"EnergyScope Multi-Cell : a novel open-source model for multi-regional energy systems and application to a 3-cell, low-carbon energy system"

Thiran, Paolo ; Hernandez, Aurélia

ABSTRACT

To fight global warming, the European Union has the ambition to tend towards zero carbon emission by 2050. The energy transition is essential to reach these objectives. For long-term planning, energy system models are necessary. This master's thesis develops a multi-regional energy model with a special focus on sector coupling, EnergyScope MC. It studies several types of energy demands - electricity, heat and mobility - and allows exchanges of different energy carriers - electricity, natural gas (NG), synthetic liquid fuel (SLF) and wood. Thanks to simple scenarios on three interconnected countries - France, Belgium and Switzerland- the consistency and reliability of the model are verified. Some general trends stand out from these analysis. The results demonstrate that inter-regional energy exchange will play a crucial role in the energy transition: exchanging several energy carriers reduces the cost of low-carbon energy systems by 21% compared to the scenario without exchanges. The main means of exchanges between countries are NG, SLF and electricity. The developed tool gives consistent results and this work is a first step for future projects. Eventually, EnergyScope MC could be used to model the European energy system.

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EnergyScope Multi-Cell : A novel open-source model for multi-regional energy systems

and application to a 3-cell, low-carbon energy system

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This master's thesis develops a multi-regional energy model with a special focus on sector coupling, EnergyScope MC. It studies several types of energy demands - electricity, heat and mobility - and allows exchanges of different energy carriers - electricity, natural gas (NG), synthetic liquid fuel (SLF) and wood.

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List of abbreviations

CAPEX Capital expenditure
OPEX Operation expenditure
CCGT combined cycle gas turbine
CHP combined heat and power
COP coeficient of performance
CSP concentrated solar power
DHN district heating network
EUD end-use demand
FEC final energy consumption
GHG greenhouse gas
GWh giga-watt-hour
GWP global warming potential
H2 hydrogen
HP heat pump
HT high temperature
HVDC high-voltage direct current
IRES intermittent renewable energy sources
LCOE levelised cost of energy
LFO liquid fuel oil
LHV lower heating value
LP linear programming
LT low temperature
MC multi-cell
NG natural gas
PHS pumped hydro storage
PV photovoltaic
RES renewable energy source
SLF synthetic liquid fuel
SNG synthetic natural gas
tc transfer capacity
TD typical day
TF transit factor
UF utilisation factor
WT wind turbine

Introduction

The European Union has set its objective of being carbon neutral by 2050, that is *an economy with net-zero greenhouse gas emissions*. This is the major objective of the European Green Deal and highly in accordance with its commitment to the Paris Agreement which aims to undertake global climate actions. According to the European Union, *all parts of society and economic sectors will play a role – from the power sector to industry, mobility, buildings, agriculture and forestry* . To establish a strategy of decarbonisation, large-scale multi-sector energy models are necessary.

To develop such a model, the following considerations have to be taken into account

- Each country has its own resources, weather and specific characteristics. To reach a low carbon and self-sufficient energy system in Europe at least cost, it is more interesting to work together and take advantage of this complementarity. This enhances the need for a model able to take into account not only one country on its own but several interconnected countries.
- Renewable energies will become the main producers in a low carbon energy system. At high penetration, their intermittency is a real technical and economical challenge. Taking advantage of the electrical interconnections between countries is seen as a one way to manage the integration of intermittent renewable energies [4, 10].
- Electricity only represents only 18.9 % of the energy carriers. For instance, currently, a large gas network can transport significant amounts of energy and is expected to take part in the energy transition [12]. Moreover, other energy carriers such as synthetic fuels are emerging and could play an important role.

Several energy models already exist in the literature and are compared in [26]. Each model has its specificity in accordance with its objectives. In this master thesis, we have chosen to work with EnergyScope TD [32, 26] for the following features:

- Multi-sector : the sectors of electricity, heat and mobility are studied with the same level of detail and cross-sectoral interactions can occur between them,
- Optimisation of the investment and operation costs,
- Hourly resolution,
- Reasonable computational time for uncertainty analysis,
- Open source in contrast to the energy models that are commercial. It is important to improve transparency in this context.

From this regional energy model, our work is to develop a multi-regional extension and allow exchanges of multiple energy carriers between the regions.

Hence, EnergyScope multi-cell (MC)[1], a multi-regional and multi-sectoral energy model is developed in this work based on the existing model of EnergyScope TD [27]. Such a model responds to the needs mentioned above for studying the energy transition at a European-scale.

> This master thesis is structured as follows :
>
> – Section 1 offers a brief explanation of EnergyScope TD and develops the methodology of the multi-regional extension, EnergyScope MC.
>
> Thereafter, the methodology is applied on a 3-cell system consisting of France, Belgium and Switzerland :
>
> – In Section 2, the case study of the 3-cell low-carbon system is described.
>
> – Section 3 illustrates the verification and analysis the 3-cell scenario with electricity exchanges.
>
> – In Section 4, a deeper study on the 3-cell scenario with all exchanges is conducted. In this scenario, the three countries are able to exchange different energy carriers.
>
> – Finally, the methodology and results are discussed in Section 5.

Thorough the whole work, we will use the following conventions :

> The paragraphs to inform the reader of what will be explained next are indicated with a grey left vertical bar.

All the conclusion paragraphs are written in boxes.

[1] This version can be found on `https://github.com/pathiran22/EnergyScope/tree/Multi_cell_2020`

Chapter 1

Model description

> In this chapter, the methodology to build a multi-regional model is detailed. Our work consists of the extension of an existing energy model : EnergyScope TD [27]. Firstly, the context in which our thesis takes place is exposed. Secondly, the existing model will be explained. Thirdly, its adaptation to a multi-regional model will be developed.

The details on the sets, parameters and variables of the mathematical model can be found in Appendix A.

1.1 Context, motivation and objective

EnergyScope is an open source energy system model that optimises the investment and operation costs of a defined area. This energy model is based on linear programming (LP). Usually applied to a region, typically a country, its main objective is to help in the decision making of energy system strategies.

It takes as inputs for the concerned area :

- The resources with their characteristics : costs, emissions, availability, etc.
- The end-use demand (EUD) of the different sectors : electricity, heat and mobility.
- A set of the existing conversion technologies with their characteristics : investment costs, operation and maintenance (O&M) costs, emissions, capacity limit, etc.

To study the energy transition, the model is used optimising the total annualised cost (investment, maintenance and operation) while setting a constraint on the greenhouse gas (GHG) emissions.

Two main versions already exist : EnergyScope Monthly and EnergyScope typical day (TD). Those two are regional models, that is, the optimisation takes into consideration one region and considers its surroundings as an external whole.

These versions allow exchanges - import or export - of electricity with the outside of the system at a fixed price. The price of this imported electricity is difficult to define because the price of electricity in one region depends on other regions that are also part of their electricity market. It is also quite volatile.

In the existing versions of the model, the exchanges of electricity are constrained by a maximum capacity but they do not take into account the fact that some other country should be able to produce/absorb this electricity.

The aim of this work is to develop a new multi-regional version taking into account multiple interconnected regions with different characteristics. The particularity and evolution between the Monthly, TD and multi-cell (MC) versions of EnergyScope are summarised in Table 1.1. They will then be presented in more details to lay out clearly the context in which this thesis arises.

Model	**EnergyScope Monthly**	**EnergyScope TD**	**EnergyScope MC**
Multi-Sector	✓	✓	✓
Total Cost Optimisation	✓	✓	✓
Multi-regional	✗	✗	✓
Time step	1 month	1 hour	1 hour
Motivation	Strategic planning of energy systems	Integration of intermittent renewable energy sources (IRES) and storage technologies	Exchanges of energy carriers in multi-regional systems

Table 1.1: Particularity and evolution between the different versions of EnergyScope.

The origin of EnergyScope takes place in the public debate in 2017 in Switzerland over the future energy system. After this, a first version of EnergyScope that optimises the energy system is born and has a monthly resolution to allow strategic planning studies on multi-energy systems at a regional scale [32].

With the energy transition, countries are heading towards a more sustainable and fossil-free energy system. Renewable energy, such as photovoltaic (PV) panels and wind turbines, has become a major topic of interest this last decade. Their integration is challenging as they are intermittent. The stochasticity of the renewable energy sources leads to a structural change of the energy system : more storage capacity is needed and electrification of the heat and the mobility will become a necessity [26]. This need of flexibility leads to a new version with hourly resolution, EnergyScope TD [26]. It allows to manage the constraints brought by intermittent energies and study more precisely the storage assets [28, 25].

The Figure 1.1 represents the structure of EnergyScope TD. The model has three different parts : the input data, the selection of the TDs (Step 1) and the energy system optimisation (Step 2).

- The **Input Data** consists of time series, parameters defining the scenario and characteristics of the technologies.

  Firstly, the time series of the energy demand and the weather conditions represent the hourly demand of the different sectors (electricity, heat and mobility) and the hourly potential production of the renewable energy technologies (PV, onshore and offshore wind turbines, hydro dams, hydro run-of-the-river, thermal solar panels and concentrated solar power (CSP)).

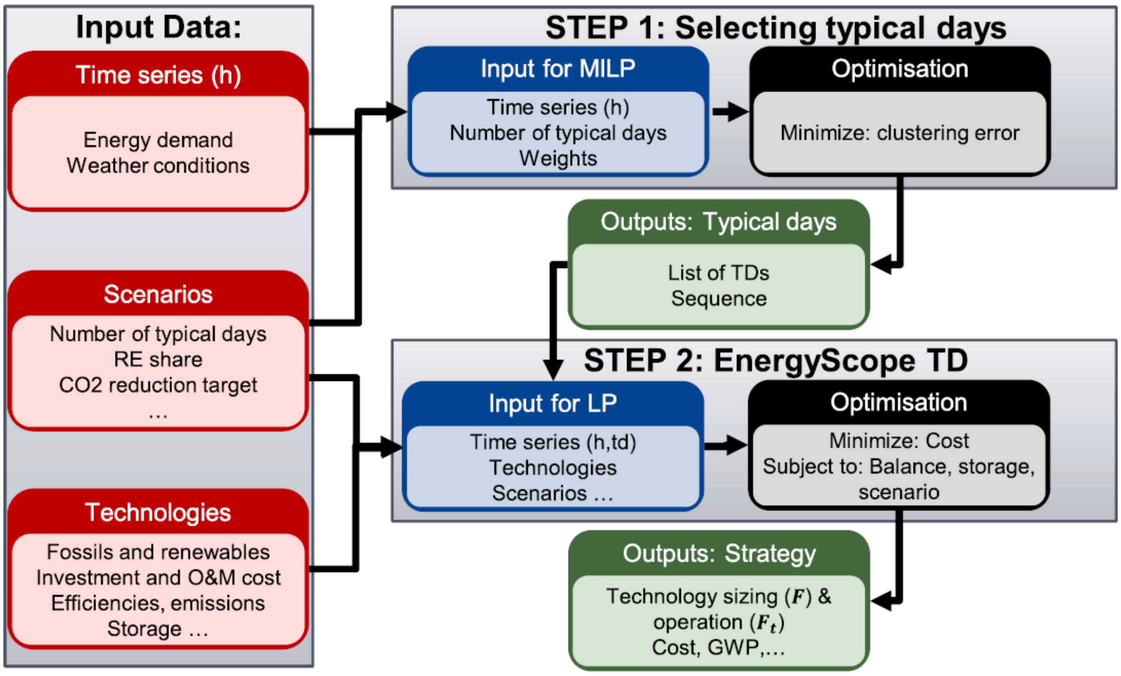

Figure 1.1: Structure of EnergyScope typical days (TD) [28]. (abbrev. : renewable energy (RE), operation and maintenance (O&M), mixed integer linear programming (MILP), linear programming (LP), global warming potential (GWP))

Secondly, the scenario in which the optimisation takes place is defined by the renewable share[1], the emission limit, the number of TD, etc.

Thirdly the existing technologies are given with their investment cost, O&M (operation and maintenance) cost, their respective emissions of construction, efficiencies, etc.

- **Step 1: The selection of the typical day (TD)**. To reduce the computational cost of the optimisation, 12 days[2] that represent well the profiles of the different days of the year are selected and are called the typical days (TDs) [19, 26]. This is realised by clustering the 365 days of the year in 12 clusters and defining for each of them a representative day. The output of this step will be the selection of the typical days, as well as their attribution to each day of the year.

- **Step 2: EnergyScope TD** From the input data and the list of TD, the total cost of the energy system is minimised while respecting the different energy balances and the scenario constraints.

  The output of this step delivers the optimised system with the sizing of the different technologies ($\mathbf{F}$) and their hourly operation ($\mathbf{F_t}$), the costs, the CO2 emissions, etc.

[1]the percentage of renewable energy produced out of the total energy produced by the system

[2]It has been demonstrated that the choice of twelve typical days is an good compromise in terms of precision and computational time in [26]. The number of typical days is thus set to 12 by default but remains the user's choice.

Figure 1.2 illustrates the objective of this thesis : model a large-scale and multi-regional interconnected energy system with a focus on sector coupling.

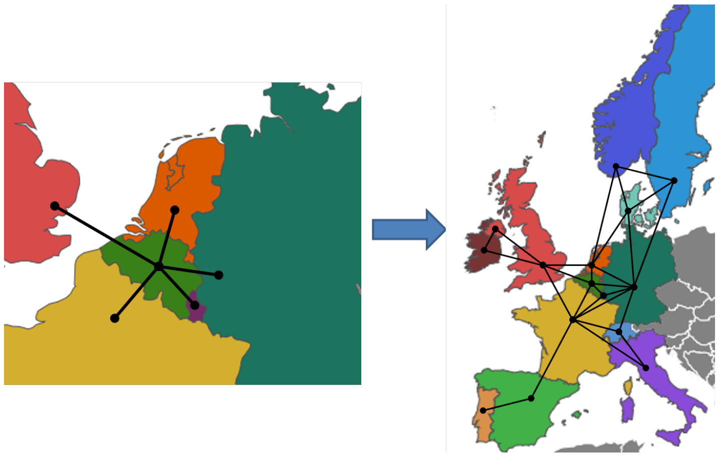

Figure 1.2: From a regional to a multi-region model.

> The new model will be developed in several steps.
> Firstly, the adaptation of the TD clustering method to a multi-regional system will be presented.
> Secondly, the resources exchange methodology in the multi-regional model, allowing exchanges of any type of energy carrier will be explained.

1.2 Step 1: Selection of the typical days

The choice of the typical days depends on the demand and the weather conditions. One has to take into account the fact that the regions do not have the same weather conditions neither the same demand. The data of the demand and weather conditions are summarised in time series which give their value for each hour of the year.

A time series consists of 8760 elements (number of hours in a year), describing for each hour of the year, either the demand or the relative output power of the renewable energy source (RES) technologies that are influenced by weather conditions. In Figure 1.3, we see that a part of the demand - lighting & co[3], space heating (heat low T - SH), passenger and freight mobility (mob. pass./freight) - has a different behaviour every hour of the year and requires a time series. But, the other part of the demand - electricity (elec), high temperature heat for industries (heat high T ind.), domestic hot water (heat low T - HW), and non-energy-use[4] products - is defined as constant every hour of the year and thus does not require time series. The intermittent technologies, that depend on weather conditions - PV, onshore and offshore windmills , hydraulic dams, run-of-the-river hydro power (hydro river), thermal solar panels (solar) and CSP (solar) - do not provide the same quantity of energy every hour, they also require time series to describe the output power provided at each hour of the year per unit of installed power. Usually time series are based on the real data of a previous year.

[3]lighting & co category includes also other variable electricity demands

[4]The non-energy end-use demand represents the use of fuels (oil or NG) into the industry to make non-energetic products such as plastics.

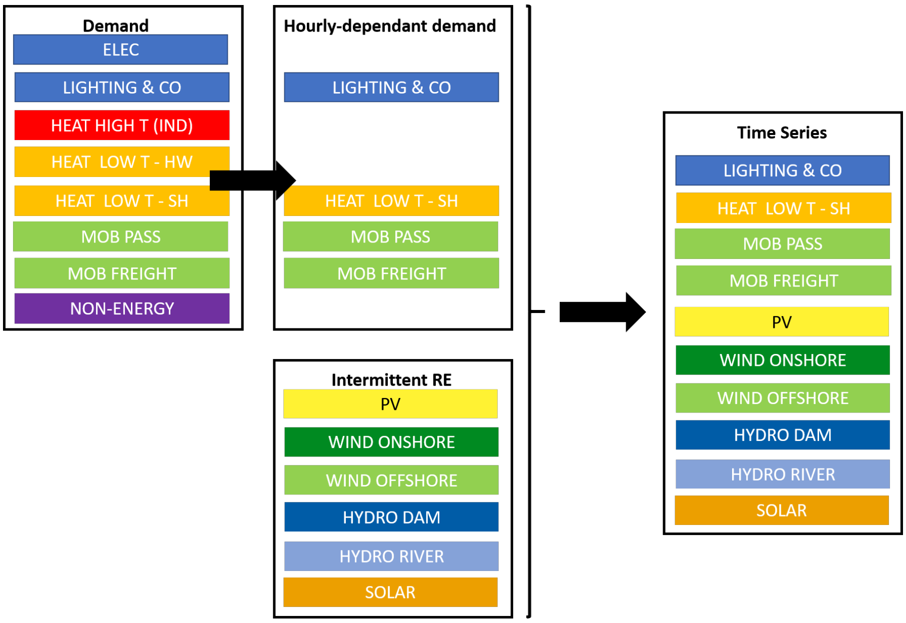

Figure 1.3: Existing time series in EnergyScope TD.

1.2.1 Clustering method of typical days

In the article of G. Limpens over EnergyScope TD [26], the reason for the use of typical day is explained as follows : *Due to computational restrictions, energy system models rarely optimise the 8760 h of the year. As an example, running our model with 8760 h time series takes more than 19 h. A typical solution in this case is to use a subset of representative days called TDs; this is a trade-off between introducing an approximation error in the representation of the energy system (especially for short-term dynamics) and computational time. Resorting to TDs has the main advantage of reducing the computational time by several orders of magnitude.*

The clustering method in EnergyScope TD uses a k-medoid algorithm. It is a partitional algorithm that defines clusters of points and their centroids in such a way that the euclidean distance between each point of a cluster and its centroid is minimal.

In this context, the centroids of each cluster represent the typical days. To compute the distance between two days of the year, a metric is necessary. The metric chosen to define a certain day of the year is the weighted sum of the normalised time series of that day, that is

$$\sum_{h=1}^{24}\sum_{j=1}^{n}\omega(j)ts(d,h,j)$$

where h represents the hours of the day, ts the value of the j-th time series at hour h on day d, and $\omega(j)$ the weight of the j-th time series. Each time series has a defined weight in order to be able to give more importance to certain time series and less importance to others.

In a multi-regional model, the metric used to define a certain day of the year is adapted. It will be the weighted sum of each time series in each region, that is

$$\sum_{c=1}^{m}\sum_{h=1}^{24}\sum_{j=1}^{n}\omega(j)ts(c,d,h,j)$$

A more detailed explanation of the TD clustering procedure can be found in Appendix A.1.

1.3 Step 2 : Energy model

> The next step is to build a system made of multiple regions and to permit the exchanges of different resources between them. In a first instance, the structure of the existing model of EnergyScope TD will be presented. Then the structure of EnergyScope MC, our new multi-regional model will be developed.

The lists of sets, parameter and variables with their units and description can be found in Appendix A.2.1

1.3.1 EnergyScope TD model

EnergyScope TD uses a linear programming (LP) to find a solution. The mathematical model consists of linear constraints (equalities = or inequalities $\geq, \leq$) and a linear objective function.

The parameters defining the resources, the technologies and the demand represent the inputs of the mathematical model.

The optimal solution defines the amount of resources used, the installed capacity of each technology, their operation at each time step, and the total cost of the system (Capital expenditure (CAPEX)+Operation expenditure (OPEX)).

For the sake of clarity, in this section, the concept of 'cell' represents a region. Figure 1.4 illustrates the structure of a cell. It consists of three main parts : the available resources, the energy conversion system and the demands.

The energy conversion system is defined by the installed capacity and operation of the different technologies.

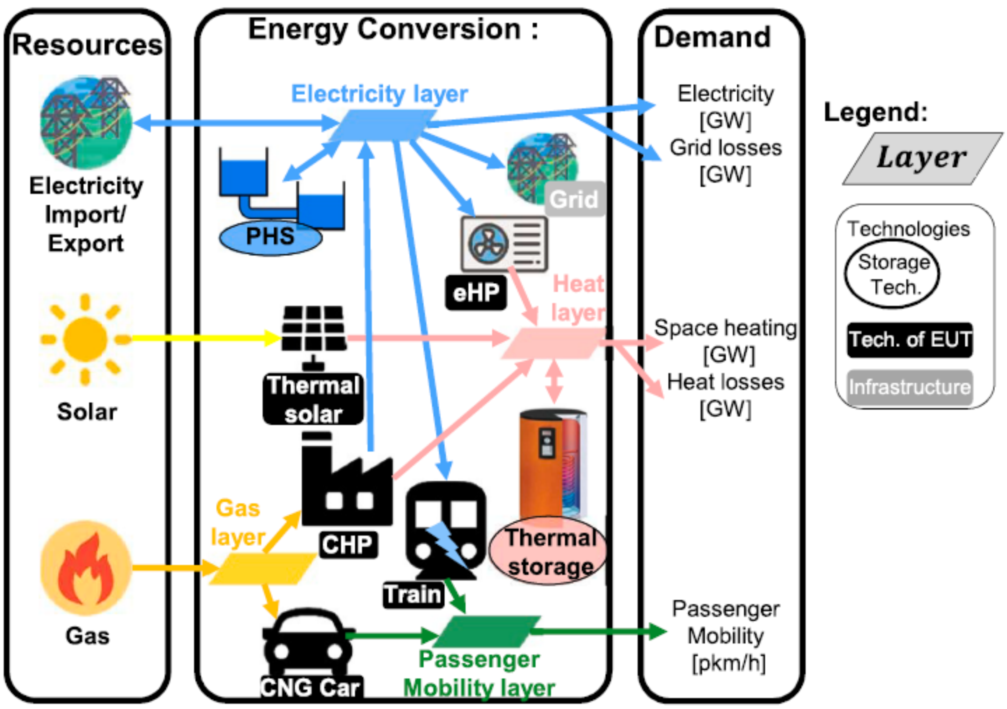

Figure 1.4: Representation of a cell [26].

EnergyScope has its own specific definition of resource. The set RESOURCES in the model regroups the primary energies (wood, waste, fossil NG, wind, solar, hydro, etc.) and the secondary energies (H2, electricity, synthetic NG, etc.). The difference between these two will be their availability. A primary energy has a certain availability, depending on the quantity that can be extracted as a secondary energy has an availability equal to zero as they are not found in nature and have to be produced through a technology to be used afterwards.

Before defining a technology, the concept of layer has to be introduced. A layer is either a resource (e.g. Natural gas layer) or an end-use demand (EUD) (e.g. low temperature heat layer) and has to be balanced at all time. It allows to respect the energy balance at each time step. This energy balance appears as an equation that constraints every layer, see Eq. 1.1.

$$
\begin{aligned}
&\sum_{i \in RES \cup TECH \setminus STO} f(i,l)\mathbf{F_t}(i,h,td) \\
&+ \sum_{j \in STO} (\mathbf{Sto_{out}}(j,l,h,td) - \mathbf{Sto_{in}}(j,l,h,td)) = \mathbf{EndUses}(l,h,td) \\
&\forall\ l \in L,\ h \in H,\ td \in TD
\end{aligned}
\tag{1.1}
$$

The variables, parameters and sets present in this equations are detailed below :

- f(i,l) : defines for all resources and technologies i, the output (positive) or input (negative) of this latter on the layer l.
- $\mathbf{F_t}$(i,h,td) represents for a resource i the quantity used at the hour h of typical td and represents for a technology i the quantity produced at the hour h and typical day td.
- $\mathbf{Sto_{out}}$(j, l, h, td) : output energy of the storage j entering layer l at hour h during typical td.
- $\mathbf{Sto_{in}}$(j, l, h, td) : input energy of storage j leaving layer l at hour h during typical day td.
- **EndUses**(l,h,td) : for the layer balance of an end-use demand, it defines value of the end-use demand required. For the leayer balance of a resource, this variable equals zero.
- RES : set of all the different resources in the model.
- STO : set of all the different storage technologies in the model.
- $TECH$: set of all the different end-use types technologies in the model.
- L : set of all the different layers in the model.
- H : set of all the hours of a day
- TD : set of all the typical days.

From this definition of a layer, a technology can be defined as a link between two layers. For example the combined cycle gas turbine (CCGT) technology links the natural gas layer and the electricity layer as it produces electricity on the electricity layer with natural gas taken from the gas layer. In the case of a storage technology, its inputs and output are linked to the same layer.

More explanations about resources, conversion technologies and EUD in EnergyScope can be found in the Appendix A.2.2.

The objective function is the minimum of the annualised total cost of the system ($\mathbf{C_{tot}}$) and is defined in Eq. 1.2. The variables used in this equation are defined as linear constraints in Eq. 1.3 to 1.6. Other constraints complete the mathematical formulation such as maximum and minimum size of technologies and resources availability. They are detailed in [26, 27].

$$\min \ \mathbf{C_{tot}} = \sum_{j \in TECH} \Big(\tau(j) \mathbf{C_{inv}}(j) + \mathbf{C_{maint}}(j) \Big) + \sum_{i \in RES} \mathbf{C_{op}}(i) \tag{1.2}$$

$$\text{s.t. } \tau(j) = \frac{i_{rate}(i_{rate}+1)^{lifetime(j)}}{(i_{rate}+1)^{lifetime(j)} - 1} \quad \forall j \in TECH \tag{1.3}$$

$$\mathbf{C_{inv}}(j) = c_{inv}(j) \mathbf{F}(j) \quad \forall j \in TECH \tag{1.4}$$

$$\mathbf{C_{maint}}(j) = c_{maint}(j) \mathbf{F}(j) \quad \forall j \in TECH \tag{1.5}$$

$$\mathbf{C_{op}}(i) = \sum_{t \in T | \{h,td\} \in T\_H\_TD(t)} c_{op}(i) \mathbf{F_t}(i,h,td) t_{op}(h,td) \quad \forall i \in RES \tag{1.6}$$

The variables, parameters and sets present in this equations are detailed below :

- $\mathbf{C_{tot}}$: total annual cost of the energy system [M€/year]
- τ(j) : investment cost annualization factor of technology j
- i_{rate} : interest rate
- *lifetime* : Technology lifetime [y]
- $\mathbf{C_{inv}}$(j) : Technology total investment cost [M€/year]
- $\mathbf{C_{maint}}$(j) : Technology yearly maintenance cost [M€/year]
- $\mathbf{C_{op}}$(i) : Total cost of resources [M€/year]
- $c_{inv}(j)$: Technology specific investment cost [M€/GW]
- $c_{maint}(j)$: Technology specific yearly maintenance cost [M€/GW/y]
- $c_{op}(j)$: Specific cost of resource [M€/GWh]
- $\mathbf{F}$(j) : Installed capacity with respect to main output [GW]
- $\mathbf{F_t}$(i,h,td) represents for a resource i the quantity used at the hour h of typical td and represents for a technology i the quantity produced at the hour h and typical day td.
- *TECH* : set of all the different end-use types technologies in the model.
- T : set of all the periods of the year (8760 hours)
- *T_H_TD*(t) : set of typical day of periods t.

1.3.2 Adaptation for the multi-regional version

EnergyScope MC is build as a global system composed of several cells which can interact with each other (black arrows in left part of Figure 1.5). A generic model allowing any resource exchanges has been developed. Each cell within the global system has the same structure as a single cell system (right part of Figure 1.5). However, in the MC version, the resource layers of the cells are connected to one another and can interact. Hence the MC extension adds the dimension 'cell' to the system.

Previously, in the EnergyScope TD model, the variable $\mathbf{F_t}$ was defined for a resource and for a technology. $\mathbf{F_t}$ of a resource was the quantity used at time step in [GWh], and $\mathbf{F_t}$ for a technology was the output of this latter at each time step in [GW]. In this MC version, as cells exchange resources, a special attention shall be given to the resources to clarify their origin. Indeed, a resource can be "extracted from the cell's soil", can be the output of an infrastructure technology, imported from another cell of the system or imported from the exterior of the system. In order to clarify these sources, the variable $\mathbf{F_t}$ will be left to the technologies output and new variables for resources will emerge :

- $\mathbf{R_{t,local}}$(c,r,h,td) : resource r extracted locally in the cell c, used at time step (h, td) [GWh]
- $\mathbf{R_{t,exterior}}$(c,r,h,td) : resource r imported by cell c from outside of the global system, used at time step (h, td) [GWh]
- $\mathbf{R_{t,import}}$(c,r,h,td) : resource r imported by cell c from the other cells of the system, at time step (h, td) [GWh]
- $\mathbf{R_{t,export}}$(c,r,h,td) : resources r exported from cell c to the other cells of the system, at time step (h, td) [GWh].

In order to find the net consumption of a resource of a cell, one must compute :

$$\mathbf{R_{t,local}} + \mathbf{R_{t,exterior}} + \mathbf{R_{t,import}} - (1 + exchanges\_losses) * \mathbf{R_{t,export}}$$

where the parameter $exchanges\_losses$ represents the share of losses [%] during the exchange. Thus in the layer balance equation, $\mathbf{F_t}$ is only summed up for technologies (and not on the resources anymore) and the new variables are added in the layer equation as follow :

$$\begin{aligned}
&\sum_{r \in RES} \Big(f(r,l) \Big(\mathbf{R_{t,local}}(c,r,h,td) + \mathbf{R_{t,exterior}}(c,r,h,td) \\
&- (1 + exchanges_losses(r)) \mathbf{R_{t,export}}(c,r,h,td) + \mathbf{R_{t,import}}(c,r,h,td) \Big) \Big) \\
&+ \sum_{i \in TECH \setminus STO} f(i,l) \mathbf{F_t}(c,i,h,td) + \sum_{j \in STO} \Big(\mathbf{Sto_{out}}(c,j,l,h,td) - \mathbf{Sto_{in}}(c,j,l,h,td) \Big) \\
&= \mathbf{EndUses}(c,l,h,td) \\
&\forall\ c \in COUNTRIES,\ l \in L,\ h \in H,\ td \in TD
\end{aligned} \tag{1.7}$$

The choice of the exchangeable resources is given to the user. A new set $NOEXCHANGE$ has been added to the model and groups the resources that are not allowed to be exchanged.

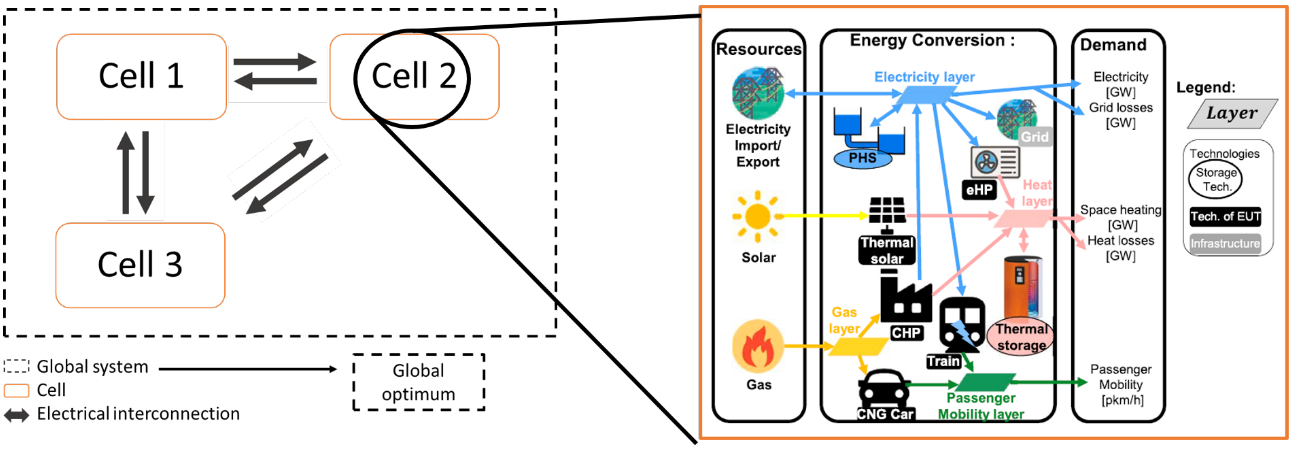

Figure 1.5: Structure of the multi-cell model (left) and zoom on a cell (right).

In this global system, the resources exchanged every hour between countries (black arrows in Figure 1.5) are added to the mathematical model as a variable. The system optimises their value at each hour in order to minimise the global annualised cost of the system. For a global system composed of n cells, the variable will be defined as:

$$\begin{aligned}&\mathbf{Exchanges}(c_1, c_2, r, h, td)\\&\forall\ c_1, c_2 \in \mathit{COUNTRIES},\ r \in \mathit{RES},\ h \in H,\ td \in TD\end{aligned} \tag{1.8}$$

The variable **Exchanges** describes the quantity of the exchanged resource between two cells at each time step, that is for every hour of each typical day. One should read $\mathbf{Exchanges}(c_1, c_2, r, h, td)$ as the quantity of resource r imported by cell c_1 from cell c_2, at hour h of typical day td.

Some constraints on the variable **Exchanges** need to be added to the model :

1. The reciprocity of exchange : if cell A is importing from cell B, then cell B is exporting to cell A:
$$\begin{aligned}&\mathbf{Exchanges}(c_1, c_2, r, h, td) = -\mathbf{Exchanges}(c_2, c_1, r, h, td)\\&\forall\ c_1, c_2 \in \mathit{COUNTRIES}, r \in \mathit{RES}, h \in H, td \in TD\end{aligned} \tag{1.9}$$
2. A country does not exchange with itself:
$$\begin{aligned}&\mathbf{Exchanges}(c_1, c_1, r, h, td) = 0\\&\forall\ c_1 \in \mathit{COUNTRIES}, r \in \mathit{RES}, h \in H, td \in TD\end{aligned} \tag{1.10}$$
3. Link between variable **Exchanges** and the existing mathematical model
$$\begin{aligned}&\sum_{c_2 \in \mathit{COUNTRIES}} \mathbf{Exchanges}(c_1, c_2, i, h, td)\\&= \mathbf{R_{t,import}}(c_1, i, h, td) - \mathbf{R_{t,export}}(c_1, i, h, td)\\&\forall\ c_1, c_2 \in \mathit{COUNTRIES}, i \in \mathit{RES}, h \in H, td \in TD\end{aligned} \tag{1.11}$$
4. The non-exchangeable resources defined in the set *NOEXCHANGE* will have their exchange variable forced to zero.
$$\begin{aligned}&\mathbf{Exchanges}(c_1, c_2, i, h, td) = 0\\&\forall c_1, c_2 \in \mathit{COUNTRIES}, i \in \mathit{NOEXCHANGE}, h \in H, td \in TD\end{aligned} \tag{1.12}$$

Remark:

- The Eq. 1.11 links the new **Exchanges** variable with the importation and exportation variables, $\mathbf{R_{t,import}}$(c_1,r,h,td) and $\mathbf{R_{t,export}}$(c_1,r,h,td), of each country at every hour of each TD. Those two variables are defined positive in the model, while the variable **Exchanges** is not. Thus if the total exchange of a country at a certain hour is positive, it will be allocated to the importation. On the contrary, if the total exchange of a country at a certain hour is negative, it will be assigned to the exportation. Those two variables are then taken into account into the electricity layer balance presented previously (Eq. 1.7). This is why Eq. 1.11 allows to link the new variables and parameter with the already existing model.

In a first time, to model the losses of exchange, each exchange was supposed to have fixed losses computed as a certain percentage of the exchanged energy (parameter *exchange_losses*). For instance, if a country A wants to import 1 GWh of wood from a country B, the latter needs to send 1GWh plus the losses. This formulation lacks of precision. An analysis using this method has been done on a 3-cell case in Appendix E.1. This method does not take into account the fact that the main mean of exchange is for some resources a network (e.g. electricity and NG) and for others freight (e.g. SLF, wood and waste). Also, losses are of different nature and amount according to the energy carrier and the means of exchange. For exchanges using freight, the losses represent the energetic cost of transporting the energy carrier by freight from one country to the other. For exchanges using a network, it depends more on the energy carrier. For electricity, losses contains the classical grid losses which are mainly due to joule effect. For NG network, losses represent the need for re-compression stations in order to keep the pressure of the NG in the proper range. For NG networks, most of the re-compression is done with NG.

> As mentioned above, a resource can be exchanged in two ways: through a network or with freight. The implementation of the limitations and the energy cost of these exchanges differ and will be detailed in the two following sections.

Resources exchanged through networks

The resources exchanged through networks are defined by the set *NETWORK_R*. They are limited by the size of the installed interconnections. The parameter transfer capacity ($tc(c_1,c_2,r)$) contains all the installed cross-border capacities between the different cells. This parameter is used to define an additional constraint limiting the maximum exchange these resources :

$$\begin{gathered} -\, tc(c_2, c_1, r) \leq \mathbf{Exchanges}(c_1, c_2, r, h, td) \leq tc(c_1, c_2, r) \\ \forall c_1, c_2 \in COUNTRIES, r \in NETWORK\_R, h \in H, td \in TD \end{gathered} \tag{1.13}$$

One has to notice that sometimes, the transfer capacity (tc) of some interconnections are not identical depending on the direction of the flow, that is:

$$\mathrm{tc}(c_1, c_2, r) \neq \mathrm{tc}(c_2, c_1, r)$$

This occurs with the electrical transmission lines and the natural gas pipelines for example. The reason of the asymmetry is different in both cases. In the context of the electricity transmission lines, this asymmetry may be due to different causes :

- the capacity and limitations of the local grid of each cell,
- the type of transmission lines: if the transmission lines are high-voltage direct current (HVDC) lines, the needed electronic converters at each end of the transmission line are sometimes designed to favour one direction more than the other. In this case, the capacity limit in the two opposite directions is not identical.

In the context of gas pipelines, the asymmetries are due to the existence of preferred directions.

Concerning the losses that occur during the transport of these resources, a certain amount of the exchanged resource is lost. This loss will be characterised by the parameter *exchange_losses*. This parameter will be applied on the exported quantity : to export a certain quantity, the exporter will have to give ($1 + exchange\_losses$) times the desired quantity so that the right quantity arrives to destination (see Eq. 1.7). This parameter is set to zero by default and the user has to define a certain value for each of the resource exchanged through a network.

Resources exchanged with freight

The resources exchanged through freight are defined by the set *FREIGHT_R*. All of them are liquid or solid fuels having a high energy density. A new variable representing the additional freight due to the exchanges of energy carriers to the model is introduced :

$$\mathbf{Exch\_Freight}(c)$$

This variable is computed over the whole year for each country and is added to the end-use demand (EUD) of freight. Knowing the lower heating value (LHV) [GWh/Mt] of a resource, it is possible to convert the quantity of energy exchanged over the whole year from giga-watt-hour (GWh) to Mt. Then by multiplying it by the distance [km] it has to cover, the additional freight demand generated is obtained (see Eq. 1.14).

$$\mathbf{Exch\_Freight}(c) = \sum_{r \in FREIGHT\_R, t \in T | [t,td] \in T\_H\_TD(t)} \left(\frac{\mathbf{R_{t,import}}(c,r,h,td) + \mathbf{R_{t,export}}(c,r,h,td)}{lhv(r)} \right) * dist(c) \quad (1.14)$$
$$\forall c \in COUNTRIES$$

This formulation introduces two additional parameters into the model:

- The new parameter *dist*(c) is the typical distance that the imported and exported energy carriers travel into each country c [km]. Hence, each country gets additional freight for each imported and exported resource. This means that both countries exchanging a resource contribute to the freight. In the model, the exporter covers the freight of the energy up to the border, and the importer from the border to inside of its country. The choice for the value of this parameter is given to the user. By default, it is set to the half of the distance between the two furthest big cities of each country.
- The new parameter *lhv*(r) defines for each resource r of the set *FREIGHT_R* its lower heating value (LHV) [GWh/Mt]. However, an exception occurs for resources that are not expressed GWh units, such as *CO2_CAPTURED* in [t_{CO_2}]. In this case, the parameter *lhv* is a conversion parameter from [t_{CO_2}] to [Mt_{CO_2}].

In Eq. 1.14, the additional freight is computed as a yearly value for each cell. This additional freight is not added to the precise hour of the exchange. Indeed, the transport with freight is not immediate and can take several hours. As the resources exchanged by freight are all liquid or solid fuels, it is supposed that they are easily stored. Hence the transport can be done in advance. The additional freight will be uniformly dispatched over the whole year.

To add this in the LP model, we faced a problem of non-linearity. The method found to tackle this problem is explained in Appendix A.2.3.

Summary of the multi-cell modelling

In summary, the adaptation of the mathematical model of EnergyScope TD to a multi-cell (MC) model is done in several steps. Firstly by adding the set *COUNTRIES* to all the variables and parameters that are country-dependent. Secondly, by giving more precision on the utilisation of resources by adding the variables $\mathbf{R_{t,local}}$, $\mathbf{R_{t,exterior}}$, $\mathbf{R_{t,import}}$ and $\mathbf{R_{t,export}}$. Thirdly, by adding the variable **Exchanges**, and three constraints (Eq. 1.10, 1.9, 1.11) to the model. And finally, by modelling the different limitations and energetic costs with on one side the parameters *exchange_losses* and *ntc* for resources exchanged thanks to a network and through additional freight (**Exch_Freight**) for resources exchanged with freight.

Chapter 2

Definition of the 3-cell system : France, Belgium and Switzerland

A scientific method requires testing and validation a posteriori before ideas are accepted [29]. To demonstrates the accuracy and reliability of the methodology implemented, a validation through comparison to a known reference case is necessary. For our multi-cell model, we don't have such a reference. We thus have to proceed to a verification of the consistency of the model. This is achieved by verifying two results on a multi-cell (MC) simple case. Firstly, verifying the balance of exchanges. Secondly, analysing the system to find out if our intuitions are confirmed by the results.

A 3-cell interconnected model composed of France, Belgium and Switzerland has been chosen to carry out this task. We have chosen those countries for two reasons. The first one is the availability of the data from our colleagues [6, 25, 27]. Secondly, it is a very polarised situation. As it will be presented in this chapter, France has a very big energy demand and a lot of resources while Belgium and Switzerland have much smaller energy demands and less resources. This makes it easier to interpret and therefore to confirm the consistency of the results.

It is important to point out that our analysis does not permit nuclear energy use in any cells. This is quite a big hypothesis, especially for France where 71% of the electricity was produced by nuclear power in 2019 [9] and which plans to produce still 50% of its electricity in 2035 with nuclear power [34]. But the aim of this study is to consider a very low carbon system and its different solutions towards the intermittency of the renewable technologies. Letting the system use nuclear power would have been a more simple solution for the system as it would have provided a large base load of nuclear power. Moreover, when forbidding nuclear power, the low carbon system is constrained to head towards renewable energies.

> This chapter presents the data and the main hypothesis of this 3-cell model. The data for Switzerland is taken from [27, 32], for Belgium from [25] and for France from Jeroen Dommisse and Jean-Louis Tychon's master thesis [6]. It is important to notice that for the Switzerland case, some information was missing as it is not part of the European Union. Sometimes, extrapolation has been done (see Appendix B.1).
>
> Firstly, the end-use demand (EUD) of each cell is developed. Then, more details on the availability of the resources and the cost of technologies are given. Afterwards, the hypothesis made for exchanges modelling are explained. Finally, the scenarios studied are defined and the emission targets are set.

Throughout the presentation of the data, some intuitions about the system will be developed.

2.1 Energy demand

The energy demand can be expressed in different forms : in terms of final energy consumption (FEC) and in terms of end-use demand (EUD). On the one hand, the final energy consumption is the *total energy consumed by end users, such as households, industry and agriculture and is defined as the "energy which reaches the final consumer's door"* [20] and thus depends on the used technology. On the other hand, end-use demand (EUD) is the energy needed for a specific demand and excludes the choice of technology. In other words, in the context of the space heating of a building : the EUD represents the quantity of energy needed to heat the building up to a certain temperature and the FEC represents the quantity of energy needed by the technology to produce this heat. If the technology is efficient the FEC can be smaller than the EUD (using heat pump for example). In this model, the choice of using the EUD is made. It allows to seperate the demand from the supply and gives full freedom to the model in order to optimise the choice of technologies.

> This section presents the total EUD for each country and its variability over the year.

2.1.1 Yearly demand

Figure 2.1 shows the relative demand of each cell in each sector.

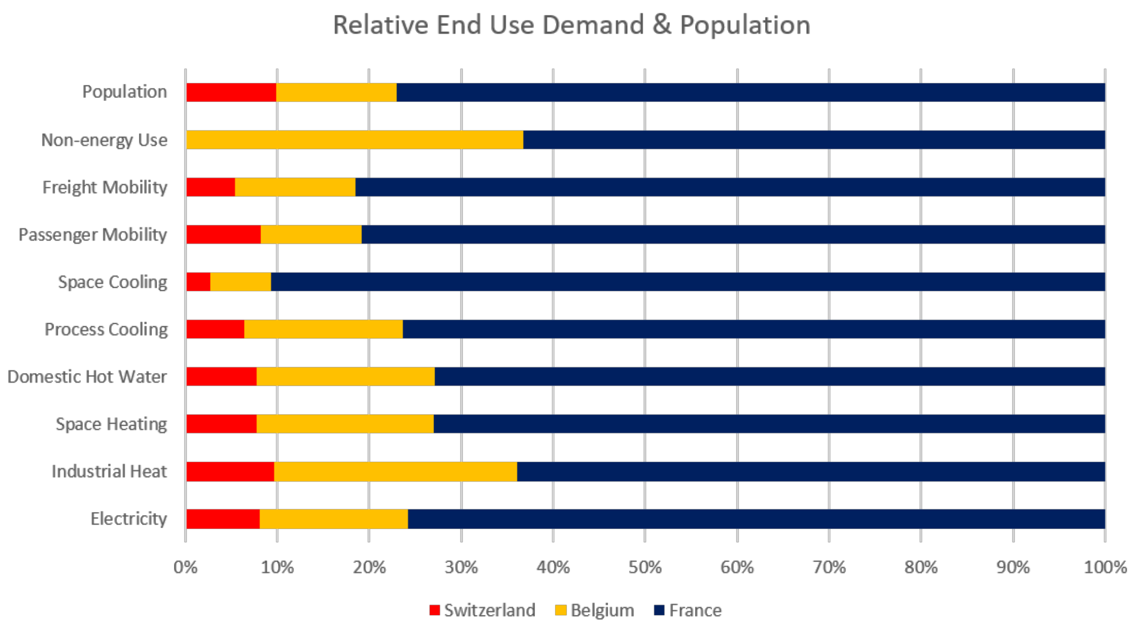

Figure 2.1: Relative share of the energy demand of the different cells.

It is clear that France is a big cell compared to Switzerland and Belgium. It's population is almost 8 times bigger than Switzerland, and almost 6 times bigger than Belgium. A good reference point is to keep in mind that Switzerland's population represents more or less 10% of the global population, Belgium 13% and France 77%. Thus, in the different sectors, it is logically observed that the demand mainly follows this allocation and that the major part is from France.

However, two sectors in particular do not reflect this expectation. These are the sectors linked to industrial activities. Firstly the non-energy use[1] sector: Belgium's demand in that

[1]The non-energy end-use demand represents the use of fuels (oil or NG) into the industry to make non-energetic products such as plastics.

sector is quite high. Indeed, almost 40% of the total non-energy use demand is consumed by Belgium. Secondly in the Industrial Heat sector, Belgium consumes approximately 25% of the demand. The high share of Belgium in these sectors is due to its high industrial activity.

The exact values of the total EUD for each country and for each end-use category can be found in Appendix B.2.

To conclude, the three systems have different sizes. One the one hand France's demand is about 4 times Belgium's demand. On the other hand, Belgium's demand is around 2-3 times the one of Switzerland. However, it depends a lot on the type of EUD. For instance, Belgium is a very industrialised country and has large industrial demands (industrial heat, freight and non-energy).

2.1.2 Variability of the energy demand

The demand presented here above can be variable from one hour to another. The yearly demand is distributed over the year thanks to the time series, explained in section 1.2. As explained in section 1.2 and shown in Figure 1.3, a part of the electrical demand, space heating, space cooling, passenger mobility and freight mobility[2] are likely to be hourly dependant. The rest of the demand, that is industrial heat, process cooling, domestic hot water and non-energy uses is less variable over the year. Hence, they are supposed constant during the year and are equally distributed over the 8760 hours of the year.

The variable demand of the global system (the three cells together) is represented in Figure 2.2. It depicts the total demand of each day of the year for space cooling, space heating and electricity. The passenger mobility is not plotted as it has the same daily pattern for each day of the year. It is at its peak during the day and falls down to zero at night.

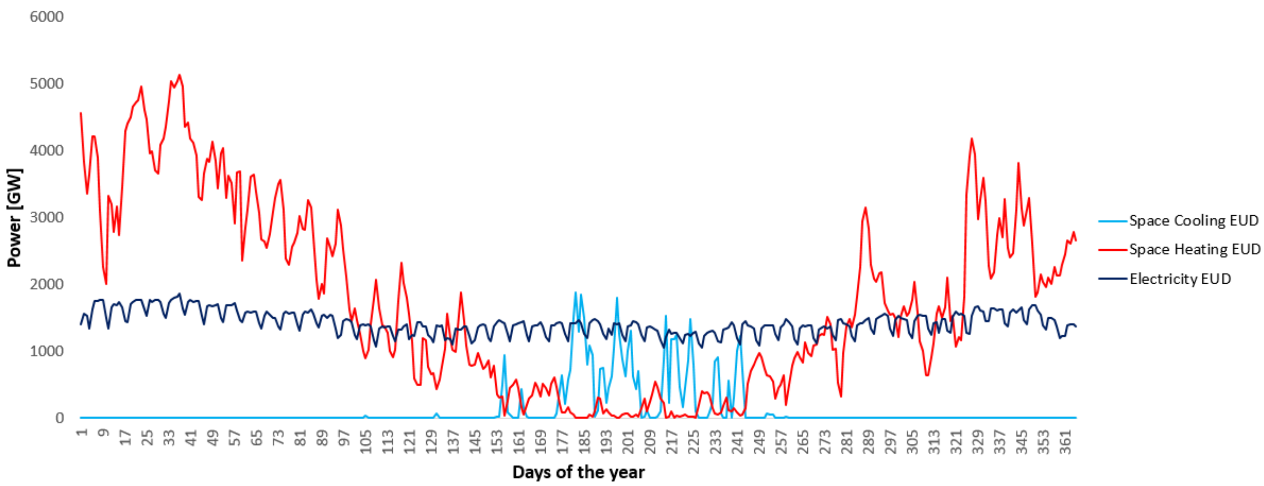

Figure 2.2: Variation of the daily electricity, space heating, and space cooling demand of the global system over the year (beginning on January 1st).

The scale of the different demands on Figure 2.2 shouldn't be compared to one another. Indeed, the conversion ratio between thermal energy and electric energy depends on the technology used (more details in Appendix B.2.1). However, this graph underlines that space

[2]Up to now, freight mobility is modelled with a constant time series dispatching its demand uniformly over the year.

heating and cooling have a strong seasonality. On the contrary, the electrical demand is not influenced by the season but drops every weekend.

Figure 2.3 shows the intraweek and intraday variations of the demand. The two extreme cases are plotted : a winter week with high space heating demand and a summer week with high space cooling demand. It is possible to underline several patterns on this figure.

During the winter, the space heating drops at noon and is higher in the morning and in the evening. On the contrary, electricity demand peaks during the day and drops at night. Also, the electricity demand is slightly lower during the weekend.

During the summer, the same tendency for electricity can be observed. The space cooling peaks at noon and is null during the night. Sometimes, the space cooling demand can be very low. During those days, some space heating is needed at night.

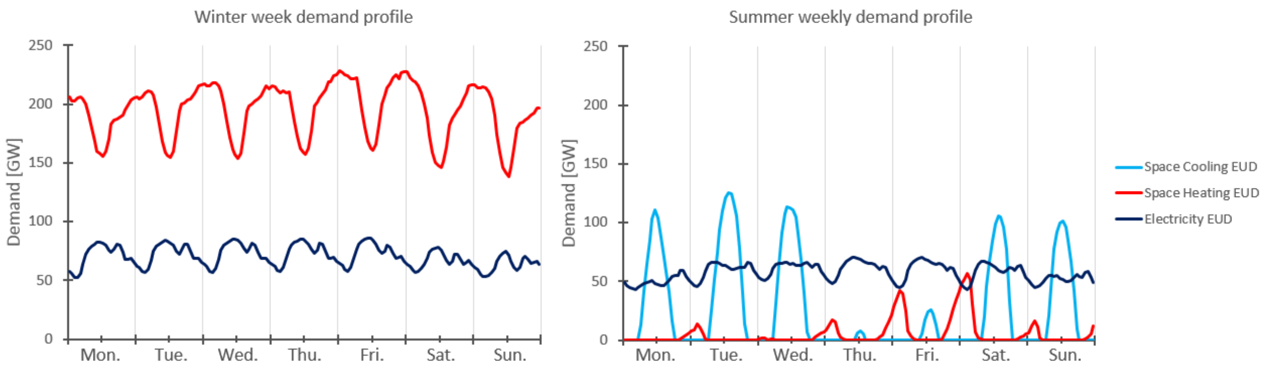

Figure 2.3: Weekly profile of electricity, space heating, and space cooling demand of the global system over the year.

2.2 Resources and RES potentials of the cells

What differentiates one cell to another, except from their size, is their access to primary energies and their potential to produce renewable energy.

In our model, a distinction is made between local and exterior resources. Wood, waste, and wet biomass are considered to be only local resources, while gasoline, diesel, liquid fuel oil (LFO), NG, coal and uranium are exterior resources. Indeed, Belgium, Switzerland and France mostly import these latter. In our model, it has been considered that the exterior resources have an infinite availability while the local resources have a finite availability which differs for every country. These availabilities and more details on the implementations of the resources lies in Appendix B.3.1.

The RESs production is limited in each cell by two main factors. Firstly, the RES technologies cannot be deployed infinitely and have in each cell a physical constraint that limits the installed power. Secondly, because of the difference of weather conditions in the different cells, the same capacity of RES will not produce the same quantity of energy from one cell to another. All those considerations are explained in more details in Appendix B.3.2.

Taking into account all those constraints, it is possible to evaluate the quantity of renewable energy that can be produced in each cell. Then, it is compared to the yearly EUD of the cell as follows [6] :

$$R = \frac{Potential_{RES}}{EUD_{tot}}$$

Figure 2.4 presents this indicator R. The biomass (wood and wet biomass) and the waste are considered as renewable energies in this indicator as the potential selected is their sustainable potential [8].

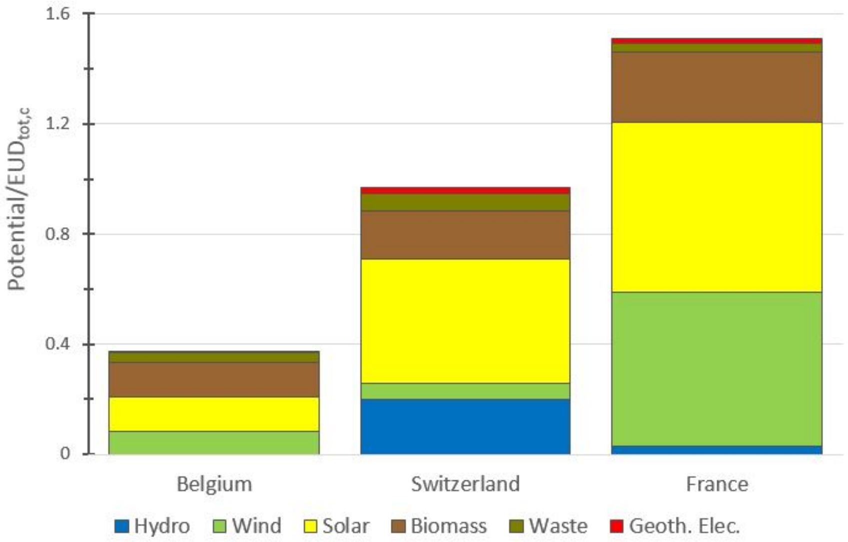

Figure 2.4: Comparison of renewable energies potential with total end-use demand (EUD) of each country [6]

Figure 2.4 allows to evaluate a priori if a country is able to provide for its demand independently with renewables or not. However, the potential computed is the yearly production and it does not take into account the intermittency of some RES (e.g. solar, wind). Indeed, IRES require storage assets which induces losses and high peaks of production can be managed by curtailing[3] the overproduction. Thus, a country would most likely need to have a ratio bigger then 1 between its potential and its EUD. Nevertheless, this indicator does not take into account either the fact that some EUD can be provided with efficient technologies. For instance, to fulfill the low temperature heat demand with heat pump (HP), only 0.25 to 0.33 [GWh] of electricity is needed to produce 1 GWh of heat. Hence, a country with a ratio a slightly lower than 1 could be able to provide for all his needs. This is the case of Switzerland, also thanks to its high hydro dam power providing flexibility [26, 32].

To conclude, the results of Figure 2.4 allow to say that France has the highest potential to provide its energy demands, followed by Switzerland and much lower Belgium. It doesn't permit to predict with certainty that France and Switzerland can achieve a 100% renewable system on their own and Belgium not. But it gives the intuition that Belgium lacks a lot of renewable potential while Switzerland is on the limit and France seems to have more than enough. That intuition should be verified in the further analysis.

Futhermore, France has a high potential of wind power which is nowadays the cheapest renewable production [23].

[3]National RE Laboratory defines curtailement as a reduction in the output of a generator from what it could otherwise produce given available resources [2]

2.3 Interconnection between the cells

> This section presents the data and the hypothesis used to model the exchanges between cells. In a first time, the exchanges of electricity and NG which occur through a network are developed. Then the parameter used to compute the freight of exchanges are defined.

2.3.1 Exchanges through a network

For the exchanges of electricity and natural gas (NG), a network is used. Figure 2.5 shows the transfer capacity of those resources between each pair of country. The data are the actual cross-border capacities of 2020 [30, 31]. The asymmetry of interconnections is mainly due to actual preferred direction of transmission. In a renewable energy system, those preferred directions of transmission will most likely change. Thus, the network might have to experience some changes. Figure 2.5 underlines that NG interconnections are bigger then electrical one. The electrical transfer capacities vary between 1 and 3 GW and NG transfer capacities between 4 and 35 GW.

As this is a fictive case, Belgium and Switzerland are not neighbours. Hence, their transfer capacities for natural gas and electricity will be extrapolated. As Germany is between Belgium and Switzerland, the transfer capacities Belgium $\longrightarrow$ Germany will be defined as Belgium $\longrightarrow$ Switzerland and Switzerland $\longrightarrow$ Germany as Switzerland $\longrightarrow$ Belgium. This methodology will be applied to the electrical interconnections and gas pipeline between Belgium and Switzerland.

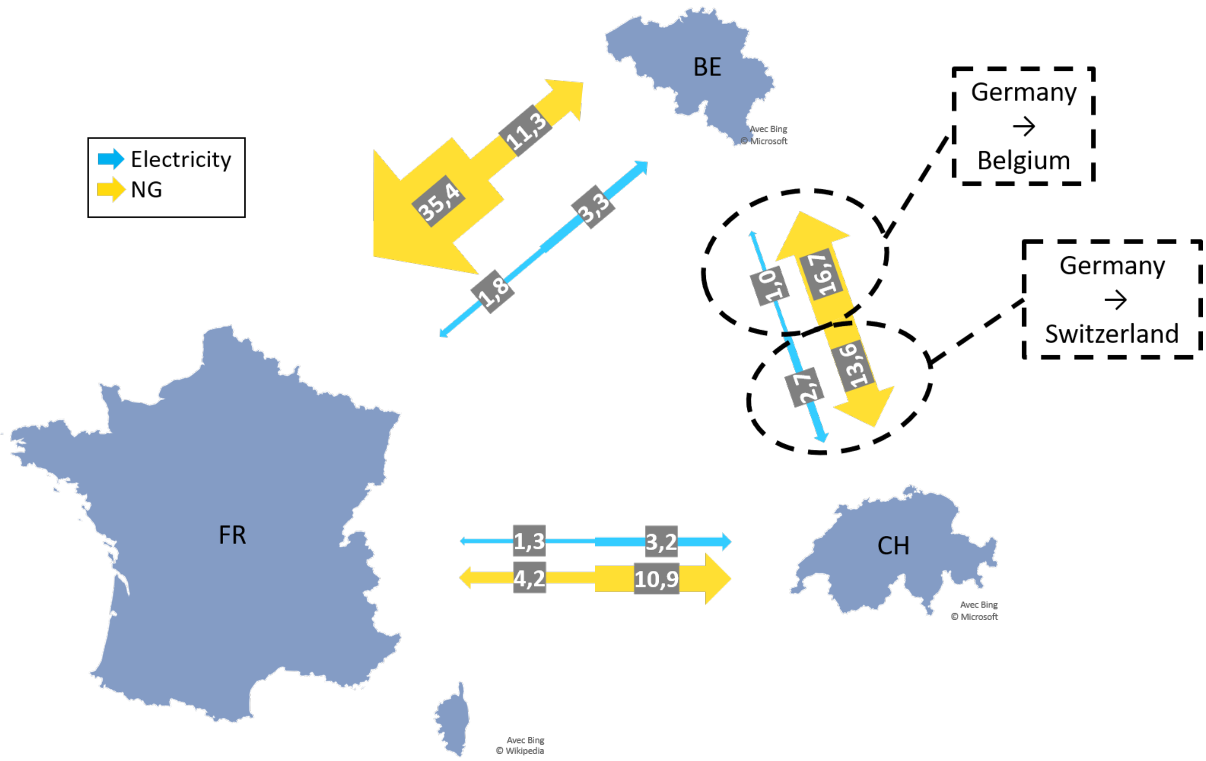

Figure 2.5: Transfer capacities (in GW) of electricity and gas between Belgium, Switzerland and France [30, 31].

The electrical transfer capacities vary between 1 and 3 GW and NG transfer capacities between 4 and 35 GW. For electricity, the total capacity of import and of export of each country is compared to their peak end-use demand (EUD) in Table 2.1. It allows to evaluate the importance of electricity exchanges in the electrical system of each country. For France, the import and export capacities only represent 4.1% and 8.6% of its electricity EUD. Hence the electrical exchanges will have a low impact on the energy system in France. However, for the two other countries it may have a big impact. In Belgium, import capacity can provide 28.7% and export capacity can absorb 30% of the peak EUD. In Switzerland, those amount to 89% and 35% of the EUD.

Country	$\mathbf{tc_{import}}$	$\mathbf{tc_{export}}$	**Peak elec. EUD**
France	3.1	6.45	75.25
Belgium	4.3	4.5	14.96
Switzerland	5.85	2.3	6.57

Table 2.1: Comparison of import and export transfer capacities [GW] of each country with its peak electricity end-use demand (EUD).

Another important parameter for energy carriers exchanged through a network are the losses. For electricity, the transmission losses are assumed to have the same values as the grid losses of each cell. [27] (add SFOE source). They represent 6.12% of the electricity transit. For gas, the losses are known to represent a much lower share of the energy exchanged. In this study, they are supposed to be of 2%. Late discussion with Fluxys revealed that the losses in NG network represent 0.08% of the NG transit (more information in Appendix B.4). Hence the value used in this verification study is overestimated.

The cost of those cross-border transmission capacities is added to the model as a fixed cost (see Table 2.2). It is expressed in million of euros per year and per gigawatt of transfer capacity ([M€/y/GW]). This cost takes into account both the investment and the operation and maintenance (O&M) expenditures. For the NG interconnections, the evaluation of the cost can be found in Appendix B.5. For the electrical interconnection the cost comes from [4].

	Elec.	**NG**
Relative cost [M€/y/GW]	28 [4]	0.541 [13]
Total transfer capacity [GW]	9.15	91.99
Total cost [M€/y]	256.20	49.77

Table 2.2: Fixed cost of transfer capacities of electricity and natural gas (NG).

The price of NG interconnections is much lower than for the electricity interconnections (50 times less expensive). It underlines the interest of exchanging not only electricity but also other resources such as NG.

To sum up, electricity exchanges may have an important impact on Belgium's and Switzerland's energy system. On the contrary, the transfer capacities are very small compared to the size of France's energy system.

Natural gas (NG) exchanges on the other hand are very interesting as they are bigger, cheaper and have less losses then electricity exchanges. Furthermore, NG is easier and cheaper to store than electricity.

2.3.2 Exchanges through freight

In this study case, 4 resources are allowed to be exchanged by freight : synthetic liquid fuel (SLF), wood, waste and captured CO_2. From Section 1.3.2, the additional freight due to exchanges is computed as in equation 2.1. It needs two new parameters : *lhv* (lower heating value) defined for each resource exchanged by freight and *dist* (distance) defined for each country.

$$\mathbf{Exch\_Freight}(c) = \sum_{r \in FREIGHT\_R, t \in T | [t,td] \in T\_H\_TD(t)} \left(\frac{\mathbf{R_{t,import}}(c,r,h,td) + \mathbf{R_{t,export}}(c,r,h,td)}{lhv(r)} \right) * dist(c) \quad (2.1)$$
$$\forall c \in COUNTRIES$$

The parameter *dist* is the average distance a resource would have to travel in one country when it is exchanged with another country. The place were this resource is collected may be very close or very far to the border. Hence the distance can vary a lot. In this case, it has been chosen to take the half distance between the two furthest big cities of each country (calculated with Google Maps). Thus most of the time, the distance is overestimated. Table 2.3 shows the cities chosen and the distance computed for each country. It means that if 1 ton of resources would have to go from France to Belgium, France would have an additional freight of 540 [tkm] and Belgium an additional freight of 153 [tkm].

Country	**City 1**	**City 2**	*dist*
France	Calais	Marseille	540
Belgium	Oostende	Arlon	153
Switzerland	Geneva	Chur	198

Table 2.3: Definition of *dist* parameter [km] and cities chosen to compute its value.

The parameter *lhv* (lower heating value) allows to convert the energy content exchanged (GWh) into mass of goods to transport (t). SLF, wood and waste do not have a fixed LHV. Table 2.4 presents the minimum, average and maximum value for each of them. The average value is used as default value for all the resources.

Resources	lhv_{min}	lhv_{avg}	lhv_{max}
SLF	3610 [24]	**4580**	5540 [32, 18]
Wood	2300 [32]	**3260**	4220 [1]
Waste	2810 [8]	**3120**	3430 [32]

Table 2.4: Minimum, average and maximum LHV for synthetic liquid fuel (SLF), wood and waste resources [GWh/Mt]. The **average** value is used as default value in the model.

For each of them, the reasons why the LHV is not fixed differ and are explained as follows. SLF can either be a mix of liquid fuels produced from the pyrolysis of wood or nearly pure methanol produced by synthetic methanolation process. Their LHV differ and it is not possible to know in advance through which process the exchanged SLF will be produced.

Wood is an aggregate containing roundwood, forestry residues, saw-dust, etc.[6] The latter have different LHV. Also, the moisture content of biomass influences a lot this LHV.

Waste refers to municipal solid waste. This is not a uniform product and its composition may vary from time to time. Hence, different values can be found in the literature.

The additional freight due to exchanges is modelled thanks to two parameters :

- The distance travelled in each country is estimated as an average distance.
- The lower heating value (LHV) gives the energy density of the resource. For synthetic liquid fuel (SLF), wood and waste it can take several values. The one of SLF is on average the highest. It shows that this resource has a high energy density and will be suitable for exchange of energy.

2.4 Definition of emission targets and scenarios

In the following chapters, three scenarios will be studied :

- **No Exchanges scenario**
- **Electricity Exchanges scenario**
- **All Exchanges scenario :** electricity, NG, SLF, wood, waste and CO_2 captured can be exchanged.

For the analysis of those three scenarios, an emission target has to be set. To determine it, we optimised the annual cost of each cell independently (no exchanges) without any emission constraints. The resulting global system emits 399 [MtCO2-eq/year], more details are given in Appendix B.6. As stated by Elia, the growth of renewable energy production in Europe leads to an increase of international electricity flows. Thus, in order to study a case where exchanges are quite significant, a system with a high share of renewable energy source (RES) should be studied.

We will analyse in the following chapters a low carbon system, where the emissions are constrained to 90% reduction compared to the case presented here above. This results in analysing the three scenarios with an emission limit set to 40 [MtCO2-eq./y].

Table 2.5 gives a preview of the main results with that limit on greenhouse gas (GHG) emissions for a three cell system : with no exchanges, with electricity exchanges, and with exchanges of several energy carriers. The total cost (C_{tot}) is the sum of the annualised investment and the O&M costs. The global warming potential $(GWP)_{op}$ takes into account all the emissions linked with the combustion of fuels (i.e. from extraction to combustion). The GWP_{tot} is the sum of the GWP_{op} and the green house gases emitted during the whole lifecycle of the conversion technologies assets.

	$\mathbf{GWP_{op} = 40}$	
Exchanges	C_{tot}	GWP_{tot}
No	126.9	78.2
Elec.	119.4	71.0
All	110.1	60.1

Table 2.5: Total cost (C_{tot}) [G€/y], operation GWP (GWP_{op}) [MtCO2-eq./y], and total GWP (GWP_{tot}) [MtCO2-eq./y] of cost minimization with $GWP_{op} \leq 40$ [MtCO2-eq./y].

A first insight one could have is that when allowing electrical exchange the total cost of the system should be equal (in the worst case) or inferior to the total cost of the no-exchange system. This intuition can be confirmed. Indeed, as detailed in Table 2.5, when optimising the total cost with the determined emission limit, the cost of the system with electrical exchanges is 7.5 billion euros per year cheaper. And if all exchanges are allowed, the cost decreases of 16.8 billion euros compared to the no exchange case. That is a drop of 13.2% of the total cost.

Furthermore, the cost of the network for interconnections of electricity and NG, defined in section 2.3.1, is of 0.306 billion euros per year. This is three order of magnitude smaller than the total cost of the system.

It has to be mentioned that in the non-exchange case, and in the electrical exchange case, the limit of PVs has been set to infinite for all cells. This hypothesis is clearly not realistic but constraining the system to 90% of its emissions is too strict for this case. However in the all exchange case, the PVs are not solicited to their limit.

	FR	BE	CH
Potential	1017.51	59.23	79.68
No	47.43	184.58	46.81
Elec.	27.99	142.69	34.26
All	32.08	19.85	24.92

Table 2.6: Comparison of photovoltaic panels (PV) potential with installed capacity in the three scenarios for each country [GW].

Conclusion

In this chapter, the inputs for the 3-cell system have been presented. The specificity of each country have been pointed out.

- The energy demand of France is huge compared to the other countries.
- Belgium has an especially high industrial demand (heat high temperature and non-energy)
- Belgium's potential to produce renewable energies covers only 37% of its end-use demand (EUD).
- France has a high potential of wind power which has become a low cost energy.

- The electricity capacity of exchange for France is very small compared to its demand.
- The capacity of electrical imports in Switzerland and Belgium represents respectively ..% and ..% of the peak EUD.
- The transfer capacity of natural gas (NG) is much higher then that of electricity and its exchange losses are very low.
- Synthetic liquid fuel (SLF) has a high energy density making it convenient for energy exchanges.

Those specificities allow to developed certain intuitions about the impact of exchanges on the system

- France acts like an infinite and zero losses storage for the other countries.
- France will provide abundant low cost electricity with its wind power.
- The import of electricity in Belgium and Switzerland will represent an important share of their production.
- The cross-border electrical interconnections will help the integration of intermittent renewable energy sources (IRES).
- NG and SLF will play an important role as means of exchange.
- The exchanges allow to take advantage of the difference between countries and bring a certain flexibility.

> The aim of the following chapters is to analyse the three scenarios - No Exchanges, Electricity Exchanges, All Exchanges - and find out whether they follow the developed intuitions. In other words, we will verify the consistency of the multi-cell model that has been developed and analyse the results on a practical case.

Chapter 3

Verification and analysis of the 3-cell scenario with electricity exchanges

> In this section, the 3-cell system with electrical interconnections is analysed. This system is the result of a total cost optimisation with an upper limit on greenhouse gas (GHG) emissions of 40 MtCO2-eq./y]. This section aims to verify the consistency of the multi-cell (MC) modelling of electrical exchanges. Therefore, we will focus on the electrical part of the system. However the entire system is analysed in Appendix C.
>
> Firstly, the electricity mix will briefly be exposed, as well as its differences with the no-exchange case. Afterwards, a focus on the exchanges is carried out.

3.1 Electricity Mix

Figure 3.1 illustrates the electricity production mix of the different cells for the no exchanges and the electrical exchanges scenarios. It allows to see the influence of interconnections on the electrical production in order to verify the model's choices. For each case, the production of the different technologies are represented. The curtailment of renewable energy source (RES) is also depicted in vertical striped pattern. The net exchanges of electricity are represented with turquoise diagonal stripped pattern.

As expected, France is mainly supplied in electricity by its wind turbines. Its electrical production mix remains quite similar in both cases. To export electricity to the other cells, France will choose to lower the electrification of its mobility through hydrogen (H2) production. Is is replaced with synthetic liquid fuel (SLF) (see Table 3.1).

Belgium's electricity is, in both cases, mainly produced by its PVs and its onshore wind turbines. In the case of electrical exchanges, it can be observed that PV production decreases. Electricity imports becomes the third source of electricity in Belgium. They behave like a flexible and reliable source of electricity coming from France. This allows the system to lower the production of the combined cycle gas turbine (CCGT).

Switzerland's electrical energy is, in both cases, mainly provided by PV and hydro power. When transiting to the scenario with electrical exchanges, Switzerland also decreases its PV production to replace it with electrical imports that behave like a reliable source of electricity coming from France. This allows to suppress the use of geothermal energy. It is an especially expensive energy in Switzerland (data from EnergyScope TD for Switzerland [26]) but it was necessary as a reliable baseload. It also allows to get rid of its CCGT and lower its use of combined heat and power (CHP).

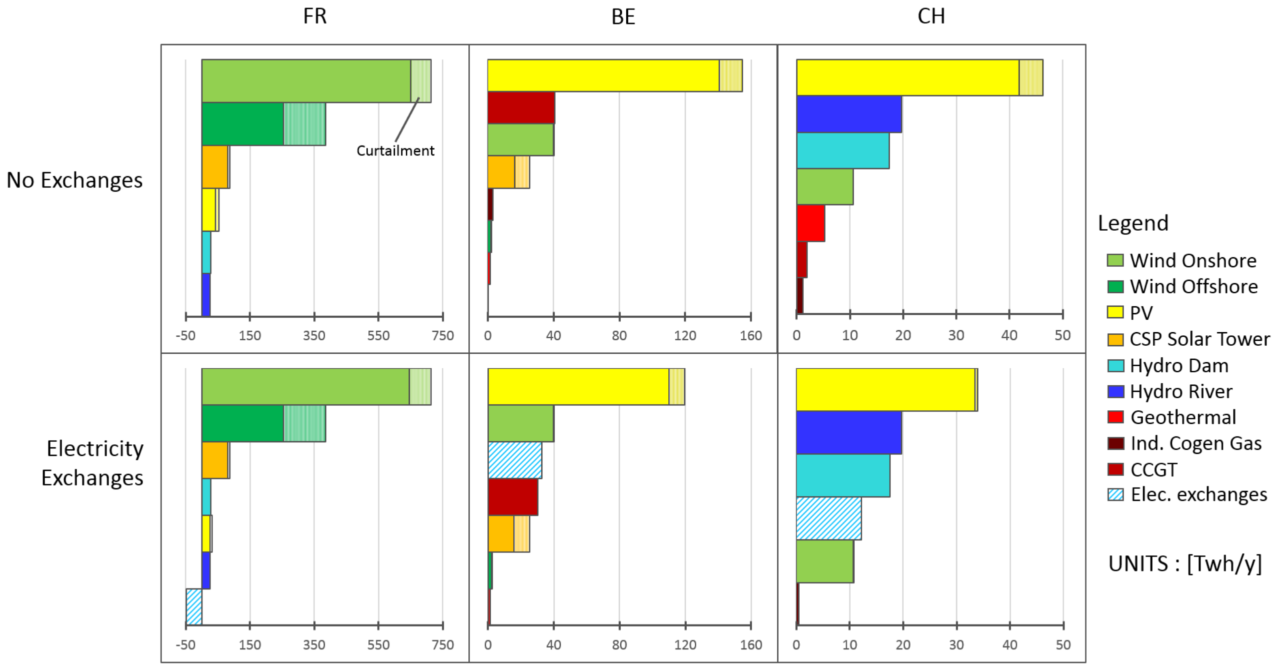

Figure 3.1: Comparison of electricity production mix of the different cells in the scenarios : no exchanges and electrical exchanges. (abbrev.: France (FR), Belgium (BE), Switzerland (CH), photovoltaic panels (PV), concentrated solar power (CSP), industrial cogeneration (Ind. Cogen) combined cycle gas turbine (CCGT), electricity (Elec.))

One can note that the exports operated by France do not represent a big share of its electrical production (4.3 %). Its curtailment is very similar in both cases. It can be guessed that Belgium and Switzerland will mainly import from France during the no-sun periods. Those periods often correspond to high wind production [22] which is convenient for the system.

In both scenarios the heat and mobility demands are highly electrified. Their electrification rates are represented in Table 3.1.

This electrification also plays a role offering flexibility on the demand side.

	Switzerland		**Belgium**		**France**	
Case	No Exch.	Exch.	No Exch.	Exch.	No Exch.	Exch.
Elec. Pass. Mobility	95	95	95	95	95	95
Elec. Freight Mobility	100	63.9	70	70	70	48.7
Elec Heat LT	70	70	63	63	63	63
Elec Heat HT	44	51	39	45	27	26

Table 3.1: Share of the electrification [%] of passenger mobility, freight mobility, heat low temperature (Elec heat LT) and heat high temperature (Elec. Heat HT) in each country for the 2 scenarios : No exchanges and Electrical exchanges.

As a summary of the analysis of the electricity mix in the scenario with electricity exchanges and its main differences with the no exchanges case, it can be stated that :

- In both scenarios, there is a high electrification of heat and mobility end-use demands (EUDs).
- When we allow electrical exchanges, the PV assets are considerably decreased in Belgium and Switzerland and replaced by flexible and reliable imports of electricity from France. This allows also to reduce the use of combined cycle gas turbines (CCGTs) in Belgium and suppress it in Switzerland.
- The electricity production of France does not change. France will decrease the electrification of its mobility and replace it with synthetic liquid fuel (SLF) (produced by pyrolysis of wood) in order to export electricity to the other cells.

3.2 Verification and analysis of exchanges

> The former section allowed to have a basic understanding of the 3-cell system with electrical exchanges. In this section, the analysis and verification of exchanges is carried out. Focusing on one type of exchanges only will permit to develop tools and indicators. They will help the analysis of the scenario with all exchanges in the next chapter.

3.2.1 Balance of electricity exchanges

Figure 3.2 depicts the balance[1] of the net imports (positive) and exports (negative) at each hour of each typical day (TD). Below each TD, the number of days of the year it represents is mentioned in order to keep a yearly overview of the exchanges.

This graph allows to confirm that the balance of exchange is respected, that is the sum of the imports equals the sum of the export at each hour.

On Figure 3.2, we observe that France exports electricity to the other countries during every early mornings, evening, and night time. During a lot of TD, it also exports electricity during entire days (TD1, TD12) or during nearly all the day (TD7, TD9, TD10) which represents more than 209 days a year. This confirms the intuition that France mainly acts like an exporter towards the other cells.

However, less frequent scenarios can also occur : for example, Belgium exporting to France and/or Switzerland, or Switzerland exporting to France.

[1] It does not take into account the losses of exchange.

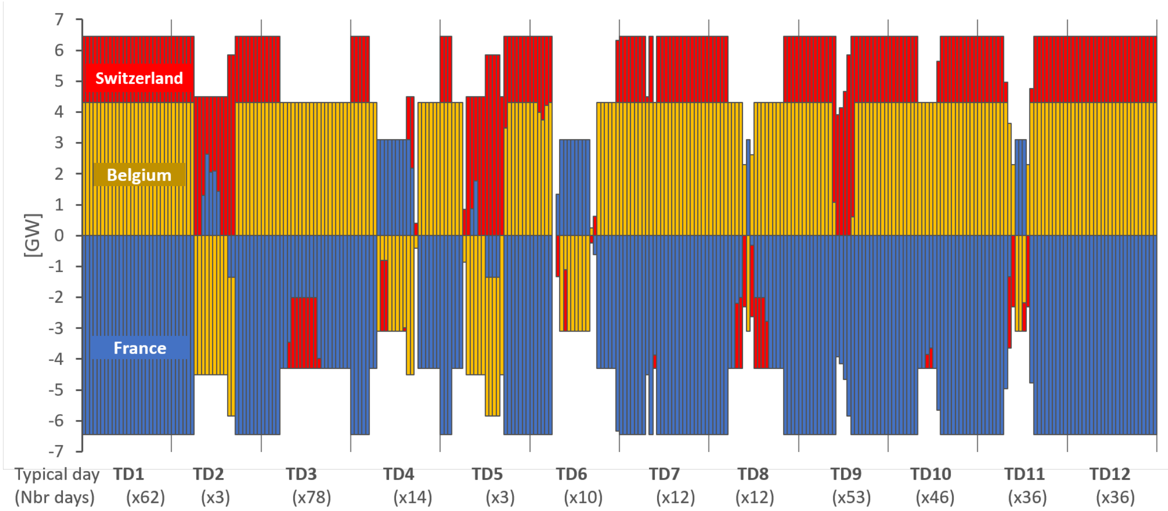

Figure 3.2: Verification of the balance of electricity exchanges between countries at each hour of each TD [GW].

The main RES assets installed in Switzerland and Belgium are photovoltaics (PVs). This technology is highly intermittent on a daily scale (day/night) and on a seasonal scale (summer/winter). It can be expected that these cells will have a high overproduction of electricity during sunny hours and a lack of electricity during dark hours. Figure 3.3 permits to confirm these insights. It represent the hourly potential of PVs in each country compared to the results of Figure 3.2. As Belgium and Switzerland install a lot of PV it is directly linked with their production.

The hourly potential capacity factor of Switzerland and Belgium clearly influence the directions of exchanges. From Figure 3.3,

- During days without sun or with very little sun in Belgium and Switzerland (TD1, TD12), France exports its maximum load to the two other countries during the whole day.

  These two typical days have the same combinations of exchanges during the whole day.

- France always exports electricity during evenings, nights and early mornings. Belgium and Switzerland always import during those periods. This reflects clearly the fact that these two countries rely mainly on solar power.

- During some TD (e.g. TD2, TD3, TD4, etc.), Belgium and/or Switzerland have a high PV production. As they have installed a lot of those assets, they overproduce around midday. Thus they dispose of this overproduction by exporting it. This happens during 66 and 150 days a year in Belgium and Switzerland respectively.

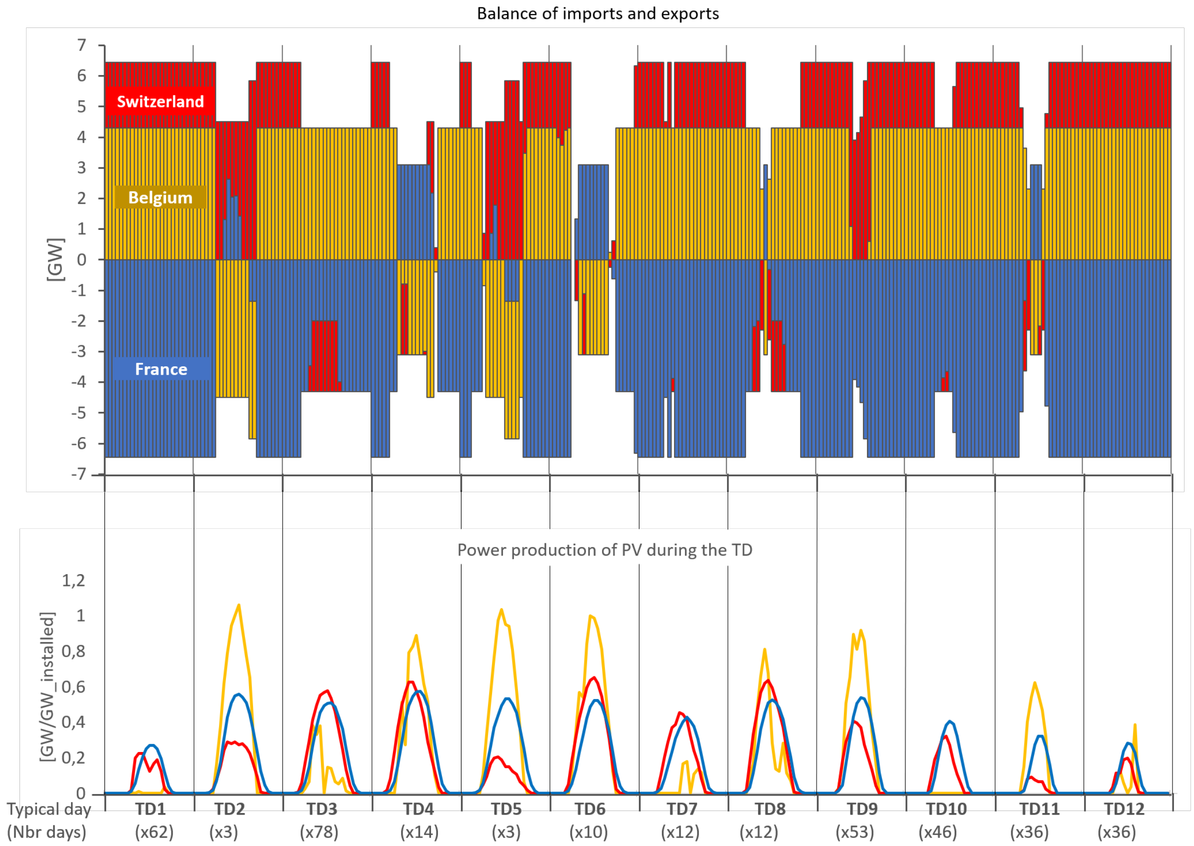

Figure 3.3: Relation between the hourly imports/exports and hourly coefficient of performance of PVs ($c_{pt,PV}$) in Switzerland and Belgium.

From Figure 3.2, we can compute the percentage of the year during which each country imports and exports. This is summarised in Table 3.2. The share of import and export doesn't add up to 100% as there are some hours when the lines are not used at all.

Country	**France**	**Belgium**	**Switzerland**
Import	4.2	92.4	71.3
Export	94.1	4.8	12.8

Table 3.2: Percentage of the year importing and exporting for each country [$\%_{\text{hours of the year}}$].

3.2.2 Transmission lines

The exchanges of electricity can also be observed through the duration curves of the transmission lines all over the year. They are represented in Figure 3.4 with the following reference: FR $\rightarrow$ BE, BE $\rightarrow$ CH, CH $\rightarrow$ FR. The transfer capacity (tc) of the lines in each direction are represented in dashed lines. As the references do not represent the preferred direction of the lines, some might be most of the time negative.

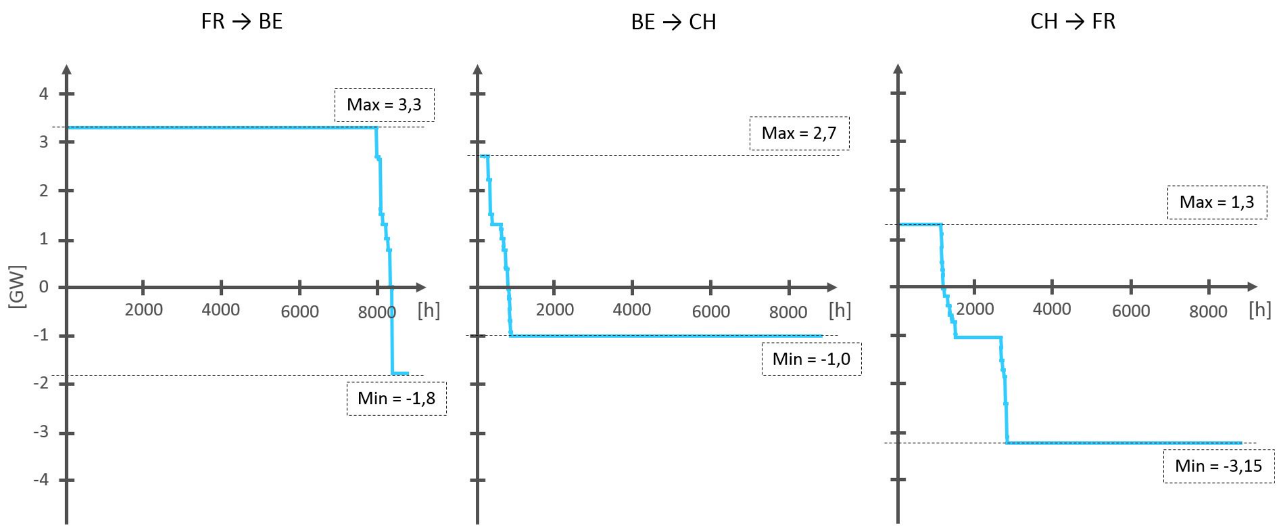

Figure 3.4: Load curve of electrical exchanges.

To study precisely how the cross-border lines are used, we need to define two concepts : the utilisation and transit factor of the lines.

Equation 3.1 defines the **utilisation factor (UF)**. For one interconnection, there are two UF, one for each direction. It represent how much this line is used compared to its full utilisation in this direction. It expresses the ratio of the energy exchanged over the year in that direction compared to the quantity that could have been exchanged if the line was always used at full capacity in that direction.

However, when a line is saturated, the system sends energy transiting through one country. For instance, the electrical line from France to Belgium is often saturated. At those moments, if Belgium wants to import more from France, the electricity will go through Switzerland to reach Belgium. We say that it is transiting through Switzerland using lines from France to Switzerland and from Switzerland to Belgium. Hence it is important to distinguish when a line is used for a "real" exchange between two countries and when it is used as a transit because another line is saturated. It is not trivial to make this disctinction based on Figure 3.4.

However, analysing the exchanges, it is possible to compute the **Transit** for each line at each hour. The **transit factor (TF)** is defined in Eq. 3.2 as the ratio between the quantity of energy which is only using this line for transit to the maximum amount that could be transported in this direction over the year. The transit factor is always smaller or equal to the utilisation factor. When it equals the utilisation, it means that all the energy using this line over the year is for transit through a country.

$$\mathbf{UF}(c_1, c_2) = \frac{\sum_{t \in T|[h,td] \in T\_H\_TD(t)} \mathbf{Exchanges}(c_1, c_2, r, h, td)}{8760 * tc(c_1, c_2, r)} \tag{3.1}$$
$$\forall c_1, c_2 \in COUNTRIES, r \in NETWORK\_R, h \in H, td \in TD$$

$$\mathbf{TF}(c_1, c_2) = \frac{\sum_{t \in T|[h,td] \in T\_H\_TD(t)} \mathbf{Transit}(c_1, c_2, r, h, td)}{8760 * tc(c_2, c_1, r)} \tag{3.2}$$
$$\forall c_1, c_2 \in COUNTRIES, r \in NETWORK\_R, h \in H, td \in TD$$

In these equations, the variables and sets used are defined as follows:

– $\mathbf{UF}(c_1, c_2)$: Utilisation factor of the line from country 2 to country 1 [%].

- **Exchanges**(c_1, c_2, r, h, td) : Exchanges of resource r from country 2 to country 1 at hour h of typical day td [GW].
- **TF**(c_1, c_2) : Transit factor of the line from country 2 to country 1 [%].
- **Transit**(c_1, c_2, r, h, td) : Transit of resource r on the line from country 2 to country 1 at hour h of typical day td [GW].
- $tc(c_2, c_1, r)$: Transfer capacity of the cross-border line from country 2 to country 1 for resource r [GW].
- *T_H_TD(t)* : matrix giving the correspond TD and hour for each hour of the year t.
- *COUNTRIES* : set containing all the countries.
- *NETWORK_R* : set containing all the resources exchanged through a network.
- *H* : set of the 24 hours of a day.
- *TD* : set of the 12 TD used in the model.

Equations 3.1 and 3.2 give a general definition of the **UF** and **TF**. It will allow in the next chapter to extend it to the NG exchanges.

Table 3.3 presents the value of those 2 factors and their ratio for each direction of electricity exchanges of each line. It also shows the percentage of hours of the year when the line is not used at all (Null) and when the line is saturated (Full).

Line	Direction	Null	Full	UF	TF	TF/UF
FR-BE	FR → BE	0.54	90.82	92.69	5.33	5.8
	BE → FR	0.54	4.6	4.6	0.74	16.1
BE-CH	BE → CH	0.23	2.25	4.87	3.92	80.5
	CH → BE	0.23	91.06	91.41	81.15	88.8
CH-FR	CH → FR	0.42	12.12	12.38	11.53	93.1
	FR → CH	0.42	68.57	74.35	25.93	34.9

Table 3.3: Comparison of electrical cross-border lines : time spend at null and full capacity [%], utilisation factor (UF) [%], transit factor (TF) [%] and TF/UF [%] (abbrev.: France (FR);, Belgium (BE), Switzerland (CH))

There are very few hours when the lines are not used. Three lines have high full capacity utilisation : the link from France to Belgium, the one from Switzerland to Belgium and the one from France to Switzerland. Those lines are also the ones with the highest utilisation factor.

Each line has a preferred direction of exchange : FR → BE, CH → BE and FR → CH. All the lines linked with France are mostly used by France to export electricity. And when they are used in the other direction, it is often for transit.

When the utilisation factor is very close from the time spent at full capacity, it means that the connections is rarely used at lower capacity. This is the case for the link from Switzerland to Belgium.

When the ratio of the transit factor and the utilisation is high, it means that most of the electricity exchanged on this line is in fact electricity from transit. For instance, the CH $\rightarrow$ FR line has a very high **TF/UF**. Indeed, most of the electricity sent from Switzerland to France is in fact sent by Switzerland and transiting through France. The line BE-CH is also used very often (in both direction) as a transit line, to procure extra transfer capacity between Belgium and France.

Adding the time spent at full capacity of the two directions of a line allows to see which share of the year the line is saturated in one direction or the other. The interconnections FR-BE and BE-CH are saturated more then 90% of the time while the line CH-FR is saturated 80 % of the time.

Despite the fact that these transmission lines have a preferential direction, 9 different configurations (in terms of directions of flows) of exchanges are found in this three cell analysis. The four more frequent cases are identified in Figure 3.5 as the other 5 configurations are very rare and represent together only 1.5 % of the hours of the year.

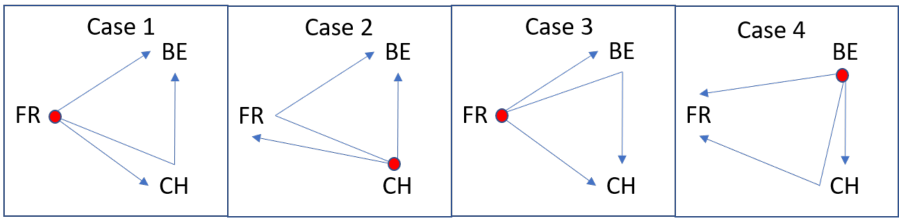

Figure 3.5: Four main patterns of exchanges in the system

These four combinations of flows have certain characteristics and occur in typical situations.

- **Case 1 :** It regroups the hours when there is no sun : mornings, evenings, night time or cloudy days (especially for Belgium). During those hours, France exports to Belgium and Switzerland.
- **Case 2 :** It regroups the hours that are sunny in Switzerland and not sunny in Belgium. Switzerland needs to evacuate its overproduction of PV power and Belgium can absorb it.
- **Case 3 :** It regroups hours that are windy in France and sunny in Belgium. Both countries can export to Switzerland.
- **Case 4 :** It regroups hours that are sunny both in Belgium and Switzerland. France absorbs their overproduction of PV power

The occurrence of these patterns are given in Table 3.4.

	Number of hours	Share
Case 1	7232	82.5
Case 2	750	8.6
Case 3	318	3.6
Case 4	311	3.6

Table 3.4: Number of hours per year and share [%] of the four man patterns of exchanges.

These different configurations are clearly not uniformly distributed over time. Case 1 is the most frequent case occurring 82.5% of the time. This case is detailed in Figure 3.6. It gives the duration curve of case 1 obtained by sorting the hours in increasing order of magnitude of the line CH $\rightarrow$ FR.

In this graph, 2 curves having the same sign means that transit is occurring through the country present in both lines. When the two lines overlap, the country in which energy transits does not interact in the exchange of electricity by adding or taking energy from the transited electricity.

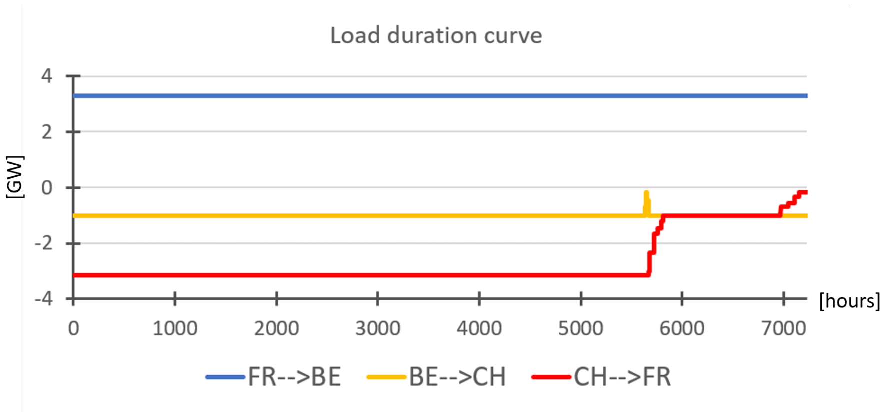

Figure 3.6: Duration curve of transmission lines in Case 1.

This curve shows that Case 1 is composed of two sub-cases. The most frequent one consists of France exporting to Belgium at full load (3.3 GW), Belgium importing from Switzerland at full load (1 GW) and Switzerland importing from France at full load (3.15 GW). This results in a net export of 6.45 GW for France exporting and a net import of 4.3 GW and 2.15 GW for Belgium and Switzerland respectively. In the other sub-case, Switzerland is not importing and just transiting electricity to Belgium.

To fully measure these quantities of imports and exports, Table 3.5 compares them to the peak electrical demand in each cell. The electrical demand consists of the electricity EUD, and the fixed electrical demand in mobility (trains, tramways) and in process cooling. The other electrical demands are a choice of the model and are flexible as they are linked with a storage (e.g. H2 electrolysis and H2 storage).

The hourly exchanges of electricity in Case 1 represent a quite high percentage of the fixed peak electrical demand of Switzerland and Belgium while for France, it is much lower.

	Exchanges [GW]	Peak elec. demand [GW]	Ratio [%]
BE	4.3	19.7	21.8
CH	2.15	8.5	25.4
FR	-6.45	91.3	7

Table 3.5: Ratio of most frequent import (>0) or export (<0) of electricity to the peak of the fixed electrical demand.

The electricity layers of the different cells are given in Appendix C.2.

3.2.3 Yearly balance of exchanges

The net exchanges of electricity during the year between the different cells are represented in Figure 3.7.

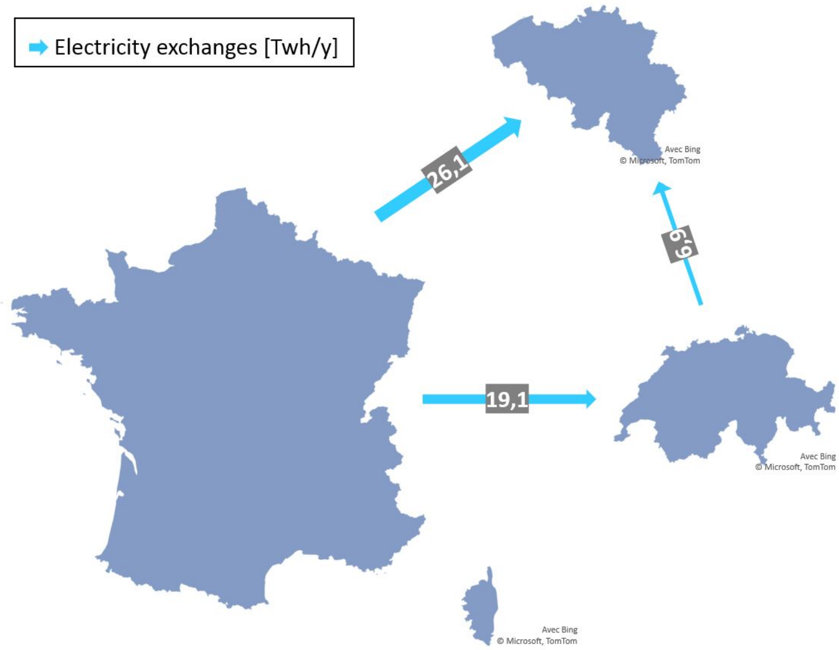

Figure 3.7: Yearly balance of cross-border transmission lines.

This graph illustrates clearly that France acts like a distributor of energy towards Belgium and Switzerland on a yearly basis. Indeed, its net export is 45.2 TWh/y, which represents about 4.3 % of its total electrical production.

Belgium clearly relies on its neighbours, importing in total 33 TWh/y. This is about 16.5 % of its yearly electrical production.

Switzerland is a net importer from France and a net exporter towards Belgium. Summing both fluxes, Switzerland is a net importer from France of 12.2 TWh/y. This covers 15 % of its electrical production.

To conclude the focus on the exchanges, it can be stated that :

- The imports and exports of electricity are balanced at each hour.
- France acts like a buffer and a distributor of electricity towards Belgium and Switzerland. It absorbs their electricity when they have too much production and supplies them with electricity when they have a too low production.
- The imports and exports of electricity are highly dependant of the photovoltaic (PV) production of Switzerland and Belgium as PVs are the biggest producer of electricity in those countries.
- Belgium and Switzerland are net importers. Their imports cover 16.5% and 15% of their electricity mix. Belgium imports during 92.4% of the year ans Switzerland during 71.3%.

- The electrical lines are often saturated. This generates a lot of transit in some lines : CH $\rightarrow$ BE, BE $\rightarrow$ CH and CH $\rightarrow$ FR. Most of this transit is used to transfer electricity from France to Belgium. It would be interesting to study a system with larger transfer capacities between countries.
- Although many combinations of exchanges are possible, one particular case sticks out (Case 1) where the power imported in Switzerland and Belgium can represent up to 21.8 and 25.4 % of their fixed electrical demand, respectively.

3.3 Conclusion

In this chapter, we have applied our multi-regional model on a simple scenario : a 3-cell system with electrical exchanges only. It was compared with another scenario without exchanges.

Thanks to the simplicity of this system, we were able to verify the results and develop a methodology to analyse the exchanges.

The main results are the following :

- France is a net exporter to Switzerland and Belgium and acts like a buffer and a producer of electricity for them.
- Allowing electricity exchanges doesn't have much impact on the energy system in France. On the contrary, energy systems in Belgium and Switzerland change a lot with electricity exchanges. The imports cover 16.5% and 15% of their electricity mix.
- Belgium and Switzerland are heavily dependant on electricity exchanges. The direction of exchanges are dictated by a lack or a surplus of electricity in those countries.

All those conclusions are in line with the intuitions developed in Chapter 2. Hence, the model is consistent and reliable in the case of a multi-region system with electricity exchanges.

A case with exchanges of more energy carriers will be verified in the next chapter.

Chapter 4

Verification and analysis of the 3-cell scenario with all exchanges

> This chapter presents the scenario where France, Belgium and Switzerland can exchange all the following resources : electricity, natural gas (NG), synthetic liquid fuel (SLF), wood, waste and CO_2 captured. The modelling of those exchanges is explained in sections 1.3.2 and 2.3.
>
> The aim is to verify the consistency of the developed model. This is done through checking that exchanges follow well the constraints of balance, transfer capacity and additional freight. We also analyse the results to find out whether they follow the intuitions developed in Chapter 2.
>
> In a first time, a Sankey diagram will allow to have an overview of the system's main characteristics. Then, a deeper analysis of the system is carried out. Finally, we will focus on exchanges as these are the particularity of our model.

4.1 Overview of the system

Figure 4.1 presents the solution for the global system (France, Belgium and Switzerland aggregated) in the form of a Sankey Diagram. It summarises the yearly energy flows of the system. The left hand side of the figure represents the primary energy sources. The right hand side of the diagram depicts the global end-use demand (EUD) of the system. It shows how the resources on the left are converted to provide the end-use demand (EUD) on the right.

In this figure, the grey blocks represent layers or conversion technologies. The coloured curves are the energy flow linking those layers and technologies. There is one colour per type of energy flow (e.g. light blue for electricity). The following example helps to understand how to read it : for instance, onshore wind turbines (WTs) produce electricity (green flow). From the electricity layer (grey box Elec in the bottom) a flow of electricity goes to the heat pumps (HPs). Those HPs produce heat low temperature (LT) which goes to the heat LT decentralised (Dec) and district heating network (DHN) end-use demands (EUDs). A part of it is stored before use. The HPs is an efficient technology converting 1 GWh of electricity to 3-4 GWh of heat. For this reason, the size of the heat flow going out of the HPs is much bigger then the electricity flow entering.

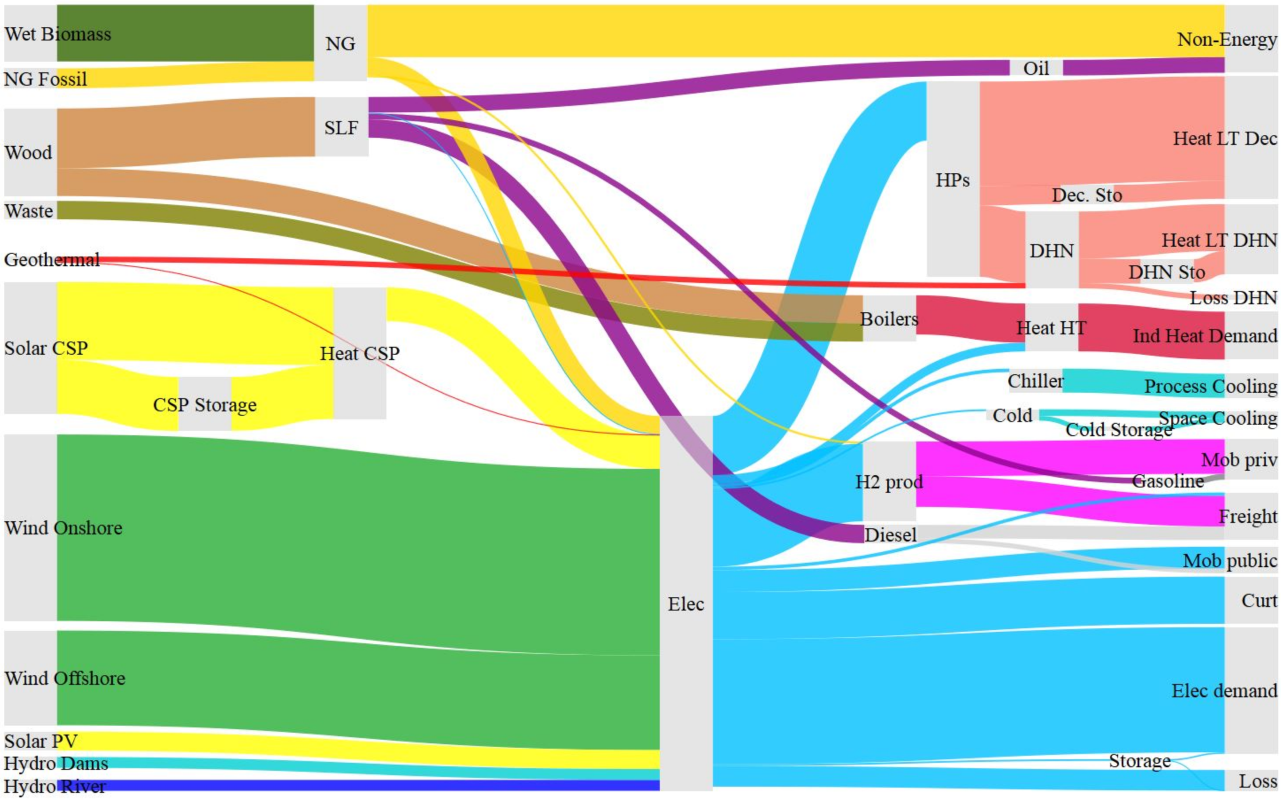

Figure 4.1: Energy flows in the overall system from primary energies (left side) to end-use demand (right side). (abbrev.: see list of abbreviations)

> This graph allows to have an overview of the global system. In the following paragraphs, we will analyse in more details the different primary energy sources used (left side of Sankey diagram), the electricity layer (Elec. grey block in the Sankey diagram) and how they satisfy the end-use demands of the different countries (right side of the Sankey diagram).

4.1.1 Resources

The major part of the resources are renewable. Indeed, wet biomass, wood, solar, wind and hydro represent 93.6 % of the resources. The non-renewable primary sources (6.4%) consist of waste and fossil natural gas (NG).

Natural gas

A share of 27 % of the NG used in the overall system is fossil. This importation of fossil NG is only necessary for Belgium. Fossil NG is the only resource imported from outside the system. The rest of the NG (73%) is produced locally through biomethanation of wet biomass and can be considered as renewable. Switzerland and France only use NG that they produce. On the contrary, Belgium has 3 main sources for its NG as detailed in Table 4.1. This natural gas plays a major role in Belgium's energy system since it covers all its non-energy EUD and allows to have a dispatchable production of electricity with combined cycle gas turbines (CCGTs)

	NG used		
Source	Fossil	Exchanges	Local prod.
Belgium	46	33	21

Table 4.1: Share of different sources of natural gas (NG) used in Belgium [%]. (abbrev. : producton (prod.))

Local resources

The global system is self-sufficient at 96.7%[1]. Therefore, local resources become of major importance. Table 4.2 summarises the use of those local resources in terms of share of their availability in each country.

The local resources of each country are fully used except waste in Switzerland which is not used at all. Waste in Belgium and France is entirely used to produce heat high temperature (HT) for the industry. All the countries use their whole wet biomass available to produce synthetic natural gas (SNG).

The case of wood is a bit more complex as it is exchanged from France to Belgium and Switzerland. In this overall system, wood is used in two ways : to produce HT heat for industries, or to produce SLF through pyrolysis for mobility and non-energy uses. In Table 4.2, Belgium and Switzerland use more wood than their local availabilities while France uses 92.11% of its own wood. Hence, the 7.89% of the wood availability left in France is exported to the others. We also notice that Belgium and Switzerland only use wood to produce heat HT. Thus the only country to produce SLF is France.

Resources	**Waste**	**Wet biomass**	**Wood**		
Use	Boiler HT	SNG prod.	Boiler HT	SLF prod.	**Tot.**
France	100	100	16.37	75.74	**92.11**
Belgium	100	100	183.46	0	**183.46**
Switzerland	0	100	148.02	0	**148.02**

Table 4.2: Use of local resources in terms of share of availability [$\%_{\text{avail}}$] in different technologies for each country. (abbrev. : high temperature (HT), synthetic liquid fuel production (SLF prod.), synthetic natural gas production (SNG prod.))

4.1.2 Electricity Mix

For each country, the electricity production mix is given in Table 4.3. The curtailment is also given and provides the ratio of its value to the total electricity produced. The curtailment is big in France, small in Belgium an negligible in Switzerland.

[1]That is, 96.7 % are local resources and have their origin inside the system

	France	Belgium	Switzerland	Overall
Wind onshore	52.3	26.2	12.3	48.4
Wind offshore	29.5	1.4	0	25.3
PV	2.5	10.8	28.4	5.2
Solar tower	10.8	10.0	0	10.4
Hydro dam	2.4	0	20.2	3.3
Hydro river	2.2	0.1	22.8	3.4
CCGT	0	30.4	0	3.5
Net elec. import	0	20.1	16.3	0
Curtailment	16.7	3.0	0.1	14.6

Table 4.3: Electricity production mix and curtailment in each country [$\%_{\text{tot. prod.}}$]. (abbrev.: photovoltaic panels (PV), combined cycle gas turbine (CCGT))

Table 4.3 allows to evaluate the relative importance of the different assets for the electricity balance in the different countries. For instance, the intermittent renewable energy sources (IRES) production, in France, represents 86.3% of the electricity mix whereas it covers 61.7% and 39.5% in Switzerland and Belgium respectively. Thus, Belgium and Switzerland will need more other sources of electricity than France.

The installed capacity of each RES asset can be found in Appendix D.1.

4.1.3 Final energy consumption

From the Sankey diagram, we can see that the system is highly electrified, as 70.3% of the FEC is electricity[2].

The low temperature (LT) heat is highly electrified. The decentralised heat is 100% supplied by electrical heat pumps (HPs). The district heating network (DHN) is electrified through HPs at 92.8% and 7.2% is generated by geothermal heat. The system favours DHN and installs it to its maximum share of 37%. More details on the countries choices are given on the right-hand side of Table 4.4.

The high temperature heat demand for industrial use is mainly supplied by waste and wood boilers (82%). It is also electrified (18%) as a small part of this demand is supplied through direct electric heaters. A more detailed overview of the use of these technologies in the different countries is summarised on the left side of Table 4.4. We note that Belgium doesn't use direct electric heaters for its HT heat demand.

The non-energy demand is mainly supplied by gas with a small contribution of oil. The distribution for each cell is given in Table 4.4.

[2]To compute this result, we consider that H2 is mainly produced by electricity (electrolysis) and apply its conversion coefficient of 1.1765.

EUD	Heat LT		Heat HT			Non energy	
Final energy	Elec. (HP)	Geoth.	Elec.	Wood	Waste	SLF	NG
France	97.94	2.06	25.72	36.46	37.82	36.18	63.81
Belgium	100	0	0	71.77	28.23	0	100
Switzerland	84.06	15.94	17.40	82.60	0	-	-

Table 4.4: Share of final energies used for the heat high temperature (HT) and low temparature (LT) end-use demands (EUD) in each country [$\%_{\mathrm{EUD}}$]. (abbrev.: heat pump (HP), geothermal heat (Geoth.))

The process cooling and space cooling demands in this 3 countries system are very small. They are entirely electrified but the system has no other choice as the only existing technologies to produce cold in the model is refrigeration cycle with electricity as input.

Passenger mobility Table 4.5 underlines that both France and Switzerland, relies mostly on electricity (tramways and trains) and hydrogen (H2). As we can see on Figure 4.1, this H2 is mostly produced through electrolysis. It is then used into fuel cell vehicles. The H2 can also be stored. This has an important role for the electricity production and consumption adequacy as it will be explained in further sections. Unlike other countries, Belgium prefers to use SLF rather than H2 for its mobility passenger.

Freight mobility France uses electricity, H2 and SLF where Belgium and Switzerland choose to not use H2. Furthermore, the sum of the shares of freight is bigger than 100% in each country. This is due to the additional freight for exchanges. It increases the demand to a higher value than the EUD.

EUD	Mob. pass.			Freight			
Final energy	Elec.	H_2	SLF	Elec.	H_2	SLF	**Tot.**
France	45	50	5	25	46.98	30	**101.98**
Belgium	35	0	65	25	0	77.86	**102.86**
Switzerland	45	50	5	60	0	41.97	**101.97**

Table 4.5: Share of final energies used for the mobility passenger (Mob. pass.), the freight and the non energy end-use demands (EUD) in each country [$\%_{\mathrm{EUD}}$]. (Abbreviations : natural gas (NG), synthetic liquid fuel (SLF))

4.2 Intermittency and flexibility providers

As explained before, the system is heavily electrified. Its electricity is mainly produced with intermittent renewable energy sources (IRES). To ensure the production and consumption adequacy, the system needs some conversion technologies which are able to bring some flexibility. This flexibility can consist of both dispatchable production and dispatchable loads.

> This section will provide some insights on how the system of each country copes with intermittency.
>
> Firstly, a comparison between the fixed electrical demand and the IRES production is pursued to establish the situation of each country.

Then the dispatchable producers, dispatchable loads and storage assets are presented in terms of power they could potentially produce or absorb.

Afterwards, the cycle duration of the storage assets is analysed. Finally, the share of those assets in the total electricity mix of each country is studied.

The analysis both in term of the power and in terms of energy allows to have a full picture.

4.2.1 Comparison of intermittent renewable power and electricity demand

Figures 4.2 and 4.3 compare the variability of the electricity demand and the IRES potential production (production if no curtailment). In those graphs, electricity demand regroups all the demand that is not flexible at all, that is the EUD, the electric public mobility, the electric freight and the process cooling. It will be referred to as the fixed electricity demand. The IRES contains the following technologies[3][4] : photovoltaic (PV), onshore and offshore wind turbine (WT) and hydro run-of-river. Hydro dams, solar towers and parabolic troughs are not considered as intermittent because they have a storage capacity. It allows them to control more their production and act as a dispatchable production asset. A deeper analysis of those technologies is done further into this section.

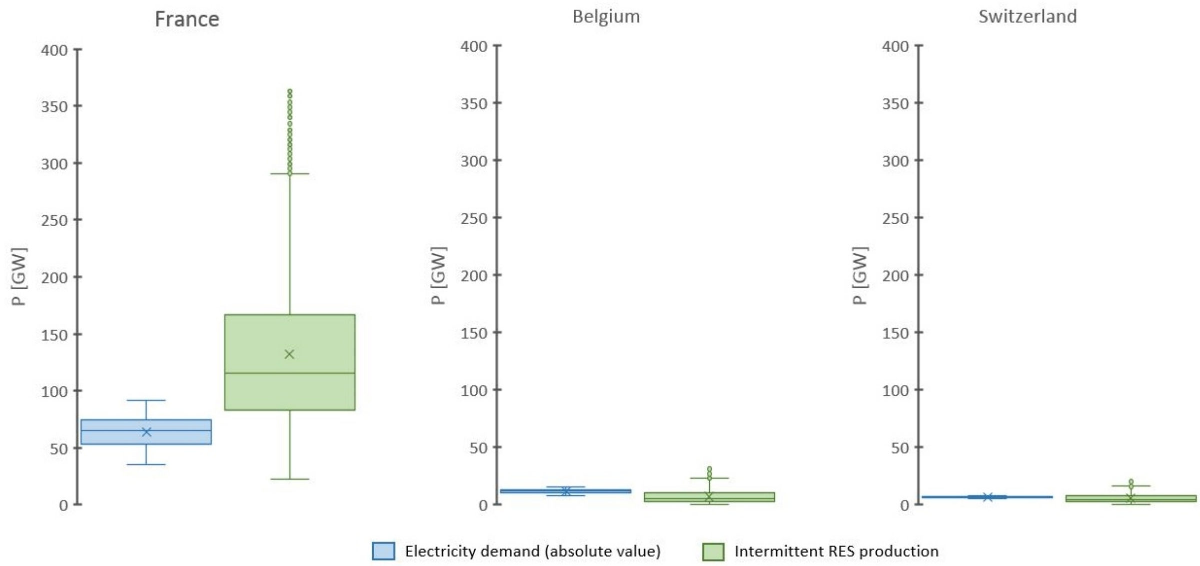

Figure 4.2: Quantitative statistics of the fixed electricity demand and the intermittent renewable energy (IRE) production.

Figure 4.2 underlines the difference in size of the electrical system in France compared to Belgium and Switzerland. It is one order of magnitude bigger than the others. The box plots of France electrical system enlighten that 68% of IRES production is above the peak demand. Also, this production in France can be very high, up to 4 times the peak demand. It means that France will need more flexible load than flexible production. It might curtail a lot too.

On the contrary, in Figure 4.3, Belgium's IRES electricity production is 79% of the time under the mean electrical demand of the country and 89% of the time under the peak production. However, the peak IRES production in Belgium is 2.3 times bigger than the peak demand.

[3]Stirling dish, tidal power and wave power technologies are not used at all by the model.

[4]Geothermal power is considered as negligible.

Hence, Belgium will need a big amount of flexible production assets and fewer flexible loads. It is also likely to curtail.

The case of Switzerland lies between the two others. The interquartile range of the production covers the interquartile range of the demand. Although the production lies during 67% and 77% of the year under the mean demand and under the peak demand, respectively. The peak production reaches up to 2.7 times the peak demand. Furthermore, Switzerland is known for having a lot of hydro dams. Hence it will need very few flexible production and a respectable amount of flexible loads.

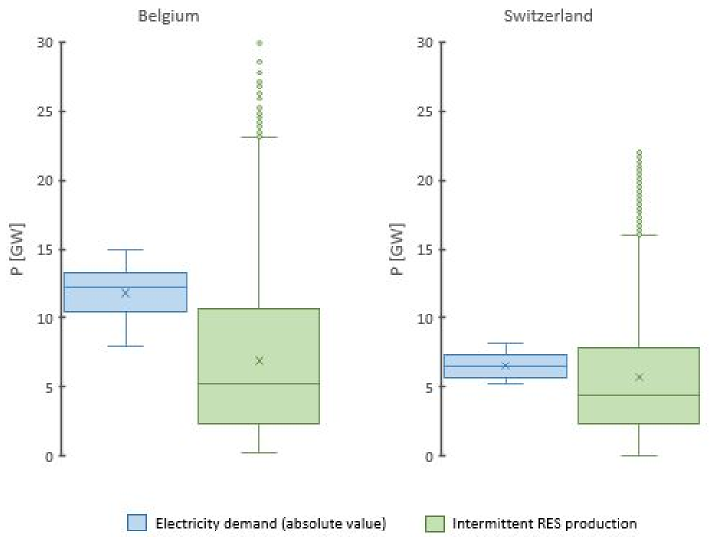

Figure 4.3: Quantitative statistics of the fixed electricity demand and intermittent renewable energy (IRE) production, a zoom on Belgium and Switzerland.

4.2.2 Power of flexibility providers

Figure 4.4 allows to verify these intuitions about the need for flexible load and flexible production. It depicts all the technologies that bring flexibility to the electrical system of each country. Each technology is represented by the quantity of electrical power it could potentially produce and/or absorb at a given hour to cope with a mismatch between the production and the demand. The production of electricity is displayed as positive and the consumption as negative. Each one of these assets has its own constraints such that it might not be able to produce and/or absorb as much power as indicated on figure 4.4 at every hour of the year. Sometimes, it might not even be able to play a role at all. To asses the importance of each technology over the year, their share in the production and consumption mix will be studied in the section 4.2.4.

The flexibility providers from Figure 4.4 can be regrouped into 6 categories according to their characteristics.

1. **Thermal back-up power plants :** The only one installed is the combined cycle gas turbine (CCGT) in Belgium and is very flexible. However, it uses NG to produce electricity. It is limited by the power installed and its supply of NG. Indeed, this NG is either produced locally through biomethanation, imported from its neighbours or from outside the global system and each one of these sources has its limits.
2. **Flexible RES :** It is composed of hydro dam and solar tower. Both technologies consist of an intermittent renewable source coupled with a storage. It enables them to shift their

electricity production according to the demand. They are limited by the size of their storage and the power of their conversion unit (see Appendix D.2 for more details on hydro dam and solar tower).

3. **Electricity storage :** The only installed asset of electrical storage is pumped hydro storage (PHS). It can be used as an additional production or demand at different hours. However, it is limited by the capacity installed and its power abilities.

4. **Electrified demand with storage :** It regroups the non-electrical EUD (LT heat, mobility, cold) that are electrified. It contains the following conversion assets with their respective storage : HPs for decentralised and DHN LT heat , H_2 electrolysis used for mobility and big split used for space cooling. Their storage allows them to become dispatchable loads. However, they are limited both by the installed power of the conversion technology, by the power and capacity of their storage and by the demand they are linked to.

5. **Industrial electrical heaters :** Those are very flexible as they are coupled with wood or waste boilers. When there is too much electricity produced, the model can choose to stop the HT heat production with wood and waste boilers and replace them with electrical heaters. This type of electricity absorber is not installed in Belgium.

6. **Electricity exchanges :** They have the capacity of both giving and taking electricity. However they are limited by the transfer capacities and the ability of the other countries to export or import the power needed at that hour.

Flexibility providers in France Following the intuitions explained with Section 4.2.1, France doesn't need to install any other flexible producer than the solar towers and the hydro dams,as can be seen on Figure 4.4. They can increase the production by 46% and 15% of the peak demand, respectively.

PHS has a minimum capacity of installation in the model, representing its actual installed capacity in France. In this solution, it installs this minimal capacity and uses it as the only electricity storage.

France also installs a huge flexible load with electrolysis and hydrogen (H2) storage. It can increase the electricity demand by 66% of the peak demand. It is followed by heating and cooling flexible demands which can represent a maximum load ranging from 14% to 15% of the peak demand. The smallest flexibility provider for France is the electricity exchanges.

The electrical transfer capacities are very small compared to the size of the system. France will be able to easily play the role of electricity producer and absorber for its neighbours. Indeed, for them, the capacities of exchange are significant compared to the size of the system.

Flexibility providers in Belgium As analysed before, Belgium has a strong need for flexible electricity production. Its CCGT is able to provide alone 93% of the peak demand. It can also rely on its solar tower and storage, 26% of the peak demand.

The PHS plays also an important role as it is able to absorb or produce up to 15% of the peak demand.

The electrification of the low temperature (LT) heat is the biggest flexible load in Belgium with a maximum power absorbed of 42% and 22% of the peak demand for the decentralised heat and DHN respectively. The smallest flexible load is the space cooling with a maximum absorption power of 11% of the peak demand.

The electricity imports and exports can play an important role. They can supply 29% or absorb 30% of the peak demand.

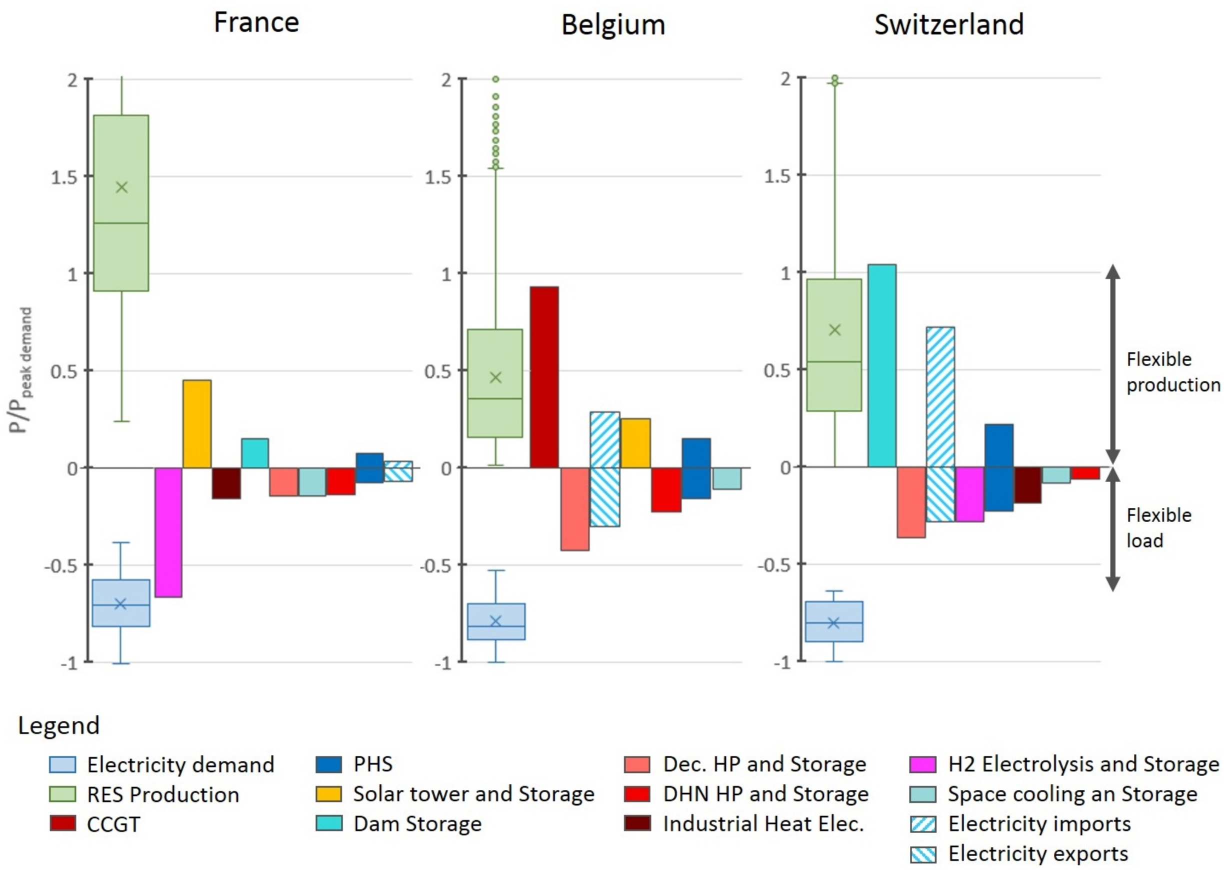

Figure 4.4: Power of flexible loads and flexible production assets compared to intermittent renewable energy sources (IRES) production and electricity demand, normalised by peak demand of the country. (abbrev. : combined cycle gas turbine (CCGT), pumped hydro storage (PHS), Decentralised (Dec.), heat pump (HP), district heating network (DHN), hydrogen (H2))

Flexibility providers in Switzerland In Switzerland, the main dispatchable producers are the hydro dams. They have an output power that can cover 104% of the fixed electricity demand.

The PHS can absorb or produce 22% of the fixed electricity demand.

The main flexible absorber of electricity are the decentralised HP with their storage. They can increase the electricity demand by 36%. The two other significant dispatchable loads in terms of power are the H2 production through electrolysis combined with its storage (28%) and the industrial electrical heaters (18%).

The electricity exchanges, limited by the transfer capacities (tc) may also bring important flexibility both in term of production (72%) and absorption (28%).

This analysis unveils the potential of the different dispatchable production and consumption technologies to help keep the adequacy between production and demand at each hour. In terms of power :

– In France, electrolysis and its H2 storage plays a major role.

– In Belgium, the CCGTs, electricity exchanges and LT heat are the most important dispatchable loads and producers.

– In Switzerland, the biggest flexibility providers are the hydro dams and the electricity exchanges.

However, to assess their actual importance in the system, we must study the quantity of energy really produced or consumed by those assets during the year. Furthermore, for storage assets, it is important to evaluate the different timescales at which they perform.

4.2.3 Storage timescales

The storage assets can be divided into two categories. The first category does mainly daily storage (energy stored for less than 24 hours) and the other, mainly longer term storage.

Figure 4.5 shows the storage technologies used for daily storage only in each country[5] and represents their equivalent number of cycles. To compute the equivalent cycle we proceed as follow. The quantity of energy that has been stored during each duration interval is computed. Then we divide by the size of the storage to compute an equivalent number of cycles.

They are heavily cycled and can reach up to 349 equivalent cycles per year for decentralised thermal storage in Switzerland.

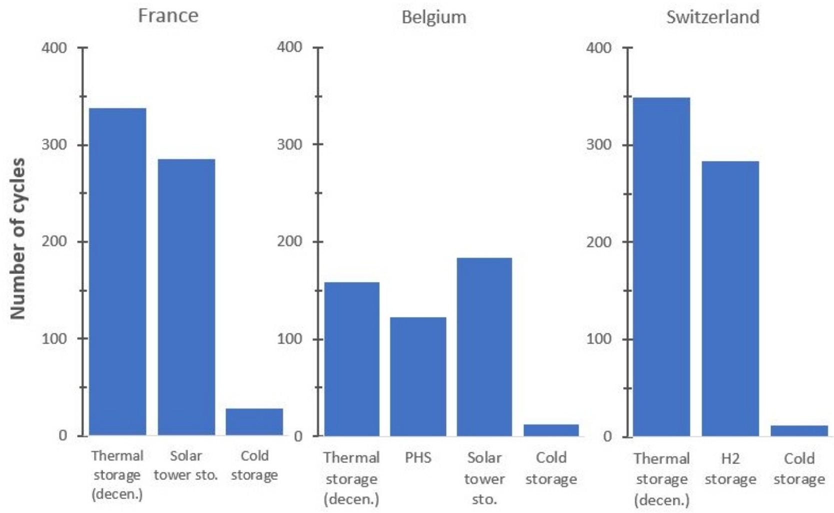

Figure 4.5: Number of equivalent cycles of daily storage in each country. (abbrev.: decentralised (decen.), storage (sto.), pumped hydro storage (PHS))

In all the countries, the thermal storage of decentralised low temperature (LT) heat and the cold storage are used as daily storages. Belgium and France both use their solar tower storage for daily storage[6]. It means that they are able to shift its solar production from day to night but not from one day to the other or seasonally. Belgium has the specificity to use its pumped hydro storage (PHS) for daily storage only and Switzerland its H2 storage.

Figure 4.6 presents the seasonal storage in each country. It allows to evaluate for each technology, the timescale at which it is the most loaded.

[5]Some of those technologies store energy for longer time periods. But the quantity of energy stored is negligible compared to the daily storage quantities.

[6]Switzerland doesn't have solar towers.

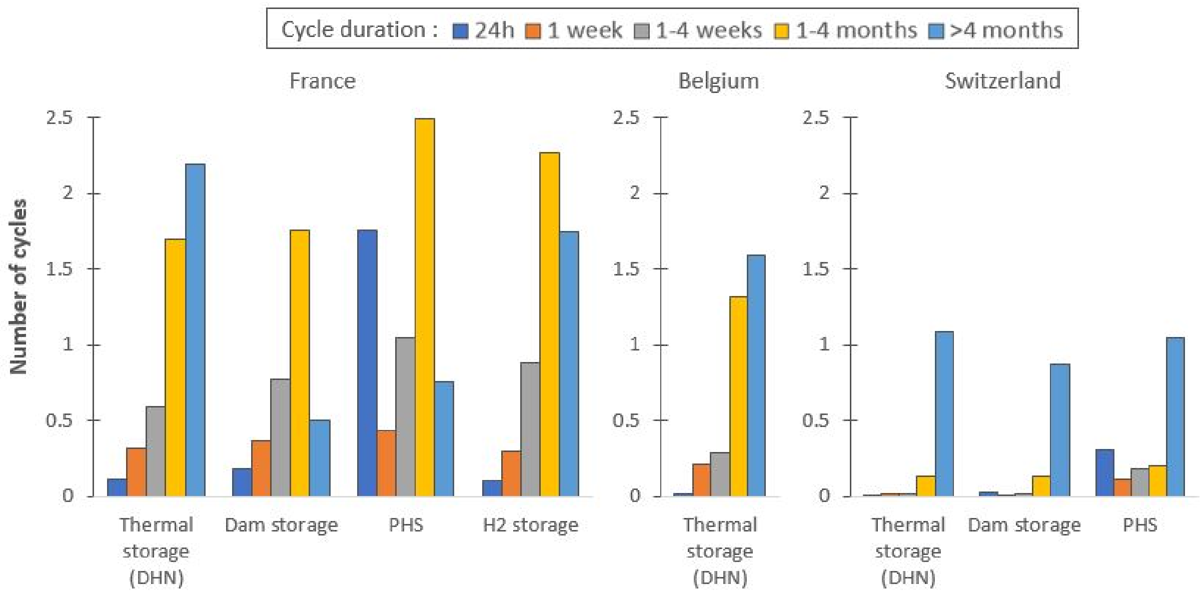

Figure 4.6: Number of equivalent cycles for mid-term and long-term storage in each country. (abbrev.: district heating network (DHN), pumped hydro storage (PHS))

The thermal storage of the district heating network (DHN) and the dam storage are used everywhere for mid and long term storage. In Belgium, DHN thermal storage is the only seasonal storage used because it has no dams.

We can see that France is using a lot of long term storage (>1month) and behaves like the seasonal storage of the overall system.

In Switzerland, each storage does around 1 full long term cycle. It shifts its production seasonally.

4.2.4 Share of the flexibility providers in the electricity mix

Figure 4.7 gives a detailed view of the relative production or demand covered by each flexibility provider over a the year. The stripped pattern represents the part that goes through storage.

Flexibility providers in France In total, the dispatchable power assets in France produce 13.3% of the yearly electricity production. Their storage shifts 5.6% of the electricity supply. The flexible loads consume 50.7% of the electricity and 10.3% of the total electricity consumed goes through their storage.

The main dispatchable producer is solar tower. It supplies 11% of the electricity . 4% of it goes through its storage.

The biggest flexible load is the H2 electrolysis (21%) and its storage (7%). It is followed by decentralised and DHN heat pumps (HPs) (11% and 5%) and their storage (1.6% both). Industrial electrical heater consumes only 3%.

Electricity exports represents 4% of total electricity demand.

Flexibility providers in Belgium In total, dispatchable power supplies 60.8% of the total yearly production in Belgium and 6.8% goes through storage before production. The flexible loads use 31.7% of the electricity. Their storage shifts 6.2% of the demand.

The main flexible producer is the combined cycle gas turbine (CCGT). It produces 30% of Belgium's electricity. It uses NG to produce electricity. The NG in Belgium comes from three sources : imported from neighbours (33%), fossil gas imported from outside the system (46%)

and locally produced by biomethanation of wet biomass (21%). Thus a part of the flexible power of the CCGT is thanks to NG exchanges. If we add that to the share of the electricity imports (20%), the exchanges allow the production of 30% of the total electricity in Belgium.

In Belgium, the main sources of flexibility for electricity consumption are decentralised and DHN HP (21% and 10%) with their storage (2.6 and 3.5%).

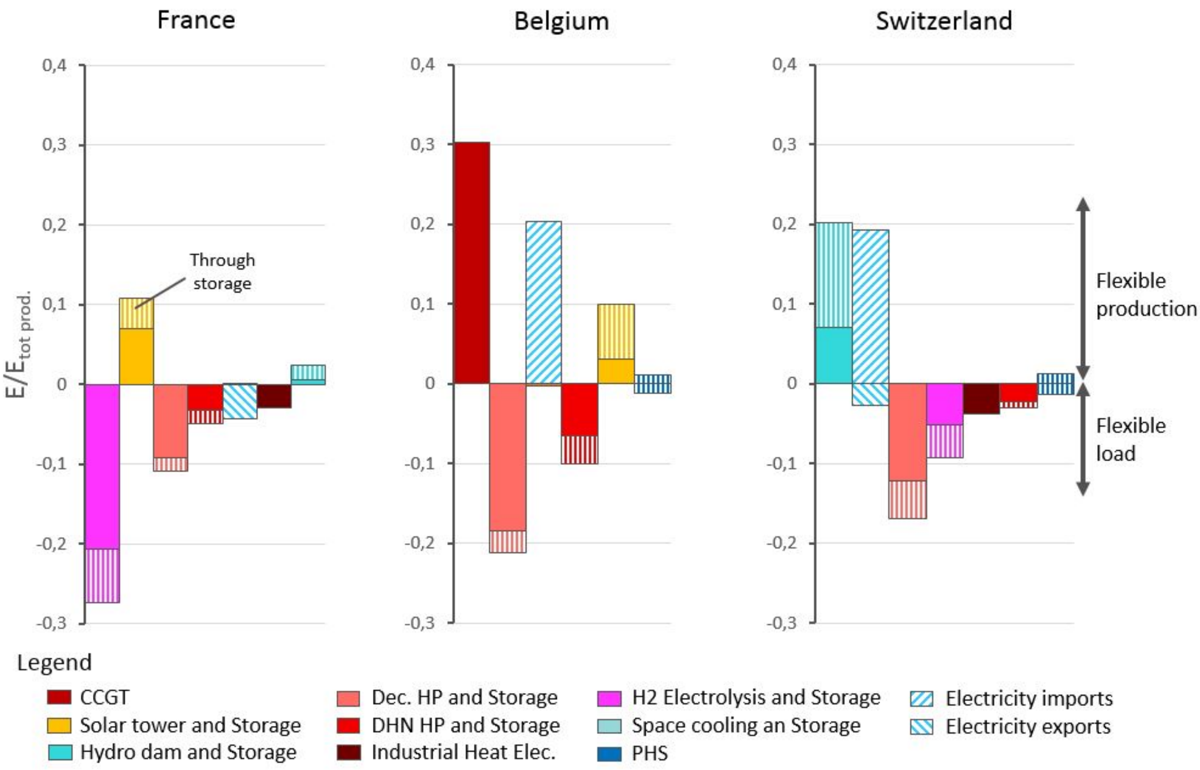

Figure 4.7: Share of the flexibility providers and their storage into the electricity production and consumption mix. (abbrev.:

Flexibility providers in Switzerland In total, the dispatchable production assets are responsible for 38.3% of the electricity mix. Their storage shifts 12.7% of the supply. The flexible loads, in Switzerland, consume 35% of the lectricity and 9.4% goes through their storage.

In Switzerland the hydro dams bring an important dispatchable production (20% and 13% through the storage). The electricity imports provide 19% of the electricity.

The two mains flexible loads int Switzerland are decentralised HPs (16%) with their storage (5%) and H2 electrolysis (9%) with H2 storage (4%). Industrial heaters (4%) and DHN HPs (2%) also play a role.

The flexibility provided by space cooling is not represented on Figure 4.7 as their share on the entire year is negligible.

To conclude on flexibility providers, we can underline two different strategies used to ensure the adequacy of production and consumption of electricity.

- The first one, occurring in France, is to install a large capacity of intermittent renewable power. Then the electrification of the mobility and heat brings the flexibility needed. It takes advantage of the low cost of H2 and heat storage. Thanks to them it can both cope with short term and seasonal variability of the production. France chooses this strategy because of its high wind potential and the low potential of electricity imports compared to its demand.

- The other strategy, occurring in Belgium and Switzerland, relies more on dispatchable production assets and imports of electricity. The load shifting happens more daily then seasonally. In the case of Belgium, natural gas (NG) imports also play an important role to provide flexible electricity production through combined cycle gas turbine (CCGT).

4.3 Verification and analysis of exchanges

As explained before, the exchanges play an important role in coping with the intermittency of power production from renewable assets. They also help countries to supply other energy demand, such as heat high temperature or mobility in Belgium.

> This section presents the verification and analysis of exchanges. This study is different for resources exchanged through a network and resources exchanged thanks to freight. It is due to the way they are modelled. In a first time, we will present the network exchanges, that is electricity and natural gas (NG). Then we will verify the exchanges of synthetic liquid fuel (SLF), wood, waste and CO_2 captured that are transported with freight.

4.3.1 Network exchanges

For exchanges through networks, the verification must be done at each hour of each typical day (TD). Figure 4.8 and 4.9 do that for electricity and natural gas (NG) exchanges respectively.

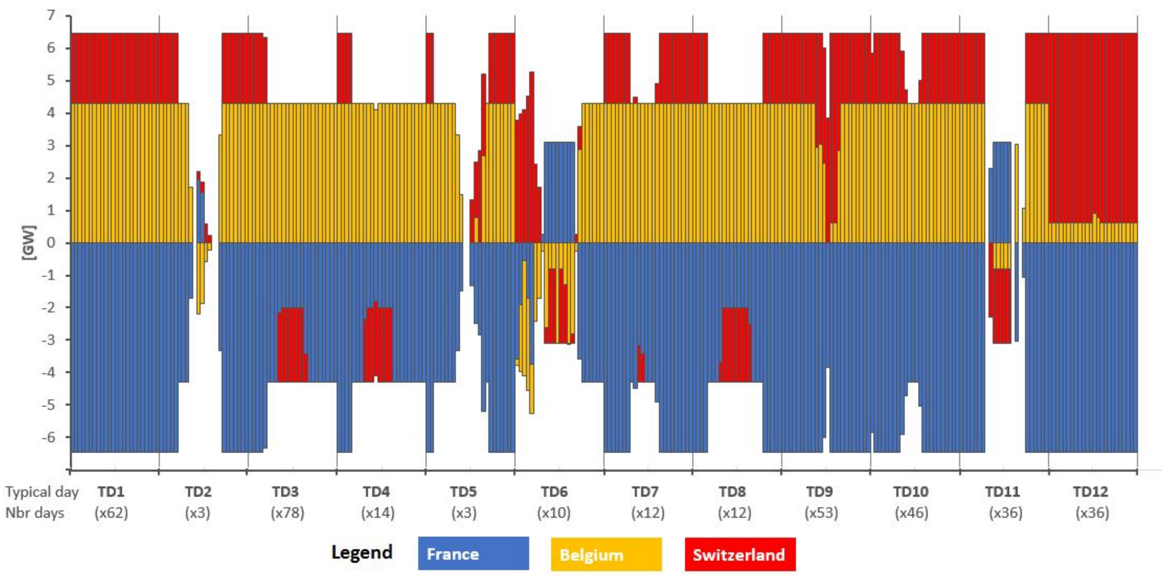

Figure 4.8: Verification of the balance of electricity exchanges between countries at each hour of each TD [GW]. A positive value means that the country imports and a negative value that it exports.

In those figures, we can check that at every hour, the total import (positive value) is equal to the total export (negative value). Under each TD, lies the number of days it represents. It allows to verify our intuitions. Most of the time, France is exporting electricity. That happens every morning and every evening and during the entire day for 349 days per year. During a total of 162 days, Switzerland exports electricity during some hours in middle of the day. Belgium has only 49 days during which it exports in the middle of the day. This patterns of exporting around midday is linked to a high production of PV.

For NG, one can notice that the only importer is Belgium and the main exporter is France. Switzerland does also export some NG to Belgium.

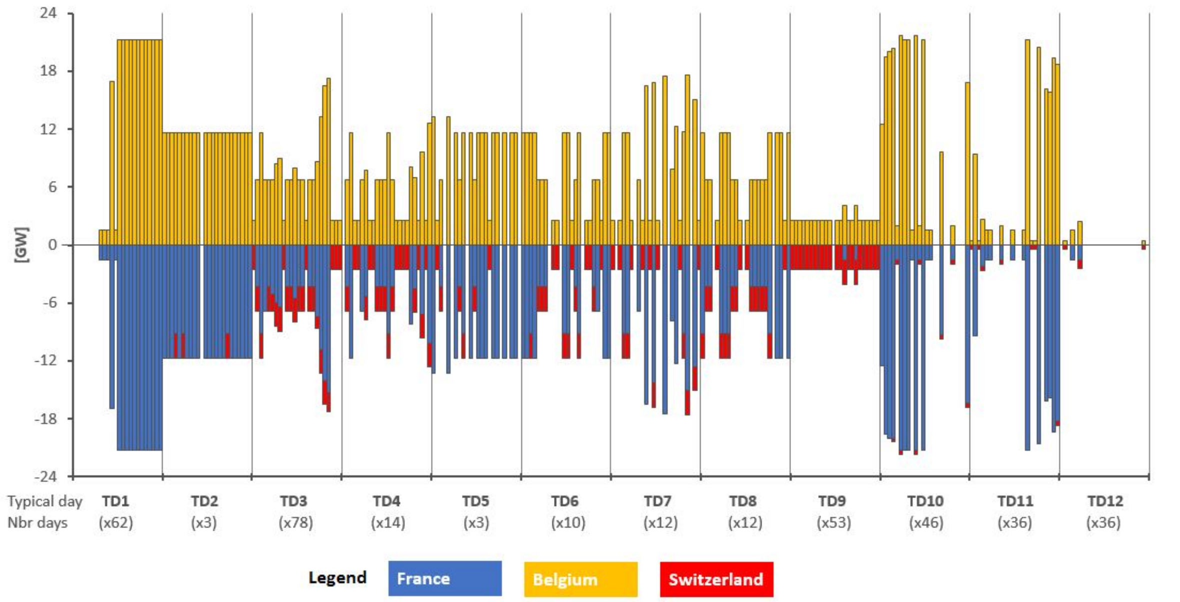

Figure 4.9: Verification of the balance of natural gas (NG) exchanges between countries at each hour of each TD [GW]. A positive value means that the country imports and a negative value that it exports.

To study the cross-border electrical lines and NG pipelines, we can use the formalism developed in Section 3.2.2. Table 4.6 presents the value of the utilisation factor (UF), transit factor (TF) and their ratio for each direction of electricity exchanges of each line. It also shows the percentage of hours of the year when the line is not used at all (Null) and when the line is saturated (Full).

There are very few hours when the lines are not used. Three lines have high full capacity utilisation the link from France to Belgium, the one from Switzerland to Belgium and the one from France to Switzerland. Those lines are also the ones with the highest utilisation factor.

Each line has a preferred direction of exchange : FR → BE, CH → BE and FR → CH. All the lines linked with France are mostly used by France to export electricity. And when they are used in the other direction, is is often for transit.

When the utilisation factor is very close from the time spent at full capacity, it means that the connections is rarely used at lower capacity. For example, this is the case for the link from Switzerland to Belgium.

When the transit factor is very close to the utilisation factor it means that most of the electricity exchanged on this line is in fact electricity from transit. For instance, the BE → CH line has a very high TF compared to its UF. Indeed, most of the electricity sent from Switzerland to Belgium is in fact sent by France and transiting through Switzerland.

Adding the time spent at full capacity full capacity of the two directions of a line allows to see which share of the year the line is saturated in one direction or the other. The interconnections FR-BE and BE-CH are saturated more then 90% of the time.

Line	Direction	Null	Full	UF	TF	TF/UF
FR-BE	FR → BE	2.0	91.54	93.06	12.75	13.70
	BE → FR	2.0	3.0	3.34	1.65	49.40
BE-CH	BE → CH	2.66	10.48	12.31	11.72	95.21
	CH → BE	2.66	81.55	81.61	71.87	88.07
CH-FR	CH → FR	2.85	10.80	11.79	8.80	74.64
	FR → CH	2.85	64.21	71.91	21.94	30.51

Table 4.6: Comparison of electrical cross-border lines : time spend at null and full capacity [%], utilisation factor (UF), transit factor (TF) and their ratio [%]. (abbrev.: France (FR);, Belgium (BE), Switzerland (CH))

Table 4.7 present the same analysis for natural gas (NG) cross-border pipelines. These are less used than electrical lines. There is only one direction of exchange which is used at full capacity : FR → BE. This happens 21.76% of the time. When this happens, we can guess that some gas is transiting through Switzerland to go from France to Belgium. Indeed, the transit factor of the NG exchanges from France to Switzerland is equal to its utilisation factor. For this reason, the pipeline CH → BE also has a high TF.

The only country importing NG is then Belgium. It generates preferred directions of exchanges which are different from the ones existing nowadays. Indeed, Belgium could send up to 35.4 GW of NG to France but never uses this potential. Assuming that changing the direction of a pipeline only needs changing the pumps, it would be interesting to study a case with other preferred direction of transfer capacities.

Line	Direction	Null	Full	UF	TF	TF/UF
FR-BE	FR → BE	46.68	21.76	34.59	0	0
	BE → FR	46.68	0	0	0	0
BE-CH	BE → CH	30.64	0	0	0	0
	CH → BE	30.64	0	16.23	9.55	58.84
CH-FR	CH → FR	78.24	0	0	0	0
	FR → CH	78.24	0	14.63	14.63	100

Table 4.7: Comparison of natural gas cross-border pipelines : time spend at null and full capacity [%], utilisation factor (UF), transit factor (TF) and their ratio [%]. (abbrev.: France (FR);, Belgium (BE), Switzerland (CH))

For more details on behaviour cross-border lines, duration curves of each interconnection for both electricity and NG can be found in Appendix D.3.1.

4.3.2 Freight exchanges

Figure 4.10 shows the yearly imports and exports of each country for resources exchanged through freight and allows to verify the balance of those exchanges.

Figure 4.10 underlines that synthetic liquid fuel (SLF) is the main resource exchanged followed by wood. However, there are no exchanges of waste and CO_2 captured. These results follow our intuitions as SLF has the highest energy density followed by wood and then waste. For CO_2

captured, there are no exchanges as the system doesn't capture CO_2. Indeed, the system does not use synthetic methanolation (SLF prod. from H2 and CO2) or synthetic methanation (NG prod. from H2 and CO2).

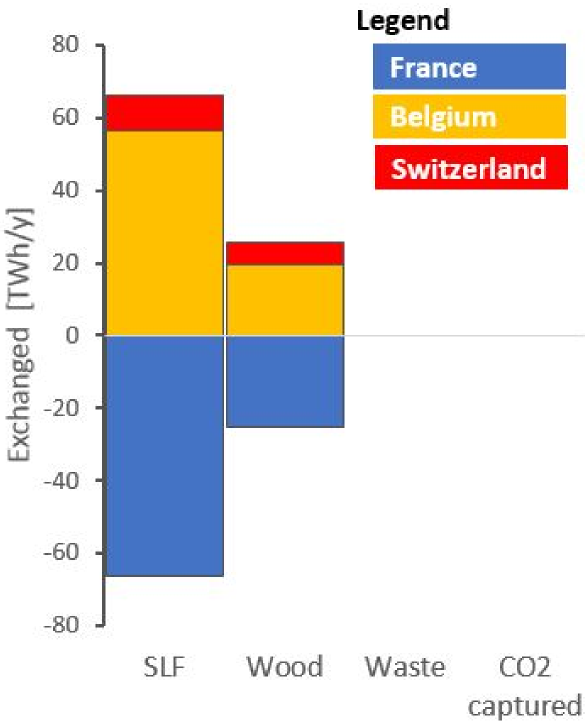

Figure 4.10: Verification of the balance of freight resources (synthetic liquid fuel (SLF), wood, waste and CO_2 captured) exchanged between countries on a yearly scale. A positive value means that the country imports and a negative value that it exports.

Table 4.8, presents the additional freight due to the exchanges of the two resources exchanged (SLF and wood). For France and Switzerland, it increases the freight demand by about 2%. In Belgium, it increases of nearly 3%. Hence the exchange through freight has a very low impact on the freight demand. The Appendix D.3.2 presents the technologies used to supply the freight in each country.

If we assume that the resources are transported with diesel trucks, it is possible to compute the quantity of diesel used. It allows to calculate the equivalent losses for each resource. They are of 7.8% for SLF and 11% for wood. This permits to compare those exchanges with the ones done through a network. As presented in section 2.3.1, electricity has exchange losses of 6.12% and NG of 2%. Hence freight resources are more expensive energetically to exchange then network resources. Their advantage however resides in the fact that they are very easy and economic to store.

	France	Belgium	Switzerland
SLF	7830.1	1886.7	429.4
Wood	4216.5	918.0	358.1
Total	12046.6	2804.7	787.5
Tot./EUD	0.0198	0.0286	0.0197

Table 4.8: Additional freight due to exchanges of synthetic liquid fuel (SLF) and wood [Mtkm/y] (no exchanges of waste and CO_2 captured).

4.3.3 Yearly balance of exchanges

For resources that can be exchanged, Figure 4.11 presents the share that is used locally and the share that is exchanged before being used.

SLF The synthetic liquid fuel (SLF) has the highest exchanged share. It is due to its high energy density and its easy storage. As a matter of fact, all the SLF is produced through pyrolysis of wood in France. It is then exported to Belgium and Switzerland where it is used for passenger and freight mobility purposes. The system prefers to exchange SLF rather then wood as it has a high energy density.

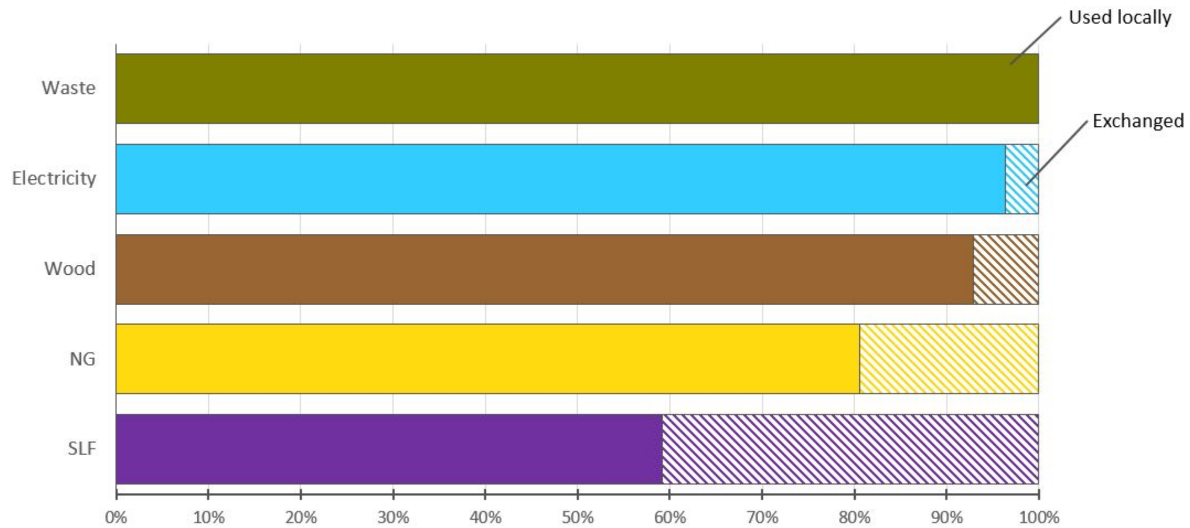

Figure 4.11: Share of resources exchanged and used locally for waste, electricity, wood, natural gas (NG) and synthetic liquid fuel (SLF).

Electricity The low share of electricity exchanged is due to two reasons. Firstly, the system is highly electrified meaning that a lot of electricity is produced in each country. Secondly, the transfer capacity of the lines limit the quantity that the countries can exchange. Most of the time, the lines are saturated.

It would be interesting to study the behaviour of the system when those transfer capacities are increased. Furthermore, the actual trend is to increase those electrical interconnections[13]. Hence, the interconnections of a low-carbon system that we might reach in 2035 or 2050 will be bigger then those of 2020 used in this study.

Natural Gas In this system, all the natural gas (NG) exchanged is produced with biomethanation of wet biomass. The availability of the latter limits the quantity of gas that can be produced and thus the quantity that can be exchanged. Another limit is the capacity of the pipeline from France to Belgium : these capacities are designed in that specific direction in the context of today's energy system. Indeed, a lot of gas transits from Belgium to the other countries [15]. It should be put into question as the pipeline from Belgium to France is huge and is never used in those results.

With a view towards a low carbon system where maybe fossil gas imports would decrease, it would be interesting to investigate the impact of exchanging the direction of those pipelines.

Wood The exchange of wood is only used to provide the industrial high temperature (HT) heat demand in Belgium. A vast amount of NG is also needed for the non-energy EUD in Belgium. It doesn't have the resources to fulfill these high industrial needs and is forced to import a lot.

Figure 4.12 presents a summary of the yearly balance of exchanges through each interconnection. It depicts clearly that France is a major exporter where Belgium is the main importer. Switzerland lies somewhere in between.

- Belgium and Switzerland import electricity, SLF and wood from France. In addition, Belgium imports NG.
- A lot of transit occurs through Switzerland : All the NG going from France to Switzerland is only transiting through Switzerland to go to Belgium and a part of the electricity does the same.
- Switzerland also behaves as an exporter towards Belgium but at a minor scale : it exports some of its own production of NG to Belgium, and to a smaller extent some of its electricity too.
- The main energy carriers for exchanges is SLF. This is due to its high energy density and economic storage. The second and third means of exchanges are electricity and NG. Some wood is also exchanged but no waste is.

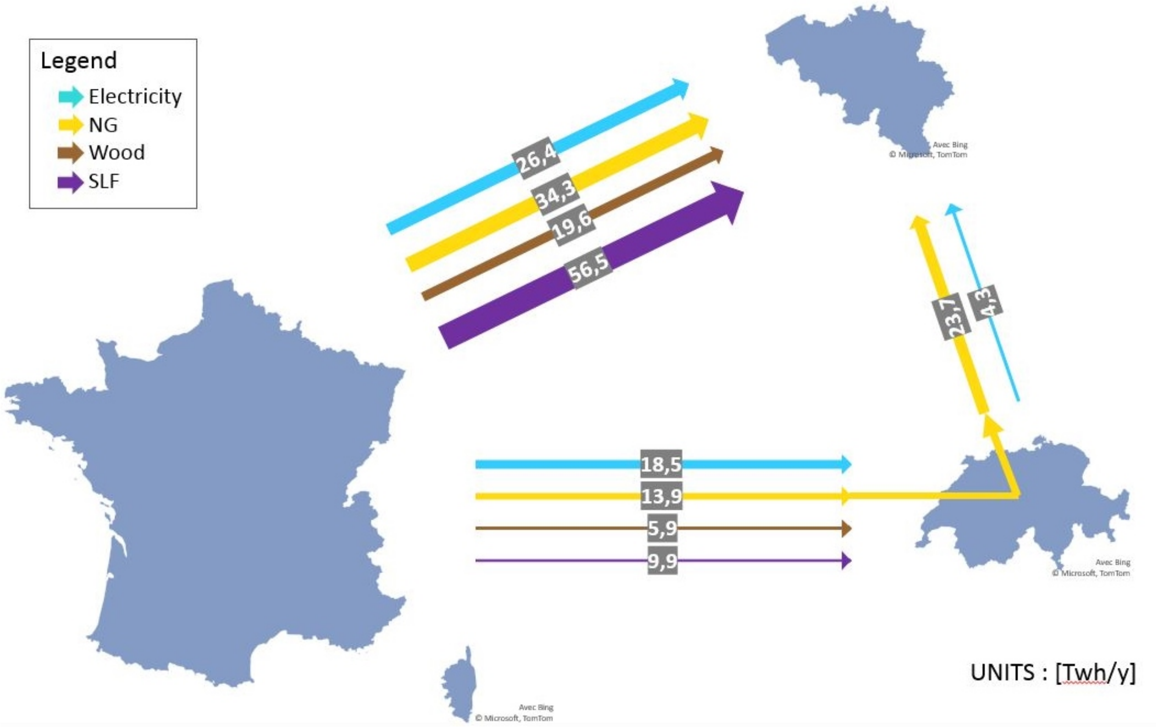

Figure 4.12: Yearly balance of exchanges for each interconnection [Twh/y].

4.4 Parametric studies

During the analysis in this chapter, we have noted several limits and questions about our new model. The most relevant ones are listed here with the associated study:

- The implemented transfer capacities of electrical lines are the ones of 2020. As explained in section 4.3.1, they seem to be to small for a low-carbon system. Indeed, they are saturated for most of the time, which leads to a transiting behaviour. It would be interesting to study the impact of installing bigger cross-border transmission lines.
- The resources exchanged by freight (synthetic liquid fuel (SLF), wood and waste) are aggregates of several products. Their energy density can vary a lot according to which product is exactly transported. This influences the quantity of additional freight. It is thus interesting to study the sensibility of the results to a change in lower heating value (LHV) or energy density of these energy carriers.
- The emission targets determined for the studied scenario are arbitrary. It is interesting to analyse different emission targets to understand what an energy transition, with gradual decrease of GHG, would look like. In the context of this thesis, it is particularly instructive to see the impact of exchanges of energy carriers on this energy transition.

> Hence three small parametric studies will be carried out. Two goals are purchased. The main one is to find out the influence of those parameters on the obtained results. The second one is to show the kind of deeper studies that our tool is able to produce. Therefore, the analysis done will not go into much detail but rather present general indicators to highlight general tends.

4.4.1 Parametric study of electrical cross-border lines transfer capacity

In the former sections, the transfer capacities used for the electrical interconnections were the ones of 2020. They were often saturated leading to an important transit phenomenon. In this section, we will study the impact of increasing all those transfer capacities by a multiplication factor of 2, 5 and 10. In each case, we will compute the cost-optimum system for the all exchanges scenario with emission target of 40 MtCO2-eq/y.

Figure 4.13 presents the evolution of the cost of the system with this increase in transfer capacities of electrical lines. The fixed investment and operation cost of electrical lines is taken into account (see section 2.3.1). At first, the cost decreases as we increase the capacity of the lines. Then, at some point, the gain in cost due to more electrical exchanges gets lower than the additional cost due to increase of transfer capacities of electrical lines. This graph underlines that our tool would permit in a particular case to evaluate how much we should increase the size of the cross-border electrical lines. The slope of the curve also changes: doubling the current transfer capacities causes a larger cost decrease per than quintupling it.

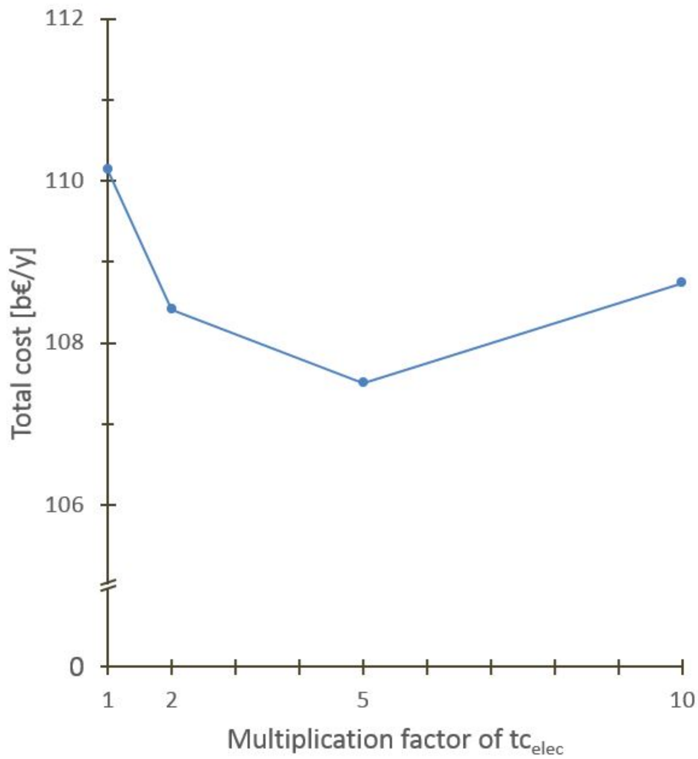

Figure 4.13: Evolution of the total annualised cost of the 3-cell system with an increase in transfer capacities of electrical lines (tc_{elec}). The increase is expressed as a multiplication factor of the 2020 transfer capacities (see Section 2.3.1).

Figure 4.14 depicts the evolution of the exchanges of each resource with the increase in electrical transfer capacities. As the transfer capacity increases, the electricity becomes the major mean of exchanges.

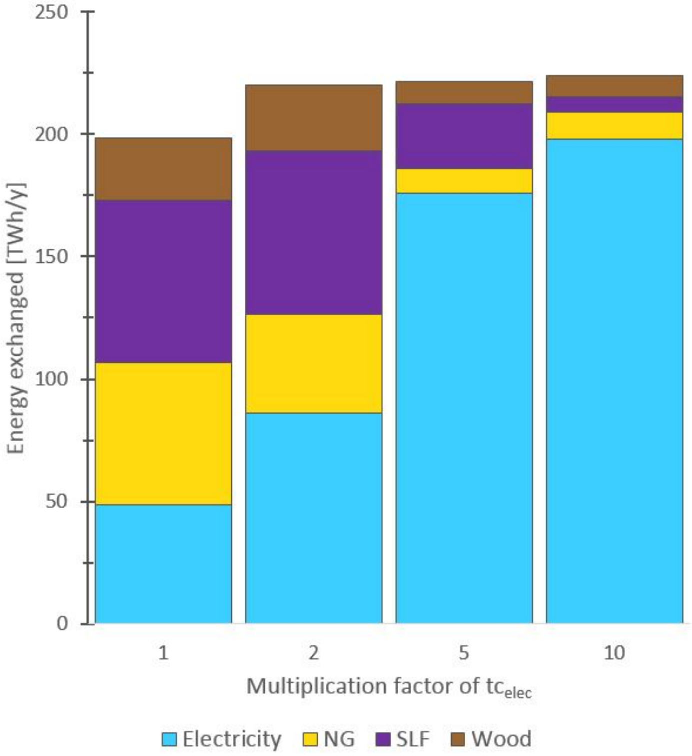

Figure 4.14: Evolution of energy exchanged by each carrier with the increase of electrical transfer capacities (tc_{elec}).

To determine whether it is useful to increase this much the transfer capacities, it is interesting to look at the time spent at full and null capacity as well as the utilisation factor (UF) and transit factor (TF). These were defined in section 3.2 for each direction of each line. Here, we will sum the two directions of each line for each one of these factors to have a global view on the line. Figures 4.15, 4.16 and 4.17 illustrate the evolution of these factors for each line as we increase the transfer capacities.

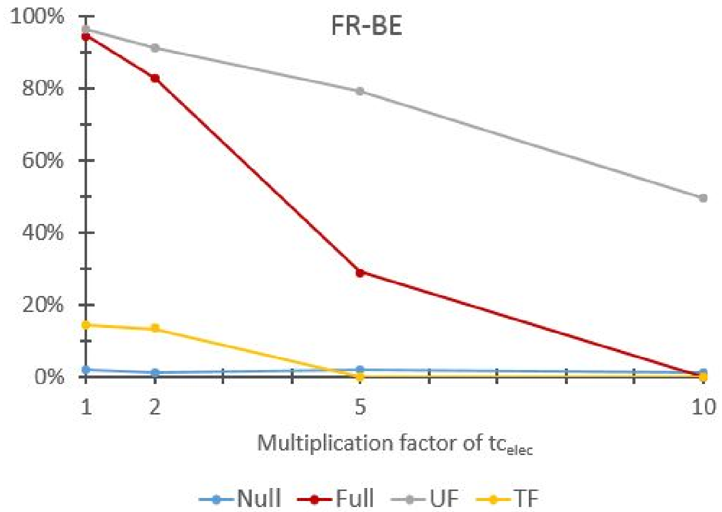

Figure 4.15: Evolution of the time spent at null and full capacity and of the utilisation factor (UF) and the transit factor (TF) of the FR-BE electrical lines with the increase in electrical transfer capacities (tc_{elec}) size.

Figure 4.15 underlines that the electrical line linking Belgium to France continues to be used even a very high transfer capacity. Its UF is of 49.4% for lines 10 times bigger than in 2020. Howerer, the full utilisation drops strongly between the 2 times and 5 times bigger transfer capacities case. It goes from 82.5% to 28.9%. Hence, the transfer capacities with a multiplication factor of 5 are used at their full capacity less than one third of the hours of the year. Maybe it is not worth it to build such big cross-border lines.

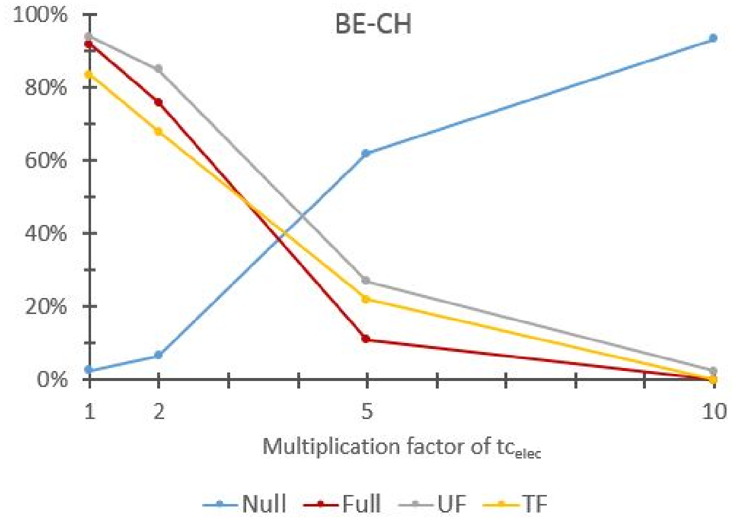

Figure 4.16: Evolution of the time spent at null and full capacity and of the utilisation factor (UF) and the transit factor (TF) of the FR-BE electrical lines with the increase in electrical transfer capacities (tc_{elec}) size.

From figure 4.16, the line from Belgium to Switzerland is mostly used from transit. Indeed, its UF and TF always stay very close. They drop together as we increase the transfer capacities. This line is not used at all 62% and 93.4% of the time for the lines with a multiplication factor of 5 and 10. Hence, it is less interesting to increase this line than the former one. It underlines the interest of studying the increase of transfer capacities with different multiplication factor for each lines.

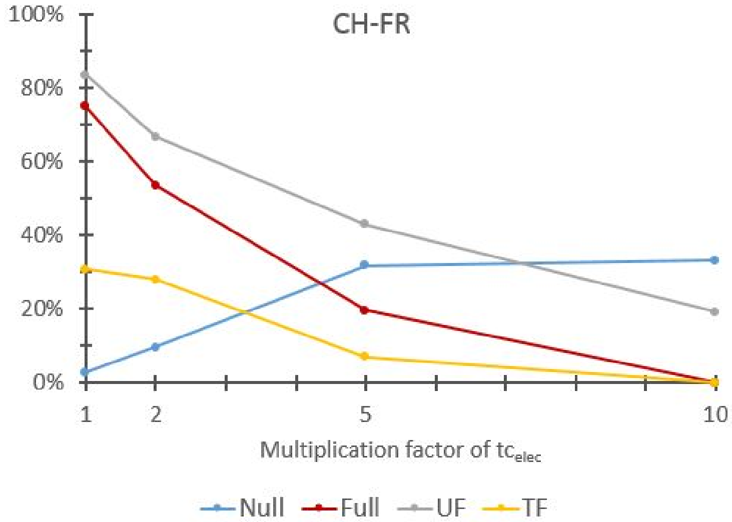

Figure 4.17: Evolution of the time spent at null and full capacity and of the utilisation factor (UF) and the transit factor (TF) of the CH-FR electrical line with the increase in electrical transfer capacities (tc_{elec}) size.

In Figure 4.17, the null utilisation of the line CH-FR climbs to 31.7% and 33.1% for lines 5 and 10 times bigger respectively. On the same time, its full utilisation drops to 19.57% and 0%. It shows that it is not interesting for this line to increase to 5 or 10 the transfer capacities.

To conclude, the tool developed in this work allows to study the impact on a system when increasing the capacity of the lines.

In the 3-cell scenario with all exchanges, the cross-border electrical lines of 2020 are undersized. This parametric study underlines the interest of increasing their transfer capacities. It shows that at some point the lines become oversized and can even increase the system's cost. The tool developed enables to estimate the best size of the electrical lines for a particular system. In this case, it lies somewhere between 2 and 5 times bigger than the actual transfer capacities. However, this multiplication factor could also be different for each line.

4.4.2 Sensitivity analysis of the efficiency on energy exchanges through freight

In this section, we will study the impact of the efficiency of energy exchanges through freight on the results. Indeed, as the resources exchanged through freight represent multiple different products, their energy density can vary. This energy density influences the efficiency of the transportation as explained in Section 2.3.2. In this section, we will study the evolution of the total yearly quantity exchanged of each resource as a function of the energy density of the resources exchanged through freight. For each one of them, we will take the smallest and biggest lower heating value (LHV) from Table 2.4.

Variation of energy density of SLF: Table 4.9 illustrates the sensitivity of the model to the energy density of SLF exchanged. The energy density is expressed through its LHV. The second column gives the quantity of energy exchanged by each energy carrier in the reference case, with average energy density for each resource exchanged through freight.
The third and fourth column express by how much % the reference value increases or decreases when the reference density of SLF is replaced by its minimal and maximal value.

It can be observed that the system is not sensitive to the energy density of SLF. The biggest exchange variations are for SLF and wood. However, these relative changes are less than 1%. Furthermore, the total cost changes less than 1% as well.

Resource	**Ref. exch**	min. lhv_{SLF}	max. lhv_{SLF}
Electricity	48.6	0	0
NG	58.8	0	0
SLF	66.4	+0.48	-0.30
Wood	25.5	-0.59	+0.97
Waste	0	0	0
CO_2	0	0	0

Table 4.9: Exchanges in the reference case [TWh/y] and their relative variations [%] when the energy density (lhv) of synthetic liquid fuel (SLF) is given its maximal and minimal value

Variation of energy density of Wood: Table 4.10 presents the variations from the reference case as the energy density (lhv) of wood is set to its minimal or maximal value.

For the maximal energy density, some changes can be observed. The exchanges of wood over the year increase by 6.4% but don't influence much the other exchanges.

For the minimal energy density, the exchanges of wood disappear. The other exchanges don't increase to compensate. Hence, under a certain energy density, the system prefers to not exchange the resources.

When the *lhv* of wood varies between its minimum and its maximum, the total cost of the system varies less than 1% as well.

To conclude, some types of wood with higher energy densities are interesting to exchange while others with lower energy density aren't. The model developed lacks of precision to take that into account.

Resource	**Ref. exch**	min. lhv_{wood}	max. lhv_{wood}
Electricity	48.6	0	-0.1
NG	58.8	0	-0.2
SLF	66.4	0	-0.2
Wood	25.5	-100	+6.4
Waste	0	0	0
CO_2	0	0	0

Table 4.10: Exchanges in the reference case [TWh/y] and their relative variations [%] when the energy density (lhv) of wood is given its maximal and minimal value

Variation of energy density of Waste: The waste was not exchanged in the reference scenario. When varying its energy density, nothing changes. It seems that all types of waste have a too low energy density to be worth trading.

4.4.3 Energy transition study

> This section studies the impact of the exchanges on the energy transition of the 3-cell system composed of France, Belgium and Switzerland.

It is rather a "pseudo-transition" analysis than a real case. Indeed, to study transition, we should consider a pathway that starts at the current energy system. Due to these temporal and practical constraints, it is not realistic to change the entire system at once to obtain a small emission reduction.

In our case, this problematic is not taken into account. Indeed, our tool is a "snapshot" tool. It designs the cost-optimal system for a specific year with specific emissions without taking into account the path to go there.

Hence, we can study the energy transition through comparing the cost-optimal system for different emission targets. This doesn't take into account the constraint of pathway explained above.

Figure 4.18 presents the Pareto frontier graph for the energy transition of our 3-cell system. It consist of the optimal cost obtained under different emissions constraints. It has been build for the no exchanges, the electricity exchanges and the all exchanges scenario. For the electricity exchanges scenario, the fixed cost of electrical cross-border lines is taken into account. For the all exchanges scenario, both the fixed cost of cross-border electrical lines and NG pipelines is taken into account (see section 2.3.1).

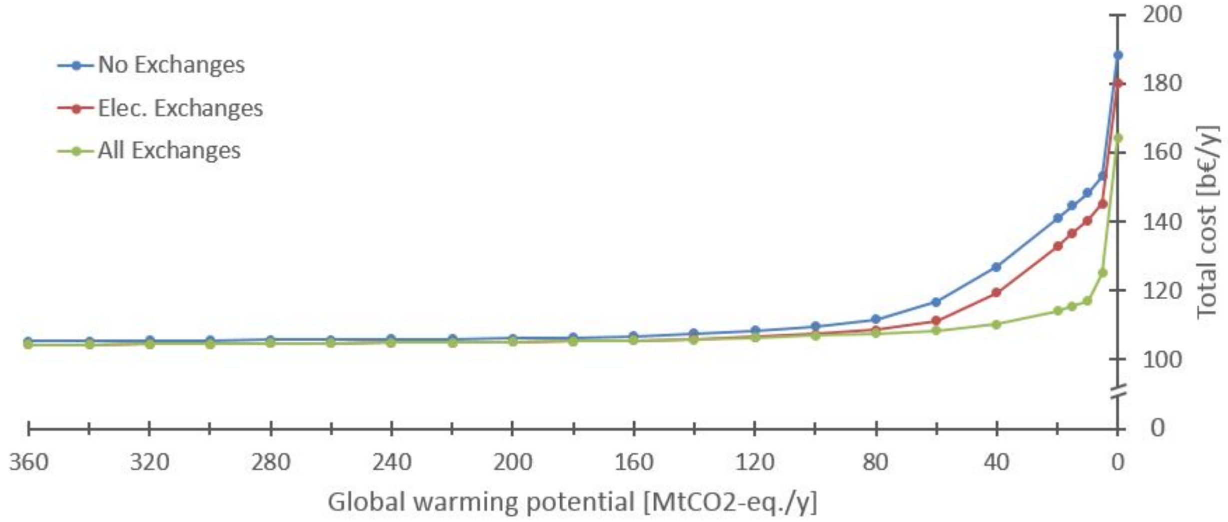

Figure 4.18: Pareto front of the cost-CO2 optima for the no exchanges, electricity exchanges and all exchanges scenarios.

At high emissions, the cost of the three scenarios are very similar. However, when reaching the very low-carbon systems, the all exchanges scenario is the least expensive.
At emissions of 80 MtCO-eq./y, the cost of the no exchanges and the electricity exchanges scenarios begin to raise exponentially. Exchanging only electricity is not sufficient to lower substantially the cost of the lower-carbon systems. On the contrary, exchanging more energy carriers allows to significantly lower the cost. It decreases the cost of 13% in the case with 40 MtCO2-eq./y, which is the emission target of the above study.
At emissions of 10 MtCO2eq./y, electricity exchanges alone can decrease the total cost of the system up to 6% compared to the no exchange scenario. However, exchanging all the resources can decrease the total cost of the system up to 21%. That represents an economy of 31.4 billion euros per year. To compare, when optimised, the Belgian system alone has a cost of around 20 billion euros per year.
At emissions of 5 MtCO2eq./y the cost of the system in the all exchanges scenario begins to raise exponentially as well. This phase corresponds to the moment when the system wants to stop use the local waste resources, wood and wet biomass. Since the model takes into account the emissions linked to the production of those resources, their operation emissions are very small but non-zero. Hence, to get to a zero operation emissions system, the model reduces the use of these resources. It is debatable whether we want to achieve such a system and totally get rid of the biomass in our energy systems. Moreover, the emissions linked to the production woord and biomass were determined by an LCA that considered current energy mixes. The model does not take into account that these emissions will be lowered when the energy system comes closer to zero-emission goals.

Figure 4.19 presents the evolution of exchanges as we lower the emission target for the all exchanges scenario.

Down to a target of 160 MtCO2-eq./y the exchanges don't vary and essentially consist of electricity and SLF. The electricity exchanges will not vary much at lower emissions target either as the lines are already saturated.

At emission targets of 140 MtCo2-eq./y, the exchanges of SLF increase and wood is starting to get exchanged. They will both peak at 80 MtCO2-eq./y to a value of 87.7 and 29.3 TWh:y exchanged respectively. They will then decrease as NG becomes to major means of exchanges.

The results at emissions lower than 20 MtCO2-eq./y, are not analysed for the reason explained above.

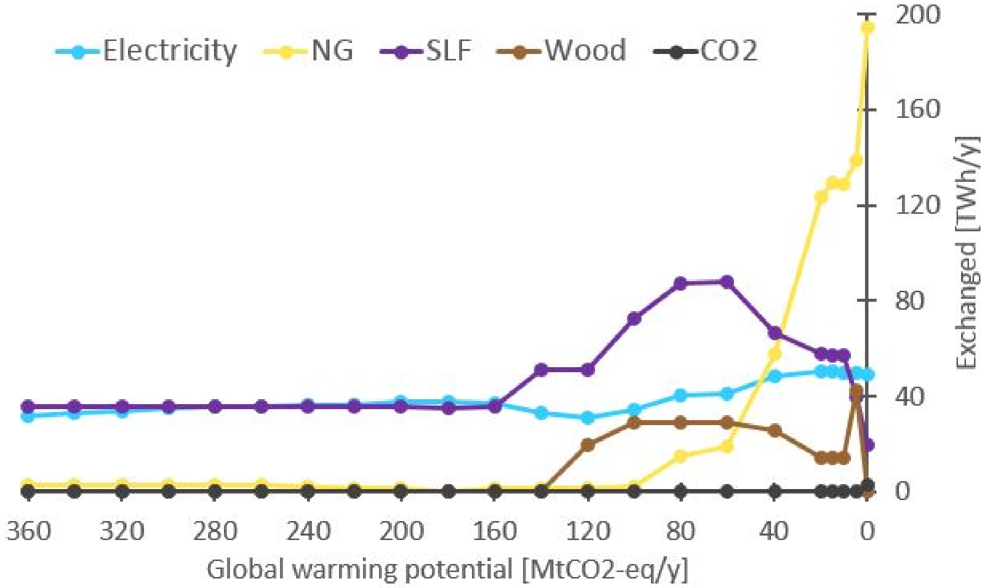

Figure 4.19: Evolution of exchanges during the energy transition of the 3-cell all exchanges scenario.

4.5 Conclusion

In this chapter, we have applied our multi-regional model on a three cell system with exchanges of multiple energy carriers. The system was allowed to exchange wood, waste, synthetic liquid fuel (SLF), natural gas (NG) and CO2 captured. The main results are summarised as follows :

- Wood, , NG, and electricity are exchanged and France is the main exporter towards Switzerland and Belgium. The main resources exchanged are : (i) SLF (ii) NG (iii) electricity.
- To face the high share of intermittent renewable energy sources (IRES), France, Switzerland and Belgium will require flexibility in their electrical mix. As France is the net exporter of the system, its strategy will be based on high production of IRES and flexible loads such as electrolysis and seasonal storage. Switzerland and Belgium are net importers and will rely on dispatchable production and daily storage. Indeed, France acts like a seasonal storage for them. In addition to the imports, Belgium's flexibility is mainly based on combined cycle gas turbines (CCGTs) and Switzerland on hydro dams.
- The balance of exchanges of all energy carriers has been verified and analysed. (i) The electrical lines are often saturated, while only one gas pipeline is often saturated (BE $\rightarrow$ FR), (ii) The additional freight due to exchanges in each country is small (2% of the end-use demand (EUD) of freight)
- The developed tool is suitable for parametric analysis and has pointed out some observations on the 3-cell case : (i) The transfer capacities of electricity are undersized and increasing its capacity from 2 to 5 times its actual capacity could be valuable in

terms of cost and utilisation factor, (ii) The sensitivity of the results on the energy density of SLF and waste is negligible (less than 1 %) while for wood, it is very sensitive. Under a certain energetic quality, wood is not suitable for exchanges, (iii) Exchanging multiple energy carriers is interesting in terms of cost for very low-carbon systems (decrease of 21 %) compared to the case with no exchanges, (iv) Synthetic natural gas appears to become the dominant exchange energy carrier when heading towards a neutral carbon system.

These conclusions confirm the consistency of the model. These findings reveal certain trends for multi-regional low-carbon systems. A real life case would enable to corroborate these trends.

Chapter 5

Discussion

Throughout this work, we have build a multi-regional and multi-sector model. It has been developed as an extension of the already existing multi-sector model : EnergyScope TD [26].

The methodology of this multi-regional model has been developed in Chapter 1. Then the practical study case composed of France, Belgium and Switzerland has been described in Chapter 2. Thanks to the insights developed in this chapter, the verification of the consistency has been conducted in two steps. First, the verification of a scenario with electrical exchanges in Chapter 3 allowed us to focus on electrical exchanges and confirm the consistency of the model. Secondly the verification of a scenario allowing 'all' exchanges in Chapter 4 enabled us to verify the consistency of a scenario exchanging multiple resources. The results of this last verification which includes our entire model, that is exchanges of multiple energy carriers will be discussed in this chapter.

In the 'all exchanges' scenario (Chapter 4), we have verified the methodology by the mean of a practical study on a low-carbon 3-cell system composed of France, Belgium and Switzerland. The 'all exchanges' scenario allows to exchange electricity, NG, SLF, wood, waste and CO_2 captured.

In this low-carbon system, a deep penetration of intermittent renewable energy sources (IRES) appears . The results in Chapter 4 demonstrate that in our model, other trades than electricity, such as NG and SLF appear to play a major role in this system. The exchanges of different resources, the complementarity of the different regions, as well as the electrification of the heating and mobility (mainly through H2) sector help the system to manage the intermittency of the renewable energy sources. Furthermore, our results showed that allowing different kinds of commodity exchanges decreases the cost of a low carbon system of up to 21%.

During this study, several tools and indicators to analyse a multi-region and multi-sector energy system have been developed.

The model developed also allows to conduct parametric studies. In Section 4.4, we carried out the following examples on the 3-cell system :

- The size of electrical cross-border interconnections has been studied. They appeared to be to small. This system could win to install 2 to 5 times larger transmission lines between countries.
- The sensitivity of the model to efficiency of transportation of resources exchanged through freight has been studied. It showed a very low sensitivity for all the resources studied

except for wood. For this resource, it showed that under a certain quality of wood in terms of energy density, it is not worth to exchange it.

– The energy transition of the 3-cell system has been studied. It was carried out for three scenarios allowing different exchanges : no exchanges, electrical exchanges and all exchanges. It showed that allowing all exchanges lowers the cost of low-carbon energy systems.

> In the rest of the section, the specificities and different limits of our multi-cell model are presented. Focusing on the limitation reveals the possible avenues for future researches.

Specificities of the model

A lot of multi-regional energy models already exist. Most of the time, those models focus on the electricity system. The specificities of EnergyScope MC are listed below :

– It is a **multi-sector** model representing with the same level of details each sector. It takes into account several sources and demands of energy and models the energy conversion system to link them. It allows to study the synergies between different sectors.

– It is a **multi-regional system connecting different countries through multiple energy carriers**. It means they can exchange not only electricity or natural gas (NG) like existing models but also other resources such as synthetic liquid fuel (SLF) and wood. Its design allows to easily add exchanges of more energy carriers such as hydrogen (H2). The trading of resources through networks and thanks to freight are implemented in two different ways based on their energetic cost and their transfer capacity limit. It allows to take into account the specificity of each kind of resource for its transportation.

– Its **hourly resolution** allows to study energy systems with a high penetration of intermittent renewable energy sources (IRES).

– It is a **linear programming (LP) optimisation** model. It optimises the total annualised cost under certain emission constraints. It takes into account both the investment and operation of the system.

– It is an **open-source** model and is part of a larger project with different open-source version for different purposes [5, 3, 6].

For all these reasons, the model developed is unique and brings a novelty to the set of models already existing [11]. It allows to both study multi-energy system and multi-region interconnected systems to underline their possible synergies.

Limitations of the model and future works

However, this multi-regional model has its limitations. It is not suitable for all types of application. Moreover, it could be subject to future versions.

Covered distance in freight exchanges

The implementation of the additional freight due to the exchanges of resources relies on the distance they travel and their energy density. This distance is estimated as the half of the biggest distance between two big cities in each country. This definition is not precise at all.

However, as seen in Chapter 4, the additional freight due to exchanges only increases the freight demand by 2%. We can guess that the distance parameter will not have a very big influence on the overall results. To verify that, a sensitivity analysis should be done. If the model is to sensitive to this parameters, it could be improved. For example, having as a parameter the potential localisation of production of SLF or the wood extraction localisation.

Mobility investment cost

The investment cost of the mobility is not taken into account in EnergyScope. This has biased the results as already mentioned in the previous sections. The model opts thus for the most efficient an most flexible technology without considering its cost. In this particular case, the model chooses to install a lot of fuel-cell mobility with hydrogen. Indeed, this technology is efficient and hydrogen can be stored in its seasonal storage when overproduction of electricity occurs. Though hydrogen mobility sometimes seen as the future of mobility [17], in practice, it is still at a research point. Its storage is also questionable as it is not mature for the moment, even though it seems to be a promising technology [15]. Thereafter, the material of fuel cells is also a technical challenge [16, 21] .

This lack of cost for the mobility could have an impact on the exchanges. In our model, the exchanges of resources with freight increase the freight demand. This is how their energetic cost is implemented. Yet, the cost of the mobility technologies are not taken into account in this model. Thus the cost of the infrastructures needed to transport resources through networks are considered (cost of electrical grid and gas network). But the cost of the trucks, boats and train necessary to transport the other resources is not considered. Although, the increase of freight is only of 2%, this implementation of cost for mobility technologies would bring more precision to the model.

Moreover, the implementation of the investment cost of the mobility will most likely change a lot the mobility system. The share of fuel cell vehicles will decrease as they are very expensive. Hence, it might influence a lot the system in terms of type of energy needed and of flexibility providers.

Modelling of the resources

Some resources are not modelled very precisely in EnergyScope. For instance, SLF, wood, waste and wet biomass resource are aggregates. Each one of them represents several products with close yet different properties. This lack of precision can influence the exchanges in the system.

From the parametric study of Section 4.4.2, we know that the exchanges are not influenced by the energy density of SLF

It has been demonstrated in the parametric studies (section 4.4.2) that not all types of wood are interesting to exchange. It depends on their energy density. The wood with the lowest energy is not worth exchanging.

Waste is never exchanged. It seems that its energy density is too low to be worth exchanging.

Concerning the wet biomass, the different energy densities of this aggregate have less influence in this multi-cell version as they are not exchangeable. However, a better classification of the different components of wet biomass could bring more precision to the biomethanation process which is used quite a lot in this system.

Transfer capacity as a variable

The parametric studies of Section 4.4.1 suggest that increasing the electrical transfer capacities to a certain extent is interesting. In our model, the value of the transfer capacities of the different networks are parameters and have the 2020 values. It would be interesting to implement the transfer capacities as variables in order to let the model define their size to optimise the total annualised cost.

The same approach could be developed for gas pipelines.

Emergence of new networks

Also, it has been demonstrated that exchanges through networks are more efficient in terms of transport. It would be interesting to add the possibility of building a network for some resources (e.g. pipelines for SLF or H2). The model could then choose to use either freight and/or a network to transport exchanged energy carriers of some forms.

This remark also stands for NG that could be transformed into liquefied natural gas in order to be transported by freight.

Other exchanges of resource

In our analysis, we have chosen to allow exchanges of electricity, NG, SLF, wood, waste and CO_2 captured. This choice could be reconsidered. For instance, hydrogen could be exchanged. Indeed, several european countries are currently testing to introduce hydrogen in their gas networks [15]. The study of energy transition of Section 4.4.3 revealed that in very low-carbon systems the NG exchanged between countries is produced from hydrogen because the availability of wet biomass has reached its maximum. It could thus be interesting to analyse this path.

Number of typical days

The number of typical day (TD) chosen for our model is the same as for the uni-cell model EnergyScope TD. This is an arbitrary choice. As for EnergyScope TD a parametric study on the numbers of TD should be conducted [26]. It would allow to choose the number of TD for our multi-region model as the best compromise between precision of the results and computational time.

Moreover, it should be studied if this best number of TD depends on the number of regions modelled. If it is the case, the procedure to choose the number of TD could be automated.

Methodology of data analysis

The solution defining the multi-regional system has a lot of output data. Indeed, no other model in the literature takes into account both multiple countries, multiple energy exchanges and multiple sector. This increases both the size and complexity of the system. Analysis tools are needed to understand some results efficiently.

During our master's thesis, we have developed some approaches to study such systems. In this work we have presented some tools : sankey diagrams, flexibility providers, utilisation factor (UF) and transit factor (TF) of interconnection lines, etc.

However, a specific methodological analysis would be beneficial for scenarios with more regions and for sensitivity analysis and parametric studies.

Computation time

The computation time of our model is approximately 30 minutes for a three cell case. A case with more cells should be done in order to have an idea of the computation time depending on the number of regions interconnected.

More flexibility in demand response

The demand response is seen as one promising way to cope with the intermittency of renewable energies [4]. It is only partially modelled in EnergyScope. Indeed, using the concept of end-use demand (EUD) to define the energy demand allows some flexibility in terms of final energy consumption (FEC). However, a part of the EUD could also be shifted to allow more flexibility and load side management. Further works could add this possibility in EnergyScope.

Realistic scenario

The three-cell case presented in this master thesis is fictive. The objective was to verify the multi-regional methodology developed. It would be interesting to analyse a real-life scenario, for example Western Europe.

Boundary conditions

In the 3-cell scenarios studied, Switzerland, France and Belgium are considered as isolated from other neighbouring countries. They can only exchange resources together and import fossil resources from the exterior of the system. For this case, this assumption is far from the reality. However, in a bigger system such as Western Europe, the interconnections with neighbouring countries of the overall system are negligible compared to the energy exchange inside the system. In such a case, the assumption of no other interconnections of boundary countries with the neighbours makes more sense. In reality, if big scenarios are considered, this hypothesis could be manageable, but in the case of a small system, boundary conditions allowing electricity imports and exports should be defined.

Validation

This thesis has verified the consistency of the model implemented. A validation comparing the EnergyScope MC results with real-life data or another energy model could be very interesting.

No detailed operation strategy

EnergyScope computes the operation of the system over the whole year with a time-step of 1 hour. However, it doesn't have enough precision to plan a detailed operation strategy. For instance, it lacks of precision in the modelling of the ramping up and down abilities of the conversion technologies. To make sure the proposed system works as intended, it should be tested with a more precise electrical modelling tool such as Dispa-Set [5].

Furthermore, EnergyScope doesn't take into account the other problems brought into the grid by IRES such as voltage changes, unbalance, harmonics, etc.

This discussion highlights the strengths and limitations of the our EnergyScope MC model. It would be interesting to address these limitations in future studies.

Conclusion

Global warming and its consequences are a major threat for humanity and global ecosystems. In this context, the European Union has set its objective to be carbon neutral by 2050. To achieve this objective, the energy sector has to face major changes. In order to plan this energy transition, there is a need for energy system models. Those systems should help building a strategy to lower the greenhouse gas (GHG) emissions and integrate a high share of renewable energies in the system. It will be important to find complementarity between European countries and synergies between different form and demands of energy.

In this master's thesis, an open-source model, based on linear programming (LP), for strategic planning of multi-regional and multi-sector energy systems has been developed : EnergyScope multi-cell (MC). This model optimises the total annualised cost (investment, operation and maintenance) under emission constrains for a global system composed of several regions. When modelling the system of each country, it takes into account all the energy end-use demand (EUD) : electricity, heat and mobility. Furthermore, the countries can exchange several energy carriers such as electricity, natural gas (NG), synthetic liquid fuel (SLF), wood and waste. It allows to study low-carbon energy systems with high penetration of renewable energies thanks to its hourly resolution.

This model has been applied to a fictive and simplistic 3-cell case composed of France, Belgium and Switzerland interconnected. In a first time, the energetic demand and potential of renewable energies in each country has been presented. It allowed to develop some intuitions on the system. Then a low-carbon system has been modelled with our tool. Three different scenarios have been studied according to the exchanges permitted between countries: no exchanges, electrical exchanges and all exchanges scenarios. The latter allowed exchanges of electricity, NG, SLF, wood, waste and CO_2 captured.

The analysis of those results linked with the intuitions developed previously allowed to verify the consistency and reliability of the model. Within the 3-cell scenario with all exchanges, some general trends have been observed :

- The main means of exchanges are SLF, NG and electricity.
- The electrification of heat and mobility plays a major role in systems with high intermittent renewable energy penetration.
- It is interesting to increase the cross-border electrical transfer capacities to a certain extent. In this case, they should increase of a factor between 2 and 5.
- Allowing "all" the exchanges, the cost of low-carbon systems can decrease down to 21% compared to a case without exchanges.

All these trends should be verified on a more realistic case, for instance Western Europe.

To conclude, the developed model sets the basis to study low-carbon of large scale multi-regional systems such as Western Europe. This model has shown consistent results. However, it has some limits which could be improved as explained in Chapter 5 and further tested. Hence, this work serves as an introduction to define the modelling framework for a holistic study of large-scale energy systems.

Appendices

Appendix A

Model description

This appendix regroups more information about the model description : detailed explanations, tables and figures.

A.1 Step 1 : Selection of typical days

> This sections presents in a more detailed and intuitive way the clustering procedure. In a first time, the clustering method in the regional version, EnergyScope TD is explained. Then the adaptation for multi-region model, EnergyScope MC is developed.

A.1.1 Clustering method of typical days in EnergyScope TD

In the EnergyScope TD, the days of the year are clustered according to their time series. Each cluster has a day, the centroid, that represents best this cluster. This day is called the typical day of the cluster. This is done through minimising the clustering error.

The FigureA.1 explains the processing of the time series for the selection of the TD. Firstly, the different time series are normalised such that their sum over the whole year is equal to 1. Then, a weight is given to each time serie to allow it to have more or less influence on the clustering results. The weights are defined by the user according to the relative importance of each time series for the TD selection. Each weighted and normalised time series is put into a matrix of size (365×24). These matrices of time series are concatenated together and form the parameter "ndata". If there are n_{ts} time series, this parameter has a dimension of $(365 \times (24 * n_{ts}))$. After that, the euclidean distance between each pair of 2 days of the year is calculated and saved into the parameter "distance". This parameter is then used into the optimisation problem to find the best clusters. A more detailed explanation of the clustering problem can be found in appendix ...

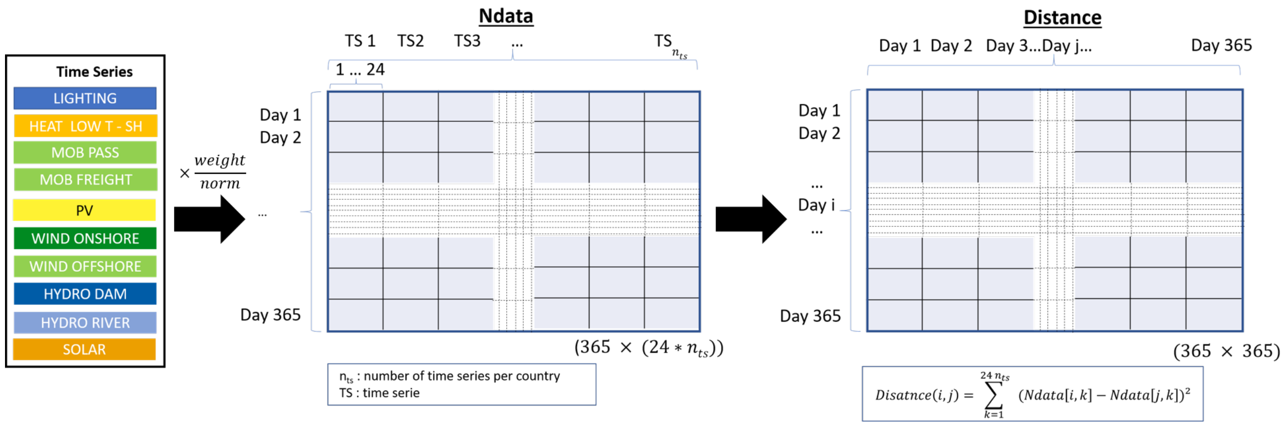

Figure A.1: Steps : From the time series to the Distance matrix (uni-cell version)

Solving the clustering problem consists in determining the optimal values for 2 variables : the Cluster matrix and the Selected_TD vector (i.e. finding the values that minimise the clustering distance). The FigureA.2 shows a visual representation of those two unknowns.

The Cluster Matrix is a matrix composed of 365 columns that represent the different days of the year and 365 lines that represent the potential typical days. Each day has to to be associated to one typical day. Hence it is a sparse matrix. Each column is a column of zeroes with only one element that has a value of 1, at the line associated to its typical day (i.e. the centroid of its cluster).

The Selected_TD is a column vector where each line is associated with a day. If a day is chosen to be a typical day, its value is 1, if not, its value is zero.

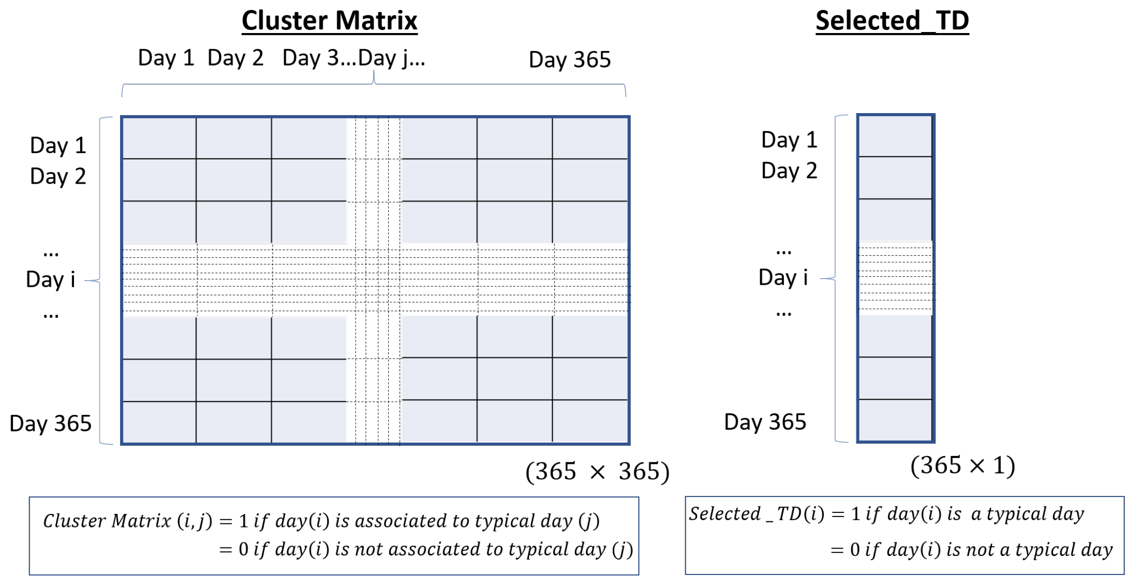

Figure A.2: The Cluster Matrix and the Selected_TD matrix

To make physical sense, these 2 matrices are constrained by three equations. Some of those are also influenced by user defined parameters.

1. The number of typical days is defined by Nbr_TD and can be chosen by the user :

$$\sum_{i \in DAYS} \textbf{Selected\_TD}(i) = Nbr\_TD \tag{A.1}$$

2. Each day can only be associated to one typical day :

$$\sum_{i \in DAYS} \textbf{Cluster\_matrix}(i,j) = 1 \qquad \forall j \in DAYS \quad \text{(A.2)}$$

3. Selected_TD is linked to the Cluster Matrix :

$$\textbf{Cluster\_matrix}(i,j) \leq \textbf{Selected\_TD}(i) \qquad \forall i,j \in DAYS \quad \text{(A.3)}$$

Finally, the choice of the typical days is done by the minimisation of the euclidean distance between the typical days chosen and their associated days from the year :

$$\min \ \textbf{Euclidean\_distance} = \sum_{i,j \in DAYS} \Big(\textbf{Distance}(i,j) * \textbf{Cluster\_matrix}(i,j) \Big) \quad \text{(A.4)}$$

The results of this minimisation is a vector of 365 elements containing the TD representative for each day of the year. At the end, only the time series of the TD will be used in the energy model.

The number of TD must be chosen carefully. It is a compromise between the computational cost and the accuracy of the results. In EnergyScope TD, it has been shown that the best compromise is 12 TD [26]. A similar analysis should be done for the MC version.

A.1.2 Adaptation to the multi-cell version

In the multi-cell version, each cell has its own times series. To choose the typical days, one must take all of them into account as the TD chosen for the different cells need to be identical. The issue here is that when cells will interact together on a certain typical day, it should be on the same physical day. Indeed, if cell 1 interacts with cell 2 during TD 1, the chosen day for TD 1 and all the days associated to it need to be the same for both cells. Otherwise, there is no physical sense of making them interact with each other on TD 1 as it is not the same day of the year. This example justifies that the choice of the TD has to be the same for every country of the set.

Hence to be able to choose these TD, the model needs to take into account the time series of all the countries of the set. In the multi-cell version, the parameter Ndata results of the concatenation of the time series of all the different countries, as shown in Figure A.3. The parameters n_c and n_{ts} represent the number of countries and the number of time series used for the clustering procedure for each country. In total, there are $N_{ts,tot} = (24 * n_c * n_{ts})$ columns in the parameter Ndata. The following steps of the TD selection procedure are the same as in EnergyScope TD : computing the euclidean distance between each pair of days and minimising the total euclidean distance of the clusters. Finally, only the elements of the time series corresponding to the chosen typical days will be used in the model.

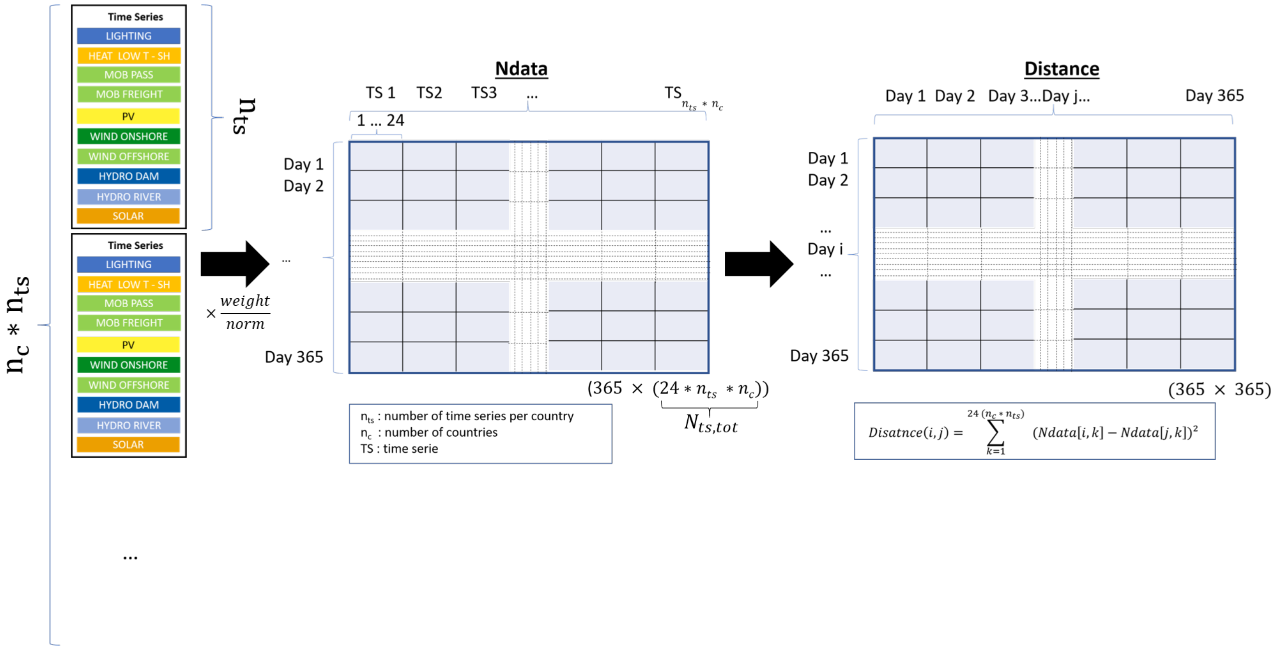

Figure A.3: Steps : From the time series to the Distance matrix (multi-cell version)

A.2 Step 2 : Energy model

A.2.1 Definition of sets, parameters and variables of EnergyScope TD

This appendix presents all the sets, parameters and variables used in EnergyScope TD and EnergyScope MC linear programming models. Sets are groups of entities that have common characteristics. Parameters are fixed inputs of the model. Variables are the unknowns.

For EnergyScope TD

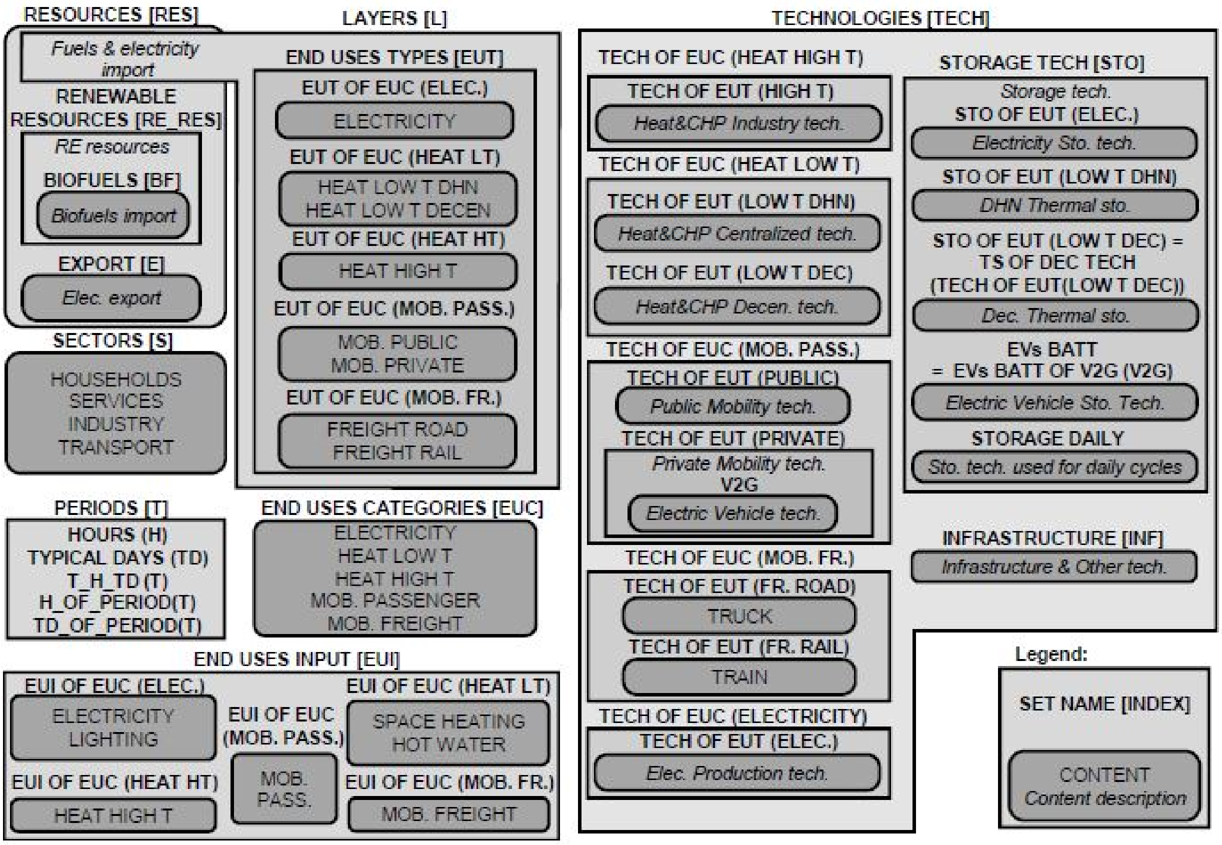

Figure A.4: Visual representation of the sets and indices of the LP framework. Abbreviations: space heating (SH), hot water (HW), temperature (T), mobility (MOB), vehicle-to-grid (V2G), thermal storage (TS).[27]

Parameter	Units	Description
$\tau(tech)$	[-]	Investment cost annualization factor
i_{rate}	[-]	Real discount rate
$endUses_{year}(eui, s)$	[GWh/y][a]	Annual end-uses in energy services per sector
$endUsesInput(eui)$	[GWh/y][a]	Total annual end-uses in energy services
re_{share}	[-]	minimum share [0;1] of primary RE
gwp_{limit}	[$ktCO_{2\text{-eq}}$/y]	Higher $CO_{2\text{-eq}}$ emissions limit
$\%_{public,min}$, $\%_{public,max}$	[-]	Lower and upper limit to $\%_{\mathbf{Public}}$
$\%_{rail,min}$, $\%_{rail,max}$	[-]	Lower and upper limit to $\%_{\mathbf{Rail}}$
$\%_{dhn,min}$, $\%_{dhn,max}$	[-]	Lower and upper limit to $\%_{\mathbf{DHN}}$
$t_{op}(h, td)$	[h]	Time periods duration (default 1h)
f_{min}, $f_{max}(tech)$	[GW][ab]	Min./max. installed size of the technology
$f_{min,\%}$, $f_{max,\%}(tech)$	[-]	Min./max. relative share of a technology in a layer
$avail(res)$	[GWh/y]	Resource yearly total availability
$c_{op}(res)$	[MCHF/GWh]	Specific cost of resources
$n_{car,max}$	[-]	Maximum number of cars
$\%_{Peak_{sh}}$	[-]	Ratio peak/max. space heating demand in typical days
$f(res \cup tech \setminus sto, l)$	[GW][c]	Input from (< 0) or output to (> 0) layers. $f(i, j) = 1$ if j is main output layer for technology/resource i
$c_{inv}(tech)$	[MCHF/GW][cb]	Technology specific investment cost
$c_{maint}(tech)$	[MCHF/GW/y][cb]	Technology specific yearly maintenance cost
$lifetime(tech)$	[y]	Technology lifetime
$gwp_{constr}(tech)$	[$ktCO_2$-eq./GW][ab]	Technology construction specific GHG emissions
$gwp_{op}(res)$	[$ktCO_2$-eq./GWh]	Specific GHG emissions of resources
$c_p(tech)$	[-]	Yearly capacity factor
$\eta_{sto,in}$, $\eta_{sto,out}(sto, l)$	[-]	Efficiency [0; 1] of storage input from/output to layer. Set to 0 if storage not related to layer.
$\%_{sto_{loss}}(sto)$	[1/h]	Losses in storage (self discharge)
$t_{sto_{in}}(sto)$	[-]	Time to charge storage (Energy to power ratio)
$t_{sto_{out}}(sto)$	[-]	Time to charge storage (Energy to power ratio)
$\%_{sto_{avail}}(sto)$	[-]	Storage technology availability to charge/discharge
$\%_{net_{loss}}(eut)$	[-]	Losses coefficient [0; 1] in the networks (grid and DHN)
$ev_{Batt,size}(v2g)$	[GWh]	Battery size per V2G car technology
$c_{grid,extra}$	[MCHF]	Cost to reinforce the grid due to IRE penetration

[a] [Mpkm] (millions of passenger-km) for passenger, [Mtkm] (millions of ton-km) for freight mobility end-uses
[b] [GWh] if $tech \in STO$
[c] [Mpkm/h] for passenger, [Mtkm/h] for freight mobility end-uses

Figure A.5: Scenario parameter list with description. Set indices as in Figure A.4 [27]. (Cost have been updated to be in [M€/y].)

Variable	Units	Description
$\%_{\mathbf{Public}}$	[-]	Ratio [0; 1] public mobility over total passenger mobility
$\%_{\mathbf{Rail}}$	[-]	Ratio [0; 1] rail transport over total freight transport
$\%_{\mathbf{DHN}}$	[-]	Ratio [0; 1] centralized over total low-temperature heat
$\mathbf{F}(tech)$	[GW][ab]	Installed capacity with respect to main output
$\mathbf{F_t}(tech \cup res, h, td)$	[GW][ab]	Operation in each period
$\mathbf{Sto_{in}}, \mathbf{Sto_{out}}(sto, l, h, td)$	[GW]	Input to/output from storage units
$\mathbf{P_{Nuc}}$	[GW]	Constant load of nuclear
$\%_{\mathbf{MobPass}}(TECH\ OF\ EUC(MobPass))$	[-]	Constant share of passengers mobility
$\%_{\mathbf{HeatDec}}(TECH\ OF\ EUT((HeatLowTDEC) \setminus \{\mathrm{Dec_{Solar}}\})$	[-]	Constant share of Heat low T decentralised supplied by a technology plus its associated thermal solar and storage
$\mathbf{F_{sol}}(TECH\ OF\ EUT((HeatLowTDEC) \setminus \{\mathrm{Dec_{Solar}}\})$	[GW]	Solar thermal installed capacity associated to a decentralised heating technology
$\mathbf{F_{t_{sol}}}(TECH\ OF\ EUT((HeatLowTDEC) \setminus \{\mathrm{Dec_{Solar}}\})$	[GW]	Solar thermal operation in each period

[a][Mpkm] (millions of passenger-km) for passenger, [Mtkm] (millions of ton-km) for freight mobility end-uses
[b][GWh] if $tech \in STO$

Figure A.6: Independent variable list with description. All variables are continuous and non-negative, unless otherwise indicated. [27]

Variable	Units	Description
$\mathbf{EndUses}(l, h, td)$	[GW][a]	End-uses demand. Set to 0 if $l \notin EUT$
$\mathbf{C_{tot}}$	[MCHF/y]	Total annual cost of the energy system
$\mathbf{C_{inv}}(tech)$	[MCHF]	Technology total investment cost
$\mathbf{C_{maint}}(tech)$	[MCHF/y]	Technology yearly maintenance cost
$\mathbf{C_{op}}(res)$	[MCHF/y]	Total cost of resources
$\mathbf{GWP_{tot}}$	[ktCO$_2$-eq./y]	Total yearly GHG emlissions of the energy system
$\mathbf{GWP_{constr}}(tech)$	[ktCO$_2$-eq.]	Technology construction GHG emissions
$\mathbf{GWP_{op}}(res)$	[ktCO$_2$-eq./y]	Total GHG emissions of resources
$\mathbf{Net_{loss}}(eut, h, td)$	[GW]	Losses in the networks (grid and DHN)
$\mathbf{Sto_{level}}(sto, t)$	[GWh]	Energy stored over the year

[a][Mpkm] (millions of passenger-km) for passenger, [Mtkm] (millions of ton-km) for freight mobility end-uses

Figure A.7: Dependent variable list with description. All variables are continuous and non-negative, unless otherwise indicated. [27] (Cost have been updated to be in [M€/y].)

For EnergyScope MC

Into the EnergyScope MC, all the sets, parameters and variables of the EnergyScope TD are kept. Some have disappeared such as the resource ELEC_EXPOR. Most of the parameters and variables will have the countries dimension added to it. Except the ones which don't change from one country to the other such as the efficiency of the conversion technologies. This subsections presents all the additional sets, parameters and variables of EnergyScope MC.

Set	**Description**
COUNTRIES	List of all the countries
CWITHOUTDAM	List of countries with no hydro dam potential
FREIGHT_R	List of resources exchanged through freight
NETWORK_R	list of resources exchanged through a network
NOEXCHANGES	List of resources that can not be exchanged

Table A.1: List of additional sets of EnergyScope MC with description

Parameter	**Units**	**Descritpion**
$tc(c_1, c_2, n\_r)$	[GW]	Transfer capacity for network resource n_r from country c_2 to country c_1
exchange_losses (r)	[-]	Losses of exchanges
lhv (f_r)	[GWh/t]	Lower heating value of freigh resource f_r
dist (c)	[km]	Average distance travelled by resources exchanged through freight in country c
$gwp_{limit,global}$	[kt$CO_{2\text{-eq}}$/y]	Higher $CO_{2\text{-eq.}}$ emissions limit for the global system
$avail_{local}$ *(c,r)*	[GWh/y]	Resource (r) yearly total local availability in country c
$avail_{exterior}$ *(c,r)*	[GWh/y]	Resource (r) yearly total exterior availability in country c
$c_{op,local}$ *(c,r)*	[M€/y]	Specific local cost of resource r in country c
$c_{op,exterior}$ *(r)*	[M€/y]	Specific exterior cost of resource r
$gwp_{op,local}$ *(c,r)*	[kt$CO_{2\text{-eq}}$/y]	Specific GHG emissions of local resource r in country c
$gwp_{op,exterior}$ *(r)*	[kt$CO_{2\text{-eq}}$/y]	Specific GHG emissions of exterior resource r

Table A.2: List of additional scenario parameters in EnergyScope MC with units and description

Variable	**Units**	**Descritpion**
$\mathbf{R_{t,local}}$ *(c,r,h,td)*	[GW]	Use of local resource (r) at each period for each country
$\mathbf{R_{t,exterior}}$ *(c,r,h,td)*	[GW]	Use of exterior resource (r) at each period for each country
$\mathbf{R_{t,import}}$ *(c,r,h,td)*	[GW]	Import of resource (r) at each period for each country
$\mathbf{R_{t,export}}$ *(c,r,h,td)*	[GW]	Export of resource (r) at each period for each country
Exchanges (c_1, c_2, r, h, td)	[GW]	Exchanges of resource r from country c_2 to country c_1 at each period
Exch_freight *(c)*	[Mtkm]	Additional freight due to exchanges
Curt *(c)*	[GWh/y]	Total energy curtailed in country c

Table A.3: List of additional variable in EnergyScope MC with units and description

A.2.2 Resources, conversion technologies and end-use demands in EnergyScope

To understand the structure of EnergyScope, it is essential to know what is a resource, a conversion technology and an end-use demand (EUD). These concepts are all linked by another one : the layer. A layer is either a resource (e.g. Natural gas layer) or an EUD (e.g. low temperature heat layer) and has to be balanced at all time. It allows to respect the energy balance at each time step. This energy balance appears as an equation that constraints every layer, see Eq. A.5

$$\begin{aligned} &\sum_{i \in RES \cup TECH \setminus STO} f(i,l)\mathbf{F_t}(i,h,td) \\ &+ \sum_{j \in STO} (\mathbf{Sto_{out}}(j,l,h,td) - \mathbf{Sto_{in}}(j,l,h,td)) = \mathbf{EndUses}(l,h,td) \\ &\forall\ l \in L,\ h \in H,\ td \in TD \end{aligned} \tag{A.5}$$

The following examples help understand this equation :

- Example of an end-use demand layer : the low temperature heat layer has to be balanced, that is at each time step, the low temperature heat produced from technologies (such as heat pumps or boilers) and the heat coming out from the storage units needs to equal the heat used as an end-use demand (such as domestic hot water or space heating demand) and the heat entering the storage units.
- Example of a resource layer : the natural gas layer has to be balanced, that is at each time step, the gas imported from outside the system, the produced gas from technologies (such as synthetic methanation) and the gas coming out of the storage units has to be equal to the gas used in technologies (such as CCGT) and the gas entering in the storage units.

A technology can be defined as a link between two layers. For example the CCGT technology links the natural gas layer and the electricity layer as it produces electricity from gas. In the case of a storage, the two layers are the same one. Figure A.8 presents all the resources, EUD and conversion technologies defined in EnergyScope.

Three types of technologies are defined :

- end-use type technology: a technology of which the output is an end-use demand (electricity production, private and public mobility, freight, industrial heat, centralised and decentralised, non-energy use and cooling on Figure A.8)
- storage technology: a technology linked to a layer that stores and restores the resource or the end-use demand to the same layer (e.g. a battery storing electricity)
- infrastructure technology: a technology that does not produce an end-use demand (other technologies on Figure A.8). Infrastructure technologies also refer to other concepts (networks and efficiency on Figure A.8).

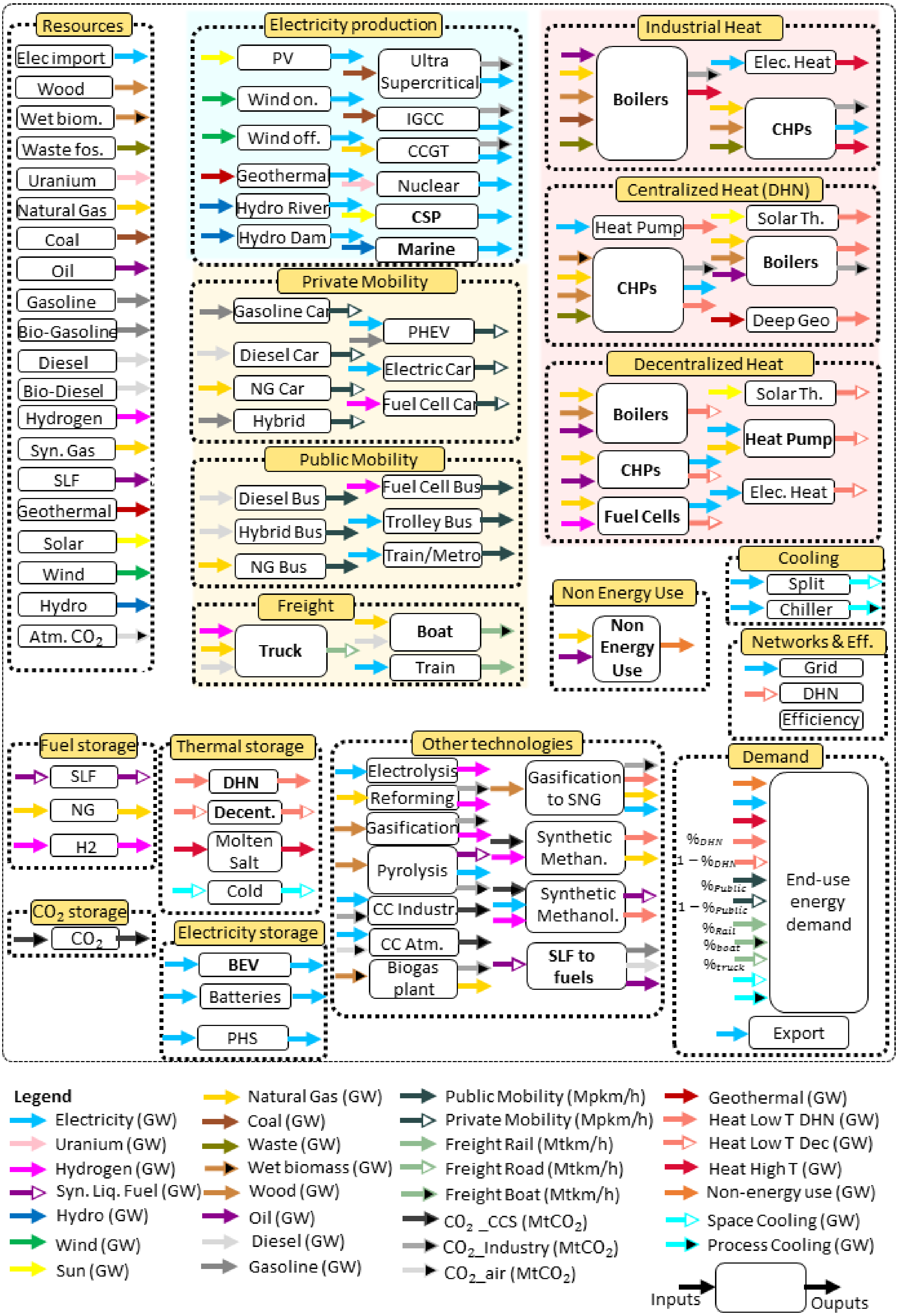

Figure A.8: Definition of all the resources, conversion technologies and EUD through the concept of layer **Bold** technologies represent groups of technologies with different energy inputs (e.g. Boilers include gas boilers, oil boilers, . . .). Decent. represents the group of thermal storage for each decentralised heat production technology.[6][26]

A.2.3 Implementation of additional exchanges freight in the LP model

The freight is modelled in EnergyScopeTD (fig A.9) as follow: From the total yearly freight EUD, the hourly demand is computed thanks its time series and dispatched into three layers : *MOBILITY FREIGHT ROAD*, *BOAT* and *RAIL*.

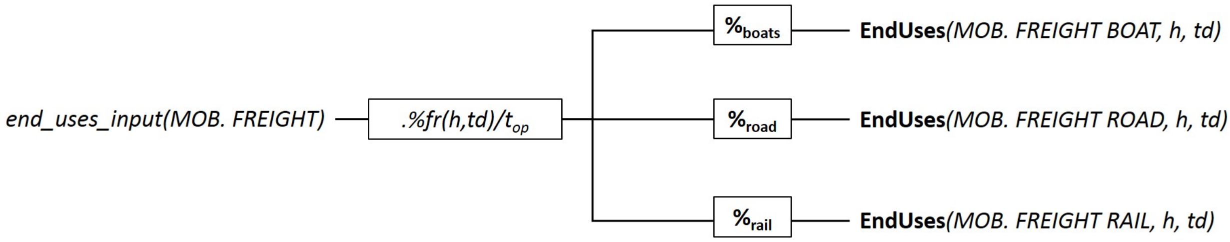

Figure A.9: Representation of the freight modelling in EnergyScopeTD

The allocation is done thanks to the variables defining the share of each type of freight, $\%_{\mathbf{boats}}$, $\%_{\mathbf{road}}$ and $\%_{\mathbf{rail}}$ which are constrained by parameters defining their minimum and maximum values.

$$\%_{min,boats} \leq \%_{\mathbf{boats}} \leq \%_{min,boats} \tag{A.6}$$
$$\%_{min,road} \leq \%_{\mathbf{road}} \leq \%_{min,road} \tag{A.7}$$
$$\%_{min,rail} \leq \%_{\mathbf{rail}} \leq \%_{min,rail} \tag{A.8}$$

The constraints regarding the mobility in EnergyScope TD are the following :

1. The defined freight end-use demand is dispatched into three variables in three equations:
$$\mathbf{EndUses}(c, MOB\_FR\_RAIL, h, td) \tag{A.9}$$
$$= end\_uses\_input(c, MOB\_FR) * \frac{timeserie\_mob\_fr(c, h, td)}{t_{op}(h, td)} * \%_{\mathbf{rail}}$$
$$\mathbf{EndUses}(c, MOB\_FR\_ROAD, h, td) \tag{A.10}$$
$$= end\_uses\_input(c, MOB\_FR) * \frac{timeserie\_mob\_fr(c, h, td)}{t_{op}(h, td)} * \%_{\mathbf{road}}$$
$$\mathbf{EndUses}(c, MOB\_FR\_BOAT, h, td) \tag{A.11}$$
$$= end\_uses\_input(c, MOB\_FR) * \frac{timeserie\_mob\_fr(c, h, td)}{t_{op}(h, td)} * \%_{\mathbf{boat}}$$

2. The sum of the three shares ($\%_{boats}$, $\%_{road}$ and $\%_{rail}$) must be equal to 1 :
$$\%_{\mathbf{boats}}(c) + \%_{\mathbf{road}}(c) + \%_{\mathbf{rail}}(c) = 1 \qquad \forall c \in COUNTRIES \tag{A.12}$$

3. This constraints defines, for each country, the share of freight end-use demand covered by each technology, $\%_{\mathbf{Mob.,Freight}}(c, j)$. This variable is constant over the time and thus forces each technology to produce the same amount of freight at each hour of the year. The purpose of this constraint is the following : as in the model, there are no investment and maintenance cost for mobility technologies, the model could install a lot of all the freight technologies and use them at its convenience. This is not realistic at all as in reality, the cost of those technologies implies that a truck will not be build only to be used a very short time of the year. To avoid this, the constraint is added (Eq. A.13).

$$\mathbf{F_t}(c,j,h,td) = \%_{\mathbf{Mob.,Freight}}(c,j) * eud(c, MOB\_FR, h, td) \tag{A.13}$$
$$\forall c \in COUNTRIES, j \in MOB.\_FR\_TECH, h \in H, td \in TD$$

In practice, the model should be able to choose the type of freight (boat, rail, road) to transport these energy carriers between the cells. To do so, the additional freight should be added to the first equations of mobility (Eq.A.10, A.9, A.11). But this would make the system non-linear as two variables would be multiplied by each other (**Exch_Freight**(c) multiplied by $\%_{\mathbf{rail}}$ in Eq. A.9, by $\%_{\mathbf{road}}$ in Eq. A.10 and by $\%_{\mathbf{boat}}$ in Eq. A.11). This doesn't work in linear programming model.

The solution found is the following :

- The dispatch equations remain unchanged (Eqs. A.10, A.9, A.11)
- The Eq. A.13 remains unchanged to keep a constant share for each freight technology.
- A new equation defining $\%_{\mathbf{Mob.,Freight}}$ is added to the model (Eq. A.14). It allows to have a total share bigger than 1 if there is additional freight due to exchanges. It will increase the freight produced by the technologies during the entire year.

$$\sum_{j \in MOB.\_FR\_TECH} \%_{\mathbf{Mob.,Freight}} = \frac{\mathbf{Exch\_Freight}(c) + eud(c, MOB\_FR)}{eud(c, MOB\_FR)} \tag{A.14}$$
$$\forall c \in COUNTRIES$$

- Furthermore, Eq. A.12 is replaced by Eq. A.15. The latter constraints the sum of the shares of each freight technology to be bigger than one if there is some additional freight due to exchanges. This will force the production of freight to be bigger than the EUD during each hour of the year through equation A.13. It also induces that the sum of shares of boat, road and rail freight is bigger than one thanks to Eq. A.15. Having bigger shares increases the hourly demand of freight (see Figure A.9).

$$\%_{\mathbf{boats}}(c) + \%_{\mathbf{road}}(c) + \%_{\mathbf{rail}}(c) = \sum_{j \in MOB.\_FR\_TECH} \%_{\mathbf{Mob.,Freight}} \tag{A.15}$$
$$\forall c \in COUNTRIES$$

Appendix B

Definition of the 3-cell system : France, Belgium and Switzerland

B.1 Adaptation of Switzerland's data

As the version of EnergyScope for Switzerland is older, some data are missing. These data correspond to the new functionalities added recently in the model (e.g. new technologies). For instance, the space cooling end use demand, the process cooling end-use demand, and the space cooling time series.

The space cooling end-use demand and process end-use demand are defined by a rule of three with Belgium's end-use demand with the ratio of the space heating and industrial heat demand of both countries. That is :

$$\text{end\_uses\_input[CH,PROCESS\_COOLING]} =$$
$$\text{end\_uses\_input[BE,PROCESS\_COOLING]} * \frac{\text{end\_uses\_input[CH,HEAT\_HIGH\_T]}}{\text{end\_uses\_input[BE,HEAT\_HIGH\_T]}}$$

$$\text{PROCESS\_COOLING[CH]} = \text{PROCESS\_COOLING[BE]} * \frac{\text{HEAT\_HIGH\_T[CH]}}{\text{HEAT\_HIGH\_T[BE]}}$$

The same methodology of extrapolation has been used for the maximal number of cars and the availability of wet biomass.

For some other new parameters, it has been chosen to set them to zero in Switzerland. This is due to the lack of data and seems to be the closest to reality in those cases :

- Share of freight by boat
- The maximum capacity of concentrated solar power (CSP) technologies (solar tower, parabolic through and stirling dish).
- The maximum capacity of compressed air energy storage (CAES).

B.2 Energy demands

Table B.1 presents the EUD for each country and each end-use. The data is taken from the year 2015. It allows to evaluate the size of each system.

In each category, the demand in Belgium is 2 to 3 times bigger than the one of Switzerland. Passenger mobility is an exception since it is only 1.3 times greater in Belgium.

Furthermore, for some categories, Switzerland has no demand. For cooling categories it is due to a lack of data. It should be completed. But it is a very small demand which is fulfilled through refrigeration cycles with a high coeficient of performance (COP). Hence it will have a very small impact on the system.

The non-energy use EUD demand is very important in Belgium but nearly nonexistent in Switzerland. In the model, it is thus set to zero.

In average, the EUDs in France are 4 times bigger than in Belgium. The ratio varies according to the type of end-use : from 1.7 for non-energy use to 13.7 for space cooling. It reaches 4.7 for electricity and around 3.7 for space heating and domestic hot water. For mobility, it stands at 6.2 for freight and 7.4 for passenger.

	Switzerland	**Belgium**	**France**
Electricity	41.8	83.2	392.5
Industrial Heat	19.0	51.8	125.3
Space Heating	49.0	121.9	462.7
Domestic Hot Water	12.1	30.1	113.4
Process Cooling	0	17.0	75.0
Space Cooling	0	3.0	41.0
Passenger Mobility	146.0	194.0	1436.0
Freight Mobility	40.0	98.0	608.0
Non-energy use	0	102.3	176.1

Table B.1: End-use demand of Switzerland, Belgium and France (units : [TWh/y] for all EUD except passenger mobility [Gpkm/y] and freight [Gtkm/y])

B.2.1 Variable demand

Figure B.1 is taken from Section 2.1.2.

As mentioned in this section, the scales of the different demands are not really the same. The electrical demand is represented in electrical GW, and heating and cooling demand are represented in thermal GW. Those thermal GW can be produced with a boiler or with heat pumps (HPs). It will change a lot the efficiency and the final energy consumption (FEC).

A good order of magnitude is to keep in mind that heat pumps produce heat with electricity with a ratio of $\frac{GW_{thermal}}{GW_{elec}}$ equal to 3 [14, 37] and cold with a ratio of 6 [33]. The variable demand in GW_{elec} equivalent, converted with this technology, is represented in Figure B.2. The heating demand becomes always smaller then the electricity demand and the cooling becomes insignificant.

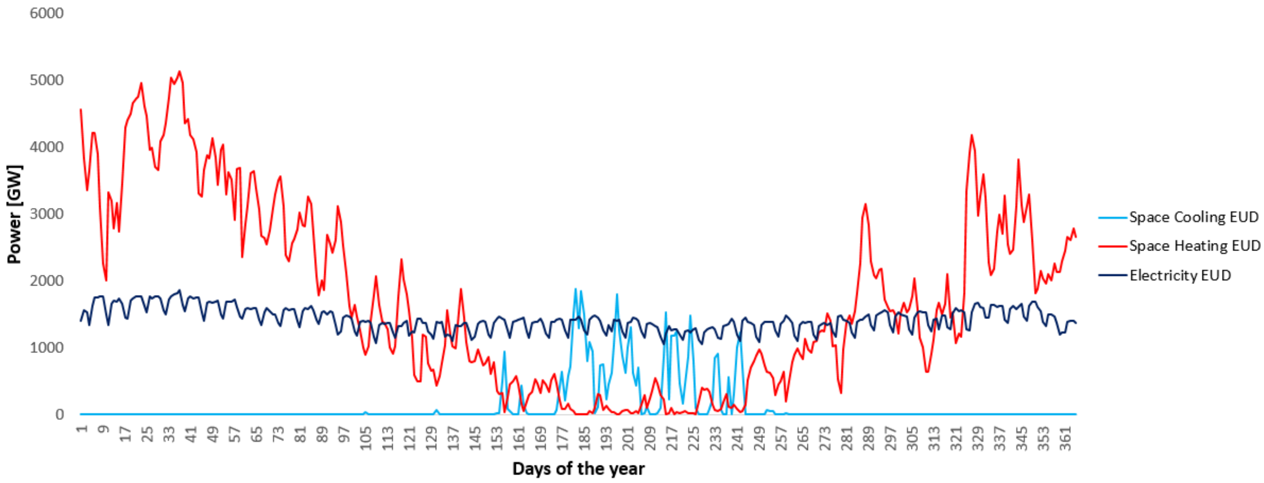

Figure B.1: Electricity, space heating, and space cooling demand of the global system

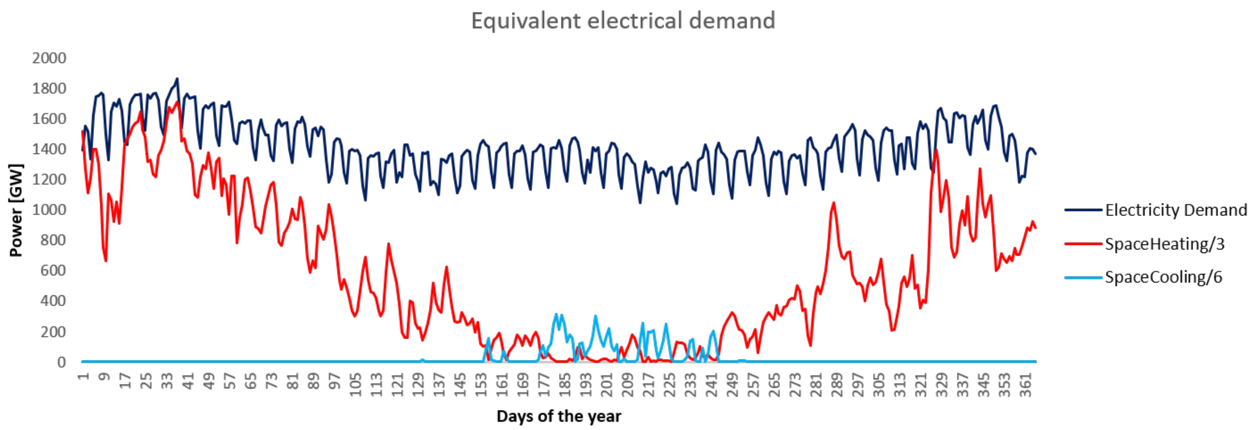

Figure B.2: Electricity, heating and cooling demand in equivalent electrical GW supposing a ratio of 3 for heat and a ratio of 6 for cold

B.3 Resources and potentials of cells

A big source of difference between countries comes from their potential to produce energy. It contains the availability of local resources (e.g. wood) as well as the capacity factor of intermittent renewable energies and their technical potential.

B.3.1 Resources

Resources	France [6]	Belgium [6, 25]	Switzerland [27, 32]
Wood	322.8	23.4	12.3
Wet biomass	173.0	38.9	20.4
Waste	57.8	17.8	11.1

Table B.2: Resources potential expressed as availability in each cell [TWh/y].

B.3.2 Renewable energy sources potential

The production of intermittent renewable energies at each hour in each country are defined by time series. They give their hourly capacity factor (c_{pt}) that informs about the GWh produced at each hour per GW installed. This value is different in each country. Indeed, PV will not produce the same amount and at the same time in Belgium or in Switzerland.

This potential production can be summarised over the year as an average capacity factor (c_p). It gives the quantity of energy produced over the year (GWh) per GW installed. It shows the interest of installing a RES tech in one country of the other. The Table B.3 presents those values for each country and each RES technology.

Technology	France [6]	Belgium [6, 25]	Switzerland [27, 32]
PV	0.130	0.096	0.113
Wind Offshore	0.472	0.337	0
Wind Onshore	0.217	0.223	0.23
Hydro dam	0.216	0	0.234
Hydro river	0.429	0.078	0.484
Solar	0.108	0.096	0.113

Table B.3: Yearly capacity factor of renewable energy sources (RES) in each country.

Furthermore, these technologies can not be installed indefinitely. They are interesting in some locations only and can not take all the territory available. Table B.4 gives the minimum and maximum capacity that can be installed in each country. The minimum capacity refers to the already installed assets in 2020.

	France		Belgium		Switzerland	
	f_{min}	f_{max}	f_{min}	f_{max}	f_{min}	f_{max}
PV	6.19	1017.51	2.92	59.23	2.52	79.68
Wind Offshore	0	93.15	0.71	0.71	0	0
Wind Onshore	10.31	375.07	1.25	20.38	0.08	5.3
Hydro dam	14.24	14.24	0	0	80.8	8.52
Hydro river	6.61	6.61	0.17	0.17	3.8	4.65
ST power block	0	41.97	0	3.84	0	0

Table B.4: Potential capacity of renewable energy sources technologies [7] (abbrev: photovoltaic panels (PV), solar tower (ST))

B.4 Evaluation of losses in the natural gas network

Thanks to Laurent Rémy from Fluxys, we have some data about the NG transmission network in 2019. The losses in the NG network in Belgium in 2019 are summarised in Table B.5.

	Energy used
Re-compression with gas	196.87
Re-compression with elec.	6.36
Other losses	171.39

Table B.5: Natural gas transmission network losses in Belgium in 2019 [GWh]. Other losses regroups : gas pre-heating, heating of the buildings and losses.

The other information he gave us is that the total amount of NG transported by the transmission network in Belgium in 2019 is : **434** [**TWh**].

Dividing the sum of the three sources of losses by the gas transported, we get average losses of **0.086%**.

B.5 Evaluation of the cost of the natural gas interconnections

To evaluate the fixed cost of the natural gas (NG) interconnections, we have done a statistic analysis of the 252 future cross-border projects in Europe for the 10 years to come [36]. Table B.6 presents some descriptive statistics of the capital expenditures (CAPEX) and operation expenditures (OPEX) of the 252 projects. It is noticeable that they have a large standard deviation and the mean is well above the median.

	CAPEX [M€/GW]	**OPEX** [M€/GW/y]
Mean	24.44	1.03
Std	36.49	5.36
Median	11.05	0.23

Table B.6: Descriptive statistics of forecast capital expenditures (CAPEX) and the operation expenditures (OPEX) of the cross-border natural gas (NG) project for the 10 coming years in Europe. (abbrev.: standar deviation (Std))

Figure B.3 presents the distribution of the distribution of the CAPEX and OPEX of those projects. They have an heavy tailed distribution. Hence the median is more representative of the sample.Thus NG pipeline have a CAPEX of 11.05 million of euro per gigawatt of interconnection and an OPEX of 0.23 million of euros per gigawatt per year.

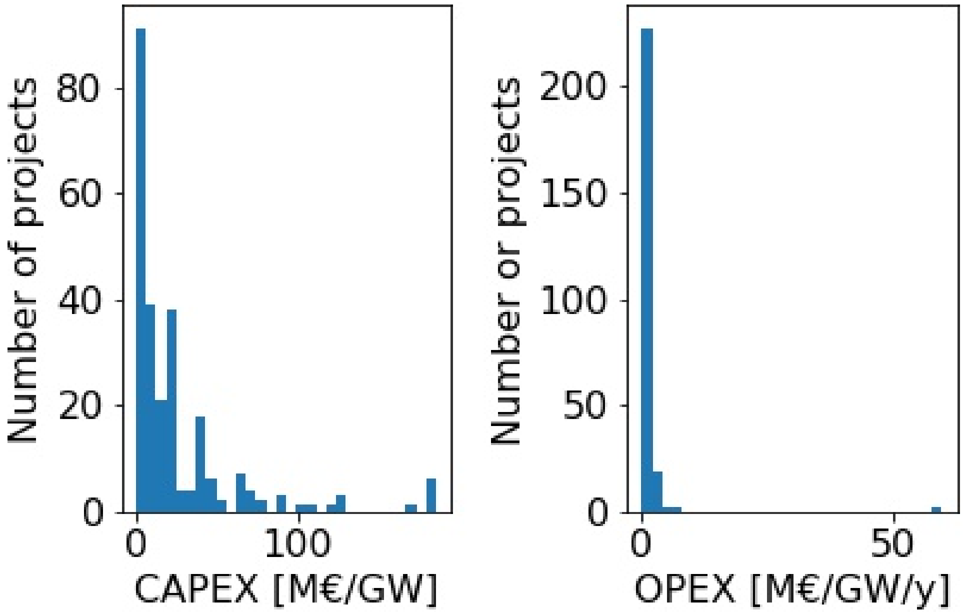

Figure B.3: Caption

The NG pipeline have a lifetime (*lifetime*) of 50 years [35]. Taking the same interest rate as the rest of the model (0.015), we can annualize the investment with the following factor (τ):

$$\tau = \frac{i_{rate}(i_{rate}+1)^{lifetime}}{(i_{rate}+1)^{lifetime}-1} \tag{B.1}$$

We get a total annualised cost of $0.32 + 0.23 = 0.54$ [M€/GW/y].

B.6 Choice of emission targets

For each scenario (no exchanges, only electrical exchanges and "all" exchanges), the global energetic system has been optimised by the model in two different ways in order to choose the emission target. On the one hand, a global cost optimisation without any emission constraints, and on the other hand a global cost optimisation with a constraint forcing to zero the GWP of operation. Table B.7 summarises the main results. The total cost (C_{tot}) is the sum of the annualised investment and the O&M costs. The GWP_{op} takes into account all the emissions linked with the combustion of fuels (i.e. from extraction to combustion). The GWP_{tot} is the sum of the GWP_{op} and the green house gases emitted during the whole lifecycle of the energy assets.

	No limit on GWPop			**$GWP_{op} = 0$**		
Exchanges	C_{tot}	GWP_{tot}	GWP_{op}	C_{tot}	GWP_{tot}	GWP_{op}
None	105.2	408.6	399.0	188.3	95.0	0
Elec.	104.4	374.4	364.5	180.2	89.0	0
All	104.3	376.6	366.7	164.8	79.0	0

Table B.7: Total cost (C_{tot}) [G€/y], operation global warming potential (GWP_{op}) [MtCO2-eq./y], and total GWP (GWP_{tot}) [MtCO2-eq./y] of 2 cases : cost minimization without GWP limit - cost minimzation with $GWP_{op} = 0$ [MtCO2-eq./y].

Appendix C

Verification and analysis of the 3-cell scenario with electrical exchanges

This section gives an overview of the cost-optimum energy system obtained. At first, the energy flows of the global system are presented in order to give a general understanding of the system . Secondly, the the choice of RES assets in each cell will be detailed and verified thanks to their levelised cost of energy (LCOE).

C.1 Energy flows in the overall system

Figure C.1 presents the solution for the global system (France, Belgium and Switzerland aggregated) under the form of a Sankey Diagram. This graph summarises the yearly energy flows of the system. It shows how the resources on the left are converted to provide the end-use demand (EUD) and allows to have a global view of the system.

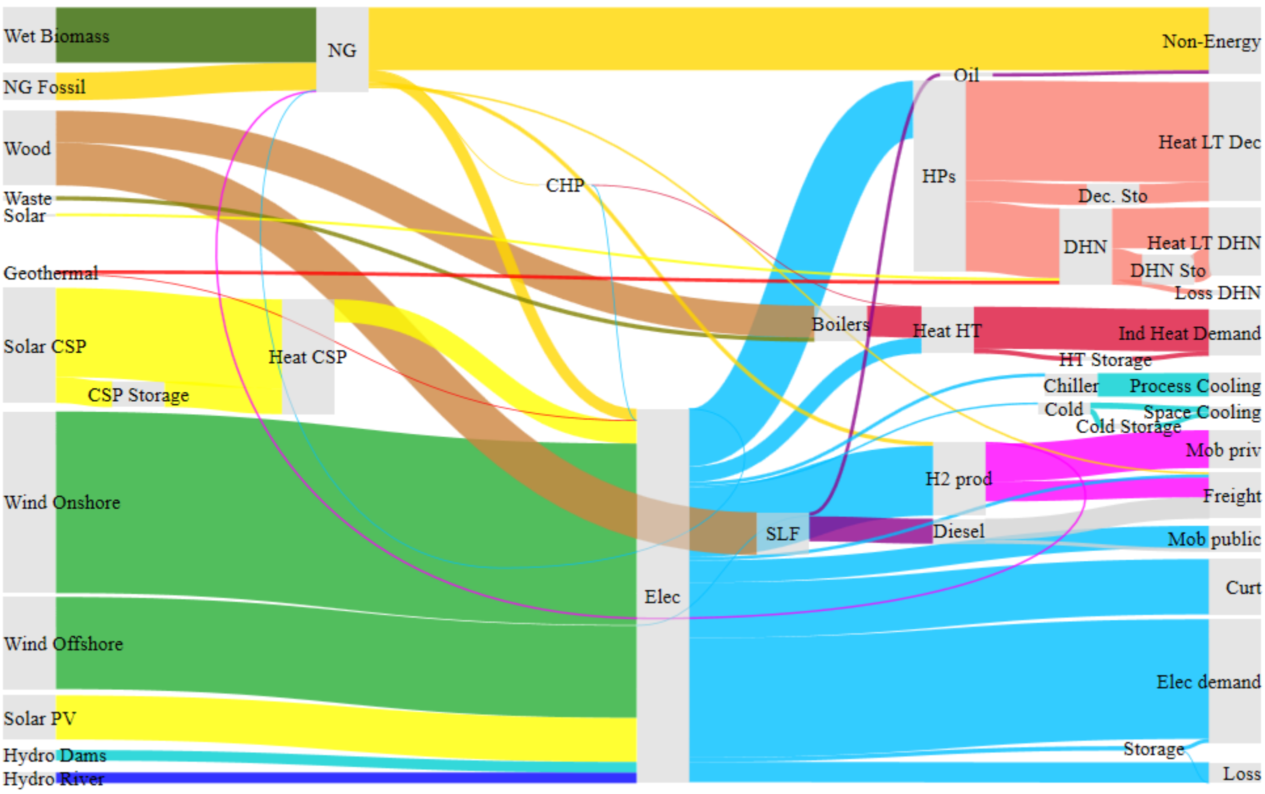

Figure C.1: Sankey diagram of the global system.

The left hand side of the Sankey diagram in Figure C.1 represents the primary energy sources and the right hand side of the diagram represents the global end-use demand of the system.

The final energy consumption (FEC) of the system is 1744 TWh. Mobility and electricity EUD are the major source of FEC and consume together 56.3 % of FEC (see Table C.1).

EUD	Share of FEC [%]
Non-energy	16
LT Heat	15.2
Ind. Heat	11.3
Process Cooling	0.8
Space Cooling	0.4
Mobility	26.5
Electricity	29.8

Table C.1: Relative final energy consumption (FEC) for each end-use demand (EUD).

The major part of the resources are renewable. Indeed, wet biomass, wood, solar, wind and hydro represent 94.8 % of the resources. The non-renewable primary sources (5.1 %) consist of waste and fossil natural gas (NG). 34% of the total amount of NG used is fossil and is the only resource imported from outside the system. Hence the global system is self-sufficient at 95.6%. Furthermore, it is only used in Belgium. The rest of the NG is produced locally through biomethanation of wet biomass and can be considered as renewable. It constitutes 66% of the NG used. Therefore, local resources become of major importance. The Table C.2 summarises the use of those local resources in terms of share of availability. The wood is used to produce synthetic liquid fuel (SLF) and high temperature (HT) heat for industrial use. Belgium and Switzerland use all the wood they can produce sustainably whereas France has some availability left. Only Belgium uses its waste to produce HT heat. All the countries use the whole wet biomass available to produce synthetic natural gas (SNG).

	Wood			**Waste**	**Wet biomass**
Use	Boiler HT	SLF prod.	**Tot.**	Boiler HT	SNG prod.
France	33.28	52.85	**86.13**	0	100
Belgium	68.48	31.52	**100**	100	100
Switzer.	83.67	16.33	**100**	0	100

Table C.2: Use of local resources in terms of share of availability [$\%_{\text{avail}}$] in different technologies for each country. (abbrev. : high temperature (HT), synthetic liquid fuel production (SLF prod.), synthetic natural gas production (SNG prod.), Switzerland (Switzer.))

A major part of electricity (98%) is supplied by renewable energy sources : mainly wind, solar and hydro. But also a small part (2%) is produced by other technologies which provide more flexibility to the production : in this case mainly NG through combined cycle gas turbines (CCGTs) and a small constribution from the combined heat and power (CHP) . Assuming that the NG used in the CCGTs has the proportions between fossil and renewable from the previous paragraph, 99.3% of the electricity is renewable and less than 1% is produced by fossil NG.

The system is highly electrified, as 71% of the FEC is electricity. To compute this result, we consider that H2 is mainly produced by electricity (electrolysis) and apply its conversion coefficient of 1.1765.

The low temperature (LT) heat is highly electrified : the decentralised heat is 100% supplied by electrical heat pumps (HPs) and the district heating network (DHN) is electrified through heat pumps at 98% and 2% is generated by geothermal heat and solar panels. The system favours district heating network (DHN) and installs it to its maximum share of 37%. More details on the cells choices are given in right column in Table C.3.

The high temperature demand for industrial use is mainly supplied by waste and wood boilers (66%). It also electrified (33%) as a small part of this demand is supplied through direct electric heaters. And less than a 1% is produced by CHPs. A more detailed overview of the use of these technologies in the different cells is summarised on the left side of Table C.3.

EUD	**Heat HT**				**Heat LT**		
Final energy	Elec.	Wood	Waste	NG	Elec. (HP)	Geoth.	Solar
France	25.87	74.13	0	0	99.27	0.72	0
Belgium	45.07	26.72	28.16	0.05	94.85	0	6.82
Switzerland	50.71	46.65	0	2.65	83.76	16.24	0

Table C.3: Share of final energies used for the heat high temperature (HT) and low temparature (LT) end-use demands (EUD) in each country [$\%_{\mathrm{EUD}}$]. (abbrev. : antural gas (NG), heat pump (HP), geothermal heat (Geoth.))

The process cooling demand and space cooling demand in this 3 countries system are very small. They are entirely electrified but the system has no other choice as the only existing technologies to produce cold in the model is refrigeration cycle with electricity as input.

The mobility is divided in 2 main groups : the passenger mobility (public and private mobility) and freight mobility. At each time of the year and in each cell, the passenger mobility is fulfilled as follow: 50% of fuel cell cars, 30 % of public trains, 15% of tramways and 5% of hybrid diesel buses. The freight mobility is mainly supplied by hydrogen (H2) and diesel (from SLF). The system opts for a lot of fuel cell mobility but this solution is biased. Indeed, it is important to point out that the investment costs of the mobility technologies are not taken into account in the actual model of EnergyScope. Hence the model chooses the most efficient solution without taking into account the fact the it may be more expensive. Furthermore, it is not proven that it would be possible to produce such a high amount of fuel cells without having material problems [21, 16]. A summary of the different technologies used in the passenger mobility and freight mobility in the different cells is given in Table C.4.

Finally, the non-energy demand is mainly supplied by gas with a small contribution of oil. The repartition for each cell is given in Table C.4.

EUD	Mob. pass.			Freight				Non energy	
Final energy	Elec.	H_2	SLF	Elec.	H_2	SLF	NG	SLF	NG
France	45	50	5	25	23.70	51.30	0	8.28	91.72
Belgium	45	50	5	25	45	30	0	0	100
Switzer.	45	50	5	60	3.93	0	36.06	0	0

Table C.4: Share of final energies used for the mobility passenger (Mob. pass.), the freight and the non energy end-use demands (EUD) in each country [$\%_{\text{EUD}}$]. (Abbreviations : natural gas (NG), synthetic liquid fuel (SLF))

RES Assets

Figure C.2 shows the installed capacity of the renewable energy source (RES) assets in the different countries. The minimum and maximum capacity of installation are represented by the black horizontal lines and their domain of solution in the dotted vertical lines. If the upper horizontal bar (maximum capacity) does not appear on the graph (only for PVs), it is understood that their maximum capacity is infinite. The minimum capacity of assets is the already installed capacity in the concerned country and the maximum capacity refers to their maximum technical and sustainable potential [7].

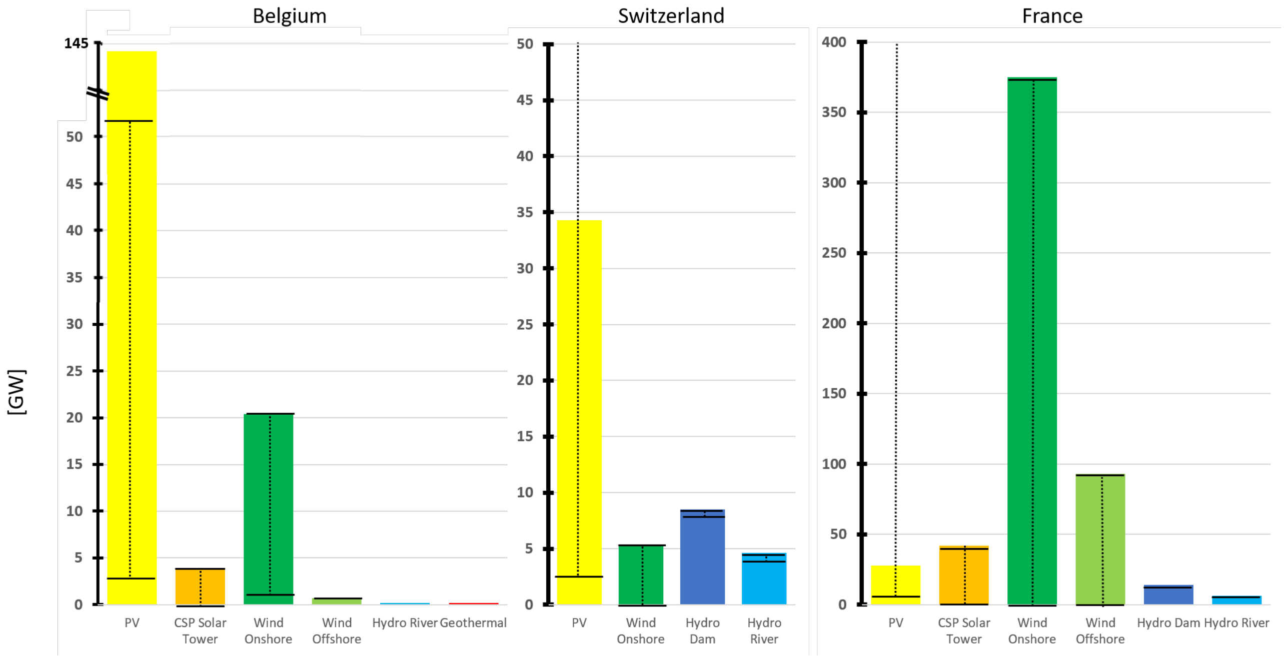

Figure C.2: Installed renewable assets of each country and their maximum and minimum potential (horizontal black line) (abbrev. : photovoltaic panels (PV))

It is observed on this graph that Belgium renewable assets are mainly composed of PV capacity (85% of its RES assets) and onshore WTs, Switzerland has a lot of PVs and hydro power and France installs a lot of WTs. Because of their high PV share, Belgium and Switzerland will have to cope with the lack of production at night and during cloudy days. They will also need a way to absorb the high PV production during sunny hours.

These choices of assets can be understood with the different levelised cost of energy (LCOE) of the different technologies for each country in Figure C.3. The LCOE is a metric giving the average price of a technology per unit of energy produced in [M€/GWh].

It has to be mentioned that hydro dams and solar tower (CSP) are not totally intermittent RES technologies. Indeed, they have a storage unit upstream of their electricity production. This permits have a more dispatchable production of electricity and play a role in adequacy of production to demand. However, this flexibility has some constraints such as storage capacity, storage losses and storage charge state.

Figure C.3, presents the actual levelised cost of energy (LCOE) of each of the RES electricity production assets. The LCOE is the ratio between the annual cost and the annual production of each asset. It gives the cost into [M€/GWh]. For the three countries, the LCOE of the wind turbines (WTs) are the lowest. It explains why the system installs its maximum capacity.

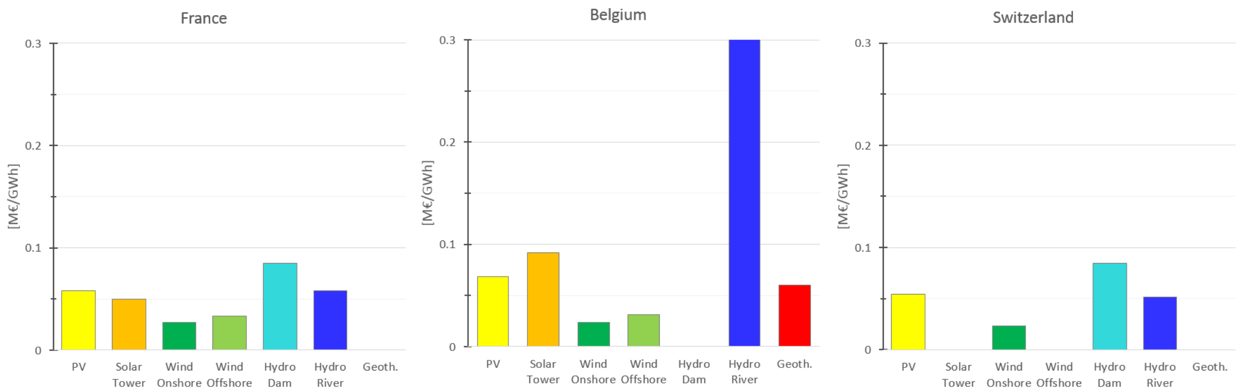

Figure C.3: Levelized Cost of Energy (LCOE) of the RES assets

For Belgium, after the WT (0.024 and 0.031 [M€/GWh]) comes the geothermal power (0.060 [M€/GWh]) followed by PV (0.069 [M€/GWh]). Hydro Rivers is the most expensive in Belgium (0.32 [M€/GWh], and it explains why the system installs its minimum capacity. Then comes PV and solar Towers. One would wonder, why the model installs the maximum capacity of CSP while the maximum capacity of PV was not limited as its LCOE is higher than PV. The reason is that as said previously this technology brings a certain flexibility to the system and a more constant production during the year, see...

In Switzerland, comes after the wind turbines, the hydro river so the system installs its maxium potential. The same reasoning can be done with hydro dams as with solar towers in Belgium, its LCOE is higher than PVs but it brings flexibility to the system and the system installs its maximum capacity of hydro dams before PVs.

For France, same reasoning, after wind turbines, the system installs its maximum potential of CSP and hydro dams to bring flexibility and to dispatch the prdocution along the year. Hydro rivers's LCOE is higher than PVs so it installs its minimum.

As a conclusion, the systems installs in first place wind turbines in the three cells. Then it installs the minimum capacity of the expensive technologies, that is hydro run-of-river in Belgium and in France. Then the system installs its maximum potential of flexible production, that is solar towers and hydro dams even though their LCOE is higher. And finally, in each country, if the demand cannot be fulfilled with these assets, the only available technology are PVs where the capacity limit is infinite.

So the only way for each country to increase its RES assets is to increase PVs. It can be stated that for the model, PVs are the less interesting as they are the most expensive.

C.2 Electricity layers

Figure C.5: Colour legend of Figure C.4

In Figure C.4, different data are represented :

- The first graph represents the imports (positive values) and exports (negative values) of the different cells of the system for each typical day. It should be kept in mind that the following graphs are represented in typical days and thus do not represent the entire year.
- The second, third and fourth graph represents the electricity layer of Belgium, Switzerland and France (with different scales)
- The fifth graph represents the hourly capacity factor of the PVs in the different cells.
- The sixth graph represents the heating time series of the different cells.
- The colour legend of the electricity layers is presented in Figure C.5

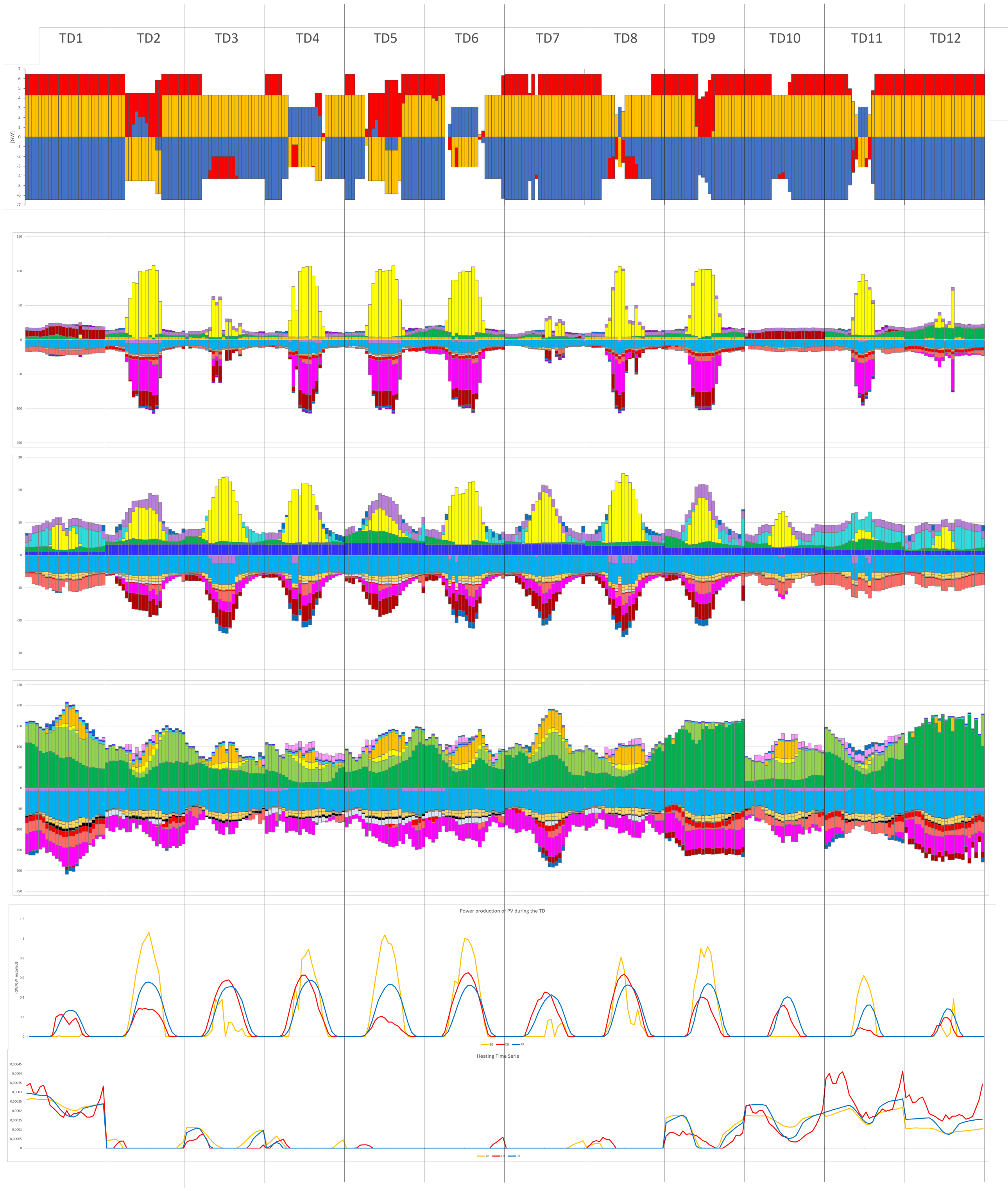

Figure C.4: 1. Imports and Exports of electricity 2. Electricity layer of Belgium 3. Electricity layer of Switzerland 4. Electricity layer of France 5. Coefficient of performance of PVs 6. Heating time series (colour code : in graph 1,5,6 : yellow : Belgium, red : Switzerland, blue : France)

Appendix D

Verification and analysis the 3-cell scenario with all exchange

D.1 RES Assets

The installed capacity of the RES assets in the different countries are represented below in Figure D.1.

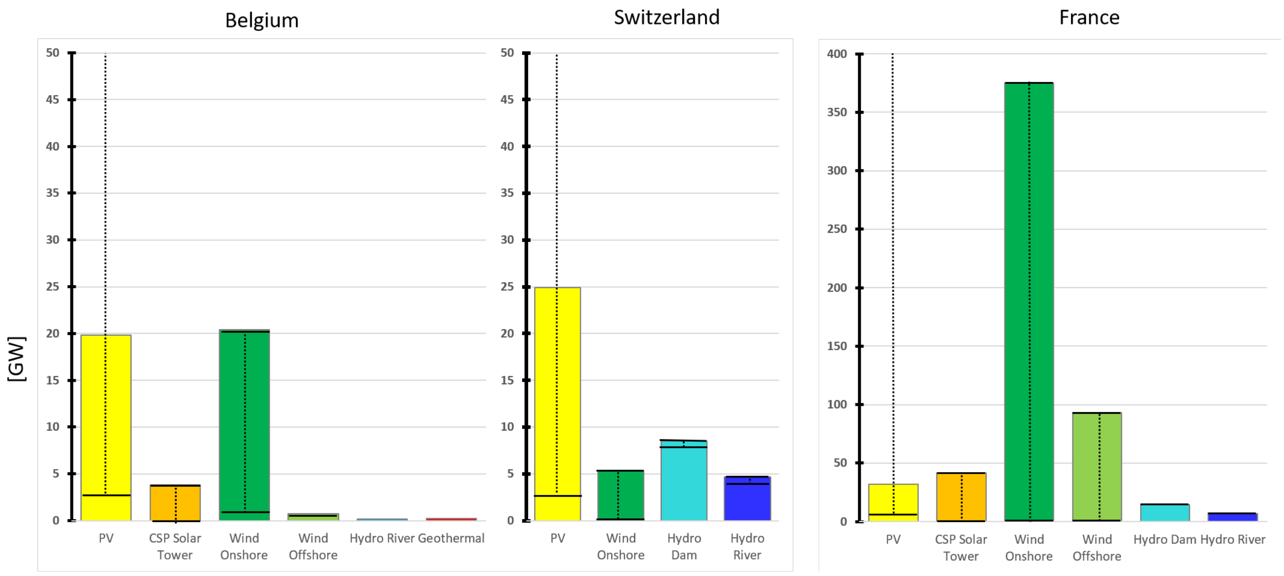

Figure D.1: RES Assets of the 3C-system with all exchanges permitted

The installed RES assets only differ from the first case on one point : the assets of the PVs. Their installed capacity is way smaller (decrease of

D.2 Hydro dams and solar tower

Hydro dams and solar tower are both RES. They rely on an intermittent source of energy but they store. The storage in the case of the hydro dams consist of the water contained in the reservoir. The storage in the case of the solar tower is under the form of heat high temperature collected from the sun. This storage allows them to dispatch their power production when needed.

Figure D.2 presents the duration curve of the hydro resource arriving into the dams in France in our all exchanges scenario. Beside it, the power output of the dams at the same hour is depicted. It shows that the power output doesn't occur at the same time as the input of resource.

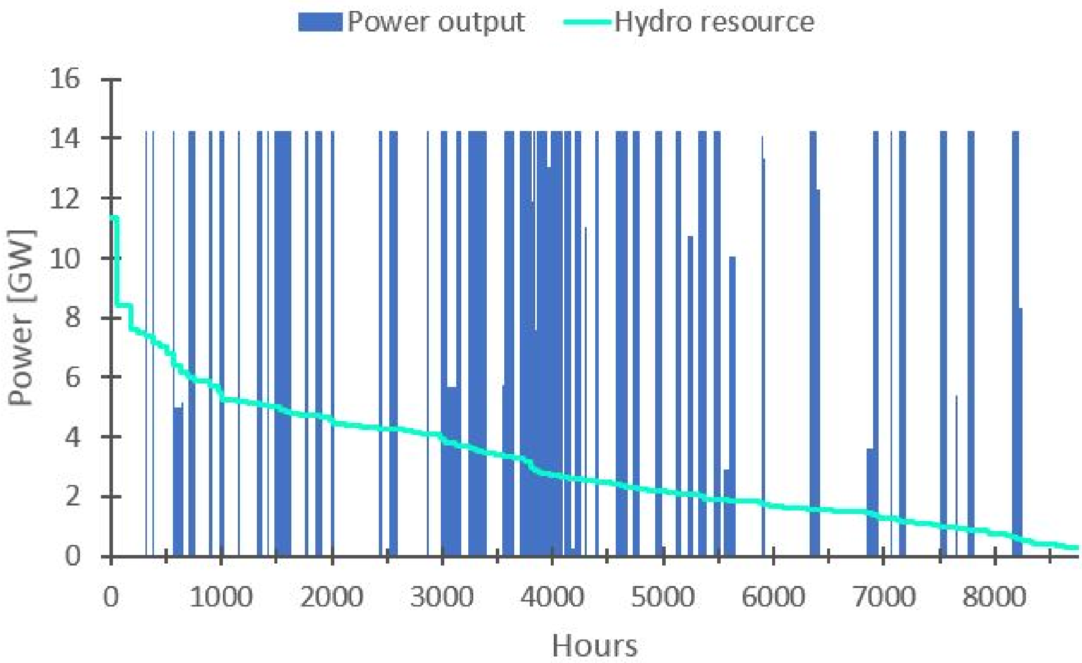

Figure D.2: Duration curve of hydro dam resource and power output in France in the all exchange scenario

Figure D.2 presents the duration curve of the heat collected into the solar tower in France in our all exchanges scenario. Beside it, the power output of the power block at the same hour is depicted. Both curves are expressed in terms of equivalent gigawatts electrical. It shows that the power output doesn't occur at the same time as when the heat of the sun is collected.

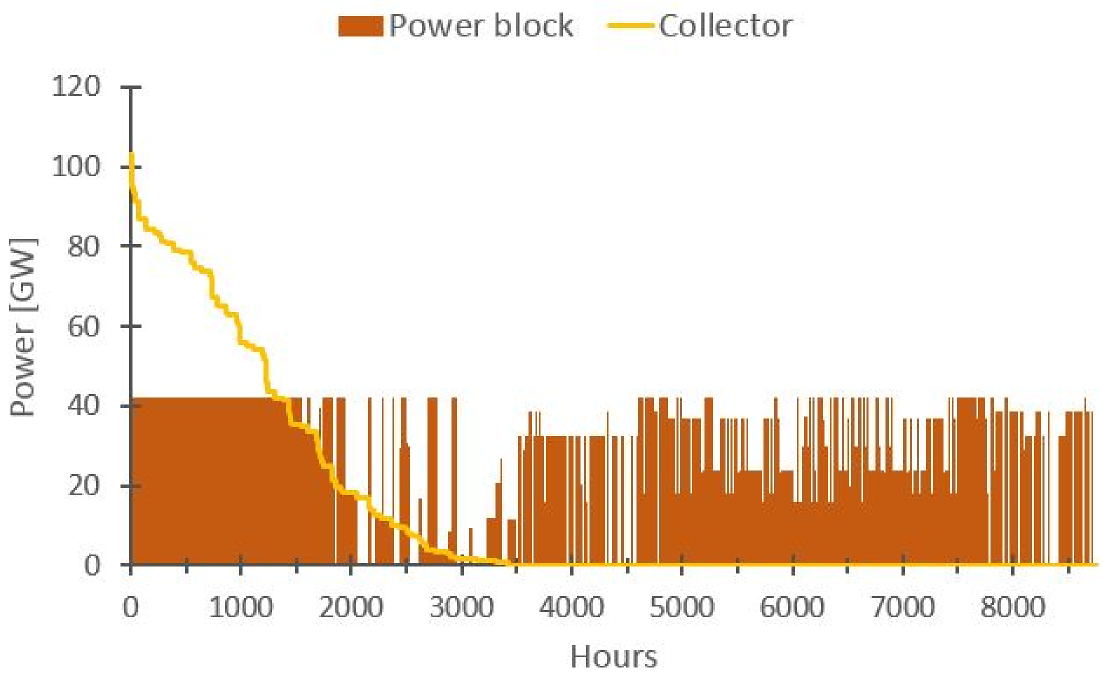

Figure D.3: Duration curve of solar tower resource and power output in France in the all exchange scenario

It should be mentioned that hydro dam can both store energy on short term and on long term. It can help deal with seasonal changes.

On the contrary, the solar tower can only act on a daily scale.

D.3 Verification of exchanges

D.3.1 Network exchanges

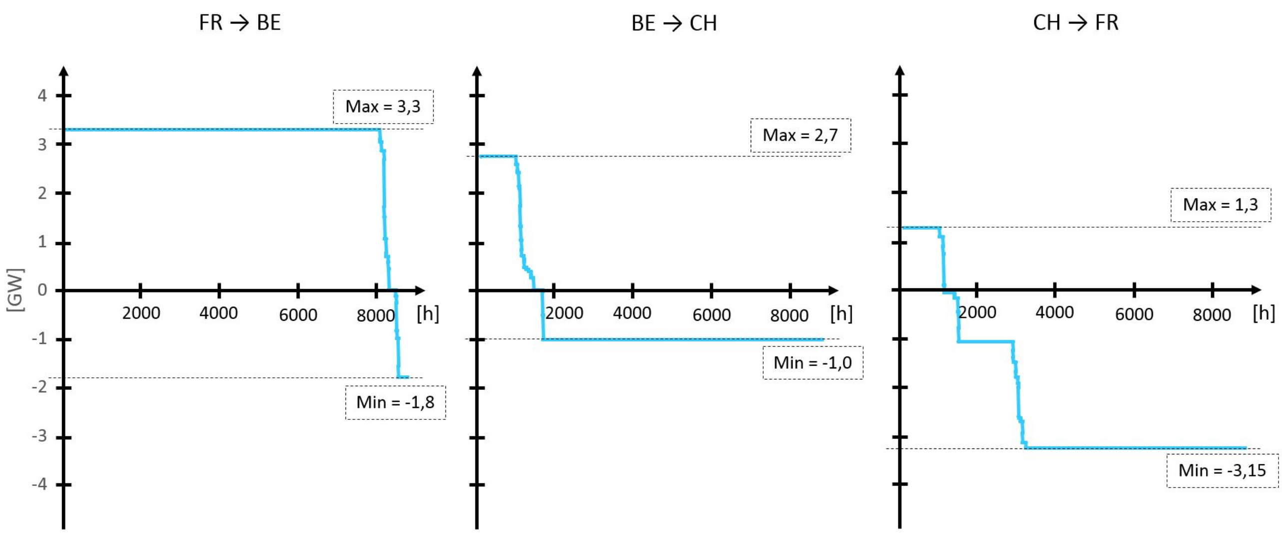

Figure D.4: Duration of electricity exchanges on each transmission line

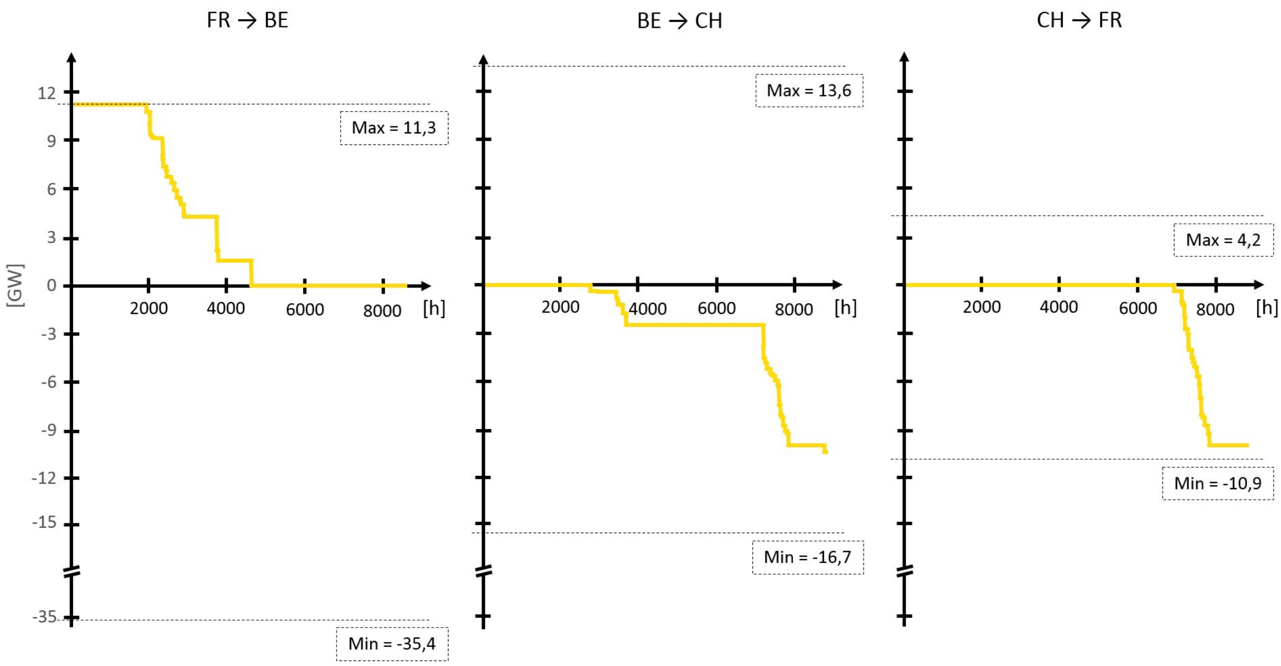

Figure D.5: Duration of natural gas (NG) exchanges on each transmission line

D.3.2 Freight exchanges

	France	**Belgium**	**Switzerland**
Train	0.25	0.25	0.6
Boat diesel	0.3	0.3	0
Boat NG	0	0	0
Truck diesel	0	0.4786	0.4197
Truck FC	0.4698	0	0
Truc NG	0	0	0
Total	1.0198	1.0286	1.0197

Table D.1: Freight share of all the technologies [Mtkm/y]

Appendix E

Analysis of other cases

E.1 3-cell scenario with all resources exchanged with 10% losses

The three cell system we will analyse is a low carbon system. The exchanges permitted between the different countries have losses associated to it through the parameter *exchanges_losses*. This parameter can be changed by the user. In this case, we will consider a 10% loss parameter for all the energy carriers

In theory, the model allows all resources to be exchanged. But for the sake of feasibility, we will only allow the exchanges of electricity, natural gas, wood, waste SLF, and CO2 captured. Electricity and NG have limited transfer capacities as they are exchanged through electrical interconnections and pipelines respectively. Wood, waste, SLF, and CO_2 captured are exchanged by freight and thus at first, we will not set a limit the transfer capacities of these resources.

> In this verification, the overall system, the installed RES assets and the overall exchanges will be analysed.

E.1.1 Global system

The solution of the global system can be resumed briefly by a Sankey diagram, in Fig. E.1.

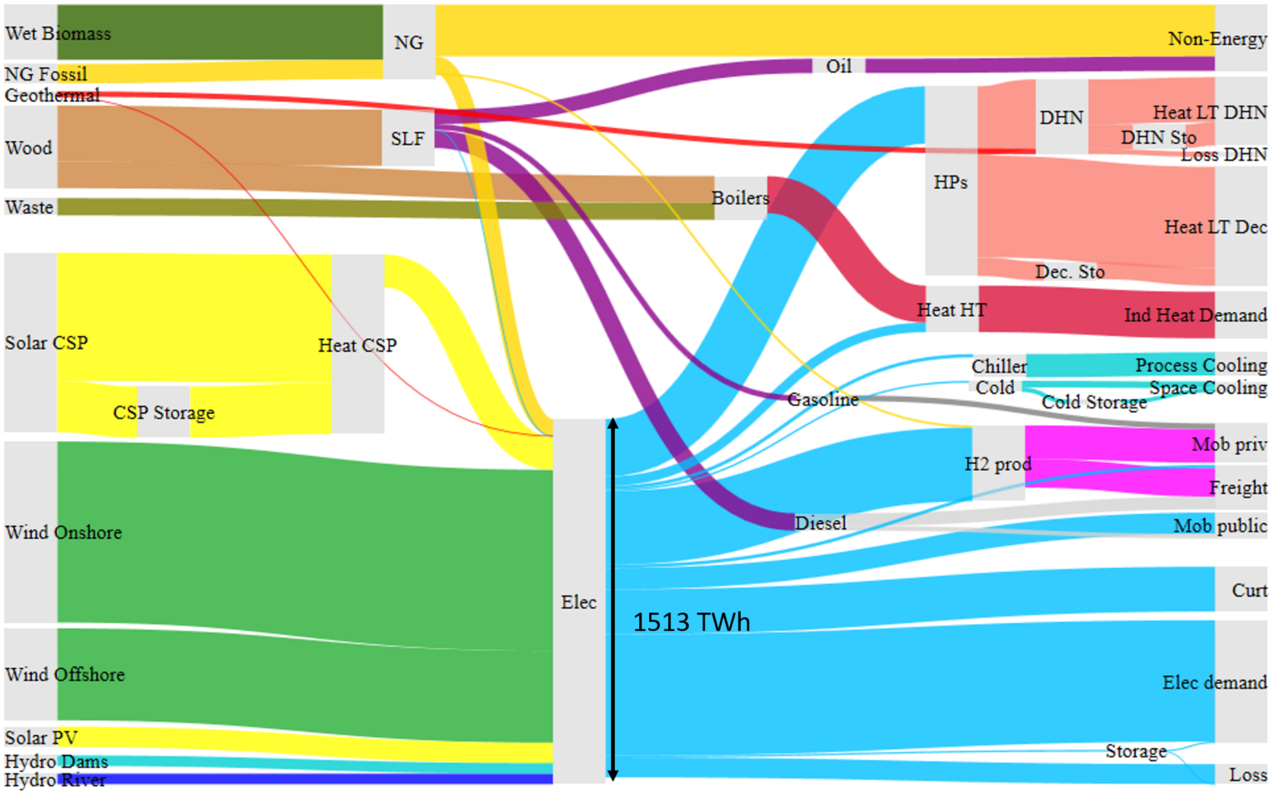

Figure E.1: Sankey diagram of the global system

The final energy consumption of the system is 1931 TWh and the relative use of each sector is detailed in Table E.1. Mobility and electricity demand are the major final energy use and consume together 56.3 % of the final energy use.

Energy Type	Relative part of final-energy consumption [%]
Non-energy use	16
LT Heat	15.2
Ind. Heat	11.3
Process Cooling	0.8
Space Cooling	0.4
Mobility	26.5
Electricity demand	29.8

Table E.1: Relative final energy consumption

The left hand side of the Sankey diagram in Figure E.1 represents the primary energy sources and the right hand side of the diagram represent the global demand of the system. It can be observed that a major part of the resources are renewable. Indeed, wet biomass, wood, solar, wind and hydro represent 94.5 % of the resources. The non-renewable sources (5.4 %) consist of waste and fossil natural gas. There are also secondary energy sources in the system such as SLF, NG and H2 : these energy sources undergo a transformation from a primary energy source. In the case of natural gas, it can be noticed that a part is extracted from the soil (fossil NG) and another part is made from biomethanation (from wet biomass). In this case, 27% of the NG is fossil and 73% is renewable.

A major part of electricity (97%) is supplied by renewable energy sources : mainly wind, solar and hydro. But also a small part (3%) is produced by other technologies that provide more flexibility to the production: in this case NG through CCGt's. The nature of the NG used in the CCGTs cannot be known, but if we keep the proportions from the previous paragraph, it could be stated that 99% of the electricity is renewable and 1% is produced by fossil NG. The system is quite electrified : as 74% of the final energy consumption is electricity.

The low temperature heat is highly electrified, the decentralised heat is 100% supplied by electrical heat pumps and the district heating network is electrified through heat pumps at 93% and 7% is generated by geothermal heat. The system allows a maximum share of DHN of 37% and the system installs 36.5% so the system clearly favours district heating network.

The high temperature demand for industrials is mainly supplied by waste and wood boilers (80%). It also a little bit electrified (20%) as a small part of this demand is supplied through direct electricity temperature .

The process cooling demand and space heating demand in this 3 cell system is very small. It is entirely electrified but the system has no other choice as the only existing technologies to produce cold in the model is electricity.

The mobility is mainly supplied by hydrogen and electricity. A smaller part is also supplied by synthetic gasoline and synthetic diesel produced from wood pyrolysis. The system opts for a lot of fuel cell mobility but this solution is biased. Indeed, it is important to point out that the investment costs of the mobility technologies are not taken into account in the actual model of EnergyScope.

E.1.2 RE Elcetrical Assets of the different cells

For each country, its installed assets of renewable is represented in Figure E.2. The minimum and maximum capacity of installation are represented by the black horizontal lines and their domain of solution in the dotted vertical lines. If the upper horizontal bar (maximum capacity) does not appear on the graph (only for PVs), it is understood that their maximum capacity is upon 25 GW for Switzerland and Belgium, and upon 400GW for France. The minimum capacity of assets is the already installed capacity in the concerned country and the maximum capacity is calculated in [7] .

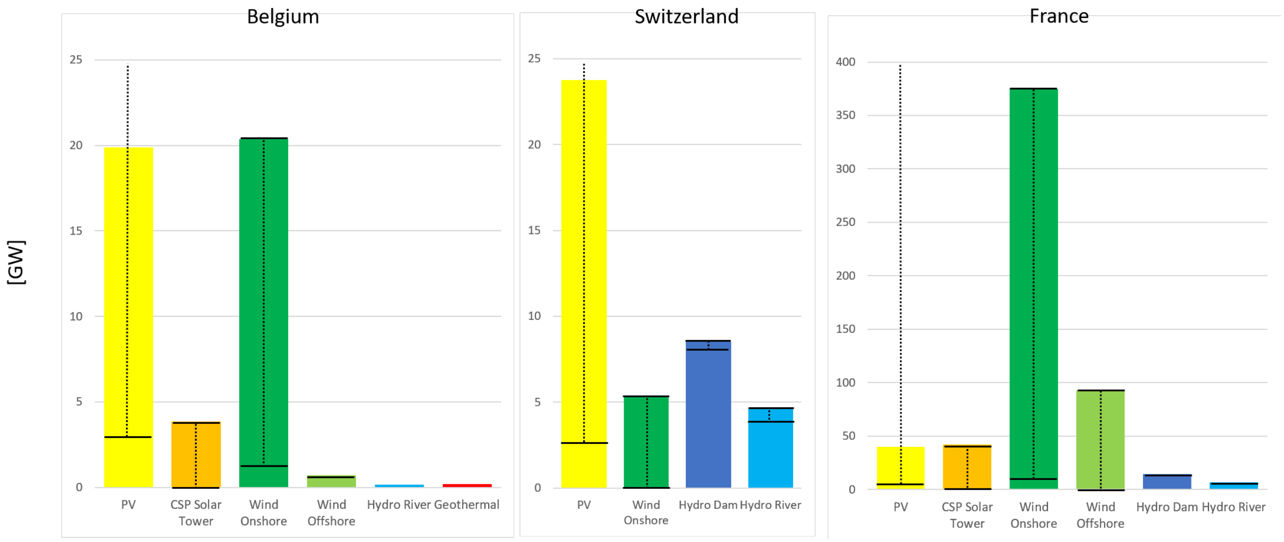

Figure E.2: RE Assets of Belgium, Switzerland and France

The installed assets in the different countries are quite different. It is important to notice again that the scale of the different graphs are not the same for France on one side, and Belgium and Switzerland on the other side. In all three cases, the model installs the maximum capacity of Wind Onshore, Wind Offshore and CSP Solar Tower. PVs are never installed to their maximum capacity. The domain of solution of Hydro dams and Hydro River is visible on this graph in Switzerland but not in Belgium and France : in both cases, its domain of solution is quite small : 0.001 GW for hydro rivers in Belgium and and 0.00006 GW for hydro dams and hydro rivers in France. In both case, the system installs their miniumum capacity for hydro rivers, and its maximum capacity (in France) for hydro dams. We can thus suppose that these capacities are fixed by the system. And finally, concerning Goethermal, only Belgium installs some, and at it's maximum capacity (not visible on the graph neither).

Now, the message of this graph is that Belgium has a lot of PV and Onshore WT, Switzerland a lot of PVs and hydro, and France a lot of WTs. It can already be state that Belgium and Switzerland will have a big intermittency day/night because of the PVs.

E.1.3 Global exchanges

Figure E.3 presents the exchanges balance in this scenario. The main resource exchanged is wood from FR to BE and then electricity from FR to other countries.

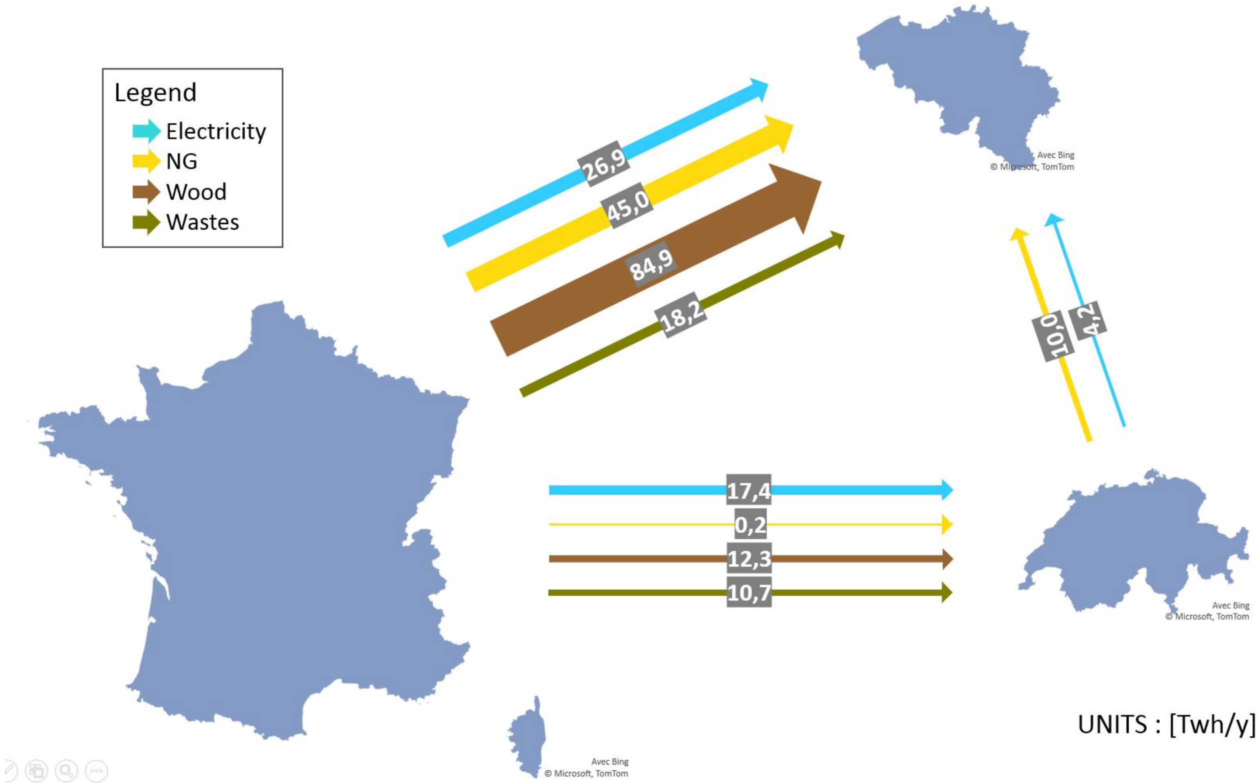

Figure E.3: Yearly balance of exchanges

Figure E.4 illustrates the use of wood in Belgium.

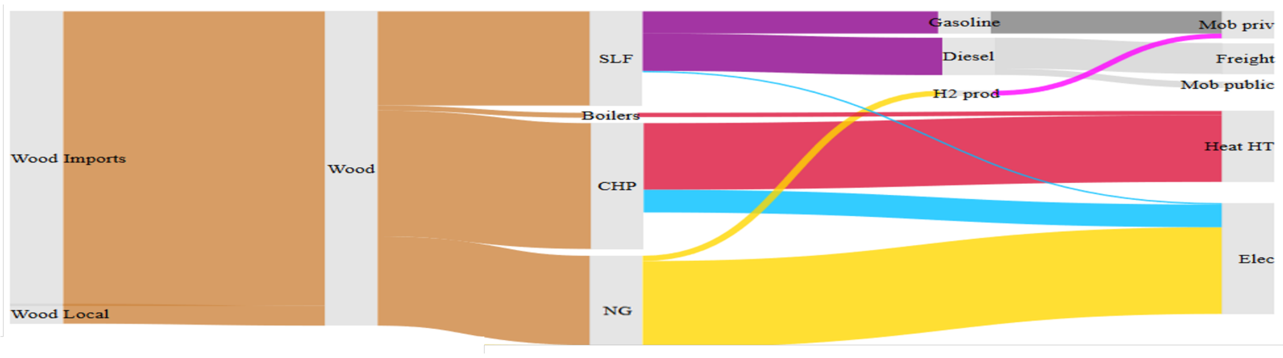

Figure E.4: Wood utilisation in Belgium

E.1.4 Conclusion

The results of this intermediate step have shown that there a need for a more precise modelling of the energetic cost of exchanging resources. Indeed, exchanging such a large amount of wood would use a tremendous amount of trucks.

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