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Soft-link between a multi-energy optimization tool and an electrical adequacy assessment tool

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Abstract

The current context of major energy changes is leading to increasingly decentralized systems, with renewable energies taking on a new role in the energy mix.

The aim of this work is therefore to establish a potential future energy system based on the literature. This system revolves around changes that are directly visible to the individual consumer. Indeed, consumers can see changes in the way they heat their homes or get around. What's more, the consumer can now play the role of producer by generating his or her own energy end also store energy.

In order to analyze such energy systems, a soft-link is used and presented in this work (available here: `https://github.com/agaignage99/MasterThesis-SoftLink`). This allows EnergyScope results to be used as input for subsequent optimization via a adequacy tool. The main purpose of this soft-link is to enable the energy network nation to be easily integrated into a system optimized by EnergyScope. To establish this soft-link, a series of assumptions and approximations are made in order to distribute the optimized system on the Belgian high-voltage network and on a future hydrogen network. These approximations and assumptions are presented throughout this work.

After using these two tools on the energy systems presented, several observations are made. The first finding highlights the nodes most affected by curtailment and loss of energy. Based on this observation, it is noted that for several hundred hours a year, some nodes experience curtailment while others lack energy. This leads to the conclusion that there is a series of weak points in the network, resulting in an inability to transport energy correctly between areas of excess and shortage.

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List of Acronyms

Mtoe Mega tonnes of oil equivalent

GHG Green House Gas

OPEX Operational Expenditure

CAPEX Capital Expenditure

ENS Energy Non-Served

EUC European Commission

RES Renewable Energy Sources

EUD End-Use Demands

ESOM Energy System Optimization Model

PSM Power System Model

MARKAL Market Allocation

EFOM Energy Flow Model Optimization

CO_2 Carbon Dioxyde

H_2 hydrogen

V2G Vehicule to Grid

LOLP Loss of Load Probability

LOLE Loss of Load Expectation

EUE Expected Unserved Energ

$CO_{2,eq}$ Carbon Dioxyde Equivalent

UCED Unit Commitment Economic Dispatch

ESTD EnergyScope Typical Day

TD Typical Days

LP Linear Programming

kt Kilo Tonne

$f_{max}(i)$ Maximum Installed capacity for a technologie i

$f_{min}(i)$ Minimum Installed capacity for a technologie i

$fmax_{perc}(i)$ Maximum share of the demand share by a technology i

$fmin_{perc}(i)$ Maximum share of the demand share by a technology i

CAR_BEV Electrical Vehicule

HP Heat Pump

NUTS Nomenclature of territorial units for statistics

GDP Gross Domestic Product

C_{inv} Investment Cost

C_{maint} Maintenance Cost

C_{op} Operating Cost

PV Photovoltaic Panel

C_{res} Cost of a ressource

η Efficiency

CCGT Combined Cycle Gas Turbine

CCGT_AMONIA Combined Cycle Gas Turbine using Amonia

CHP Combined Heat and Power

MTTF Mean Time to Fail

MTTR Mean Time to Repair

LF Load Factor

E_{year} Electrical Energy produced over one year

COAL_US Ultra-supercritical coal power plant

COAL_IGCC Intagrated gasification combined cycle with coal

IND_COGEN_GAS Gas fired Industrial Cogeneration

IND_COGEN_WOOD Wood fired Industrial Cogeneration

IND_COGEN_WASTE Waste fired industrial Cogeneration

DHN_COGEN_GAS Heat Network gas Fired Cogeneration

DHN_COGEN_WOOD Heat Network Wood Fired Cogeneration

DHN_COGEN_WASTE Heat Network Waste Fired Cogeneration

DHN_COGEN_WET_BIOMAS Heat Network Biomass Fired Cogeneration

DHN_COGEN_BIO_HYDROLYSIS Heat Network Bio Hydrolysis Cogeneration

DEC_COGEN_GAS Decentralized Gas Fired Cogeneration

DEC_COGEN_OIL Decentralized Oil Fired Cogeneration

DEC_ADVCOGEN_GAS Decentralized Gas Fired Cogeneration

DEC_ADVCOGEN_H2 Decentralized Hydrogen Fired Cogeneration

CAR_PHEV Plug-in Hybrid Vehicule

CAR_BEV Electrical Vehicule

TRAMWAY_TROLLEY Tram

TRAIN_PUB Passenger Train

TRAIN_FREIGHT Freight Trains

TRUCK_ELEC Electrical Truck

IND_DIRECT_ELEC Industrial Direct Electrcity

DEC_DIRECT_ELEC Decentralized Direct Electricity

DHN_HP_ELEC Heat Network Electrical Heat Pump

DEC_HP_ELEC Decentralized Electrical Heat Pump

ATM_CCS Atmospheric Carbon Capture and Storage

Industry_CCS Industrial Carbon Capture and Storage

H_2_RE Renewable Hydrogen

SMR Steam Methane Reforming

H2_BIOMASS Biomass to Hydrogen

H2_ELECTROLYSIS Electrolysers

CAR_FUEL_CELL Car fuel cell (H2)

TRUCK_FUEL_CELL Truck fuel cell (hydrogen)

BUS_COAC_ FC_HYBRIDH2 Bus fuel cell (H2)

WEM With Existing Measures

WAM With Additional Measures

M.pass.km Mega passenger kilometer

M.pass.km/h Mega passenger kilometer per hour

NECP National Energy and Climate Plan

CAR_NG Natural Gas Vehicles

BATT_LI Batteries

DEC_THHP_GAS Thermal heat pump gas (decentralised)

DEC_SOLAR Solar thermal (decentralised)

GWP_{op} Operational Global Warming Potential

GWP_{constr} Construction Global Warming Potential

kton kilo tonne

TWh Tera Watt Houre

LOL Loss of Load

LOE Loss of Energy

LOLE Loss of Load Expectation

LOEE Loss of Energy Expectation

Chapter 1

Introduction

"Clean and sustainable energy" is the title of the 7th of the 17 Sustainable Development Goals included in the 2030 Agenda for Sustainable Development adopted by all UN member states in 2015. By 2030, this goal aims to *"ensure access to affordable, reliable, sustainable and modern energy for all"* [1]. This will be achieved by significantly increasing the share of renewable energies in the global energy mix and doubling the rate of improvement in global energy efficiency. But also by strengthening international cooperation in terms of research and infrastructure [2].

Although access to energy in Belgium can be taken for granted, sustainability is still a long way off. In fact, in 2022, Belgian primary energy consumption stood at 52.1Mega tonnes of oil equivalent (Mtoe) ($\approx$ 605.9 TWh), of which almost 68% was fossil fuel-based (oil, gas, solids) [3]. Fossil fuels are responsible for 2/3 of the Green House Gas (GHG) emissions responsible for the 1.1°C rise in global average temperature compared with the period 1850-1900 [4]. To curb this rise, in 2015, the Paris agreements were signed by 196 countries. These agreements aim to maintain *"the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels"*[5].

To achieve this, the European Commission (EUC) has adopted the Green Deal, which includes *"a series of proposals to make the EU's climate, energy, transport and taxation policies capable of reducing net greenhouse gas emissions by at least 55% by 2030"* [6]. Such a reduction requires a review of energy systems.

Electrification will play a key role in decarbonizing these new systems. Indeed, it will make it possible to do without carbon-based vectors to satisfy the various End-Use Demands (EUD) (heat, mobility, electricity, non-energy). However, this massive electrification will lead to a drastic increase in electricity consumption, so non-carbon-based means of production such as Renewable Energy Sources (RES) will have to be employed on a much larger scale. The two main contributors to RES are sun and wind, but the latter are uncontrollable and intermittent. A high rate of RES penetration in an energy system therefore leads to random behavior, making the system less predictable. This calls for a more in-depth study of energy systems as a whole, to determine whether they are capable of satisfying the various EUD, and at what cost. But it is also vital to know whether energy transmission infrastructures are sufficiently adapted to such changes. In addition, the emergence of new energy carriers such as hydrogen will also contribute to the evolution of energy systems. These elements and their interactions must therefore also be taken into consideration when designing a system.

In order to design an energy system, the first type of tool used here is called Energy System Optimization Model (ESOM). These tools take as input a whole series of EUDs from all sectors (heat, electricity, mobility, non-energy). Based on these inputs, the model determines the technologies to be integrated into the system. These technologies enable energy to be produced or consumed in order to cover the various EUDs. The model therefore ensures that for each time step, the EUDs are covered. In addition, the model's objective function is to minimize the cost of installing and operating the system. These models generally incorporate a GHG emission limit in addition to the objective function of cost minimization.

The second type of tool is called Power System Model (PSM). These tools are not used to design an energy system, but to optimize the use of different energy system technologies in order to minimize the system's operating costs, as well as the costs associated with the system's inability to supply sufficient energy (Energy Non-Served (ENS)). In addition, these tools integrate the notion of networks, which are a set of nodes connected by lines. Modeling brings us closer to reality. Indeed, in a given energy system, energy is not always consumed where it is produced, and must therefore be transported via a network, resulting in a series of limitations. These limitations can then be analyzed. In addition, these tools can integrate various probabilistic notions to assess the impact and consequences on the network of a potential failure of a transmission line or production unit.

The aim here is to link two tools of each type. This is done via what is known as a Soft-Link. The aim of the Soft-Link is to input data representing an ESOM-optimized system, directly usable by a PSM.

The ESOM used here is EnergyScope, an open-source model originally developed by EPFL and now the subject of collaboration with UCLouvain. The version used here was mainly developed by Gauthier Limpens (UCLouvain) and is detailed in his work. This tool aims to establish a system based on Operational Expenditure (OPEX) and Capital Expenditure (CAPEX) optimization. An entire section of this work is devoted to introducing how EnergyScope works. The PSM used here is a matching tool developed by Aurélia Hernandez (UCLouvain). It integrates two energy carriers, electricity and hydrogen. The tool performs an optimal DC power-flow based on a Monte Carlo method. This enables optimization and probabilistic analysis of an energy system.

Once this stage has been completed, in order to evaluate and test the soft-link, a scenario is drawn up based on data available in the literature. This scenario is

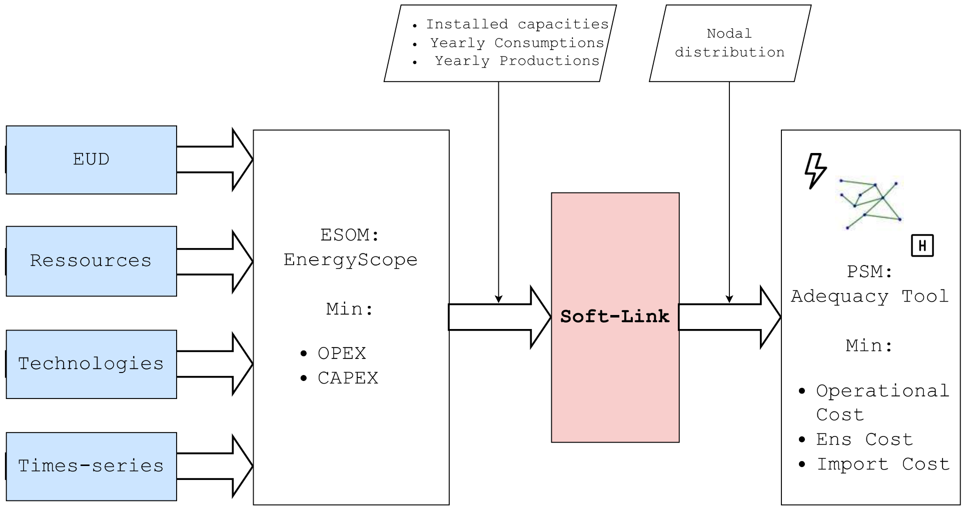

Figure 1.1: Main objectif

summarized in a series of constraints applied to the ESOM. The data generated by this tool is then processed by the Soft-Link to serve as input parameters for the PSM. The final step consists in analyzing the results of the latter tool to determine the behavior of such an energy system on the Belgian high-voltage grid and on a future hydrogen (H_2) network.[1]

[1]This work was partly written with the help of DeepL.

Chapter 2

State of the Art

In this context of energy transition and changes in the way energy is consumed, energy systems are evolving and are different because they incorporate new constraints linked, for example, to the intermittency of RES. This leads to a reduction in the controllability of an energy system. In order to understand and guard against these new stochastic behaviors, the adequacy and flexibility of energy systems need to be studied. To achieve this, two types of tools are needed: the first enables us to establish an energy system based on the needs and constraints of the land. The second is used to evaluate the suitability and flexibility of this system on a defined electrical network.

The first type of tool implements an energy system as a whole ESOM, i.e. it takes into account a large list of EUD (as in electricity, heat, mobility, etc.). Tools of this type can be distinguished by the type of energy technology they integrate, the function they seek to optimize, and the constraints they face.

The second type of tool focuses solely on the power system side of the equation , i.e. it checks whether the demand for electricity is being met by the system's ability to produce it. Here, 3 different tools of this type are analyzed , comparing how they work, how they model a power system, and at what resolution. Or whether they integrate energy vectors other than electricity.

In order to take advantage of the strengths of each of these two tools, a great deal of work has been done on how to link these two types by means of a Soft-Link. To do this, there are several types of soft-link available to solve very different problems. Finally, we'll describe several types of problem that can be analyzed using the results obtained with a soft-link.

2.1 Energy System Optimazation Model

2.1.1 TIMES

TIMES combines Market Allocation (MARKAL) and Energy Flow Model Optimization (EFOM) models to generate techno-economic models of energy systems [7]. These can be established at different scales (regional, multi-regional, national). TIMES provides a technological basis for estimating the dynamics of an energy system. The analysis is generally done on all energy sectors but it is also possible to focus on a smaller number (only electricity for example). TIMES is qualified as a deterministic inter-temporal model, which calculates a dynamic inter-temporal partial equilibrium. To do this, the objective function aims to maximize the total surplus by minimizing the cost of the system while corresponding to the various environmental and technical constraints [8].

The different input components are the energy demand of the different sectors, the supply (i.e. the cost and potential of each resource), a scenario (corresponding to a political objective) and finally a technical-economic component. Each sector is described by technologies that are characterized by economic, technological and environmental parameters. TIMES can be used for different short, medium and long time scales but is mainly used for long term projections and has a temporal resolution af an hour [9]. The temporal mesh will depend on the computing capacity and the time scale. Each period is divided into 12 sub-periods which are defined by day, night and time points for the four seasons.

In TIMES the demand for electricity is evaluated endogenously so that the demand of each sector is optimally matched to the capacity of the sector. The different parameters of the technologies included in TIMES can be found in the document [10]. The operation of TIMES is shown in the figure 2.1.

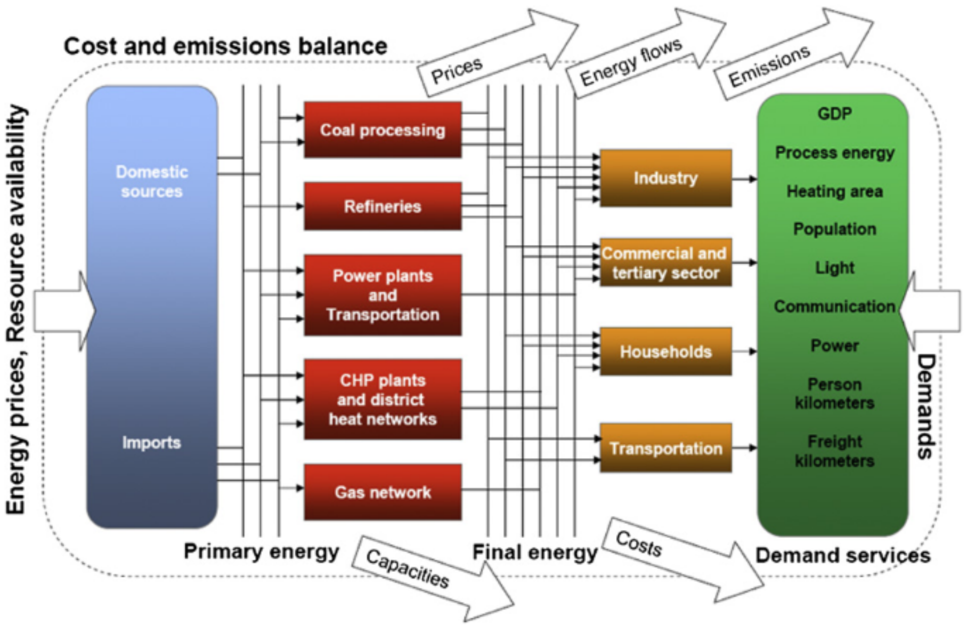

Figure 2.1: TIMES Representation. Figure taken from [11]

2.1.2 Callipode

This open source tool can be used to develop energy model schedules on several scales. What's more, it's quite versatile, with several temporal resolution scales down to half an hour, and it's possible to select and integrate a large number of energy technologies. Finally, it can be used on different geographical scales, from the modeling of a neighborhood to an entire continent [12].

The model is based on linear optimization to optimize the operation of an energy system and establish the different capacities to be installed according to the integrated technologies. Its main function is to reduce the socio-economic costs of a system. To achieve this, a range of costs can be included, from the installation, operation and maintenance of a technology, to fuel prices and the cost of Carbon Dioxyde (CO_2) [12].

The constraints introduced into the model will be a series of demands, such as for heat, cooling, electricity or transport. Several different technologies can be used to meet the same demand. The model ensures that the demands are met at each time step. A special feature of electric mobility is that the demand for electricity is met during recharging, rather than during the use of the technology itself. The situation will be the same for hydrogen-powered mobility. Conversely, the demand for fuel for vehicles is considered to be something that can always be met. It should also be noted that the model does not include certain features such as intelligent recharging or Vehicule to Grid (V2G) [12].

2.2 Power System Model

2.2.1 Plexos

Plexos is first and foremost a commercial tool developed by Energy Exemplar. It simulates an energy market. It enables dispatching between different technologies, whether conventional or RES power generation. In addition to power matching, Plexos can also integrate gas, hydrogen and water constraints [13].

In addition to studying grid congestion (which is the focus of this work) through nodal or zonal analysis, Plexos can also carry out market projections to optimize the use of a particular technology, such as storage. Its aim is to minimize the total cost of power generation. To achieve this, Plexos uses a time resolution in hours [14].

The PLEXOS tool is used here to model the power system. This commercial software is used worldwide to model and plan power systems. The goal of this type of model is to minimize an objective function, often a cost, taking into account a multitude of constraints such as fuel costs, production costs, transportation costs, operational characteristics of the production units (rate of maintenance or failure), but also various constraints related to environmental regulations. The advantage of this software is that the mathematical model on which PLEXOS is based is accessible, so we speak of a transparent model.The paper focuses on a short-term deterministic model, i.e. the model perfectly anticipates the wind generation and the different forced outages. PLEXOS models the shutdown and start-up decisions of each generator in a way that matches the technical parameters of the generators. These parameters include the minimum stable production, the start-up time and the number of minimum shutdowns of the generators over a year. An objective function is defined, which tries to equalize the capacity reserves over the different point periods. A Monte-Carlo method is used to give a random character to the failures from the failure severity rate frequencies [7].

2.2.2 DISPA SET

Dispa-set is an Unit Commitment Economic Dispatch (UCED) model useful for balancing and flexibility problems on the European power grid. This tool was developed by the Research Centre of the EUC in partnership with the University of Liège and the KU Leuven [15].

This model provides a short-term representation of a large-scale power system with a high level of detail. The model assumes the existence of a central operator with comprehensive information on the technical and economic characteristics of each power unit. But also with information such as the demand at each node and the characteristics of the transmission network [16].

This makes it possible to solve a so-called unit commitment problem. This problem is a simplified representation of the reality faced by a network operator in charge of managing the various production players in a day-ahead power market. To do this, demand is aggregated at each node, and the transmission network is modeled as a transport problem [16].

The unit commitment problem is divided into two sub-problems. The first consists in planning the start-up, use and shut-down of units. This is a binary problem. The second aims to distribute the total power demand among the available power units, with the objective of minimizing the total cost of the system. It is therefore a dispacth economic problem that continuously determines the output of each unit [16].

The system's constraint is that there must always be a balance between power supply and demand, for each time period and each geographical area for the day-ahead market. This balance consists of an equilibrium between different elements at each node. On the one hand, there is the power consumed and the cumulative power produced by the units, and on the other, the power supplied by any neighboring nodes. The balance must also be maintained by taking into account the lack of power from intermittent generation units, the power supplied or absorbed by storage and, finally, interrupted load and load shedding [16].

2.2.3 NEPLAN

This program is developed by BCP Inc. in corporation with ABB Utilities GmbH and Swiss Federal Institute of Technology [17].It can be used to analyze, optimize and simulate different types of networks, whether for electricity, gas, heat or water. For the purposes of this work, it is the electricity-related characteristics that will be of interest. It works for both AC and DC networks, and can integrate various standards (US and European)[18].

NEPLAN can therefore be used to analyze load flows and energy losses in a network. It can also be used for power quality analysis, and incorporates a dynamic dimension to take into account phenomena linked to motor starting, or harmonic analysis at different scales [19]. NEPLAN can be used for both transmission and distribution networks. It can also be used to model the network of an industrial site or power plant. For example, it can model a network comprising a large number of bus bars (over 500,000) [18].

2.3 Soft-link of the literature and case studies

2.3.1 Soft-link TIMES and PLEXOS

With the objective of reducing CO_2 emissions, this work establishes various scenarios for reducing the Republic of Ireland's CO_2 emissions by 80% by 2050 compared to 1990 [7]. In order to achieve this goal, there is a need to electrify the transportation and heat production sectors. This would result in a significant increase in the share of electricity in total final consumption from 18% in 2015 to 31%-47% in 2050 [10]. This electrification and the need to use non-carbon energies will lead to a significant use of wind and solar generations. However, the variable and uncertain behavior of these energy sources requires further analysis to quantify the impact on power system reliability. To evaluate and quantify the reliability of the system certain metrics are used such as Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE) and also Expected Unserved Energ (EUE). LOLP measures the probabilty that load exceed the production capacity of the system. LOLE represents the number of hours that the production can not meet the load. EUE represents the amount of energy that isn't supply. The goal of Power Systems Models is to calculate these metrics thanks to temporal information such as *maintenance outages, forced outages rates, mean time to repair modes and load information.* This soft-link uses electricity and renewable profiles as inputs. The methodology is established in 7 steps:

- A model is chosen with a scenario and a target year to run the energy system model.
- The target year data is extracted to build a production portfolio for the power system model.
- The annual demand profiles are converted to half-hourly profiles. These profiles are used by the power system model.
- In order to study the impact of the change of chronological resolution, the Power System model is run with a half-hourly resolution for the first time without any additional technical constraints.

- The number of technical constraints are progressively increased to determine their impact on the model.
- The results of the models are compared with the different levels of constraints in order to examine the reliability of the system. This step allows to highlight the role of the different types of generators on the electrical network.
- The impact of a low wind year on reliability is determined.

Finally, different scenarios have been established, those that complicate the behavior of the generators, adding a start-up cost to the plants, a minimum stable generation, a limit ramp rate, additional reserve and replacement requirements.The paper ends by comparing the load factor of the different technologies for the different scenarios as well as the results directly from TIMES. The number of starts of the different generators are compared between scenarios and also the emissions related to the scenarios.

2.3.2 Soft-link and results between Energy Scope and DISPA-SET

In the same perspective as the previous soft-link, i.e. the decarbonization of the energy system and a significant increase in the penetration of RES [20]. This soft-link aims at establishing a long-term planning model of the energy system by taking into account short-term variations related to RES. The aim is to create a multi-sectorial soft-link between Energy Scope ESOM and DISPA-SET. This is qualified here as bi-directional soft-link, a characteristic that will be detailed later in the description of the methodology. In order to test the convergence between the two models, two scenarios are considered. The first one corresponds to a reduction of Carbon Dioxyde Equivalent ($CO_{2,eq}$) emissions of 70 % compared to 2015 and the second one of 90 %.

A bi-directional soft-link allows an improvement of the accuracy of the results when the share of RES increases, the results between the UCED and the ESOM deviate. The methodology for performing the bi-directional soft-link is as follows:

- 1. Establish a shared database (timeseries, heating/power demands, costs) between ESOM and UCED.
- 2. Select the ESOM parameters linked to a scenario (GHG limits, time target, resources availablility).
- 3. Run ESOM
- 4. Extract from ESOM data such as capacity mix, fuel and carbon prices to feed UCED
- 5. Execute UCED an iterative loop with stop condition.
- 6. Compare the system suitability and flexibility results of the two models.

- 7. Determine the accuracy of the modeling as well as the modeling errors, then check if the stopping condition is met. If it is not, go to the next step. If not, stop the iterative process and save the results.

- 8. From the results obtained, introduce new constraints and restart point 3.

The stop condition is defined from the convergence error between the two models. The condition is reached when the error is lower than the numerical accuracy of the UCED model. The error is composed of three variables *ShedLoad*, *SlackLoad* and *LostLoad*. This way the volumes of the non-electric domains remain the same between the two models.

The convergence condition is reached after 2 iterations. Various conclusions can be drawn about the system. Firstly, an increase in the cost of the system due to the increase in the size of the Combined Cycle Gas Turbine (CCGT) and the seasonal storage of thermal energy. The increase the number of CCGT allows to cover extreme events. The system can cope with the intermittencies linked to RES thanks to the back-up generation, storage and sectorial coupling (ex V2G).

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Chapter 3

Energy Scope TD

This section introduces the EnergyScope Typical Day (ESTD) tool and is based on its documentation. It briefly explains how ESTD works. Then a series of elements of interest is presented. The aim is to provide a better understanding of how two important elements of this work are constructed: the creation of a soft-link from ESTD and the creation of energy scenarios.

3.1 Presentation of the model

EnergyScope is an open-source model developed in collaboration between UCLouvain and EPFL, optimizing the design and operation of an energy system for a given region and target year. The model represents the 4 Belgian energy sectors (electricity, heat, mobility and non-energy demand). The different sectors can be coupled, as electricity can be used to cover heat or mobility demand, for example. ESTD integrates 28 energy carriers, 112 Technolgies and 12 EUD.

Another important advantage is that the model has a relatively short computation time (around 1 minute). This is made possible by the use of subset representative days called Typical Days (TD). Here, EnergyScope uses 12 TD to represent the 8760 hours of the year. This introduces a series of approximation errors into the representation of the energy system, but the time saving is considerable (initially around 19h). Consequently, the computation is performed in two stages:

- Step 1 determines the set of TD using a clustering method. This part will not be of interest in this work.
- Step 2 establishes the optimal model of the energy system and its operation. This stage selects and sizes the technologies used in the system.

The objective function aims to minimize the cost of the system under a series of constraints and parameters. The model is mathematically formulated as a Linear Programming (LP) problem. The main and most important constraint is the Global Warming Potential limit. This translates into an annual carbon emission limit (given in Kilo Tonne (kt) $CO_{2,eq}$/year). The model parameters are divided into 3 categories:

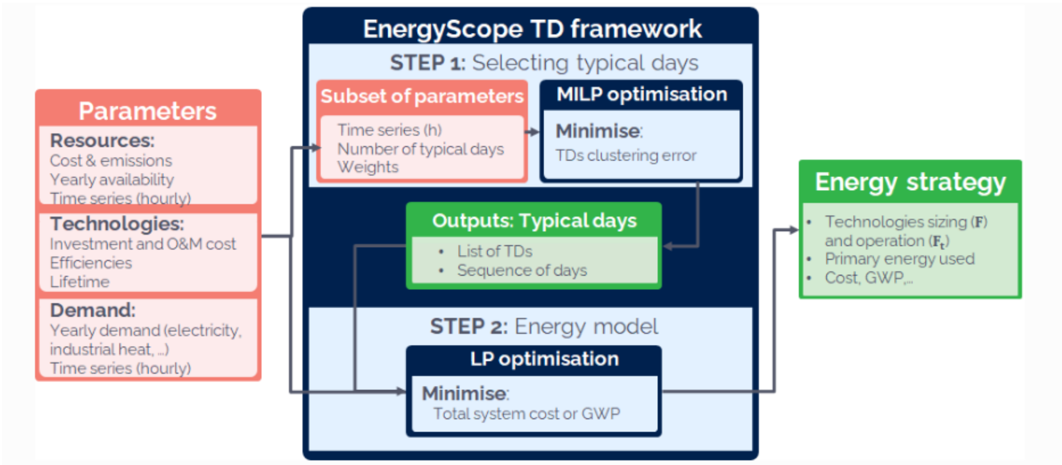

Figure 3.1: Overview of the ESTD framework in two-steps. Figure and legend taken from [21]

- Resources are characterized by their costs and emissions, their annual availability and their time series (hourly).
- Technologies are defined by their investment, operating and maintenance costs, efficiency and service life.
- Demand is defined by annual demand (electricity, heat, industrial).

3.2 Element of interest

In the context of this work, certain elements of EnergyScope require particular attention: variable values, constraints and layers. Indeed, the development of the Soft-link and the elaboration of scenarios are based on a good understanding of the latter. The various EnergyScope files associated with these elements are also presented.

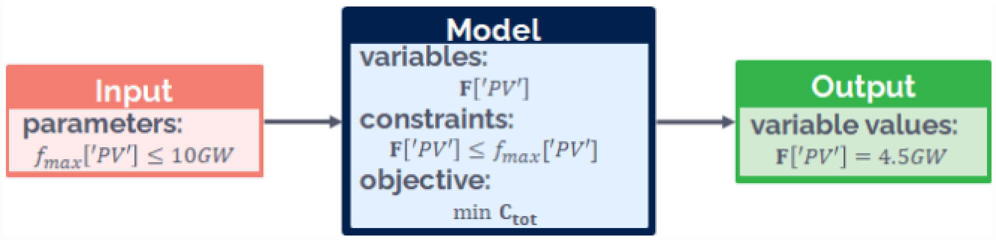

Figure 3.2: Conceptual illustration of a LP problem and the nomenclature used. Figure and legend taken from [21]

Here is two files from ESTD's basic data set wich are useful for the Soft-Link:

- `Resources.csv`: Gives the availability and direct and indirect emissions linked to the use of a ressource.It includes prices for various items such as electricity, fuels and hydrogen wich are usefull to determine the operational cost of a technology
- `Layers_in_out.csv`: Gives coeficients between a technology and the different layers.

- `Technologies.csv`: Gives a constraints for variable values (limits capacity installed) and other data such as costs of investment and maintenance or emissions per unit of installed capacity.

- `Time_series.csv`: Gives the differents time-series.

3.2.1 Constraints

Constraint manipulation is useful for imposing a scenario. To establish a list of constraints, certain input parameters are modified. Constraints are defined as a series of equalities or inequalities that must be satisfied. Here are the different types of parameters and their nomenclatures that are modified in section 6.

- Maximum Installed capacity for a technologie i ($f_{max}(i)$)
- Minimum Installed capacity for a technologie i ($f_{min}(i)$)
- Maximum share of the demand share by a technology i ($fmax_{perc}(i)$)
- Maximum share of the demand share by a technology i ($fmin_{perc}(i)$)

The parameter the figure 3.2 is entered in EnergyScope as follow:

```
config['all_data']['Technologies'].loc['PV', 'f_max'] = 10
```

Listing 3.1: Maximum Installed capacity of Photovoltaic Panel (PV)

3.2.2 Variable Values

The variable values are important in the realization of y the soft-link, as they are the main inputs. Indeed, it is these values that provide the optimum installed capacities for power generation, load and storage. Here's the list of ESTD files from which variable values are extracted to feed the soft-link and an example of how they are used:

- `assets.txt`: Gives the installed capacities of each technologie (PV, Electrical Vehicule (CAR_BEV), Heat Pump (HP)...)

- `year_balance.txt`: Gives the yearly production/consumption of each technology (Electrcity, hydrogen, gasoline...)

- `resources_breakdown.txt`:Gives the yearly consumtpion of each ressources .In this work it is used to determine the yearly amount of imported electricity

- `cost_breakdown.txt`: Gives the installation (in M€/GW) and maintenance (in M€/GW/y) costs per year of each technolgies for the optimized system. Also gives the yearly cost of imported energies (Electrcity, uranium, hydrogen...)

3.2.3 Layers

Layers are defined as all the elements in the system that need to be balanced in each time period. As an example, the electricity layer must be balanced at any time, meaning that the production and storage must equal the consumption and losses. These layers are connected to each other by technologies. We define three types of technologies: technologies of end-use type, storage technologies and infrastructure technologies. [21] The layers of electricity and hydrogen are of particular interest here. They represent the production or load associated with each technology.

- `layer_ELECTRICITY.txt`: Gives the interaction of each technolgogie with electrical balance.
- `layer_H2.txt`: Gives the interaction of each technolgogie with H_2 balance.

Chapter 4

Soft-link Methodology Electricity

4.1 Introduction

The aim of this section is to list the various technologies that interact with the ESTD layer_ELECTRICTY. In order to establish a serie of hypotheses that enables these technologies to be distributed over the Belgian high-voltage electrical grid.

4.1.1 High-voltage electrical Grid

The network of nodes used here to represent the high-voltage network is developed by Aurélia Hernandez. The network consists of a set of 44 nodes spread across Belgium, which is a model of Elia's 380/220 kV transmission network of 2022 [22]. Eleven of these nodes are referred to as transfer nodes, as they have no associated load. These nodes generally serve as intermediaries or are associated with certain electrical installations that have no load of their own, such as the Coo-trois-Pont storage or the interconnection with the UK Nemo link. There are 73 connections between nodes, plus 7 which model the connections between 380kV and 220kV on the same node. The figure 4.1 is the graphical representation of the implemented grid. Nodes and lines are synthesized in tabs C.1 & C.2

4.1.2 Main Distributions

The different ESTD technologies follow their own network distribution. However, a number of technologies can use one of the 3 main distributions. These are SharePop, ShareProvincial and ShareHub, and are described here.

SharePop

A significant proportion of electricity consumption is linked to population, i.e. the more inhabitants there are in a geographical area, the more electricity it will consume, and consequently the greater the load applied to the associated node. To do this, we'd like to know the number of inhabitants associated with each node in the Elia network. However, this type of data is not available. Thus a distribution is created that tries to approximate reality as closely as possible.

Figure 4.1: Implemented Electrical Grid

A multitude of databases exist, providing population data at different scales with. These data bases use scales named Nomenclature of territorial units for statistics (NUTS). The scales available are regional, provincial and municipal [23]. The regional (NUTS-1) and provincial (NUTS-2) scales seem rather coarse for such a distribution. Given the large number of communes in Belgium, an intermediate scale is needed. The NUTS-3 scale is used, which corresponds to the Belgian judicial districts 4.2. There are 43 of these, which seems to be a good balance between the 581 communes, the 10 Belgian provinces and the Brussels region.

The first step is to locate the high-voltage load nodes and associate each node with a district. This can easily be done using Elia's map and Google Map, as most of them are referenced there (the location of the nodes is done by Aurélia Hernandez). Once the nodes have been precisely located, the corresponding arrondissement can be found directly. Some districts have several high-voltage nodes (i.e. Liège district BE332), while 21 districts have no nodes at all (i.e. Brussels-Capital district BE100). It is therefore necessary to analyze the Elia map in order to assign one or more nodes to these districts. The population and nodes associated with each district are available in the appendix A.2.

Thanks to this step, each arrondissement is assigned one or more nodes based on the reality on the ground. By knowing the population of each arrondissement [24], this one is therefore evenly distributed across the associated nodes. If a node is associated with several arrondissements, the population shares of the various arrondissements are summed at the node. The distribution thus established is summarized in the table 4.1.

Figure 4.2: NUTS-3 map. Figure taken from [23]

Table 4.1: Share of population on each node 01/01/2023

Node	SharePop	Node	SharePop	Node	SharePop
ACHEN	0.0113	GOUY	0.0985	RIMIE220	0.0089
AUBAN220	0.0103	GRAMM	0.0049	RIMIE380	Transfert
AUBAN380	Transfert	HORTA	0.0246	RODE+	0.0246
AVLGM	0.0735	IZGEM	0.038	ROMSE	0.0089
AWIRS	0.0089	JUPIL	0.0089	SENO+	0.0014
BERN	Transfert	LINT	0.0683	SERAI	0.0089
BRUEG	0.0671	LIXHE220	0.0179	STAM+	0.017
BRUME	0.0248	LIXHE380	Transfert	STEVN	0.0285
BUGG+	0.0178	MAERL	Transfert	TIHA1	0.0121
CHAMP	0.0276	MARC+	0.0031	VANYK	0.022
COO	Transfert	MASSE	0.0307	VERBR	0.0918
COURC	Transfert	MEERH	0.0408	VILLE	0.0087
DOEL	0.0112	MEKI+	0.0588	ZANDV	0.0307
EEKLN	0.0076	MERCA	0.0241	ZUTE+	0.0456
GEZEL	0.0122	NEMO	Transfert		

ShareProvincial

A series of databases available on Eurostat which are used here are at the NUTS-2 scale, corresponding to the Belgian provinces and the Brussels-Capital region. To distribute certain ESTD technologies, notably in terms of mobility, these NUTS-2 scale databases are used.

When a value is given for a province, it is distributed uniformly across all nodes within that province. However, the province of Brabant-Wallon and the Brussels-Capital Region have no nodes on their territory. Consequently, requests associated with Brabant-Wallon are attached to the GOUY node, and those from Brussels to the VERBR, BRUEG and MEKI+ nodes. These nodes are then summed up with the demand linked to their own province, plus that of areas without nodes. The table 4.2 shows a summary of nodes and provinces.

Table 4.2: Load nodes associatd to each province

Provinces	Nodes
Antwerp	LINT,MASSE,MEERH,ZANDV
Brussels	VERBR,BRUEG,MEKI+
East Flanders	DOEL,EEKLN,MERCA,RODE+
Flemish Brabant	VERBR,BRUEG,MEKI+
Hainaut	GOUY,STAM+
Liège	AWIRS,BRUME,GRAMM,JUPIL,LIXHE220 RIMIE220,ROMSE,SERAI,TIHA1
Limburg	ZUTE+
Luxembourg	AUBAN220,MARC+,SENO+,VILLE
Namur	ACHEN,CHAMP
Walloon Brabant	GOUY
West Flanders	AVLGM,IZGEM,STEVN

ShareHub

An important list of technologies implemented in EnergyScope are linked to industrial activities interacting with the layer_ELECTRCITY, so it is necessary to be able to distribute these technologies across the electrical network. Note that some technlologies consume and others produce electricity.The aim here is to identify the Belgian industrial clusters where these technologies are found, then to quantify the importance of these clusters in relation to each other. And finally, to list the high-voltage network nodes associated with these industrial zones, so as to be able to distribute the electrical impact of these technologies on the grid.

Initially, the thinking is based on the Next-gen Belgium recovery plan [25]. This identifies 5 industrial clusters in Belgium. However, the plan considers Brussels and its region as an industrial cluster. Here, however, we're focusing on heavy and process industries. It is therefore decided to exclude Brussels from the industrial clusters and to establish only 4 main industrial clusters. These 4 industrial zones are Antwerp, Ghent, Liège and a Hainaut cluster comprising Mons and Charleroi.

To quantify the importance of these clusters, Gross Domestic Product (GDP) is used as an indicator. Although this indicator encompasses many more economic elements than industrial production, it appears to be a good first approximation to the problem. What's more, Eurostat provides this data very precisely at NUTS-3 level [26]. As a result, each cluster is associated with the GDP of one arrondissement, or two for the Hainaut cluster. The table 4.3 shows the GDP associated with each cluster.

Next, the high-voltage nodes near the industrial clusters are identified. This step is performed using the Elia map. The table 4.3 shows the clusters and the assigned nodes, so that the electricity demand of a cluster is distributed evenly over the nodes associated with that cluster.

Table 4.3: Nodes and GDP of each industral cluster. Data from [26]

Clusters	**Nodes**	**GDP$_{2021}$ [M€]**
Antwerp	LINT,MASSE,ZANDV,DOEL	55857.6
Charleroi-Mons	GOUY,STAM+	18600.93
Ghent	HORTA,RODE+	30326.13
Liège	AWIRS,LIXHE220 RIMIE220,ROMSE,SERAI	34715.34

Once these last steps is completed, all the nodes are summarized under consideration and assign them a share of industry-related electricity demand, as summarized in the table 4.4.

Table 4.4: Share associated od the industral need to each nodes

Hub Node	**Share**	**Hub Node**	**Share**
AWIRS	0.049	RIMIE220	0.049
DOEL	0.101	RODE+	0.217
GOUY	0.067	ROMSE	0.049
LINT	0.101	SERAI	0.049
LIXHE220	0.049	STAM+	0.067
MASSE	0.101	ZANDV	0.101

4.2 Power Generation

This section lists all the EnergyScope technologies that generate electricity for the layer_Electrcity. The aim of this section is to establish the various assumptions that enable these technologies to be distributed over the network of high-voltage nodes. It also details how the cost of using a generator is calculated.

4.2.1 Generators operating costs

Excluding the Investment Cost (C_{inv}) of a generation unit, the cost of operating a unit is calculated on the basis of two parameters. The first is the so-called Maintenance Cost (C_{maint}), expressed in [M€/GW/y], i.e. the cost of maintenance for one GW installed per year. The second parameter is the cost of the resources used (e.g. fuels) by the generator, referred to here as the Operating Cost (C_{op}) (M€/GWh). On the other hand, certain technologies such as PV naturally have no resource-related costs.

Annual maintenance costs are included in the EnergyScope data, so the values are simply extracted from the `Technologies.csv` file.

The operating cost of a power unit is based on Cost of a ressource (C_{res}) and on the unit's Efficiency (η), which depends on the technology used. The yield is determined from the `layer_in_out.csv` file, which gives the interaction between the various layers. For example, in 2030, the "NUCLEAR" technology using "URANIUM" as a resource to produce electricity uses 2.77 "URANIUM" units to produce 1 unit of electricity. Thus the effiency of this technologie is ≈ 0.36 . The operating cost is therefore calculated as :

$$C_{op} = C_{res} \cdot \frac{1}{\eta} \tag{4.1}$$

It's important to note that some technologies use more than one type of resource for the same technology. This is the case when there is a biofuel substitute, such as for gas, hydrogen or ammonia. In EnergyScope, these alternatives are listed as nomenclature with a "_RE" for renewable. These biofuels (fuel_RE) have a different cost from a traditional fuel (fuel), so it's necessary to calculate the average price this resource will have. The annual quantities consumed of the two types of fuel (qtt_{fuel}, qtt_{fuel_RE}) are used to weight the costs and thus calculate the average cost of a resource.

$$\begin{aligned} qtt_{tot} &= qtt_{fuel} + qtt_{fuel\_RE} \\ C_{res} &= C_{fuel} \cdot \frac{qtt_{fuel}}{qtt_{tot}} + C_{fuel\_RE} \cdot \frac{qtt_{fuel\_RE}}{qtt_{tot}} \end{aligned} \tag{4.2}$$

To facilitate the territorial distribution of certain technologies presented later in this work, these technologies have been aggregated (e.g. CCGT and Combined Cycle Gas Turbine using Amonia (CCGT_AMONIA)). Aggregated technologies do not have identical maintenance and operating costs. It is therefore necessary to calculate average costs for approved technologies. For a technology 1 and 2 (tech1 , tech2) aggregated into a technology 3 (tech3), the costs are given by weighting the costs of technologies 1 and 2 with the energy produced by these technologies (E_{tech1} and E_{tech2}). Average costs thus become :

$$\begin{aligned} E_{tot} &= E_{tech1} + E_{tech2} \\ C_{op,tech3} &= C_{op,tech1} \cdot \frac{E_{tech1}}{E_{tot}} + C_{op,tech2} \cdot \frac{E_{tech3}}{E_{tot}} \\ C_{maint,tech3} &= C_{maint,tech1} \cdot \frac{E_{tech1}}{E_{tot}} + C_{maint,tech2} \cdot \frac{E_{tech3}}{E_{tot}} \end{aligned} \tag{4.3}$$

4.2.2 Power Plants

The aim here is to list all power plants currently operating in Belgium, and to classify them by type (Nuclear, Gas, Coal, Combined Heat and Power (CHP)). Once listed, a node is associated with each power plant, based on the Elia map. These selected nodes serve as the basis for distributing ESTD results across the network. The nodes

Table 4.5: Power,nodes, share associate to nuclear sites. Data taken from [27]

Reactor	Power [MWe]	Node	Share [-]
Doel 1	455	DOEL	0.49
Doel 2	455	DOEL	
Doel 3	0	DOEL	
Doel 4	1039	DOEL	
Tihange 1N	481	TIHA1	0.51
Tihange 1S	481	TIHA1	
Tihange 2	0	TIHA1	
Tihange 3	1038	TIHA1	
Total	3929		

are weighted according to their importance in the current situation. Mean Time to Fail (MTTF) and Mean Time to Repair (MTTR) specific to each tehcnology is added.

Then, for each technology, we extract from EnergyScope various characteristics of these technologies, such as the installed capacity and the Load Factor (LF)calculated as follows, the electrical Electrical Energy produced over one year (E_{year}), and P is the electrical power of a power plant:

$$LF = \frac{E_{year}}{P * 8760} \tag{4.4}$$

Nuclear

The case of nuclear power is quite simple. All nuclear power generation is split between two separate sites. All Belgian reactors are listed in the table 4.5. Note that the Doel 3 and Tihange 2 reactors are shut down due to their planned dismantling. Each nuclear site has its own node on the high-voltage network. This is not the case in reality, as each reactor is connected to its own bus, but here, for ease of use, everything is aggregated into a single node per central unit.The installed nuclear power will therefore be distributed over the two nodes (DOEL,TIHA1) of the network.

With today's reality, a ratio of installed power can therefore be established between these two nodes. So no matter how much power ESTD decides to install, this ratio between the nodes remains the same.

Gaz

The two EnergyScope technologies, CCGT and CCGT_AMONIA, are combined under the name gas. In order to reduce carbon emissions, a gas turbine combined cycle can be converted to use ammonia.

The distribution of GAs technology to the various nodes is based on data supplied by Elia[27].These data also include the power output of these plants. Turbo-jet units are not considered, as ESTD does not integrate this technology. Based on this data, the various gas-fired power plants are listed and assigned a node (see table A.1).It's also interesting to note that a plant is considered in its entirety. If it has several cycles or turbines of different power ratings, these are aggregated into a single power production unit. It can be seen that several power plants share the same node. The GOUY, SERAI and RODE+ nodes are concerned. Power plants sharing the same node will therefore be aggregated into a single virtual power plant, so that for a given node there is at most only one associated gas power plant.

Coal

It is clear that coal-fired power generation is no longer used in Belgium. However, in the interests of robustness of the soft-link, these technologies should still be considered. Awirs and Rodenhuize are the two power plants included in elia's data [27] that until recently used coal. These two plants are the only ones listed as "conventional". As Rodenhuize was the last to close, the decision is taken to place all coal power generation there. This may seem a relatively strong assumption, but it is important to note that it is highly unlikely that these technologies Ultra-supercritical coal power plant (COAL_US), Intagrated gasification combined cycle with coal (COAL_IGCC) are employed by Energyscope. All the power is therefore transferred to the RODE+ node. For the load factor, the methodology is the same as for GAZ, since two technologies have been aggregated.

CHP

Here, three ESTD technologies are brought together under the CHP name, regardless of the fuel used. These technologies are:

- Gas fired Industrial Cogeneration (IND_COGEN_GAS)
- Wood fired Industrial Cogeneration (IND_COGEN_WOOD)
- Waste fired industrial Cogeneration (IND_COGEN_WASTE)

They are therefore used to produce both electricity and heat, although heat production is not the focus here. Once the various power plants have been listed using ELIA data [27], the methodology used is similar to that used for CCGTs. Equally, if a single plant has several power generation units, these are initially aggregated. A node is assigned to each plant, and if a node has more than one CHP plant associated with it, these plants are aggregated into a single node. Each node is assigned a coefficient of proportion to the total installed power. Given the redundancy of the process, the final result is given in the following table. The complete list of CHP plants considered is given in the table A.3.

In addition to an annual LF, the soft-link will calculate a respective LF for each month of the year. In fact, as CHPs can produce both electricity and heat, they will be used to generate electricity and heat at the same time. In addition, the demand for heat will be greater in winter, and so CHPs will be more heavily used during these cold periods.

Synthesis

All types of value generated by the soft-link are then in the tab 4.6:

Table 4.6: Values genarated by soft-link

Node	P_{max} (GW)	C_{maint}	C_{op}	Type	MTTF	MTTR	LF

4.2.3 Renewable Energy Sources

This section focuses solely on offshore wind power, as it is connected to Elia's transmission grid. Currently, all offshore wind farms are connected to a single STEVN node. All the capacity supplied by ESTD will therefore be associated with this node. However, with future hybrid interconnection projects with the United Kingdom (Nautilus [28]) and Denmark (TritonLink [29]), as well as the construction of the Princess Elisabeth energy island [30], the situation evolves and this section needs to be updated in the futur. In addition to this, ESTD uses time series for offshore wind power, which are extracted and used for the matching tools.

4.2.4 Renewable Energy Sources connected to distribution grid

In contrast to the previous section, this section includes RESs connected to the electrical distribution network. In Belgium, on-shore wind farms, PV installations and hydroelectric power plants are not connected to the high-voltage grid, in order to limit connection costs. These technologies must therefore be treated differently from off-shore wind power. It should be noted that the matching tools have their own time series for wind and solar, so only installed capacity will be extracted from ESTD.

PV

At present, there is a considerable disparity between provinces in terms of installed PV capacity. This is the result of various regional policies adopted in recent years. The table 4.7 shows the installed capacity according to ELia [31] in May 2023 in each province and in the Brussels-Capital Region in relation to their respective populations on January 1, 2023[24]. Using a distribution that follows that of the population would be too strong an assumption.

By 2030, $11GW_p$ of photovoltaic capacity is expected [27], and there are several options for distributing this future capacity across Belgium, compared with $7.5GW_p$ mid-May 2023. There are several possible options for distributing this future capacity over the Belgian territory, and therefore over the nodes.

Table 4.7: PV power disparity per inhabitant

Province	Wp/hab
Antwerp	741
Brussels-Capital reg.	199
East Flanders	919
Flemish Brabant	335
Hainaut	381
Liège	682
Limburg	856
Luxembourg	563
Namur	430
Walloon Brabant	565
West Flanders	972

In order to distribute future photovoltaic installations, it is assumed that the disparities caused by politics will disappear. To do this, the BREGILAB [32] tool is also used to calculate the photovoltaic potential of each province. This tool not only shows current installations, but also the photovoltaic potential at provincial and municipal level. For the sake of simplicity, the potential at provincial level is used here.

The tool also distinguishes between 3 types of installation: 'Roadside', 'Commercial and Industrial' and 'Residential'. Roadside' refers to roadside installations, 'Commercial and Industrial' to installations on commercial sites and businesses, and 'Residential' to domestic panels on homes. This distinction is useful for the distribution of storage batteries, which is presented later.

Initially, in order to distribute PV technology over the network of high-voltage nodes, this distinction will not be of interest to us. Therefore the potential of installations are collected in each province plus the Brussels-Capital region. Knowing the nodes associated with each province, the photovoltaic installation capacity supplied by ESTD can easily be distributed over the network of nodes. As neither the province of Brabant-Wallon nor the Brussels-Capital region have a node on their territory, their installations are distributed over the VERBR, BRUEG and MEKI+ nodes for Brussels, and GOUY for Brabant-Wallon. The table 4.8 shows the potential and nodes associated with each province, and the distribution of nodes can be found in the table 4.9 .

Onshore Wind

Many onshore wind farms are not connected directly to the electricity transmission grid for economic reasons. It is therefore difficult to use Elia's map as a basis for distributing them on the grid. The aim here will therefore be to allocate a share of on-shore wind generation to each node of the high-voltage network.

The BREGILAB tool is used to work out the allocation. This tool provides the capacity of wind turbine installations in each municipality and each province, but can

Table 4.8: PV potentiel per porvince and associated nodes

Provinces	**Nodes**	**Pot [MW_p]**
Antwerp	LINT,MASSE,MEERH,ZANDV	18004
Brussels	VERBR,BRUEG,MEKI+	5194
East Flanders	DOEL,EEKLN,MERCA,RODE+	17400
Flemish Brabant	VERBR,BRUEG,MEKI+	10391
Hainaut	GOUY,STAM+	13254
Liège	AWIRS,BRUME,GRAMM,JUPIL,LIXHE220 RIMIE220,ROMSE,SERAI,TIHA1	9830
Limburg	ZUTE+	9802
Luxembourg	AUBAN220,MARC+,SENO+,VILLE	4070
Namur	ACHEN,CHAMP	4969
Walloon Brabant	GOUY	3240
West Flanders	AVLGM,IZGEM,STEVN	16515
Total		112669

Table 4.9: PV share per node

Node	**Share**	**Node**	**Share**	**Node**	**Share**
ACHEN	0.023	GOUY	0.082	RIMIE220	0.01
AUBAN220	0.009	GRAMM	0.01	RIMIE380	0
AUBAN380	0	HORTA	0	RODE+	0.039
AVLGM	0.049	IZGEM	0.049	ROMSE	0.01
AWIRS	0.01	JUPIL	0.01	SENO+	0.009
BERN	0	LINT	0.04	SERAI	0.01
BRUEG	0.046	LIXHE220	0.01	STAM+	0.059
BRUME	0.01	LIXHE380	0	STEVN	0.049
BUGG+	0	MAERL	0	TIHA1	0.01
CHAMP	0.023	MARC+	0.009	VANYK	0
COO	0	MASSE	0.04	VERBR	0.046
COURC	0	MEERH	0.04	VILLE	0.009
DOEL	0.039	MEKI+	0.046	ZANDV	0.04
EEKLN	0.039	MERCA	0.039	ZUTE+	0.087
GEZEL	0	NEMO	0		

also provide the potential of these administrative divisions. BREGILAB uses the Vestas V112 3.3MW [33] wind turbine as a reference model to determine this potential. For the sake of simplicity, the provincial scale is used.

Table 4.10: Provincial wind potential and share. Data taken from BREGILAB

Province	Poteniel $[MW_p]$	Share [-]
Antwerp	1825	0.100
Brussels-Capital reg.	30	0.001
East Flanders	2627	0.144
Flemish Brabant	650	0.036
Hainaut	2350	0.129
Liège	2072	0.114
Limburg	1534	0.084
Luxembourg	3551	0.195
Namur	2049	0.112
Walloon Brabant	340	0.019
West Flanders	1204	0.066
Total	18232	

Thanks to BREGILAB's data [32], each province is allocated a share of the installed capacity. EnergyScope also provides this total installed capacity, thus this capacity can be distributed over the territory. Provinces associated with nodes are also knwon , so we can distribute the installed capacity across the nodes of the high-voltage network. The potential and the share of this potential for each province are shown in the table 4.10. The nodal distribution can be found in the appendix tab4.11.

Table 4.11: Wind share per Node

Node	Share	Node	Share	Node	Share
ACHEN	0.056	GOUY	0.083	RIMIE220	0.013
AUBAN220	0.049	GRAMM	0.013	RIMIE380	0
AUBAN380	0	HORTA	0	RODE+	0.036
AVLGM	0.022	IZGEM	0.022	ROMSE	0.013
AWIRS	0.013	JUPIL	0.013	SENO+	0.049
BERN	0	LINT	0.025	SERAI	0.013
BRUEG	0.011	LIXHE220	0.013	STAM+	0.064
BRUME	0.013	LIXHE380	0	STEVN	0.022
BUGG+	0	MAERL	0	TIHA1	0.013
CHAMP	0.056	MARC+	0.049	VANYK	0
COO	0	MASSE	0.025	VERBR	0.011
COURC	0	MEERH	0.025	VILLE	0.049
DOEL	0.036	MEKI+	0.011	ZANDV	0.025
EEKLN	0.036	MERCA	0.036	ZUTE+	0.085
GEZEL	0	NEMO	0		

Hydro

In 2023, Belgium had 116 MW of hydroelectric capacity spread over 166 different sites (6 MW in Flanders and 110 MW in Wallonia)[34]. Almost all the hydroelectric potential in Belgium is exploited. The few possible future improvements are due to repowering and improving the efficiency of the sites already exploited.

It is obviously complicated to model all these sites one by one. In order to simplify the task, all the hydroelectric potential will be spread over 13 different sites. These sites are those represented on the map of the Elia high voltage network. These 13 sites represent 91 MW of the installed capacity [35],[36],[37],[38].The method developed here aims at associating a hydroelectric coefficient to the different nodes of the grid. After having listed the sites, a grid node is associated to them. This step is done visually from the map of Elia. If a node has no associated hydro sites, its hydro coefficient will be null. For each site the nominal power can be found in the literature. This power rating allows to associate to each site a ratio/coefficient of the total installed capacity provided by ESTD. When this step is done, the sites sharing the same node are aggregated so that the nodes concerned have only one hydro coefficient. Finally, after having performed these different steps, a table 4.12 is obtained with the associated hydro coefficient for the concerned nodes .

Table 4.12: Hydro Power central and share per Node. Data taken from [35],[36],[37],[38]

Hydro Central	Pmax [MW]	Node	Share
Pont-barrage de Lixhe	16	LIXHE220	0.175
Pont-barrage de Monsin	20	JUPIL	0.233
Barrage de la Vesdre	0.633	JUPIL	
Barrage de la Gileppe	0.642	JUPIL	
Barrage de Butgenbach	2.3	BRUME	0.211
Barrage Bevercé	9	BRUME	
Heid de Goreux	8	BRUME	
Barrage de la Vierre	2	AUBAN220	0.022
Pont-barrage d'Ivoz-Ramet	10	AWIRS	0.11
Écluse d'Ampsin-Neuville	10	TIHA1	0.109
Centrale Hydroélectrique d'Andenne	7	GRAMM	0.077
Ecluse des Grands Malades	5	CHAMP	0.063
Floriffoux	0.8	CHAMP	

Synthesis

For each of these technologies, the installed capacity and associated times series are extracted from ESTD

4.2.5 Generation units on distribution grid

This section describes the different types of cogeneration units. These units produce both electricity and heat. Two categories can be distinguished if they are connected to a heating network. In addition, there are other sub-categories to distinguish them: the type of fuel used. The type of fuel used will greatly influence the emissions linked to the use of these technologies. In this case, the units will be connected to the electrical distribution network.

Direct heat network

This EnergyScope technology represents heating networks and has sub-categories depending on the type of fuel used. There are 5 sub-categories, as follows:

- Heat Network gas Fired Cogeneration (DHN_COGEN_GAS)
- Heat Network Wood Fired Cogeneration (DHN_COGEN_WOOD)
- Heat Network Waste Fired Cogeneration (DHN_COGEN_WASTE)
- Heat Network Biomass Fired Cogeneration (DHN_COGEN_WET_BIOMAS)
- Heat Network Bio Hydrolysis Cogeneration (DHN_COGEN_BIO_HYDROLYSIS)

In this problem, the production of electricity by a cogeneration unit is point of interest. So we'll leave heat aside. Heat networks enable savings to be made in terms of fuel use, and consequently a reduction in CO_2 emissions[39].

In Belgium, there are already many heat networks in operation, such as the one used on the UCLouvain site. In addition, there are other projects at different levels of development [40]. However, these projects require substantial investment, complicated administrative procedures and are only of interest in areas with a high population density[39]. But Belgium's high population density means it has great potential, and the number of heat networks at different scales is set to multiply in the years ahead.

It is therefore difficult to predict the exact location of these future networks, and so it is decided here that cogeneration units linked to heat networks on the high-voltage node network will follow that of the population presented before (SharePop). In addition, the cogeneration unit must be located close to the demand, which is represented by the population, which reinforces our idea of using this allocation.

In order to implement this technology in the adequacy tool, some ESTD results are extracted. Note that despite the similarity of these technologies, it is decided not to aggregate them. As a result, each type of unit have its own power and load factor.

Decentralized

These technologies correspond to decentralized cogeneration units, and are also divided into sub-categories according to the fuel used. These sub-categories are:

- Decentralized Gas Fired Cogeneration (DEC_COGEN_GAS)
- Decentralized Oil Fired Cogeneration (DEC_COGEN_OIL)
- Decentralized Gas Fired Cogeneration (DEC_ADVCOGEN_GAS)
- Decentralized Hydrogen Fired Cogeneration (DEC_ADVCOGEN_H2)

As with the previous point, it is the production of electricity from these units that interests us, and not the production of heat. However, since heat production also has to be close to where it is needed, i.e. the population. We also decide to distribute this technology according to population distribution (SharePop). It is also decided not to aggregate the subcategories. Power and load factor are found in the same way as the previous point.

Geothermal

The "Geothermal" technology presented here is designed to generate electricity. The use of geothermal energy for domestic heating or in heating networks is note usefull here. In Belgium, there are few geothermal power generation projects in the pipeline. The most advanced project is located in Mol[41]. It plans to produce 4MW of electricity from 5 to 6 wells [42]. Indeed, the Campine region seems to have the most potential in Belgium. Unfortunately, the injection of cold water has on a number of occasions caused small earthquakes, resulting in projects being brought to a standstill [43].

Given the slow progress of other projects, and with a view to placing geothermal power generation on the high-voltage grid, it is assumed that all geothermal power capacity is located in Mol. After analysis of the high-voltage map, this corresponds to the `MEER` node.

Synthesis

All types of value are synthesized in the following tab:

Table 4.13: Values generated by the soft-link for generation units on distribution grid

Type	Pmax	E_{year}	LF	C_{maint}	C_{op}

4.3 Import/Export Elec and Storage

4.3.1 Import Data

For electricity import data, simply the maximum import power and the total electrical energy imported over a year are extracted from ESTD. A last value is extraced it is cost of teh electrcity imported (M€/GWh).

4.3.2 Import Lines

Electricity is imported and exported via 14 different lines linking the Belgian grid to Germany, the Netherlands, France and Luxembourg. The inventory and summary of these lines are produced by Aurélia Hernandez.

4.3.3 Storage

With the ever-increasing penetration of RES and the resulting intermittency of production, storage elements play a key role in energy systems more than ever. In this section, attention is focused on storage systems that can be used to generate electricity directly. Consequently, the different types of thermal storage are not a point of interest here. For each technology efficiencies are needed and are available in ESTD

Pumped Hydro Storage

For this technology, two parameters are required: storage capacity and the power it can deliver. These parameters are easily accessible in ESTD. Pumping and turbining efficiencies are also necessary for the Adequacy tool, these values are available in ESTD.

In Belgium, there are two pump-and-turbine sites, Coo-Trois-Ponts and the Plate Taille dam. The breakdown is fairly straightforward and is summarized in the following table 4.14. It should be noted that by 2025 the power and capacity of the Coo site will have increased by 79MW and 450MWh respectively [44], so this improvement is already taken into account. Unlike Coo, the Platte-Taille site does not have its own node on the high-voltage network. After analyzing the network, connecting this site to the `GOUY` node is decided.

In order to allocate the installed power and storage capacity between the two sites calculated by EnergyScope, the 2025 projection is taken as a reference. These distributions are also shown in the table

Table 4.14: Power and Capacity breakdown for PHS

Site	Node	Power [MW]	Storage [MWh]	Share Power [-]	Share Storage[-]
Coo-Trois-Ponts	COO	1159	6450	0.89	0.90
Plate taille	GOUY	144	700	0.11	0.10

Batt_Li

According to Elia's data and projections for battery storage, there are two scales: large and small. The large is referred to as "in-the-market" and the small as "out-of-market". Elia also provides the breakdown for capacity and power between these two scales up to 2030. According to Elia's projections, the split between the two scales in terms of power and capacity will stabilize by 2030. This year will therefore initially serve as a reference, but this distribution will be a parameter and therefore easily modifiable. EnergyScope, on the other hand, only provides total installed capacity, but makes no distinction between these two scales. It is also possible to find the power that this technology draws from the grid, as well as the power reinjected. The table 4.15 shows the distribution of power and storage capacity between the two scales. This distinction is important, as the distribution over the network of nodes will not be the same for the two scales.

Table 4.15: Power and Capacity Large and small scale

Scale Sotage	Power [MW]	Share [-]	Capacity [MWh]	Share [-]
Large	676	0.62	676	0.35
Small	418	0.38	1253	0.65

Currently, large-scale battery storage is designed to regulate grid frequency. These batteries are installed at sites such as the Drogenbos gas-fired power station [45]. However, in the near future, these batteries are used to compensate for the intermittency linked to the level of RES penetration. Consequently, to distribute this type of storage, the distribution is base on renewable energy installations (wind and solar). For wind, the STEVN node is used, to which the entire off-shore network is currently connected. The distribution used for onshore wind, as described above is alos employed. For solar, the distinction between the 3 types of solar presented above is made. In fact, for large-scale storage, only the potentials linked to "road side" and "Commercial and Industrial" PV are used. Residential PV is used for the distribution of smaller-scale storage. For this, the BREGILAB tool already presented is used. The nodal distribution linked to the sum of the 3 renewable sources can be found in the table 4.16.

Small-scale storage is the term used to describe storage on domestic batteries, which sometimes accompany photovoltaic installations. These batteries are used not only to increase a building's self-sufficiency, but also to reduce the cost of feeding electricity back into the grid when production exceeds consumption. Once again, regional policies differ, and the penetration rate varies from one part of the country to another. Despite these disparities, in order to distribute the share of the small scale, we assume that the distribution of domestic storage will follow that of domestic photovoltaics. The distribution on nodes is available in table 4.17

Table 4.16: Nodes and Large Scale Share

Node	Share	Node	Share	Node	Share
ACHEN	0.027	GOUY	0.075	RIMIE220	0.01
AUBAN220	0.017	GRAMM	0.01	RIMIE380	0
AUBAN380	0	HORTA	0	RODE+	0.036
AVLGM	0.041	IZGEM	0.041	ROMSE	0.01
AWIRS	0.01	JUPIL	0.01	SENO+	0.017
BERN	0	LINT	0.036	SERAI	0.01
BRUEG	0.034	LIXHE220	0.01	STAM+	0.054
BRUME	0.01	LIXHE380	0	STEVN	0.11
BUGG+	0	MAERL	0	TIHA1	0.01
CHAMP	0.027	MARC+	0.017	VANYK	0
COO	0	MASSE	0.035	VERBR	0.034
COURC	0	MEERH	0.035	VILLE	0.017
DOEL	0.036	MEKI+	0.034	ZANDV	0.036
EEKLN	0.036	MERCA	0.036	ZUTE+	0.079
GEZEL	0	NEMO	0		

Table 4.17: Nodes and Small Scale Share

Node	Share	Node	Share	Node	Share
ACHEN	0.024	GOUY	0.096	RIMIE220	0.01
AUBAN220	0.008	GRAMM	0.01	RIMIE380	0
AUBAN380	0	HORTA	0	RODE+	0.037
AVLGM	0.047	IZGEM	0.047	ROMSE	0.01
AWIRS	0.01	JUPIL	0.01	SENO+	0.008
BERN	0	LINT	0.037	SERAI	0.01
BRUEG	0.049	LIXHE220	0.01	STAM+	0.061
BRUME	0.01	LIXHE380	0	STEVN	0.047
BUGG+	0	MAERL	0	TIHA1	0.01
CHAMP	0.024	MARC+	0.008	VANYK	0
COO	0	MASSE	0.037	VERBR	0.049
COURC	0	MEERH	0.037	VILLE	0.008
DOEL	0.037	MEKI+	0.049	ZANDV	0.037
EEKLN	0.037	MERCA	0.037	ZUTE+	0.089
GEZEL	0	NEMO	0		

4.4 Load

In this section, all ESTD technologies that consume electricity are listed. A series of assumptions is then made to distribute the load of these technologies on the high-voltage network.

4.4.1 Private Mobility

Two of the technologies generating private mobility use electricity. The first is what are known as Plug-in Hybrid Vehicule (CAR_PHEV), which are vehicles that use both an internal combustion engine and an electric motor. These vehicles have a greater purely electric range than "conventional" hybrid vehicles. They must therefore be recharged via the electricity grid. The other technogy is Electrical Vehicule (CAR_BEV) corresponds to 100% electric vehicles.

Eurostat [46] data is used to allocate the load of these technologies on the grid. These provide the number of cars at provincial level (NUTS-2) in 2021. Each province is therefore assigned a share of the total number of cars (see table 4.18). This makes it easy to allocate the high-voltage nodes.

Table 4.18: Number and share of cars per porvince in 2021. Data taken from [46]

Provinces	Nbr of car 2021	Share [-]
Antwerp	939272	0,159
Brussels	493994	0,083
East Flanders	742587	0,125
Flemish Brabant	798357	0,135
Hainaut	662791	0,112
Liège	547941	0,093
Limburg	483171	0,082
Luxembourg	150651	0,026
Namur	253372	0,043
Walloon Brabant	216514	0,036
West Flanders	627665	0,106
Total	5916315	

From EnergyScope, the charging profile of these vehicles can be restored from the layer_ELEC file. It can be seen that this profile is the same every day; the figure 4.3 shows the load profile over a week. These profiles is useful for the adequacy tool.

4.4.2 Public Mobility

Tram

EnergyScope uses the Tram (TRAMWAY_TROLLEY) technology to meet the demand for public mobility. This technology consumes electricity, which is why it is

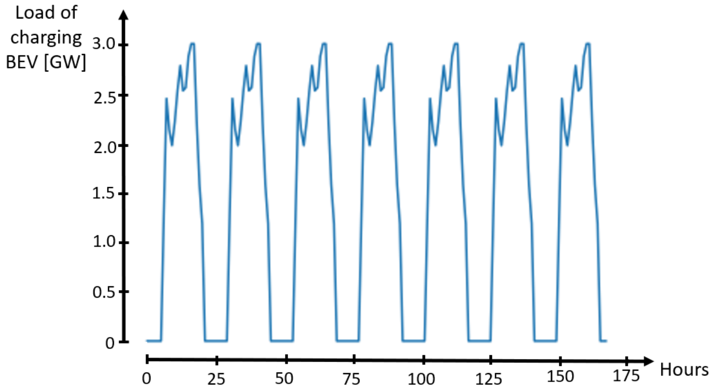

Figure 4.3: Charging BEV profile

of interest here. However, not all Belgian cities are equipped with tramway or metro networks. These include Antwerp[47], Brussels[48], Charleroi [49], Ghent[50], the Belgian coast [51] and, in the near future, Liège[52]. It is therefore necessary to quantify these different networks, as once again EnergyScope only provides the total quantity installed in Belgium.

The values supplied by ESTD must therefore be distributed over the territory, and therefore over the nodes of the high-voltage network. The different companies don't supply the same kind of annual statistics, which makes comparisons more difficult. For this reason, the network comparison here is based on the length of the respective networks. The table 4.19 shows the combined size of the tramway and metro networks and the high-voltage nodes in the various cities concerned.

Table 4.19: Length and nodes of tramway network

City	Length [km]	Nodes
Antwerp	185.9	MASSE, LINT
Belgian Coast	32	STEVN
Brussels	110.1	MEKI+,BRUEG,VERBR
Charleroi	33.3	GOUY
Ghent	67	RODE+
Liège	11.7	JUPIL, SERAI

Based on this data, it's easy to allocate nodes. In addition, like electric vehicles, the streetcar's electricity consumption profile is redundant every 24 hours. From ESTD is therefore extract a profile representing consumption over 24 hours.

Train

Just like tram, Passenger Train (TRAIN_PUB) technology is the answer to EUD in public mobility. In order to distribute the electrical consumption of trains on the network. The data provided by Infrabel on monthly electricity consumption are used. These data are given for each region of Belgium (Brussels, Wallonia and Flanders). The

Table 4.20: Node breakdown of tram share

Node	Share [-]	Node	Share [-]
BRUEG	0.141	MEKI+	0.141
GOUY	0.076	RODE+	0.073
JUPIL	0.013	SERAI	0.013
LINT	0.125	STEVN	0.152
MASSE	0.125	VERBR	0.141

Table 4.21: Consumption of Electricity by train per Region in 2022. Data taken from [53]

Region	Consumption [MWh]	Share
Brussels	51916	0.51
Wallonia	11780	0.11
Flanders	38908	0.38
Total	102604	

first step is to calculate the average annual consumption of each region for the year 2022 [53]. Each region is then assigned a share of total consumption, as shown in the table 4.21. Once this step has been completed, each region's demand is distributed evenly to the nodes within the region's territory. Note that as the Brussels region has no nodes on its territory, the region's consumption is distributed to the nodes on its periphery, i.e. the VERBR, BRUEG and MEKI+ nodes. The nodal distribution is given in the table 4.22. Electricity consumption is recurrent, as it is for trams.

4.4.3 Freight

In EnergyScope, there are two ways of filling the freight EUD using electricity. Via Freight Trains (TRAIN_FREIGHT), of course, but also via Electrical Truck (TRUCK_ELEC). Note that these technologies have a constant demand for electricity. The demand is therefore extracted only once and carried forward to each hour of the day.

Truck

In order to distribute the load associated with electric truck technology, the same database as the previous point 4.3 is used and proceed in the same way. The data is summarised in the table 4.23, and the nodal distribution can be found in the table 4.24.

Train Freight

The same distribution by passenger trains is used.

4.4.4 Heat

This section covers the technologies used to fill EUDs of low- and high-temperature heat using electricity.

Table 4.22: **Node repartition for train's demand**

Node	Share	Node	Share	Node	Share
ACHEN	0.0223	GOUY	0.0223	RIMIE220	0.0223
AUBAN220	0.0223	GRAMM	0.0223	RIMIE380	0
AUBAN380	0	HORTA	0	RODE+	0.0337
AVLGM	0.0337	IZGEM	0.0337	ROMSE	0.0223
AWIRS	0.0223	JUPIL	0.0223	SENO+	0.0223
BERN		LINT	0.0337	SERAI	0.0223
BRUEG	0.072	LIXHE220	0.0223	STAM+	0.0223
BRUME	0.0223	LIXHE380	0	STEVN	0.0337
BUGG+	0	MAERL	0	TIHA1	0.0223
CHAMP	0.0223	MARC+	0.0223	VANYK	0
COO	0	MASSE	0.0337	VERBR	0.072
COURC	0	MEERH	0.0337	VILLE	0.022
DOEL	0.0337	MEKI+	0.072	ZANDV	0.0337
EEKLN	0.0337	MERCA	0.0337	ZUTE+	0.0337
GEZEL	0	NEMO	0		

High Temperature

High-temperature heat is produced here using Industrial Direct Electrcity (IND_DIRECT_ELEC) technology. The electricity demand for this technology will follow the ShareHub distribution. In fact, the need for high-temperature heat is only necessary in the industrial sector. EnergyScope can be used to extract the power and annual consumption of this technology.

Low Temperature

To produce low-temperature heat from electricity, ESTD can use 3 different technologies:

- Decentralized Direct Electricity (DEC_DIRECT_ELEC)
- Heat Network Electrical Heat Pump (DHN_HP_ELEC)
- Decentralized Electrical Heat Pump (DEC_HP_ELEC)

The first, as its name suggests, uses electricity to produce heat, while the other two use a heat pump. Again, the aim is to reduce energy consumption, and thanks to its Coefficient of Performance, the heat pump is a good way of achieving this. These two heat pump technologies are increasingly developed in the future.

First, from EnergyScope is extracted the installed capacity of these 3 technologies. The hourly demand is reconstituted from typical days. Thanks to the hourly demands the monthly electrcial consumtpion is calculated for each technologies. This monthly distribution is usefull because the EUD of heat is more important during winter. It helps to get closer to reality

Table 4.23: Number and share of trucks per porvince in 2021. Data taken from [46]

Provinces	Nbr of Lorries 2021	Share [-]
Région Bruxelles-Capitale	83115	0,088
Antwerpen	144221	0,153
Limburg	88854	0,094
Oost-Vlaanderen	129414	0,137
Vlaams-Brabant	91396	0,097
West-Vlaanderen	129169	0,137
Brabant Wallon	26495	0,028
Hainaut	98111	0,104
Liège	83720	0,088
Luxembourg	27250	0,028
Namur	43394	0,046
Total	945139	

4.4.5 Carbon Capture

EnergyScope takes into account 2 carbon capture technologies:

- Atmospheric Carbon Capture and Storage (ATM_CCS)
- Industrial Carbon Capture and Storage (Industry_CCS)

Again, these technologies are not yet deployed in Belgium, but they will play a role in the not-too-distant future. Assumptions need to be made in order to establish their future disposition on the territory. We'll assume that industrial capture Industry_CCS will take place directly near the big carbon emitters, so we'll place them on the nodes associated with gas-fired power stations. The second technology ATM_CCS, for optimum efficiency, should be placed in areas where the concentration of CO_2 in the atmosphere is highest, and therefore close to industries. For this technology, the industrial hubs share is used.

4.4.6 Industrial Process

This section brings together 10 ESTD technologies corresponding to various industrial processes 4.25.Many of these processes are not yet used on an industrial scale, so it is difficult to predict exactly where they are positioned in the future, but these technologies have enormous potential as energy carriers in a carbon-neutral scenario. These processes have different characteristics, as some act as a capacity and others as an electrical charge. Here, it has been decided to aggregate them all to create a total load and capacity in terms of electrical power (recovered from `assets.txt`). The total amount of electricity consumed and produced by these technologies is retrieved from the `year_balance.txt` file to establish a total annual production and consumption of these technologies. The distribution on the high-voltage network follows that of the industrial hub.

Table 4.24: Nodal repartition of truck demand

Node	Share	Node	Share	Node	Share
ACHEN	0.023	GOUY	0.081	RIMIE220	0.01
AUBAN220	0.007	GRAMM	0.01	RIMIE380	0
AUBAN380	0	HORTA	0	RODE+	0.034
AVLGM	0.046	IZGEM	0.046	ROMSE	0.01
AWIRS	0.01	JUPIL	0.01	SENO+	0.007
BERN	0	LINT	0.038	SERAI	0.01
BRUEG	0.061	LIXHE220	0.01	STAM+	0.052
BRUME	0.01	LIXHE380	0	STEVN	0.046
BUGG+	0	MAERL	0	TIHA1	0.01
CHAMP	0.023	MARC+	0.007	VANYK	0
COO	0	MASSE	0.038	VERBR	0.061
COURC	0	MEERH	0.038	VILLE	0.007
DOEL	0.034	MEKI+	0.061	ZANDV	0.038
EEKLN	0.034	MERCA	0.034	ZUTE+	0.094
GEZEL	0	NEMO	0		

Table 4.25: Technologies of indsutrial process

Load Elec	Capa Elec
SYN_METHANOLATION	BIO_HYDROLYSIS
METHANE_TO_METHANOL	PYROLYSIS_TO_LFO
HABER_BOSCH	PYROLYSIS_TO_FUELS
OIL_TO_HVC	BIOMASS_TO_METHANOL
GAS_TO_HVC	
BIOMASS_TO_HVC	

4.4.7 H_2 Electrolysis

This technology has a key role to play. It links the two dimensions of the adequacy tool, by consuming electricity to produce hydrogen. We need to collect both electrical and hydrogen-related data from ESTD. We will therefore be collecting the maximum electrical power of the electrolysers installed. But also the total quantity of hydrogen produced over a year and the maximum production rate.

Chapter 5

Soft-link Methodology Hydrogen

The aim of this section is to establish and describe a hydrogen pipeline network suitable for Belgium. This network includes points for hydrogen production and consumption, storage, import and export. The aim is then to list all the technologies from ESTD that interact with layer_H2. These technologies are then distributed and distributed over the established network.

5.1 Network

Unlike the electricity grid, there is as yet no hydrogen network in Belgium. It is therefore necessary to model such a network ourselves .However, the government is determined to develop such a network. Under the Next-Gen Belgium plan [25], the aim is to create a 100 to 160 km network of hydrogen pipelines linking the main industrial clusters. Fluxys has already carried out a series of projections for a future network, notably by partly reusing existing natural gas infrastructures. Most of the assumptions made in this section are based on the short-term network map 5.1 from the document "Indicative Investment Plan Fluxys Belgium & Fluxys LNG 2022-2031" [54]. The figure 5.2 represents the implemented H_2 grid in the soft-link.

ESTD uses hydrogen to meet a whole range of EUD, including private and public mobility, freight transport, heat and electricity. But hydrogen is also needed in certain industrial processes.

5.1.1 Nodes

Based on this map, 13 nodes are selected, 6 of which are for hydrogen consumption and 7 for hydrogen import and export. The 6 consumption nodes model the main clusters of future hydrogen consumers. These clusters are Antwerp, Brussels, the Albert Canal, Ghent, Liège and the Hainaut zone, which includes Mons and Charleroi. All nodes are listed in the table 5.1. Wherever possible, the names of electrical nodes have been reused.

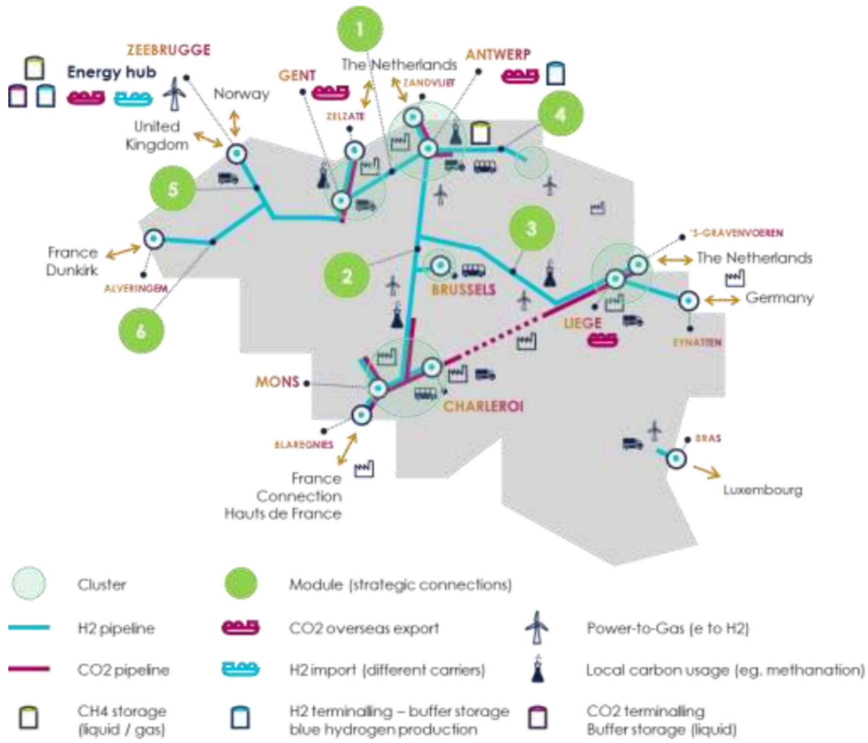

Figure 5.1: Short-term options for the deployment of the H2/CO2 backbone. Figure taken from [54]

Table 5.1: Nodes of Hydrogen network

Load Node		**Transfert Node**	
Name	Node	Name	Node
Antwerp	LINT	Zeebruge	STEVN
Brussels	BRUEG	Alveringem	ALVER
Albert Canal	ALBRT	Zelzate	ZELZA
Ghent	RODE+	Zandvliet	ZANDV
Hainaut	COURC	sGravenvoeren	SGRAV
Liège	SERAI	Eynatten	EYNAT
		Blaregnies	BLARE

5.1.2 Import of Hydrogen

Belgium's future hydrogen needs will be met mainly by imported hydrogen. These imports are modeled in ESTD as H_2 and Renewable Hydrogen (H_2_RE). Since equivalent carbon emissions are a key limit in the optimization, ESTD makes a distinction in the case of imports in order to assign a carbon emission equivalent to this hydrogen that is closer to reality. Imported hydrogen may have been produced in a number of "hydrogen rainbow" ways, and therefore have a highly variable carbon impact. Belgium's ambition is to serve as an entry point for hydrogen in Europe and then export it to neighboring countries thanks in particular to the Zeebrugge gas terminal. Therefore, in this model, the only import node will be the STEVN node associated with Zeebrugge.

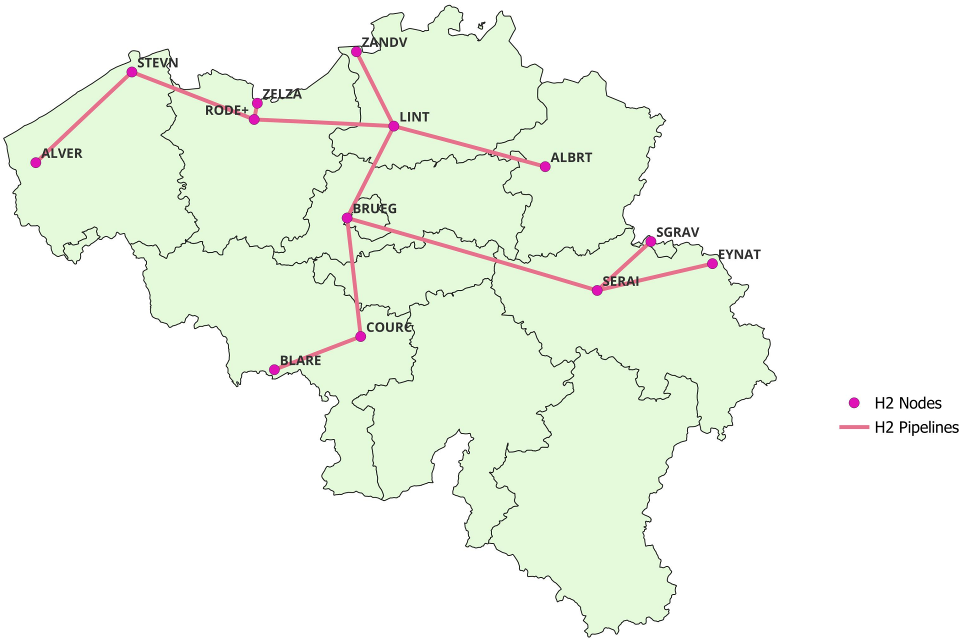

Figure 5.2: Implemented H_2 Grid

5.1.3 Hydrogen PipeLine

In the network modeled on the Fluxys map, 18 hydrogen pipelines have been established, 6 of the pipes are for the export of hydrogen to neighboring countries (France, Germany, the Netherlands) see tab 5.2.

Table 5.2: Pipelines of Hydrogen network

From Node	To Node	From Node	To Node
LINT	RODE+	SERAI	SGRAV
LINT	BRUEG	SERAI	EYNAT
LINT	ALBRT	STEVN	ALVER
LINT	ZANDV	ALVER	France
BRUEG	COURC	ZELZA	Netherlands
BRUEG	SERAI	ZANDV	Netherlands
RODE+	STEVN	SGRAV	Netherlands
RODE+	ZELZA	EYNAT	Germany
COURC	BLARE	BLARE	France

5.2 Production

Although much of the hydrogen used will be imported, some will be produced in Belgium. EnergyScope lists 3 technologies for direct hydrogen production:

- Electrolysers (H2_ELECTROLYSIS)

- Steam Methane Reforming (SMR)
- Biomass to Hydrogen (H2_BIOMASS)

To integrate this hydrogen production into the network, it has to be distributed among the nodes. Apart from a few projects still underway, such as the Columbus project in the Charleroi region [55], it's difficult to have an overall view of the future distribution of local hydrogen production. As a result, it's decided to distribute production almost evenly across the 6 load nodes associated with the hydrogen consumption clusters. The distribution among clusters is shown in the table 5.3.

Table 5.3: Distribuation of hydrogen porduction

Clusters	Share Production
Antwerp	0.17
Brussels	0.15
Canal Albert	0.17
Ghent	0.17
Hainaut	0.17
Liège	0.17

Note that the near-uniformity is due to rounding, so it is decided to remove the difference to the Brussels node.

5.2.1 Amonia to H2

The entire hydrogen production from ammonia has been placed at the STEVN node. In fact, this system takes into account the fact that the ammonia arrives via the port of Zeebrugge, is converted into hydrogen and is injected into the grid.

5.3 Load

Hydrogen consumption is distributed across the load nodes described above. These distributions differ according to the technologies considered. As the hydrogen network is not only different from the electrical network, but also much less dense, the distributions between nodes differ from those presented in the previous section. The entire hydrogen demand of a province is aggregated with the culster located there. However, some provinces do not have load nodes on their territory. As a result, hydrogen demand in these provinces is linked to clusters in neighboring provinces.

As a result, the demand from the province of West Flanders is attached to the Ghent cluster. Demand from Flemish Brabant to the Brussels cluster. That of the province of Luxembourg to the Liège cluster. For the province of Namur, half goes to the Hainaut cluster and half to the Liège cluster. The province of Walloon Brabant has one half attached to Brussels and the other to Hainaut.

5.3.1 Fuel Cell cars and Fuel Cell Truck

Here, the previously used database is used [46]. It provides the number of vehicles and trucks by Province (NUTS-2). Using the above assumption, the table 5.4 shows the distribution of hydrogen consumption by vehicle and truck, by cluster/node.

Table 5.4: Share of FC cars and FC trucks by hydrogen cluster

Clusters	Share FC Cars	Share FC Trucks
Antwerp	0.159	0.153
Brussels	0.237	0.199
Canal Albert	0.082	0.094
Ghent	0.231	0.273
Hainaut	0.152	0.141
Liège	0.139	0.14

Private Passenger Mobility

Car fuel cell (H2) (CAR_FUEL_CELL) meet the demand for private passenger mobility. The hydrogen demand in the EnergyScope for these cars is similar to the electricity demand for electric cars described above. To model hydrogen demand for this technology, the 24-hour demand profile is extracted and generate a .txt file containing these values.

Freight

Freight demand can be met by Truck fuel cell (hydrogen) (TRUCK_FUEL_CELL). These trucks behave like the electric trucks described above. Therefore from EnergyScope the constant hydrogen demand of trucks is extracted.

5.3.2 Passenger Public Mobility

The EUD of plublic mobility can be reached by using the technologie Bus fuel cell (H2) (BUS_COAC_ FC_HYBRIDH2) in ESTD. The breakdown of hydrogen demand for buses is based on the annual reports (to 2022) provided by the 3 bus operators in Belgium (TEC, STIB/MIVB, De Lijn). TEC [56] provides the total distances covered by its buses by province. From these provincial figures, hydrogen demand can be easily distributed over the various clusters established above, using the hypothesis made in section 4.3. The entire demand of the STIB/MIVB [57] network is attached to the Brussels cluster. De Lijn does not, however, provide provincial-scale values in its annual report [58], but only the cumulative distance covered by its buses across its entire network. In order to distribute demand a little more precisely over the Flemish clusters, the passenger figures per "Flemish transport region" (Vlaamse Vervoerregio's) [59] is used. There are 15 of these. Once this new breakdown has been taken into account, the distribution of total hydrogen demand for fuel cell buses is summarized in the table 5.6.

Table 5.5: **Share of FC Buses by hydrogen cluster**

Clusters	Share of Buses
Antwerp	0.136
Brussels	0.234
Canal Albert	0.034
Ghent	0.145
Hainaut	0.196
Liège	0.255

ESTD models hydrogen demand from buses as repetitive for each typical day. Here 5.3, the hydrogen consumption profile for the 12 typical days is shown. A 24-hour profile in .txt format is extracted from ESTD.

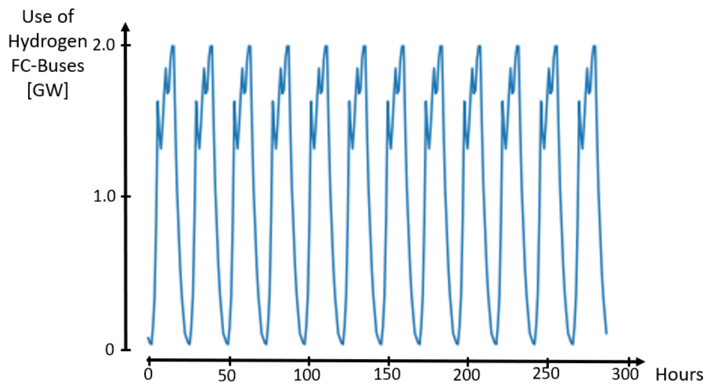

Figure 5.3: Use of hydrogen by FC buses

5.3.3 Industrial

The 4 industrial hubs presented here are Antwerp, Ghent, Liège and Hainaut (Mons and Charleroi). These are already hydrogen consumption clusters. In order to quantify the importance of these hubs, we use the district's GDP as an indicator. This gives the following breakdown in table.

Table 5.6: Share of industrial use of hydrogen by cluster

Cluster	Share of Industrial
Antwerp	0.401
Ghent	0.217
Hainaut	0.133
Liège	0.249

5.4 Hydrogen Storage

Referring again to the map provided by Fluxys, hydrogen storage is located at the ports of Antwerp and Zeebrugge. As there aren't any concrete figures on the scale of storage at these two locations, the storage is divided between these two sites into two equal parts. Consequently, 50% of storage is associated with the LINT node and 50% with STEVN. EnergyScope provides the storage size and also the maximum filling and refilling rate.

Chapter 6

Scenarios

The aim of this section is to present the different scenarios that are used to test the soft-link presented in this work. These scenarios are presented here in the form of constraints that are imposed on EnergyScope. The different ESTD results from the different scenarios are then processed via the soft-link presented in this work so that they can be used as input values for the adequacy tool. All the scenarios presented here have 2030 as their base year. This year has been chosen because of the wide availability of projection data on the deployment or use of specific technologies.

The different scenarios have elements in common, such as the same annual limit on greenhouse gas emissions. In addition, in the different scenarios, the V2G (linked to CAR_BEV and CAR_PHEV is blocked. Indeed, it seems highly ambitious to envisage the use of V2G on a large scale in 2030. What's more, this technology is not currently taken into account in the matching tools, so in order to remain consistent between the two tools, the decision has been taken to set this technology aside. Note that in 2030 there will still be 2GW of nuclear capacity.

6.1 Blocking V2G

Blocking V2G requires some manipulation. ESTD distinguishes between batteries and electric vehicles (see figure 6.1). The vehicle battery is the link between the layer_Electrcity and the car. The vehicle itself is linked to the layer_Mobility. As a result, the electricity coming out of the battery can either reach the vehicle or the layer_Electrcity, and thus serve as electrical storage for the grid. Thus to prevent V2G, the condition that all electricity leaving the batteries ($\mathbf{Sto_{out}}$) must go to the cars and not on the power grid. This means modifying certain equations within EnergyScope.

In the ESTD documentation [21], in the section 'Model formulation' the equations (Eq.31 and Eq.32)that need to be modified can be found:

$$\begin{aligned} \mathbf{Sto_{out}}(j, Elec, h, td) \geq -f(i, Elec)\mathbf{F_t}(i, h, td) \\ \forall i \in V2G, \forall j \in \text{EVs\_BATT OF V2G}(j), \forall h \in H, td \in TD \end{aligned} \tag{6.1}$$

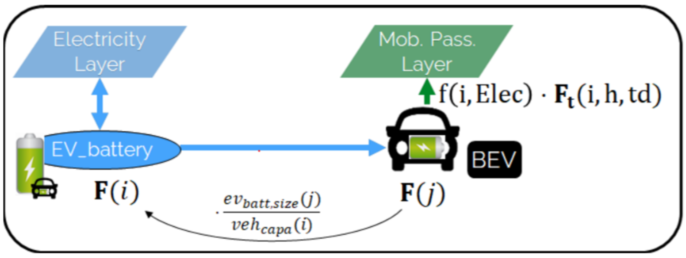

Figure 6.1: Illustrative example of a V2G implementation. Figure taken from [21]

$$\begin{aligned}\mathbf{Sto_{in}}(j,l,h,td)t_{sto_{in}}(\mathrm{j}) + \Big(\mathbf{Sto_{out}}(j,l,h,td) + f(i,Elec)\mathbf{F_t}(i,h,td)\Big)\cdot t_{sto_{out}}(\mathrm{j}) \\ \leq \left(\mathbf{F}(j) - \frac{\mathbf{F}(j)}{veh_{capa}(j)} ev_{batt,size}(j)\right)\cdot \%_{sto_{avail}}(j) \\ \forall i \in V2G, \forall j \in \text{EVs\_BATT OF V2G}(j), \forall l \in L, \forall h \in H, \forall td \in TD\end{aligned} \tag{6.2}$$

Since all the electricity leaving the battery must be converted to mobility, the inequation 6.1 becomes the equation 6.3.

$$\begin{aligned}\mathbf{Sto_{out}}(j,Elec,h,td) = -f(i,Elec)\mathbf{F_t}(i,h,td) \\ \forall i \in V2G, \forall j \in \text{EVs\_BATT OF V2G}(j), \forall h \in H, td \in TD\end{aligned} \tag{6.3}$$

From this new equation, equation 6.2 is simplified into equation 6.4.

$$\begin{aligned}\mathbf{Sto_{in}}(j,l,h,td)t_{sto_{in}}(\mathrm{j}) \leq \left(\mathbf{F}(j) - \frac{\mathbf{F}(j)}{veh_{capa}(j)} ev_{batt,size}(j)\right)\cdot \%_{sto_{avail}}(j) \\ \forall i \in V2G, \forall j \in \text{EVs\_BATT OF V2G}(j), \forall l \in L, \forall h \in H, \forall td \in TD\end{aligned} \tag{6.4}$$

To apply these modifications to EnergyScope, Eq 2.19-bis and Eq 2.31 are mofified in the ESTD_model.mod file.

6.2 Basic Scenario 2030

This scenario serves as a reference for comparisons with other scenarios. This scenario is described as basic because all the ESTD parameters are left by default.Apart from the few constraints mentioned above, all other constraints are left unrestricted. ESTD creates therefore a scenario from scratch and, when optimising it, only takes into account technologies that are already installed as well as projections for the deployment of future technologies.

6.3 House Scenario

The aim of this scenario is to quantify the impact on the high-voltage network of changes in housing and consumption habits. In fact, with the aim of decarbonising society, certain residential technologies are going to be deployed in a major way. Here we have decided to focus on 4 technologies that act on 3 types of EUD (heat, electricity, private mobility). These technologies are linked to the image that the general public may have of the home of the future.These technologies are the large use of photovoltaic panels, private electric vehicles, heat pumps and finally the use of residential battery storage. To quantify the importance of these different technologies,data from ELIA [27] are used and the National Energy and Climate Plan (NECP) [1]. Apart from the values listed below, EnergyScope has no other constraints.

6.3.1 PV

The NECP provides for two scenarios between now and 2030, a scenario With Existing Measures (WEM) [60] and a scenario With Additional Measures (WAM) [61]. This report was approved in 2019, so some of these values are out of date. The scenario with existing measures forecasts 7.8 GW in 2030, but in July 2023 installed capacity was already 7.6 GW (Elia). The scenario with additional measures forecasts a capacity of 11 GW. However, the pace of new installations has accelerated recently due to the current context (rising energy prices), and companies and private individuals have launched into the installation of photovoltaic panels on a massive scale. As a result, this figure of 11GW installed by 2030 is also likely to become obsolete. Pending more recent projections, the value of 11GW is kept here. This parameter is entered into ESTD as:

Table 6.1: EnergyScope Input

Technology	f_{min} **[GW]**	f_{max} **[GW]**
PV	11	11

6.3.2 Heat Pumps

The NECP provides two values for the penetration rate of heat pumps. The WEM scenario forecasts 2.3% and the WAM scenario 3.6% penetration. The WAM scenario is selected as in the previous point. This leads to the most constraints in terms of electricity. The ESTD technologie corresponding to this scenario is DEC_HP_ELEC. This technologie meet the demand for decentralized low-temperature heat.

Table 6.2: EnergyScope Input

Technologies	$fmin_{perc}$ [-]	$fmax_{perc}$ [-]
DEC_HP_ELEC	0.036	0.036

[1] https://www.nationalenergyclimateplan.be/en

6.3.3 Electrical Vehicules

Elia and the NECP forecast between 0.57 and 1.44 million electric vehicles by 2030. The assumptions associated with these vehicles are a consumption of $17kWh/100km$ and an average distance travelled of 15,000 km per year per vehicle. However, it is not possible to enter a number of vehicles directly into ESTD. It specifies the private mobility in Mega passenger kilometer (M.pass.km) which is covered by an "installed capacity" F in Mega passenger kilometer per hour (M.pass.km/h) . To convert the number of vehicles for input into EnergyScope, we use the following equation 6.5 with the occupation rate τ [pass/veh], average speed v_{moy} [km/h] and number of cars in million N:

$$F = \tau \cdot v_{moy} \cdot N \tag{6.5}$$

ESTD assumes a fill rate of 1.26 passes/veh and an average speed of 40 km/h. With 1.44 million vehicles in Elia's scenario, calculate the limit to be introduced into ESTD.

Table 6.3: EnergyScope Input

Technology	f_{max}
CAR_BEV	72.576

6.3.4 Domestic Batteries

ESTD does not distinguish between small and large-scale battery storage, unlike the data provided by Elia. Battery storage is in ESTD referred to as Batteries (BATT_LI). Elia provides projections for 2030 for battery power and storage capacity. Elia forecasts a cumulative maximum power of 1094 MW and a storage capacity of 1929 MWh on a small and large scale.

Table 6.4: EnergyScope Input

Technology	f_{min} **[GWh]**	f_{max} **[GWh]**
BATT_LI	1.929	1.929

6.4 EneryScope Results

The aim of this section is to compare the results of the scenarios presented. Compare how ESTD optimizes the system when stronger constraints are imposed on certain technologies, while demands remain the same. Finally, compare the different costs and emissions of the two systems.

6.4.1 Private mobility

When the ESTD constraints are not modified, the system uses only CAR_BEV to meet the EUD for private passenger mobility. In the House scenario, the number of electric vehicles is limited, so the system uses almost 2 times fewer electric vehicles. To complement the EUD, the system uses Natural Gas Vehicles (CAR_NG). It should be noted that the system also uses other technologies, such as hybrid and plug-in-hybrid vehicles, and fuel vehicles (gasoline, diesel and methanol), but these are negligible compared with the fleet of electric or natural gas vehicles.

Table 6.5: Capacity Private mobility [M.km.pass/h]

Tech:	Basic	House
CAR_BEV	164.9	72.6
CAR_NG	0	92.3

6.4.2 Low temperature heat

The observation is similar to the previous point, but to a greater extent. In fact, as the penetration rate of electric heat pumps has been severely limited, the house scenario system will resort to Thermal heat pump gas (decentralised) (DEC_THHP_GAS) to supplement the EUD with decentralized low-temperature heat. Both systems also use solar and electric heating technologies Solar thermal (decentralised) (DEC_SOLAR),DEC_DIRECT_ELEC, but to a negligible extent. Installed capacity values are shown in the table 6.6. The respective sum capacities are similar for both scenarios.

Table 6.6: Capacity of Production Heat Low Temperature decentralised [GW]

Techn:	Basic	House
HP_ELEC	20.25	0.72
THHP_GAS	0	19.60

6.4.3 Electrical storage

In terms of electrical storage, apart from the 6.5 GWh of pumped storage, the systems in the two scenarios are quite different. In fact, the unmodified system does not use BATT_LI. Whereas the second scenario requires 1.929 GWh of battery storage. This additional storage allows the system to be less sensitive to the intermittency of RES, for example. The storage capacities of the two scenarios are shown in the figure 6.2.

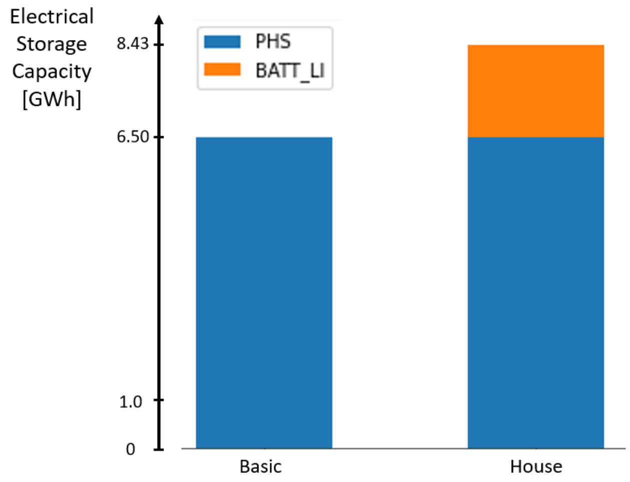

Figure 6.2: Capacity of electrical storage from EnergyScope

6.4.4 Power generation

In terms of power generation, the system resulting from the house scenario has a much lower power production capacity than the so-called basic system 6.3. This is because the house scenario introduces a more restrictive constraint on PV capacity. As a result, the system has installed the maximum allowed by this constraint. What's more, this scenario does not use a CCGT, unlike the basic scenario.

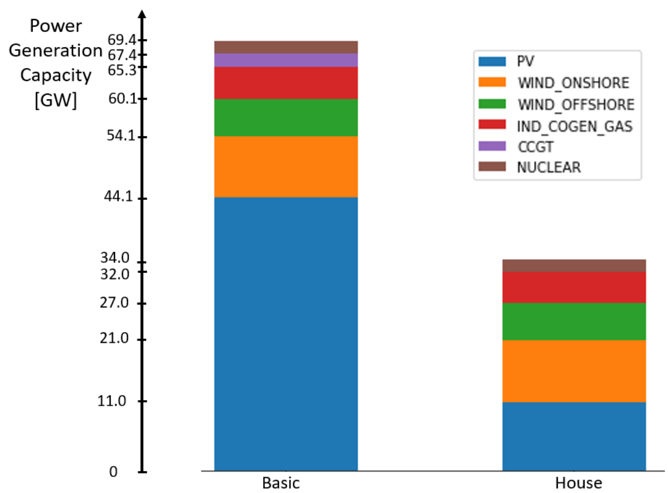

Figure 6.3: Power Generation Capacity from EnergyScope

Although the difference in capacity between the two scenarios is significant (69.4 GW for the base scenario and 34 GW for the House scenario), the difference in electricity generated does not reflect the difference in capacity 6.4. This is due to the low load factor of photovoltaic panels in general, but also to the greater electrical storage capacity (see section 6.4.3). In addition, the basic scenario requires more electricity, as private mobility and decentralized low-temperature heat production are fully electrified.

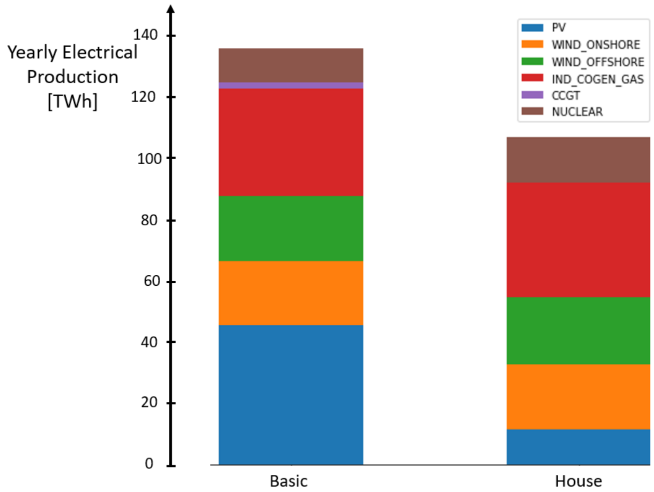

Figure 6.4: Power Generation Capacity from EnergyScope

6.4.5 Costs and emissions

Although the C_{inv} of the house scenario is the lowest, the system derived from the basic scenario is less expensive. This is because the C_{maint} and C_{op} costs of the house scenario are higher (see tab 6.7).

Table 6.7: Costs of each system [M€]

Cost	**Basic**	**House**
Inv	24484.26	21928.27
Maint	5837.34	6932.99
Op	13264.1	16966.19
Total	43585.7	45827.45

In terms of emissions linked to system Operational Global Warming Potential (GWP_{op}), these are identical for both scenarios, as this is a limiting constraint that both systems share. In terms of emissions due to system Construction Global Warming Potential (GWP_{constr}). The system resulting from the house scenario stands out for its much lower emissions (1946.7 kilo tonne (kton)$CO_{2,eq}$ vs. 4522.25 kton$CO_{2,eq}$ for the basic scenario).

6.4.6 Sankey Diagrams

Here are the sankey diagrams for each scenario (Basic and House), summarizing the primary energies used and all the transformations and vectors leading to the EUDs.

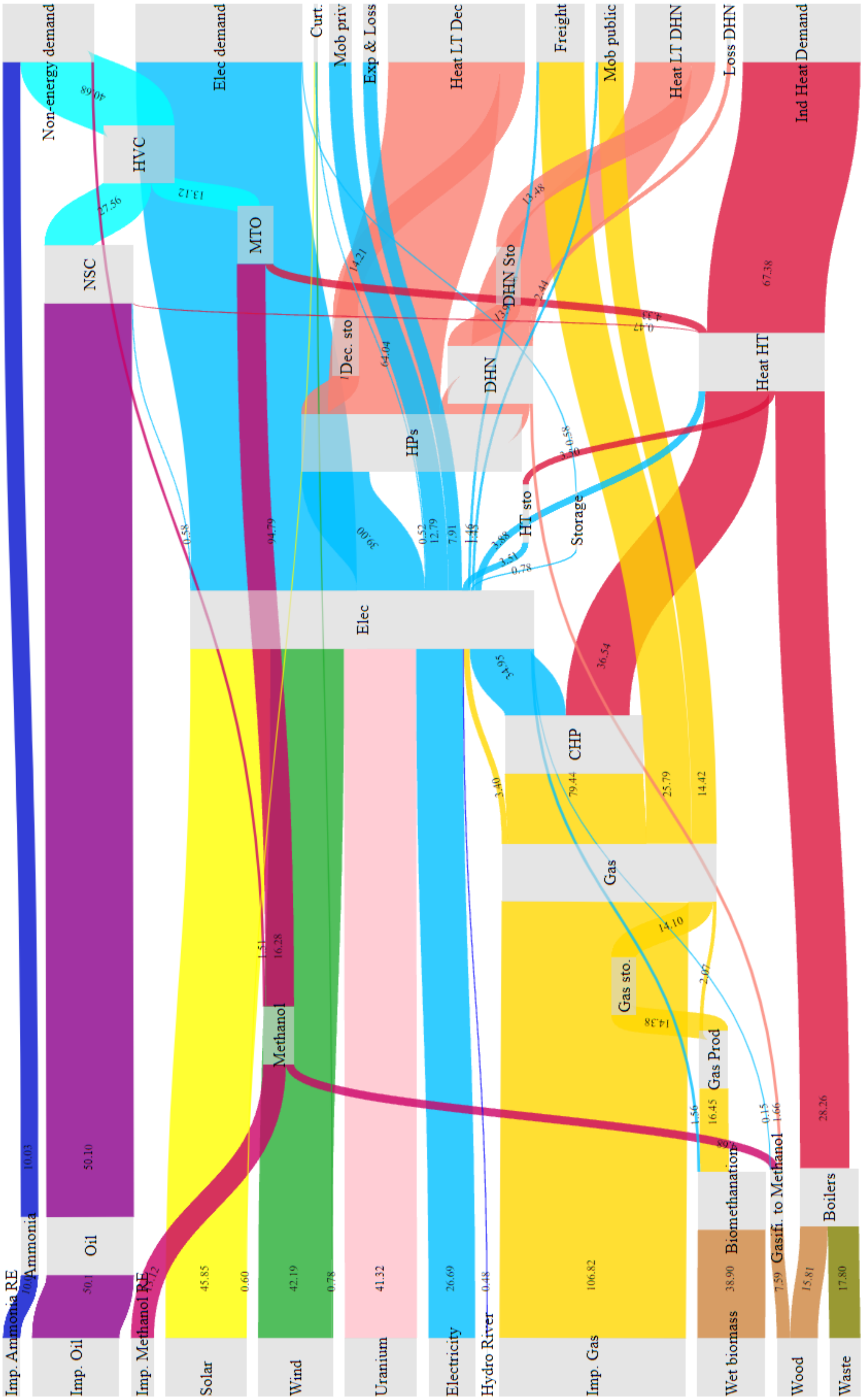

Figure 6.5: Sankey diagram of the Basic scenario Tera Watt Houre (TWh).

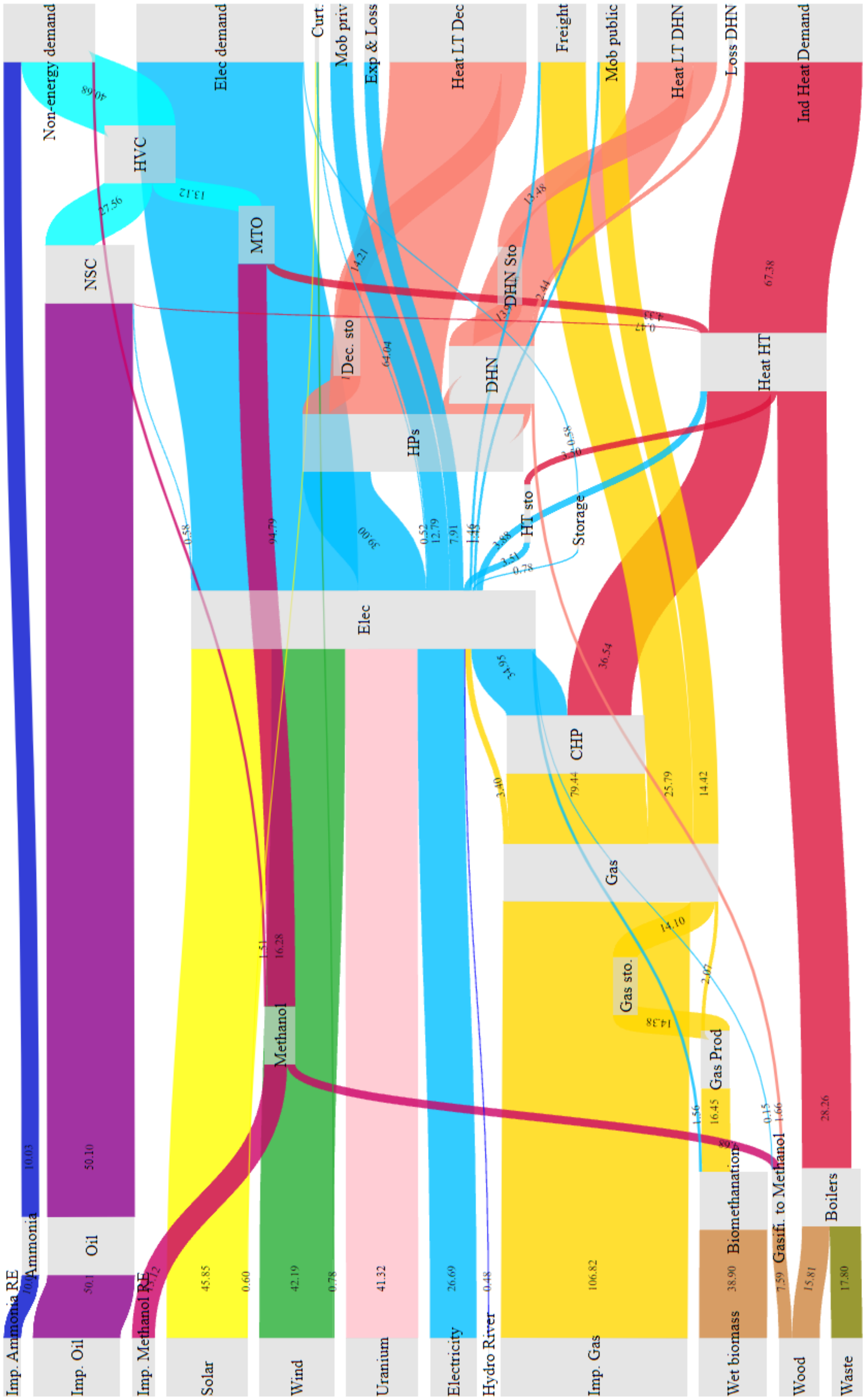

Figure 6.6: Sankey diagram of the House scenario TWh.

Chapter 7

Adequacy Results

This section consists of analyzing the systems presented in section 6 using a matching tool. This allows us to analyze and take into account the behavior and limitations due to the power grid when operating the systems described in the scenarios.

The tool developed by Aurélia Hernandez is a Monte Carlo-based method.This is a probabilistic model performing DC power flow optimization. This tool will enable systems to be tested over a large number of years in order to highlight potential faults in the system. This is done while optimizing the overall cost of the system. System cost is determined by several elements. The first two are the C_{op} of the power or hydrogen production units. The rest of the cost is determined by the compensation that must be paid when a consumer's demand for electricity or hydrogen cannot be met. This second part of the cost can be very significant when the system is unable to meet demand on a regular basis. System operating costs are based on scenarios optimized by ESTD. While unserved energy allowances are set so that it is always more profitable to serve a consumer with an expensive unit than not.

This tool therefore makes it possible to perform matching on both an electrical network and a hydrogen network simultaneously. However, due to the size of the network modeled (50 nodes and 80 lines) and the use of a Monte Carlo method, computation is relatively slow, taking almost 48 hours for 80 Monte Carlo years. Added to this is the fact that the method used to allocate the different production or consumption technologies has the effect of multiplying the number of variables and therefore slowing down the optimization.

7.1 Flexibility inputs

This section presents the flexibility introduced on the different demands. Flexibility on a demand consists in shifting this demand when available capacities are not sufficient to cover it. Consequently, a demand can be either fixed, i.e. the electricity or H_2 consumption of each hour linked to this demand cannot be shifted. Flexibility can be introduced on several scales: daily, monthly, annual. Daily flexibility is the strictest, meaning that demand on any given day must be met, but not necessarily every hour.

For monthly flexibility, monthly demand must be met. And finally, annual flexibility is the least stringent, requiring only annual demand to be met.

In order to limit execution time, when flexibility is introduced on a request, it will be introduced on a daily basis. The next two sections present the introduction or non-introduction of flexibility to the different demands and consequently to the technologies linked to these demands.

7.1.1 Electrical Flexibility

The electrical demand for private and public EUD mobility is set here. Consequently, the demand for the following technologies must be met for every hour of the year:

- Public: TRAMWAY_TROLLEY, TRAIN_PUB
- Private: CAR_BEV,CAR_PHEV

The following sectors and associated technologies have a daily flexibility:

- Freight mobility: TRUCK_ELEC TRAIN_FREIGHT
- Industrial: Industrial Process ATM_CCS Industry_CCS
- Heat: Decentralized Heat Pumps, Heat Network Heat Pumps, IND_DIRECT_ELEC

7.1.2 Hydrogen Flexibility

As in the previous section the demand due to public and private mobility is fixed for the following technologies:

- CAR_FUEL_CELL
- BUS_COAC_ FC_HYBRIDH2

Other demands in hydrogen have daily flexibility as the following technologies:

- Freight Mobility: TRUCK_FUEL_CELL
- Industrial hydrogen process

7.2 Summary of scenarios

This section summarizes the scenarios presented in Section 4, as well as the additional assumptions made with regard to the ESTD-optimized systems (Basic and House). In addition, as flexibility is introduced for certain demands, this new notion is put into perspective in relation to system demand in general.

In contrast to the methodology presented in Section 4, an approximation to the LFs of the generators is applied here to ensure that the adequacy tool works properly. In Section 4, LFs are calculated for the various generators. Here, however, no LFs are introduced for the generators. This is a very strong approximation between the system optimized by ESTD and the system introduced in the Adequacy tool.

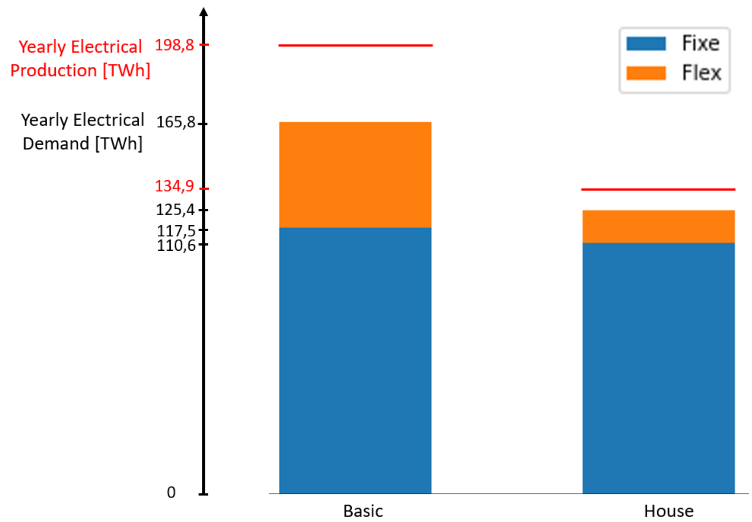

Figure 7.1: Yearly production and consumtpion (fixed and flexible)

Figure 7.2 shows that, for both scenarios, the annual electricity production potential is sufficient to meet annual demand (imports are also taken into account here). As in section 6, it can be seen that the Basic scenario is far more electrified than the House scenario. The margin between production and consumption in the Basic scenario is greater than in the House scenario. Figure 7.2 also shows that the fixed components of consumption in each scenario are fairly similar. But the flexible part is much larger in the Basic case.

From this first, fairly summary analysis, it can be expected that the system will be able to cover the system's electricity demand. In addition to this, a certain degree of demand flexibility adds security to the system's ability to meet demand.

7.3 Loss of Load and Energy

In order to further analyze a system's ability to meet demand, two new concepts need to be introduced. The notion of Loss of Load (LOL) exprimed in houre, expressed in hours, represents the time during which the system's electricity demand cannot be converted. This value is generally calculated on a yearly basis. The second notion, Loss of Energy (LOE) exprimed in GWh or TWh, represents the amount of energy required to cover the system's needs over a year.

In addition to these two notions, LOLE and Loss of Energy Expectation (LOEE) represent the expected values for LOL and LOE respectively. For example, in the European Union, the most common LOLE value is 3 hours per year. This mean the demand must be satisfied 99.97% of the time [62].

Since the matching tool does not distinguish between a large shortage over a short time interval and a small shortage over a long time interval, the study of LOL and LOLE is less relevant than the study of LOE and LOEE. Consequently, this section will focus on LOE.

7.3.1 Results

Here, in order to compare the two scenarios more accurately, the annual LOE is plotted against the annual electricity demand for each scenario. From figure 7.2, we can see that the Basic scenario will have an median electricity shortfall of 5.17%. The House scenario is less affected by electricity shortages, with an median shortfall of 4.15%. In this case, however, the shortage range is more spread out for the House scenario. As seen in section 6, this scenario has more EUDs covered via vectors other than electricity (such as natural gas) which explains its lower median.

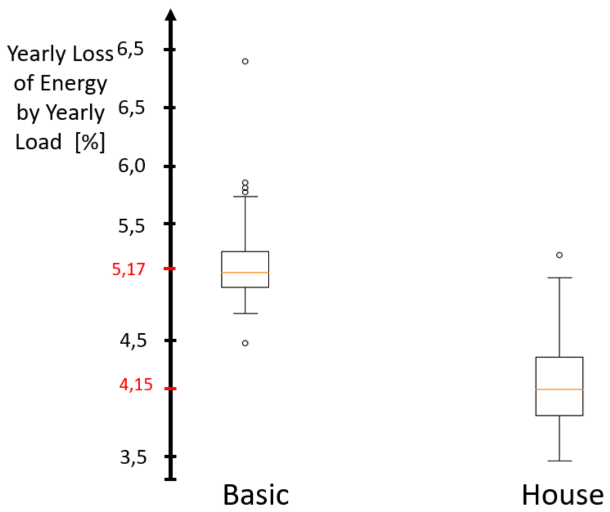

Figure 7.2: Yearly LOE compared to Yearly Electrical Load

7.3.2 Most affected Nodes

Not all nodes are equally affected by LOE. Depending on the layout of the high-voltage network, nodes may be more or less exposed to LOE. Nodes connected to the rest of the network via a small number of lines or low-capacity lines are more likely to be affected by LOE. In addition, certain nodes located at network dead-ends are also more exposed. Here we present the nodes most affected by LOE in each of the two scenarios.

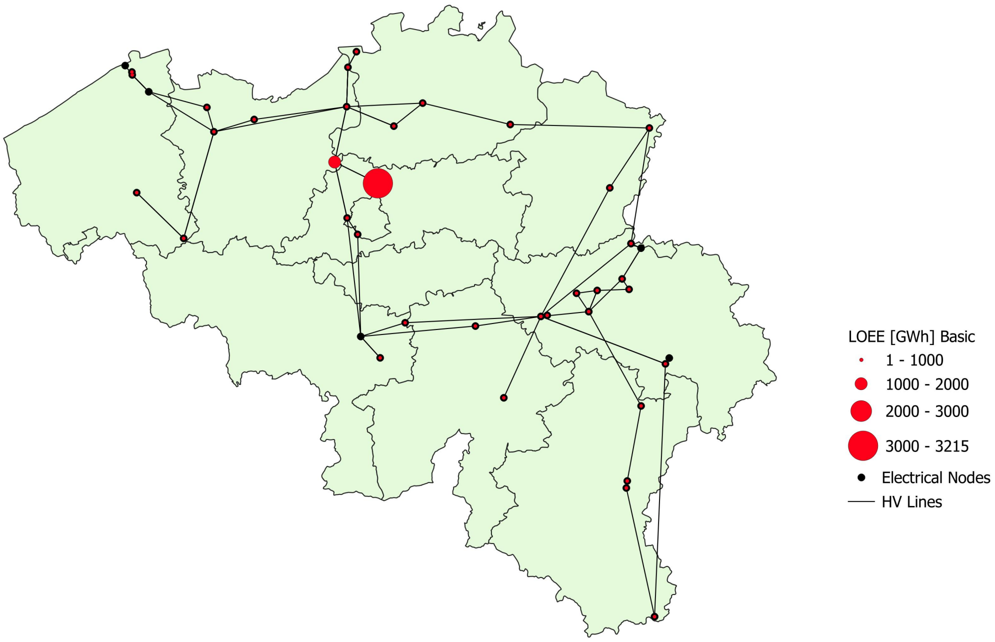

Figure 7.3: Most affected nodes by LOE in Basic Scenario

Table 7.1: Most affected nodes by LOE

Basic		House	
Node	$\frac{\text{Node LOE}}{\text{Total LOE}}$ [-]	Node	$\frac{\text{Node LOE}}{\text{Total LOE}}$ [-]
VERBR	0.375	VERBR	0.439
BUGG+	0.123	BUGG+	0.151
BRUEG	0.107	BRUEG	0.08

Table 7.1 shows the 3 nodes most affected by LOE. In order to compare the nodes, the node-specific LOE is brought down to the total LOE of the system. For both scenarios, the most affected node is VERBR, located on the outskirts of Brussels. To determine the reason, further analysis is required.

After analysis of the results, no correlations between LOE and the node's own electricity production or load could be established. The focus is on the local layout of the node in relation to nu networks. It is located in a cul de sac of the network, and is therefore connected to only one node (BUGG+) via two lines (see table C.2).

When there is an LOE at the VERBR node, the LF of lines (9 and 10 see tab C.2) tends to be relatively low, meaning that very little electricity is imported in this situation. For the opposite trend, when the LF of these lines is close to zero, it is not observed that this implies an LOE at this node.

However, it can be seen that when the VERBR node is subjected to LOE in both scenarios, the two lines with the highest LF for the entire network are lines 15 and 17

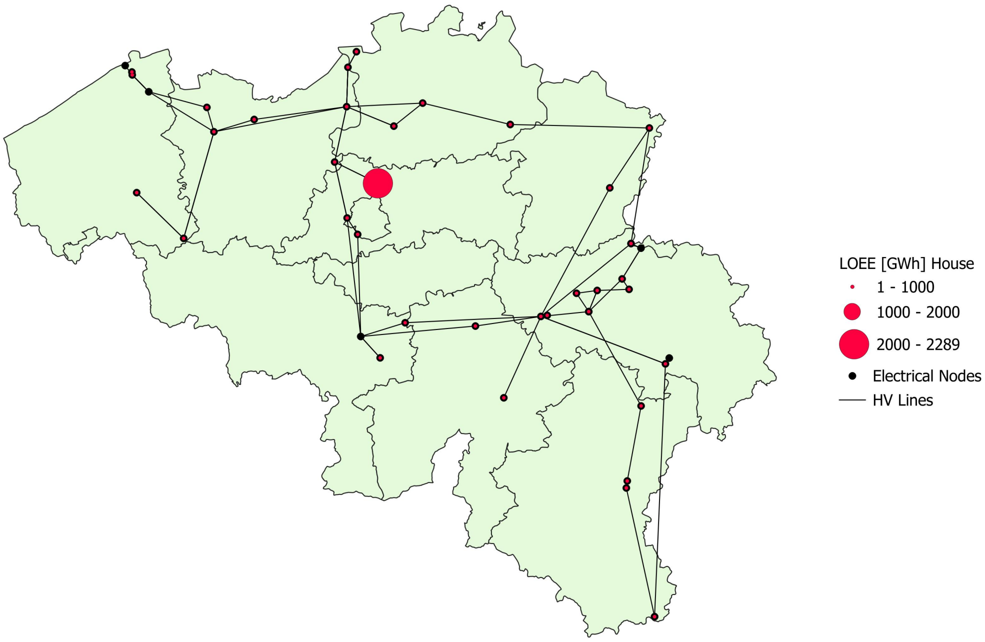

Figure 7.4: Most affected nodes by LOE in House Scenario

(see tab C.2). These two lines are adjacent to the BUGG+ node. Line saturation could explain the LOE experienced at VERBR nodes.

Table 7.2: Most affected Lines while LOE at VERBR in Basic Scenario

Basic			
N° Line	From Node	To Node	Avg LF
9	BUGG+	BRUEG	0.85
10	BUGG+	BRUEG	0.76
15	BUGG+	MERCA	0.98
17	BUGG+	MERCA	0.89

Figures 7.2 and 7.3 show the average annual *LF* of lines 15 and 17 from BUGG+ to MERCA, and lines 10 and 9 from BUGG+ to BRUEG. In fact, these lines tend to saturate when there's LOE at the VERBR node, which could explain why this node suffers most from this phenomenon.

7.4 Curtailment

Curtailment corresponds to electricity production that could not be consumed, and is therefore wasted. To avoid network-damaging curtailment, the network operator will deactivate certain power generation units. To avoid network-damaging curtailment, the network operator will deactivate certain power generation units, giving priority to units that can easily switch on/off, but also to the most expensive units.

Table 7.3: Most affected Lines while LOE at VERBR in House Scenario

House			
N° Line	From Node	To Node	Avg LF
9	BUGG+	BRUEG	0.76
10	BUGG+	BRUEG	0.68
15	BUGG+	MERCA	0.99
17	BUGG+	MERCA	0.80

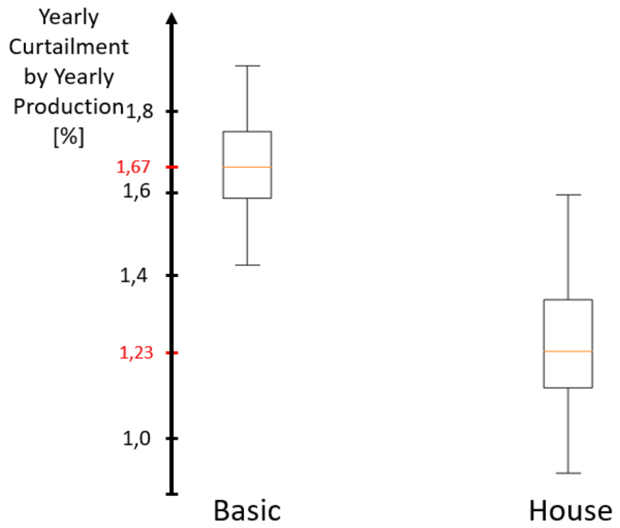

Figure 7.5: Yearly Curtailment compared to Yearly Electrical Production

Figure 7.5 shows the annual amount of curtailed production as a proportion of total annual production. This makes it possible to quantify the proportion of total electricity produced that will not be consumed by the system and is therefore lost. Reducing it to the total annual production for each scenario allows us to compare the importance of curtailment in both cases.

Figure 7.5 shows that the median curtailment for the Basic scenario is 1.67% and for the House scenario 1.23%. The House scenario is therefore less prone to curtailment. Figure 7.5 also shows that curtailment is always present somewhere on the network. Indeed, the lowest visible curtailment values are around 0.9% for the House case, and no point lies outside this range.

Figure 7.6 puts the curtailment peak into perspective with the demand peak. This highlights the significant peak in production compared to load. The figure shows that the system resulting from the house scenario is less exposed to this curtailment phenomenon. Indeed, as we saw in section 6, the production capacities associated with this scenario are much lower. What's more, the difference in power generation capacity between the two scenarios is mainly due to the quantity of PV installed, a unit that is not controllable and therefore more prone to generating peaks.

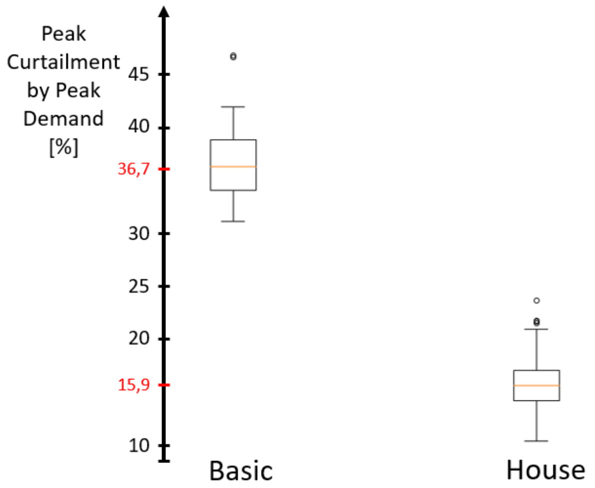

Figure 7.6: Curtailment Peak compared to Load Electrical Peak

7.4.1 Most affected Nodes

Table 7.4 shows the nodes most affected by curtailment. In order to compare the nodes with each other, the node-specific curtailment is related to the total system curtailment. For both scenarios, the same node predominates. This is STEVN, which has the particularity of being connected to the entire offshore wind production. Figures 7.8 and 7.8 show the average node curtailement over all Monte Carlo years.

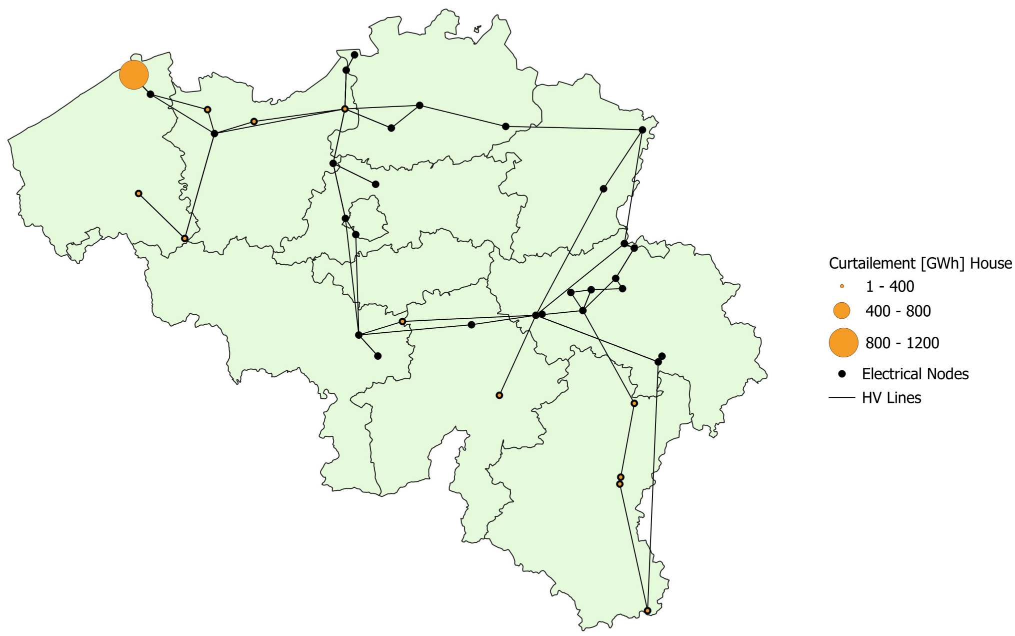

Figure 7.7: Most affected nodes by Curtailment in House Scenario

In the first instance, it can be observed that when curtailment takes place, offshore production is at a high level. However, the reverse is not observed. The different loads

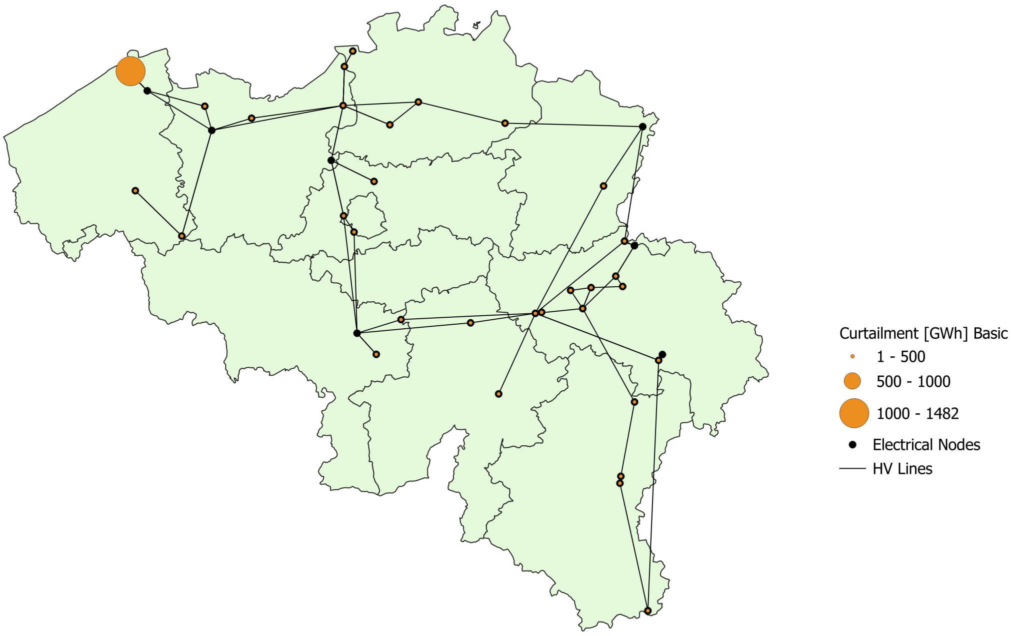

Figure 7.8: Most affected nodes by Curtailment in Baisc Scenario

Table 7.4: Most affected nodes by Curtailment

Basic		House	
Node	$\frac{\text{Curt Node}}{\text{Curt total}}$ [-]	Node	$\frac{\text{Curt Node}}{\text{Curt total}}$ [-]
STEVN	0.44	STEVN	0.72
MARC+	0.11	MARC+	0.20
RODE+	0.06	SENO+	0.05

or production units (PV, onshore...) connected to the nodes do not allow us to establish a correlation between the latter and the appearance of curtailment at the STEVN node.

Secondly, it may be noted that when the curtailment phenomenon is present on the STEVN node, off-shore wind power generation tends to be very high (between 4 and 6 GW). However, a high level of production from offshore wind farms does not specifically lead to the certailment phenomenon.

It can also be seen that when STEVN is curtailed, lines 33 34 35 36 (see tab C.2) correspond to the four lines between GEZEL and MAERL. These lines are extensions of the lines between STEVN and MAERL. Saturation of these lines, combined with high production from offshore wind farms, could explain the curtailment observed at the STEVN junction.

Tables 7.5 and 7.6 show the average annual LF of each of these 4 lines when curtailment is present at the STEVN node for each of the two scenarios. These 4 lines tend to be more saturated in the House scenario. One explanation could be that the House scenario

Table 7.5: Most affected Lines by Curtailment in Basic Scenario

Basic			
N° Line	From Node	To Node	Avg LF [-]
33	GEZEL	MAERL	0.88
34	GEZEL	MAERL	0.72
35	GEZEL	MAERL	0.89
36	GEZEL	MAERL	0.80

Table 7.6: Most affected Lines by Curtailment in House Scenario

Basic			
N° Line	From Node	To Node	Avg LF [-]
33	GEZEL	MAERL	0.95
34	GEZEL	MAERL	0.95
35	GEZEL	MAERL	0.96
36	GEZEL	MAERL	0.96

is less electrified and therefore has a lower electricity demand, combined with the fact that the system has equivalent installed offshore capacity to the Basic scenario.

7.5 Curtailment with Loss of Energy Analysis

An additional analysis is carried out here, to determine whether there are time intervals during which the STEVN node curtails and the VERBR node undergoes LOEE. This is a good way of highlighting network weaknesses. The number of hours during which these two phenomena occur is counted over 5 different years. Clearly, it's not possible to determine a trend over just 5 years, but it does give an initial impression. Table 7.7 summarizes the values for these 5 years.

Table 7.7: Time range while LOE at BRUEG and Curtailment at STEVN in Basic and House Scenarios

Year	Basic [h]	House [h]
1	413	413
2	386	384
3	246	543
4	276	477
5	308	527
Mean	325.8	468.8

Tables 7.8 and 7.9 show which lines are most heavily used when there is LOE at BRUEG and curtailment at STEVN. This shows that the lines between STEVN and BRUEG tend to saturate. As a result, excess generation at STEVN cannot be properly routed to the VERBR node. A better network infrastructure would both reduce curtailment when LOE exists elsewhere on the network.

Table 7.8: Most affected lines while LOE at BRUEG and Curtailment at STEVN in Basic Scenario

Base			
N° Line	From Node	To Node	Avg LF
15	BUGG+	MERCA	1
17	BUGG+	MERCA	0.9
33	GEZEL	MAERL	0.97
34	GEZEL	MAERL	0.98
35	GEZEL	MAERL	0.99
36	GEZEL	MAERL	0.99
58	MERCA	RODE+	0.91

Table 7.9: Most affected lines while LOE at BRUEG and Curtailment at STEVN in House Scenario

House			
N° Line	From Node	To Node	Avg LF
15	BUGG+	MERCA	1
17	BUGG+	MERCA	0.88
33	GEZEL	MAERL	0.94
34	GEZEL	MAERL	0.97
35	GEZEL	MAERL	0.98
36	GEZEL	MAERL	0.98
9	BRUEG	BUGG+	0.82

Chapter 8

Discussion

Implementing the soft-link required a large number of assumptions and approximations. The aim of this section is to reference the main approximations made during implementation. But also to give different ways to improve it.

Most of the approximations made for the distribution of technologies on the network use figures for current installations. The use of year-specific projections, when available, would enable more realistic distributions in the future.

A common approximation is the uniform distribution of demand in a given geographical area. This approximation is valid when the geographical area is small, but quickly becomes out of touch with reality when the scale used is provincial or regional. The use of one scale rather than another is mainly induced by the data available for the distribution in question. Consequently, the more precise the database used, the closer the geographical distribution will be to reality.

The distribution of industrial applications is also very approximate. Indeed, aggregating a large number of ESTD technologies qualified as industrial is already a significant approximation. To counter this, a more in-depth individual analysis of these technologies would enable a more accurate distribution. Consequently, a breakdown specific to each of these technologies would be more accurate. The second approximation consists of distributing these technologies over just 5 sites in Belgium. Once again, a study specific to each technology would make it possible to avoid grouping them together in a hub. Finally, using GDP to quantify the importance of a hub is also very approximate, as this indicator encompasses far more elements than industrial production.

For CHP units, aggregating the different units regardless of fuel is also an important approximation. The fuels used by these units are not easily interchangeable.

Some technologies, such as generators on the distribution network or different heating technologies, follow the same distribution as that established for the population. And this under the guise of justifying that the demand for heat is made where the population is located. To avoid using this distribution system indiscriminately, a detailed inventory of these units is required. This allows us to have a specific distribution for each of these technologies.

The distribution made for electricity consumption by the rail network is undoubtedly one of the most crude in this work. In fact, the data used is at regional level, which is inevitably a very crude vision of reality. The other available data are too important to be managed by hand. Consequently, using the resources available via the SNCB/NMBS API is a good way of improving distribution.

In this work, the scenarios presented have a 2030 horizon. However, the distributions presented are based on the current high-voltage network. Consequently, for each target year, we would need our own network, including future network modification projects.

Finally, the hydrogen network implemented in the soft-link is not based on any numerical values. This is because the hydrogen infrastructure project has not yet published any figures. In the future, it may be worthwhile adapting the network implemented thanks to the publication accompanying the current project.

Chapter 9

Conclusion

In the context of the energy transition, ways of producing and consuming energy are changing. New technologies are gradually being integrated into existing energy systems, influencing their behavior. In addition, the future use of new large-scale energy carriers will change the way energy is transported within systems.

Consequently, it is becoming increasingly necessary to model these future systems in order to anticipate their behavior. To this end, two tools are used in this work, namely ESTD and a adequacy tool. In order to benefit from the advantages of these two tools, a soft-link has been created. This allows a system previously optimized by ESTD to be implemented directly in the matching tool. To implement this soft-link, it is first necessary to map all the technologies implemented in ESTD that interact with the two energy carriers considered here (electricity and gas). To represent these energy carriers, two separate networks are implemented. In order to achieve this soft-link, a series of assumptions and approximations based on the literature are made and described in this work. These assumptions are used to justify the different technology distributions.

Once this soft-link has been implemented, two scenarios are presented, with the target year 2030. The first scenario, described as basic, adds no constraints to ESTD and provides a point of comparison. The second scenario attempts to model the impact of future changes in population habits. To do this, this scenario takes into account the deployment of photovoltaic panels on private homes, the significant use of electric mobility and the deployment of heat pumps. It also takes into account the deployment of domestic batteries, based on Elia's projections.

Once these scenarios have been defined, they are implemented as additional constraints in ESTD. The result is an optimized system based on cost and $CO_{2,eq}$ emissions. The resulting systems are processed by the soft-link so that they can be easily implemented in the adequacy tool.

As the tool is based on a Monte Carlo method, a new optimization is performed by the matching tool over 60 and 80 years respectively for the Basic and House scenarios. The results of these two new optimizations are then analyzed. A general trend is drawn from these results. This shows that part of the network is saturated when certain phenomena such as curtailment or loss of energy occur.

The main criticism of these results is that the high-voltage network implemented here does not match that of the target year, due to a lack of data. Consequently, the modifications to be made will help to avoid these undesirable phenomena.

In conclusion, it's important to remember that the best energy system can only exist if everyone is energy sober.

Appendices

Appendix A

Tables

Table A.1: Power,node and share to each gas central. Data taken from [27]

Power Plant	**Power [MWe]**	**Node**	**Share node [-]**
Amercoeur	451	GOUY	0.258
Marcnielle Energie TGV	413	GOUY	
Saint-Ghislain STEG	350	GOUY	
EDF Luminus Angleur	178	SERAI	0.137
EDF Luminus Seraing	470	SERAI	
EDF Luminus Ham	155	RODE+	0.179
EDF Luminus Ringvaart STEG	385	RODE+	
Zelzate 2 Knippegroen	305	RODE+	
Drogenbos	460	MEKI+	0.098
Hardesbrug	480	GEZEL	0.102
T-Power	425	MEERH	0.09
Vilvoorde	255	VERB	0.054
Zandvliet Power	386	ZANDV	0.082
Total	4713		

Table A.2: Population, nodes and NUT-3 code associate to each District

District	Nuts-3	Pop	Load Nodes
District of Brussels-Capital	BE100	1235192	VERBR,BRUEG,MEKI+
District of Antwerp	BE211	1075443	LINT,MASSE,ZANDV
District of Mechelen	BE212	356069	LINT,VERBR
District of Turnhout	BE213	476215	MEERH
District of Hasselt	BE221	428343	ZUTE+
District of Maaseik	BE222	257233	VANYK
District of Tongres	BE223	208889	LIXHE220,ZUTE+
District of Aalst	BE231	301924	BRUEG,MERC
District of Oudenaarde	BE232	127403	AVLGM
District of Eeklo	BE233	88508	EEKLN
District of Ghent	BE234	574269	HORTA,RODE+
District of Sint-Niklaas	BE235	261834	DOEL,MERCA
District of Dendermonde	BE236	206267	BUGG+
District of Halle-Vilvoorde	BE241	663717	BRUEG,MEKI+,VERBR
District of Leuven	BE242	522879	VERBR,LINT
District of Bruges	BE251	285442	GEZEL,STEVN
District of Kortrijk	BE252	299521	AVLGM
District of Diksmuide	BE253	52451	IZGEM
District of Veurne	BE254	61702	IZGEM,STEVN
District of Ostend	BE255	159198	STEVN
District of Roeselare	BE256	157930	IZGEM
District of Tielt	BE257	95112	IZGEM
District of Ypres	BE258	107786	IZGEM
District of Nivelles	BE310	412770	GOUY
District of Ath	BE321	130103	AVLGM,GOUY
District of Charleroi	BE322	397930	GOUY,STAM+
District of Mons	BE323	260164	GOUY
District of Soignies	BE325	107556	GOUY,MEKI+
District of Thuin	BE326	92607	GOUY
District of Tournai-Mouscron	BE328	224682	AVLGM
District of La Louvière	BE329	142104	AVLGM
District of Huy	BE331	115655	GRAMM,TIHA1
District of Liège	BE332	625192	AWIRS,LIXHE220 RIMIE220,ROMSE,SERAI
District of Waremme	BE334	83752	TIHA1
District of Verviers	BE335	289639	BRUME
District of Arlon	BE341	64920	AUBAN220
District of Bastogne	BE342	50444	MARC+,SENO+,VILLE
District of Marche-en-Famenne	BE343	57527	ACHEN,MARC+,VILLE
District of Neufchâteau	BE344	65619	VILLE
District of Virton	BE345	55137	AUBAN220
District of Dinant	BE351	112927	ACHEN
District of Namur	BE352	322313	CHAMP
District of Philippeville	BE353	66719	GOUY

Table A.3: Power,node and share to CHP. Data taken from [27]

CHP Power Plant	**Power [MW]**	**Node**	**Share**
Syral Aalst	48	BRUEG	0.047
Beveren Ineos Phenol Chem	25	MERCA	
INESCO	138	MERCA	
Lillo Degussa	85	MERCA	
Oorderen Bayer	43	MERCA	
Monsanto Lillo WKK EBL	43	MERCA	
Scheldelaan Exxonmobil	140	MERCA	
Wilmarsdonk Total	129	MERCA	
Zwijndrecht Lanxess	58	MERCA	
Borealis Kallo	58	MERCA	0.667
Euro-Silo	12.9	RODE+	0.066
STORA LANGERBRUGGE	50	RODE+	
TAMINCO Gent	6.3	RODE+	
Greenpower Oostende	20	GEZEL	0.058
Fluxys LNG Zeebrugge	40	GEZEL	
IZEGEM	20	IZGEM	0.019
Jemeppe-sur-Sambre	106	STAM+	0.102
Sappi Lanaken	43	ZUTE+	0.041
Total	1065.2		

Appendix B

How to Use the soft-link

B.1 PreData

Firstly, a folder containing a series of data required by the soft-link but not dependent on EnergyScope results. This data is divided into 5 files (1 .csv and 4 txt). Each file is associated with an .xlsx file, allowing you to view the file more easily. This also makes it easier to modify, by simply modifying the .xlsx file and saving it in the required format (.txt or .csv).

- `BusesShare.txt` file contains the nodes of the Belgian high-voltage grid with data such as name, type of node (load/transfer), nominal voltage and geographical position (done by Auréli Hernandez) .This file also contains non-electric nodes that will be used in the hydrogen network. For each of these nodes (elec and hydrogen) there are associated shares that enable the different technologies to be distributed across the networks.The methodologies for establishing the electrical and hydrogen shares are described in the following sections 4 & 5 and shown in table B.1. **Please note that the distributions proposed here can be modified at the reader's convenience**.

Table B.1: All Share Names

SharePop	SharePV	ShareOnShore	ShareHydro
ShareDist_gen	ShareGeothermal	Share_Batt_Li_Large	Share_Batt_Li_Small
Share_Heat_Elec	Share_Indu_Heat_Elec	Share_HubELEC	Share_CCS_Industry
Share_Tram	ShareCar	ShareTruck	Share_TrainFreight
Share_TrainPass	H2Share_Electrolysis	H2ShareImport	H2ShareExportH2
H2ShareAMMONIA_TO_H2	H2ShareProduction	H2ShareCarFuelCell	H2ShareBusHybridH2
H2ShareFreight	H2ShareIndustrial	H2ShareH2toP	H2ShareStorage

- `H2Export.txt` contains the hydrogen network's connections with neighboring countries and capacities in terms of hydrogen of connections. Methodology available in section 5.1.3
- `H2Pipeline.txt` contains the interconnections and capacities between nodes of the hydrogen network. Methodology available in section 5.1.3.

- `ImportLines.txt` file contains the lines used to import electricity from abroad, as well as the characteristics of these lines. (done by Aurélia Hernandez)
- `EarlyDataLines.csv` file contains the connections between high-voltage network nodes, as well as various data such as line length, voltage and nominal current. It also contains geographical data and physical characteristics such as resistance, reactance and line capacitance. And statistical data such as MTTF and MTTR. (done by Aurélia Hernandez)

The `TDtoD.txt` file converts a time of year into a Typical Day and an hour associated with this typical day. This file is based on EnergyScope's `EST_12TD.dat` file. It must therefore be updated with the results of each EnergyScope run. To do this the file `TDtoD.txt` must be filled in manually by copying and pasting the 8760 lines after `set T_H_TD :=` from `EST_12TD.dat` file in the file `TDtoD.txt`. `EST_12TD.dat` is located in `"Path to EnergyScope file/case_studies/ref_run/"`

B.2 Data from EnergyScope

A series of files from EnergyScope are required for the Soft-Link to function properly. A part of these files are from EnegyScope's input data : `Resources.csv`, `Technologies.csv`, `Time_series.csv` and `Layers_in_out.csv`. These files are different depending on the scope year. The easiest way to use those files is to introduce directly the path to EnergyScope's data of the corresponding files in the Soft-Link and introducte the target `YEAR` as shown in the listing B.1.

```
Resources_df=pd.read_csv("Path to EnergyScope
   file/Data/YEAR/Resources.csv", delimiter=";")
Technologies_df=pd.read_csv("Path to EnergyScope
   file/Data/YEAR/Technologies.csv", delimiter=";")
Time_series_df=pd.read_csv("Path to EnergyScope
   file/Data/YEAR/Time_series.csv", delimiter=";")
layer_in_out_df=pd.read_csv("Path to EnergyScope
   file/Data/YEAR/Layers_in_out.csv", delimiter=";")
```

Listing B.1: Files from intput EnergyScope's data

On the other hand files are from EnergyScope's output data: `assest.txt`, `layer_ELECTRICITY.txt`, `year_balance.txt`, `resources_breakdown.txt`, `layer_H2.txt`, `cost_breakdown.txt`. The easiest way to introduce these files in the soft-link is described in listing B.2

```

assets_df=pd.read_csv("Path to EnergyScope
   file/case_studies/ref_run/output/assets.txt", delimiter="\t")
layer_ELEC=pd.read_csv("Path to EnergyScope
   file/case_studies/ref_run/output/hourly_data/layer_ELECTRICITY.txt",
   delimiter="\t")
```

```
year_balance_df=pd.read_csv("Path to EnergyScope file/case_studies/ref_run/output/year_balance.txt", delimiter="\t")
resources_breakdown_df=pd.read_csv("Path to EnergyScope file/case_studies/ref_run/output/resources_breakdown.txt", delimiter="\t")
layer_H2=pd.read_csv("Path to EnergyScope file/case_studies/ref_run/output/hourly_data/layer_H2.txt", delimiter="\t")
cost_breakdown_df=pd.read_csv("Path to EnergyScope file/case_studies/ref_run/output/cost_breakdown.txt",delimiter="\t")
```

Listing B.2: Files from output EnergyScope's data

B.3 Generated Files

The soft-link generates a file `my_data.xlsx` and a series of `.txt` files containing profiles of loads and time series,Profile_DEC_DIRECT_ELEC.txt, Profile_DEC_HP_ELEC.txt, Profile_DHN_HP_ELEC.txt, Profile_END_USE_ELEC.txt, Profile_HYDRO_RIVER.txt, ProfileBUS_COACH_FC_HYBRIDH2.txt (use H2ShareBusHybridH2), ProfileCAR_BEV.txt (use ShareCar), ProfileCAR_FUEL_CELL.txt (use H2ShareCarFuelCell), ProfileCAR_PHEV.txt (use ShareCar), ProfileTRAIN_PUB.txt (use Share_TrainPass), ProfileTRAM.txt (use Share_Tram). Time_series_Electricity.txt, Time_series_Space_Heating.txt, Time_series_Passanger_mobility.txt, Time_series_PV.txt, Time_series_Wind_onshore.txt, Time_series_Wind_offshore.txt, Time_series_Hydro_river.txt

B.4 SpreadSheets

Now the various spreadsheets in the `my_data.xlsx` file will be presented as follows:

- Related technologies
- Associated shares
- Values extracted from EnergyScope
- Any .txt file generated

Generale

VOLL [M€/GWh], Base Voltage of HV grid [kV]

Nodes

It includes data from `BusesShare.txt`

Lines

It includes data from `EarlyDataLines.csv`

Gen

Technologies: NUCLEAR, CCGT(_AMONIA), COAL_US/IGCC, IND_COGEN_GAS/WOOD/ELEC
Generator, Name, Node, Pmax_GW, Cost_maint_M€/GW/y, Cost_op_M€/GWhe, Type, MTTF, MTTR, LF

DistRES

Technologies: PV, WIND_ONSHORE, HYDRO_RIVER
Psolar_GW and use SharePV + `Time_series_PV.txt`
Onshore_GW and use ShareOnShore + `Time_series_Wind_onshore.txt`
PowerHydro_GW and use ShareHydro + `Time_series_Hydro_river.txt`

Dist_Gen

Technologies: DHN_COGEN_GAS/WOOD/WASTE/WET_BIOMASS/ BIO_HYDROLYSIS, DEC_COGEN_GAS/OIL, DEC_ADVCOGEN_GAS/H2, GEOTHERMAL
DHN & DEC :Type, Power (GW), Energy (yearly GWh), LF, Cost_maint_M€/GW/y, Cost_op_M€/GWhe and use ShareDist_gen.
Geothermal: Type, Power (GW), Energy (yearly GWh), LF, Cost_maint_M€/GW/y, Cost_op_M€/GWhe and use ShareGeothermal.

Res

Technology: WIND_OFFSHORE
RES, Node, Pmax_GW

Imp_Data (data of electrical import)

Imp_Emax_GWhe, Imp_Pmax_GWe, Price_Meuro/GWh

Imp_Line (data of electrical import lines)

Name, Node, Pmax_GW, Type, Inom, Unom, MTTF, MTTR, Country, Emax_TWh (done by Aurélia Hernandez)

Phs

Technology: PHS
PHS, Node, Pmax_GW, Emax_GWh (storage capacity), eff_pump, eff_turb

Batt

Technology: BATT_LI
Pmax_GW Large, Emax_GWh Large (storage capacity), eff_in/out and use Share_Batt_Li_Large
Pmax_GW Small, Emax_GWh Small (storage capacity), eff_in/out and use Share_Batt_Li_Small

CCS

Technologies: ATM_CCS, INDUSTRY_CCS
Pow_ATM_CCS (GW)+ Energy_ATM_CCS (GWh) and use Share_HubELEC
Pow_INDUSTRY_CCS (GW)+ Energy_INDUSTRY_CCS (GWh) and use Share_CCS_Industry

Freight

Technologies: TRAIN_FREIGHT, TRUCK_ELEC the profile is constant for each technology
Power Elec GW for TRUCK_ELEC and use ShareTruck
Power Elec GW for FREIGHT_ELEC and use Share_TrainFreight

IndustrialProcess_ELEC

Technologies: BIO_HYDROLYSIS, PYROLYSIS_TO_LFO, PYROLYSIS_TO_FUELS, SYN_METHANOLATION, METHANE_TO_METHANOL, BIOMASS_TO_METHANOL, HABER_BOSCH, OIL_TO_HVC, GAS_TO_HVC, BIOMASS_TO_HVC
Power_Process GW, Year_Power_Process GWh and use Share_HubELEC
Load_Process GW, Year_Load_Process GWh and use Share_HubELEC

Electrolyzer_ELEC

Technology:H2_ELECTROLYSIS
PowerElectrolyzer (GW), Yearly_EnergyElectrolyzer (GWh) and use H2Share_Electrolysis

IndustrialHeat

Technology: IND_DIRECT_ELEC
Power_IND_DIRECT_ELEC + Yearly_Energy_IND_DIRECT_ELEC and use Share_Indu_Heat_E

ResidentialHeat

Technologies: DEC_HP_ELEC, DHN_HP_ELEC, DEC_DIRECT_ELEC
Power (GW elec) for each technology. For each technology there is yearly consumption profile generated (`Profile_DEC_DIRECT_ELEC.txt`, `Profile_DEC_HP_ELEC.txt`, `Profile_DHN_HP_ELEC.txt`) and use Share_Heat_Elec

H2Import

Technologies: H2, H2RE
Values of import flux are constant : FluxImportH2, FluxImportH2RE, Cost_H2_Meuro/GWh, Cost_H2_RE_Meuro/GWh, Cost_H2_Mean_Meuro/GWh and use H2ShareImport.

H2Pipeline

It includes data from `H2Pipeline.txt`

H2Export

It includes data from `H2Export.txt`

H2Production

Technologies: H2_ELECTROLYSIS, SMR, H2_BIOMASS, AMONIATOH2
For each technology: MaxFluxH2 (GW), TotalH2 (GWh year), MTTF, MTTR and use H2ShareProduction

H2Freight

Technology: TRUCK_FUEL_CELL
Constant: FluxH2TRUCK_FUEL_CELL (GW) and use H2ShareFreight.

H2Industrial

Technologies: SYN_METHANATION, SYN_METHANOLATION, HABER_BOSCH
TechnologyH2, FluxH2 (GW_H2), TotalH2 (GWh_H2) and use H2ShareIndustrial

H2toP

Technology: DEC_ADVCOGEN_H2
FluxH2 (max GW H2), TotalH2 (GWh H2 year), eff, MTTF, MTTR and use H2ShareH2toP

H2Storage

H2_STORAGE_Pin (GW max), H2_STORAGE_Pout (GW max), EmaxStorageH2 (GWh) and use H2ShareStorage.

Appendix C

Modelized Grid

Table C.1: Nodes of the grid

Node	Name	Node	Name
1	ACHEN	26	MASSE
2	AUBAN220	27	MEERH
3	AUBAN380	28	MEKI+
4	AVLGM	29	MERCA
5	AWIRS	30	NEMO
6	BERN	31	RIMIE220
7	BRUEG	32	RIMIE380
8	BRUME	33	RODE+
9	BUGG+	34	ROMSE
10	CHAMP	35	SENO+
11	COO	36	SERAI
12	COURC	37	STAM+
13	DOEL	38	STEVN
14	EEKLN	39	TIHA1
15	GEZEL	40	VANYK
16	GOUY	41	VERBR
17	GRAMM	42	VILLE
18	HORTA	43	ZANDV
19	IZGEM	44	ZUTE+
20	JUPIL	45	ALBRT
21	LINT	46	ALVER
22	LIXHE220	47	ZELZA
23	LIXHE380	48	SGRAV
24	MAERL	49	EYNAT
25	MARC+	50	BLARE

Table C.2: Lines of the grid

Line	FromNode	ToNode	Line	FromNode	ToNode
1	ACHEN	GRAMM	41	GRAMM	ZUTE+
2	AUBAN380	BRUME	42	GRAMM	TIHA1
3	AVLGM	HORTA	43	GRAMM	TIHA1
4	AVLGM	HORTA	44	GRAMM	STAM+
5	AVLGM	IZGEM	45	GRAMM	TIHA1
6	AVLGM	IZGEM	46	GRAMM	TIHA1
7	BRUEG	MEKI+	47	GRAMM	RIMIE380
8	BRUEG	COURC	48	HORTA	MAERL
9	BRUEG	BUGG+	49	HORTA	MERCA
10	BRUEG	BUGG+	50	HORTA	RODE+
11	BRUME	GRAMM	51	LINT	MERCA
12	BRUME	GRAMM	52	LINT	MASSE
13	BRUME	COO	53	LINT	MERCA
14	BRUME	COO	54	LIXHE380	VANYK
15	BUGG+	MERCA	55	MASSE	MEERH
16	BUGG+	VERBR	56	MASSE	MERCA
17	BUGG+	MERCA	57	MEERH	VANYK
18	BUGG+	VERBR	58	MERCA	RODE+
19	CHAMP	GRAMM	59	VANYK	ZUTE+
20	CHAMP	COURC	60	AUBAN220	VILLE
21	COURC	STAM+	61	AWIRS	SERAI
22	COURC	MEKI+	62	AWIRS	RIMIE220
23	COURC	GOUY	63	JUPIL	RIMIE220
24	COURC	GOUY	64	SERAI	RIMIE220
25	DOEL	ZANDV	65	MARC+	RIMIE220
26	DOEL	ZANDV	66	MARC+	SENO+
27	DOEL	MERCA	67	RIMIE220	SERAI
28	DOEL	MERCA	68	ROMSE	SERAI
29	DOEL	MERCA	69	SENO+	VILLE
30	DOEL	MERCA	70	ROMSE	JUPIL
31	EEKLN	HORTA	71	JUPIL	BERN
32	EEKLN	MAERL	72	JUPIL	BERN
33	GEZEL	MAERL	73	BERN	LIXHE220
34	GEZEL	MAERL	74	AUBAN380	AUBAN220
35	GEZEL	MAERL	75	AUBAN380	AUBAN220
36	GEZEL	MAERL	76	LIXHE380	LIXHE220
37	GEZEL	STEVN	77	LIXHE380	LIXHE220
38	GEZEL	STEVN	78	RIMIE380	RIMIE220
39	GEZEL	NEMO	79	RIMIE380	RIMIE220
40	GRAMM	LIXHE380	80	RIMIE380	RIMIE220

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