta = 150\,lm/W$

The final lighting demand in Belgium for the households is **203.2 GWh**.

Fixed and variable electricity demand As explained in Section 2.1, the term "lighting" in the demand matrix (of `EnergyScope TD`) refers to the variable part of the electricity demand, and not directly to the lighting demand. That is why the same ratio as in the maximum energy demand scenario will be used. For households, 35% of the electricity demand is variable [27], that is **1222.7 GWh**. The constant part of the demand is **2270.6 GWh**.

B.3.2 Space heating

The data of the Global Building Performance Network (GBPN) [28] is used to define the heating intensity of the households. As the minimum energy demand is required in this scenario, the buildings considered here are the "advanced new" ones. They are the new constructions, with the best practice heating intensities. This is not feasible to replace every building by new ones in a near future, it is clear that this is an approximation that is considered only in a scenario with minimum energy requirement. In urban areas, multifamily buildings are used, while single-family ones are used in rural areas. The former has lower heating requirements. The GBPN offers energy intensities in function of the location of the area in the world and the heating and cooling demands. Belgium is located in the Western Europe category (WEU), and requires a high heating demand and a low cooling demand. In this category, the heating intensity is the same for urban and rural areas, which is 14.4 kWh/m^2. Each person then consumes 432.6 kWh/year of surface heating EUD. This sums up to **4815.6 GWh** for the entire residential sector in Belgium.

B.3.3 Hot water

The energy required for hot water consumption is determined by the energy required to heat one litre of water, multiplied by the volume of hot water consumed.

Water consumption The total direct consumption of water in the households is composed of four different sources: drinking water, sanitation, bathing, and food preparation.

The volume of drinking water consumption recommended depend largely on the climate and the lifestyle. It is recommended to drink between 1 and 1.5 mL/kcal of food consumed [43]. As it was considered a consumption of 2000 kcal of food per capita and per day, the final consumption of drinking water is 2-3 L/cap/day.

Then, the minimum volume of water used for sanitation is 20 L/cap/day. The volume of water used for bathing/showering is 15 L/cap/day. The volume of water used for food preparation is 10 L/cap/day [43].

The final minimum volume of water required is then 48 L/cap/day.

Drinking	3 L
Sanitation	20 L
Bathing	15 L
Food preparation	10 L
Total	**48 L**

Table B.3: Water consumption.

Hot water consumption Amongst this water requirement, a certain portion must be heated. In the "Decent Living" article, 100% of the water used for bathing/showering, as well as 25% of the water used for sanitation is considered to be heated. It represents a volume of 20 L/cap/day, which equals to 7300 L/cap/year.

Heat required The heat required to heat the water is computed with the following equation:

$$E_{HW} = c_p V \rho \, (T_{out} - T_{in})/\eta \tag{B.4}$$

where c_p is the specific heat capacity of water ($c_p = 4184$ [J/kg K]), V is the volume of water to heat, ρ is the density of water (0.997 kg/L) and η is the heat transfer efficiency of the boiler (95%) [2]. As `EnergyScope TD` only considers the EUD (instead of the FEC, see Section 2), the heat transfer efficiency is not taken into account to dimension the hot water energy requirements. T_{out} and T_{in} are respectively the target and starting temperatures. T_{out} is set to $50°C$ and T_{in} is more complicated to know precisely.

The mean temperature in Belgium was 9°C in Belgium between 1961-1990 [44]. This temperature is increasing due to the climate change and the world mean temperature in 2050 will depend on the $CO_{2,eq}$ emissions of the future years. The more $CO_{2,eq}$ emission, the highest temperature increase. To have an idea, in 2020, the Belgian mean temperature was 12.2°C, which is the absolute record in mean temperature during a whole year. The IRM (Institut Royal de Météorologie) projects a mean temperature between 10.6 and 10.8 °C in 2050 [44]. These values are approximate. The important parameter for water heating is the temperature delta, rather than T_{out} and T_{in}. As T_{out} is fixed arbitrarily, the temperature delta can be fixed at 40 °C.

This sums up to **4243.4 GWh** for water heating in the households sector.

B.4 Services

This section shows the methodology used for the services sector in the "Decent Living" article. The methodology is based upon the surface of the different services. The different domains forming the services sector are: education, health, retail, offices, and others (hotels, restaurants, etc.). They advance services surfaces that are global and do not reflect the Belgian reality. The Climact scenario "CORE95" for Belgium [29], obtains lower surfaces, for every service, except for education. The former values for surfaces will be used, even for education buildings, to be coherent.

The surfaces and the heating intensities of the different services are shown in Table B.4.

	Surface [Mm^2]	Heating intensity [kWh/m^2]	**EUD 2050 [GWh]**
Education	30.9	13.0	**400.6**
Health	9.9	11.7	**115.8**
Retail	39.6	11.5	**456.7**
Offices	97.5	10.5	**1024.6**
Others	32.6	14.4	**470.2**
Total	**210.4**	**11.7**	**2467.9**

Table B.4: Services space heating EUD.

The total heating demand for the services sector is **2467.9 GWh**. Millward-Hopkins et al. estimate that the space heating energy requirement half of the tertiary sector consumption (fixed and variable electricity, and hot water consuming the other half) [2]. The distribution between these three EUD is considered to be the same distribution as in the European Commission scenario: 42.7%, 33.3%, 24%, respectively. The summary of the EUD for the tertiary sector is shown in Table B.5.

The assumption of setting the heat demand as half of the service sector's energy consumption may seem strong. But when compared with the high consumption scenario in Section 4.3.2, the ratios are similar. This means that this assumption is coherent.

EUI [GWh]	Energy consumption
Electricity	1054.5
Lighting	822.7
Space heating	2467.9
Hot water	590.7
Total	**4935.8**

Table B.5: EUD of the tertiary sector.

B.5 Industry

As explained previously, the methodology of the "Decent Living" article is a bottom-up one, meaning that the cultural and wealth differences between countries are not considered, as the energy demand is defined by the same needs for everyone (still depending on some parameters, like the age distribution, the temperature, the urbanization etc.). Then, the industry demand is composed of the embodied energy in goods and infrastructures that are used amongst the other sectors. It is considered that every good and infrastructure used in Belgium are constructed and manufactured in Belgium.

B.5.1 Passenger mobility embodied energy

The energy used in the industry for the mobility sector is located in the manufacture of the vehicles, and in the infrastructures used by these vehicles. `EnergyScope TD` doesn't consider aviation, nor soft mobility. Then, their embodied energy and their infrastructures won't be included in the computation of the industry EUD.

The methodology considered for the passenger mobility is to make a first estimation for the embodied and infrastructure energy required, based on different articles, and to discuss these values in order to decrease them. The energy required is expressed in MJ/pkm, rather than for a specific vehicle. Then, the energy required for the infrastructure of a bus will differ from the one required for a car, even though they share the same infrastructure, as the bus transports more people, so the energy needed for one passenger kilometre will be lower.

Cars The initial energy considered for manufacturing cars (for each passenger kilometre) is 0.37 MJ/pkm [45] or 0.38 MJ/pkm [46]. This energy required is established for a sedan of 1.4t, and assuming an occupancy rate of 1.6. In order to reduce the energy required, the weight will be considered to be 1t (inclusive of passengers) and the occupancy rate to be 3 [2]. They consider that the energy requirement is directly proportional to these parameters. Moreover, Allwood et al. predict a more efficient manufacturing process for steel, cutting the energy requirement by 33% more (steel is used as an approximation for the whole car) [47]. The energy embodied in the cars is then **0.097 MJ/pkm**.

Then, the energy required for the infrastructure used by cars lays between 0.11-0.4 MJ/pkm [45][46]. "Decent Living" article uses 0.25 MJ/pkm as a starting value. Again, this value is adapted to an occupancy rate of 3, rather than 1.6. A 22% improvement in the cement production efficiency is considered (cement is used as an approximation for road infrastructure) [48]. This leads to an energy consumption of **0.104 MJ/pkm** for the car infrastructure.

Buses The same methodology as for cars is used. The minimum energy requirement for manufacturing buses is 0.07 MJ/pkm [46]. A 33% improvement in manufacturing efficiency is assumed [47]. It brings the energy required to **0.047 MJ/pkm**.

Then, the energy required for infrastructure is 0.07 MJ/pkm. This value is lower than for cars, as buses transport more people. As the infrastructure is shared between cars and buses, the same improvement in the material manufacturing is considered, 22%. The energy required is then **0.055 MJ/pkm**.

Trains The initial embodied energy in trains is 0.01 MJ/pkm [46]. This value is low, as a train can transport a lot of people in long distances. The main material used is also steel (also used as an approximation for trains). The forecast improvement is then also 33% [47]. The energy required is then **0.007 MJ/pkm**.

The infrastructure is more important, as trains require their own infrastructure, the rails. The initial energy required is 0.33 MJ/pkm [46]. As the main material is steel, the 33% efficiency improvement is used, which finally gives **0.221 MJ/pkm**.

Computation Table B.6 summarises the energy needed for the embodied energy in vehicles and infrastructures. The less consuming mean of transport is the bus. When multiplying the totals of Table B.6 with the distance travelled per capita by mean of transport (Table B.7), and then sum, we obtain the total EUD for the passenger mobility per capita, depending on their location (urban or rural). The results are shown in Table B.8.

	Cars	Buses	Trains	Units
Embodied	0.097	0.047	0.007	[MJ/pkm]
Infrastructure	0.104	0.054	0.221	[MJ/pkm]
Total	**0.201**	**0.101**	**0.228**	**[MJ/pkm]**

Table B.6: Industrial energy requirement related to passenger mobility.

	Urban	Rural	Units
Trains 40%	1564	2406	[pkm/cap]
Buses 40%	1564	2406	[pkm/cap]
Cars 20%	782	1202	[pkm/cap]
Total	**3910**	**6014**	**[pkm/cap]**

Table B.7: Distance travelled by mode of transport.

	Urban	Rural	Units
Trains	356.3	548.0	[MJ/cap]
Buses	158.7	244.2	[MJ/cap]
Cars	157.2	241.8	[MJ/cap]
Total	**672.2**	**1034.0**	**[MJ/cap]**

Table B.8: Embodied and infrastructure energy of the passenger mobility.

The EUD required for the industry linked to the passenger mobility is **2442.8 GWh**.

B.5.2 Freight mobility embodied energy

The methodology used to compute the energy required for the industry linked to freight mobility (embodied in vehicles and infrastructures) consists in multiplying the embodied energy consumption of the passenger mobility by the same factor as between the direct energy consumption of passenger and freight mobility. These factors are computed in Table B.9, and are 1.35 for rail transportation and 2.6 for road transportation. The same factors are assumed for vehicles manufacturing and infrastructures. It gives the values presented in Table B.10.

	Rail	Road	Units
Passengers direct	0.06	0.18	[MJ/pkm]
Freight direct	0.08	0.48	[MJ/tkm]
Factor	**1.35**	**2.6**	**[tkm/pkm]**

Table B.9: Multiplying factor between passenger and freight direct energy consumption.

	Rail	Road	Units
Embodied	0.009	0.122	[MJ/tkm]
Infrastructure	0.298	0.142	[MJ/tkm]
Total	**0.307**	**0.264**	**[MJ/tkm]**

Table B.10: Embodied and infrastructure energy of the freight mobility.

The EUD related to the energy embodied in the vehicles and infrastructures of the freight sector is found by multiplying the population, the tons-km for each inhabitant and the energy intensity. It results in **2136.5 GWh**.

B.5.3 Construction

The construction sector is an important one in the industry. It represents the construction of the households and the service buildings. An energy intensity will be affected to each of the construction sectors. This will be multiplied by the total surface, in order to give the yearly energy requirements of the industry sector of construction.

To define the energy intensity, Millward-Hopkins et al. consider construction in each country to be either low or high intensity [2]. Low intensity category represents the countries in which timber buildings dominate the constructions, and high intensity category represents the countries in which concrete, masonry and steel buildings dominate the constructions. The low intensity regions are North America, Oceania, and Africa. The high intensity regions are Europe, Asia, and Latin America [49]. Belgium is then considered as a high construction intensity country.

Households infrastructures The surface of one household is 70 m^2, for 2.5 people on average (given in Section B.3). This gives a total surface for households of 334 Mm^2.

The energy intensity for residential buildings' construction is defined by Ramesh et al. [50]. Their lowest embodied energy for the high intensity category is 13 kWh/m^2 for each year. This gives **4341.4 GWh** each year for the whole residential buildings' construction.

Services infrastructures For the high consumption category, Ramesh et al. advance a minimum energy intensity for office construction of 40 kWh/m^2 [50], which is about three times more than for houses. This energy intensity is also used for education and retail buildings. For the health buildings, the energy intensity considered is three times more than for offices. This is 120 kWh/m^2 [2].

	Total surface [Mm^2]	Energy intensity [kWh/m^2]	Total embodied energy [GWh]
Education	30.9	40	1234.7
Health	9.9	120	1189.9
Retail	39.6	40	1583.6
Offices (and other)	130.1	40	50203.0
Total	**210.45**	/	**9211.2**

Table B.11: Energy required for services buildings construction.

The total energy required for the construction of service buildings is **9211.2 GWh**.

B.5.4 Communication and information

Phones The same phone as in Section B.3.1 is considered, namely the Fairphone. In the repair scenario, with refurbishment, the Fairphone's lifetime increases from 3 years to 5 years, with an energy consumption of 166.1 MJ for the production phase [41]. The transport is not considered here, as it is already taken into account in the freight mobility. This leads to a consumption of 33.2 MJ/phone y. Multiplying by the number of phones owned by Belgians, this gives **97.4 GWh**.

Computers Deng et al. suggest a range of 3010-4340 MJ for the production of one laptop [42]. Considering a lifetime of 10 years (twice that of a phone), it gives 301 MJ/laptop y. This means **398.9 GWh** for the annual production of laptops.

Network infrastructure Ercan et al. offer an estimate of the Wi-Fi network and data centre's electricity consumption [51]. They consider three levels of usage: low, representative and high users. In order to choose the level of usage, we compare the electricity usage of the Fairphone (4.9 kWh/phone y) and decide to use the representative level, which is the closest to this value. To this level correspond a network use of 33.3 kWh/phone y. According to Millward-Hopkins et al., the network use for laptops is five times larger than for phones (166.5 kWh/laptop y) [2]. This leads to an electricity consumption of **1145.7 GWh** every year. The energy consumption related to network infrastructure is scaled upon its usage, considering the ratio between emitted emissions for the production and the use phases. The embodied energy is 22% of the use one [51], leading to 7.4 kWh/phone y. As previously considered, laptops require 5 times more network and data centres, leading to 37 kWh/laptop y. This becomes **254.6 GWh** for the annual energy requirements of the construction phase of networks and data centres.

B.5.5 Manufacturing goods

Cold storage and cooker manufacturing The energy embodied in one fridge-freezer is defined on the basis of its use. Indeed, 81% of its life-cycle energy usage is consumed during its use phase, while 19% is consumed during its production phase [52]. As the use phase energy consumption was already computed in Section B.3.1, the annual energy need for the production of one fridge-freezer is 39.3 kWh.

Millward-Hopkins et al. consider an induction cooker of first generation, which requires 1 GJ to be produced [53]. The same cooker of the fifth generation only requires 0.8GJ to be produced. The latter will be considered here, with a lifetime of 10 years, which gives 80 MJ/cooker y (=22.2 kWh/cooker y).

Each household needs 61.60 kWh every year for the production of one fridge-freezer and one cooker. The total energy needed is **293.9 GWh**.

Clothes The annual energy required to produce clothes is estimated for each category of clothes (tops, bottoms, jackets, jumpers, underwear, and shoes) based on its lifetime, its embodied energy, and the efficiency improvement of the production of its material. This information is expressed in Table B.12. The efficiency improvement is defined in the "Decent Living" article for cotton (-76%), wool (-44%) and rubber (-58%), and then was attributed to each of the clothes categories by assuming the main material used in its production. The total energy per capita for clothing is then 307.2 MJ/cap y. When adding 20% of this total to account for non-clothing items, like bedsheets and towels, it brings the total up to 368.7 MJ/cap y.

	Lifetime [days] [54]	Embodied energy [MJ] [40]	Savings [%]	Total energy [MJ/cap y]
Tops	112.5	62	-76	48.3
Bottoms	300	172	-76	50.2
Jackets	562.5	111	-44	40.3
Jumpers	337.5	172	-44	104.2
Underwear	125	12	-76	8.4
Shoes	365	133	-58	55.9

Table B.12: Embodied energy in clothing.

In addition to clothes production, the embodied energy of the washing machine must be taken into account. Millward-Hopkins et al. estimate that the energy required for the production phase is about 30% of the one of the use phase, when averaged to annual values [2]. It leads to 70 MJ/cap y for washing machine production.

The total annual energy consumption for the production of the clothing sector (clothes and washing machine) is **1453.8 GWh**.

B.5.6 Food industry

The agriculture is not taken into account into `EnergyScope TD`, but the rest of the food industry must be considered in the industry sector. The transport is not considered here, as it is already in the freight mobility section. The food industry is divided in the processing and distributions categories. Distribution includes packaging and retail. The processing is 130% of the agriculture share of the food industry. This is 150% for the distribution share [55]. The FAO suggests that the processing of the food can be reduced from 130% to 100% [36]. Then, the "Decent Living" article considers that this total can be halved, leading to only 50% for processing. In addition, the unavoidable waste is added to the consumption. It represents 15% of the agriculture consumption. The agriculture accounts for 3380.0 GWh. Then, the addition of the food processing (50%), the distribution (150%), and the unavoidable waste (15%) gives a consumption for the food industry of **7266.9 GWh**. As explained previously, the agriculture is not taken into account in this consumption.

B.5.7 Collective services

Water supply Before estimating the direct energy consumption of water supply, the level of water scarcity for Belgium must be fixed. Indeed, depending on the region of the world, some countries are subject to higher water stress than others. The *World Resources Institute (WRI)* defines a scale from 0 to 5 for water stress :

- 0-1 : low stress (<10% of available water withdrawn, for consumption, every year)
- 1-2 : low to medium stress (10-20%)
- 2-3 : medium to high stress (20-40%)
- 3-4 : high stress (40-80%)
- 4-5 : extremely high stress (>80%)

The score of Belgium for water stress is 3.16, placing it in the *high stress* category [56]. Millward-Hopkins et al. defines 5 intensities for the different categories of water stress, by using values of Godskesen et al. for the central intensity [57] and of Plappally et Lienhard for both the extreme intensities [58]. The low and high intensities are set as averages to fill the gaps. Belgium's intensity is "high". Its direct and infrastructure energies are 11.6 and 2.4 MJ/m^3, respectively. As computed in Section B.3.3, the daily water consumption is 48 L/cap. The total energy required for water supply is then **812.6 GWh**.

Waste management The assumption considered here is that the energy requirement per capita for waste management is the same average energy requirement as for water supply [2]. They consider 0.18 GJ/cap. This assumption is particularly crude, given that the total consumption in their scenario is considerably different from anything currently existing, and so there is no precise source to compare. This leads to an energy consumption for the waste management of **596.3 GWh**.

Power supply The power supply infrastructure also requires energy to be constructed. Hertwich et al. estimate that 0.10 kWh will be necessary for the infrastructure for each kWh transported by the power supply infrastructure. There is no distinction between electricity and heat carriers. The energy transported by the power supply infrastructures is the sum of the household, service, industry, and transportation sectors EUD. The transports are considered to be electrified, and their direct energy use is 2358.7 GWh and 2593.2 GWh for passenger and freight mobilities, respectively. The other sectors EUD are 12552.38 GWh, 4935.8 GWh and 30452.1 GWh, for household, services and industry, respectively.

The energy contained in the power supply infrastructure is **5289.2 GWh**.

B.5.8 Non-energy demand

The non-energy demand is not estimated in the "Decent Living" article. Then, it is estimated to be the same share in the industry sector as in the European Commission scenario (high demand), i.e. 27.7%. This equals **13704.7 GWh**.

B.6 Low energy demand matrix

Table B.13 summarises the demand by sectors, as presented in the previous sections.

	HOUSEHOLDS	SERVICES	INDUSTRY	TRANSPORT.	Units
ELECTRICITY	2270.6	1054.5	12776.9	0	[GWh]
LIGHTING	1222.7	822.7	4208.4	0	[GWh]
HEAT_HIGH_T	0	0	14128.5	0	[GWh]
HEAT_LOW_T_SH	4815.6	2467.9	3675.3	0	[GWh]
HEAT_LOW_T_HW	4243.4	590.7	952.3	0	[GWh]
MOBILITY_PASSENGER	0	0	0	39225.1	[Mpkm]
MOBILITY_FREIGHT	0	0	0	27539.4	[Mtkm]
NON_ENERGY	0	0	13704.7	0	[GWh]

Table B.13: Energy demand matrix of the LD scenario.

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