"Energy exchanges between countries for a future low-carbon Western Europe : merging cells in EnergyScope MC to handle wider regions"

Cornet, Noé ; Eloy, Pauline

ABSTRACT

The European Union wants to be carbon neutral by 2050. This implies a transition of the energy systems, which needs to be planned. In order to be cost-efficient and to capture at best the complexity of the problem, a whole-energy system approach should be adopted. Moreover, some countries cannot reach carbon neutrality independently, hence the transition should take advantage of energy exchanges between countries. In this work, Western Europe is modelled using EnergyScope Multi-Cell to consider interconnections between countries and cover the different sectors of energy production and consumption. The countries energy systems are cost-optimised, under EU's 2030 emission target. The exchanges and operating strategies are analysed. Several energy carriers can be used for exchanges, and the possibility to use hydrogen as a new carrier is assessed. To allow the model to optimise a large region at decent computational cost, a methodology is developed to merge data of neighbouring countries. It results that energy exchanges will help to integrate intermittent renewable energies. Most importantly, onshore wind can be used at full potential globally. Regions that have a high potential −the Iberian Peninsula and Scandinavia− can then supply energy to other regions. This requires large electricity interconnections. Hydrogen exchanges is found useful to reduce the capacity of electricity interconnections: it can cover part of the exchanges, especially the part dedicated to fuel-cell mobility.

École polytechnique de Louvain

Energy Exchanges between Countries for a Future Low-Carbon Western Europe

By merging cells in EnergyScope MC to handle wider regions

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Academic year 2020–2021
Master [120] in Electro-mechanical Engineering
Master [120] in Mechanical Engineering

Abstract

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Acknowledgements

First of all, this work would not have been the same without the help of Gauthier Limpens and Paolo Thiran. We are very grateful to them for all the time they spent to advise and motivate us during this special period.

We also would like to thank our thesis supervisor Professor H. Jeanmart for his advice along the year.

Our gratitude goes to Professor E. De Jaeger to be our reader and for the help on specific issues related to his field.

Thank you to the other students of our master thesis group for listening, advising and sharing ideas all along the year.

We express our thanks to Jean-Louis Tychon and Jeroen Dommisse for their work on which this master thesis is based for the data, as well as Paolo Thiran and Aurélia Hernandez for their work on the model we used.

Finally, we would like to thank our families and our friends for proofreading this work and for all the support during these five years at EPL.

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Introduction

To mitigate climate change, the European Union (EU) aims to be carbon-neutral by 2050 [1]. The energy sectors represent 75 % of the greenhouse gases emissions [2], which highlights the need for an energy transition. Such a transition has to be planned because it implies important changes and large investments.

Renewable energy sources (RES) are needed for the transition, but most of them are intermittent (iRES) [1]. Their availability is dictated by weather conditions. Therefore, their integration in the energy system is challenging. To take them into account, the use of models to plan energy systems become necessary.

Historically, energy system optimisation models have been focusing on electricity. However, it has been shown that sector-coupling is much more effective to reach a sustainable energy system [3, 4]. Moreover, electricity only represents 20 % of today's energy consumption in Europe. Whole-energy system approaches aim at considering most of the conversion pathways between primary resources and the end-use energy demand, covering and coupling different energy sectors [4]: electricity, heating, cooling, mobility, or even non-energy use of fuels.

In their master thesis, J.-L. Tychon and J. Dommisse [5] used such a whole-energy system model. They modelled each country of the EU individually, in order to assess their ability to supply their demand with local, renewable resources. They found out that some countries could not reach carbon neutrality independently in view of the lack of renewable resources available on their territories to fulfil their own needs. Belgium, the Netherlands, Slovenia, Germany and Italy can most likely not fulfil their energy needs with their own renewable potential. Some other countries have the capacity to produce excess of energy with their RES, such as the United Kingdom or Spain. Globally, there would be enough energy in Europe to fulfil the total demand [5], and there is hence a need of interconnecting several countries together by letting them exchange energy. Furthermore, regions that do not have enough renewable potential are mostly located in the same area. This further challenges the energy exchanges between countries and highlights the need of strong interconnections, across a wide region. Similar claims are raised by the ENTSOE [6], according to which additional solutions for cross-border electricity exchange are needed to achieve the objectives of the European Green Deal.

Several studies have modelled Europe on an interconnected basis. A. S. Brouwer [7] studied options to integrate iRES in an interconnected Western Europe through the electricity sector. T. Brown [8] went further in what regards sector-coupling in Europe by adding several sectors to the model PyPSA, which is originally dedicated to electrical power systems. However they do not take into account all energy sectors, and only electrical lines are used for interconnections.

This master thesis therefore takes a whole-energy system approach to answer the question **"How can energy exchanges help to reach a low-carbon Western Europe at least cost?"** To extend the possibilities of sector interactions, several energy carriers can be exchanged between countries (*e.g.* electricity, gas or wood). The question will be addressed by analysing the exchanges themselves, but also the production and conversion strategies that drive them. Western Europe is the region of interest because it includes a good diversity in terms of energy potential, demand, and interconnection routes. Moreover, most of the EU countries that lack of potential according to [5] are located in Western Europe.

The model used is EnergyScope TD [3], the same model as used in the master thesis of J.-L. Tychon and J. Dommisse [5]. An extension called EnergyScope Multi-Cell was developed by P. Thiran and A. Hernandez in their master thesis [9] to allow energy exchanges in form of various type of energy fluxes. This latter version is improved in the present work in order to be applicable to the studied area. A methodology is developed to be able to run the model on a large region: some countries are merged to reduce the computational cost. In this process, a loss of information is unavoidable, and choices have to be made to limit it.

In Chapter 1, the methodology is presented. This includes a presentation of EnergyScope Multi-Cell with the contributions performed in this work, the merging methodology, and a description of the method and tools used in the next chapters to analyse the results.

Chapter 2 then presents the studied system and scenarios. The studied area is described, with the characteristics of each country. Then the distribution of countries into wider regions is presented. The different scenarios that are analysed in the following chapters are defined there.

The validation of the merging methodology is presented in Chapter 3, in order to know how well the results are preserved when merging countries together.

Chapter 4 presents the results of the main scenario (Baseline) in which the main energy vectors used currently can be exchanged. Chapter 5 then presents the results of alternative scenarios by focusing on what differs compared to the Baseline. This last chapter includes the addition of hydrogen as a vector for exchanges, and an analysis of the impacts of stricter greenhouse gas emissions limits.

Chapter 1

Model description and merge methodology

In the work of J.-L. Tychon and J. Dommisse [5], the tool used to perform the analyses is EnergyScope Typical Days (EnergyScope TD): an open-source model that optimises the design and operation of a regional energy system, based on the end use demand (EUD), the resources and a set of conversion technologies. Most importantly, it takes a whole-energy system approach, so that multiple energy sectors and their coupling are taken into account. The principle of the model is more detailed in Section 1.1.

Recently, an extension was added to take into account several cells (*i.e.* distinct regions). It allows to optimise the energy system of several regions at the same time by letting cells exchange energy. This version, called EnergyScope Multi-Cell (EnergyScope MC), was implemented by A. Hernandez and P. Thiran [9] and tested on a 3-cell system. The version of the model presented in Section 1.1 includes this extension.

As mentioned above, interconnections between European countries are needed to reach carbon neutrality. In order to study that, each European country could be represented by its own cell in EnergyScope MC. However, models are complex and have a high computational cost, especially when using a whole-energy system approach. Therefore, EnergyScope MC cannot easily handle a high number of cells: as a general idea, the memory usage increases a bit more than linearly with the number of cells, and the computational time doubles with each additional cell. Computational time is especially crucial when performing parametric analyses. Given the location of countries that lack of potential, the need of studying a large region remains.

The work presented here extends the abilities of EnergyScope MC, to easily handle wider regions, by lowering the spatial resolution. This is done by merging several neighbouring cells together to create what is called a macro-cell. This approach needs to truly capture and represent the behaviour of each cell, such as weather conditions and consumption profiles, in order to provide results similar to EnergyScope MC with non-merged cells. This procedure is described in Section 1.2

Defining macro-cells can be considered as relevant because some neighbouring countries present similarities (in weather conditions, consumption profiles, or geography), and have strong networks to exchange resources between them (by road, grid, or pipelines). A similar approach that groups several countries has already been applied in [7], which focus on the same region as this work.

Finally, Section 1.3 presents the method used to analyse the results in the following chapters, including definition of the metrics that are used.

1.1 Description of the model

EnergyScope TD is an open source model to help in the decision making of energy system strategy. It is a linear programming (LP) model that optimises the total cost of an energy system for a defined area under some constraints including a global warming potential (GWP) limit. It provides an optimal energy system design and operation from where it is possible to highlight main technologies and strategies that will help to reach a low-carbon system.

The principle of EnergyScope TD is to model the energy fluxes of a territory over an entire year, with an hourly resolution. The area is considered as a whole, called a cell, and therefore the geographical distribution of the production plants and demand are not taken into account. With the Multi-Cell version used here, several cells are optimised at the same time. Each cell has its own characteristics, but they can exchange energy between them.

1.1.1 Working principle of a cell, and objective function

In view of having a good trade-off between model granularity and computational time, the different days are represented by a chosen number of typical days (TDs). The model runs in 2 main successive steps. Based on input data (weather conditions and EUD), TDs are selected thanks to a clustering method during the first step. The second step is the optimisation of the energy system over the chosen TDs. More mathematical details are given in the reference paper [3]. Figure 1.1 presents an overview of the working principle of the model.

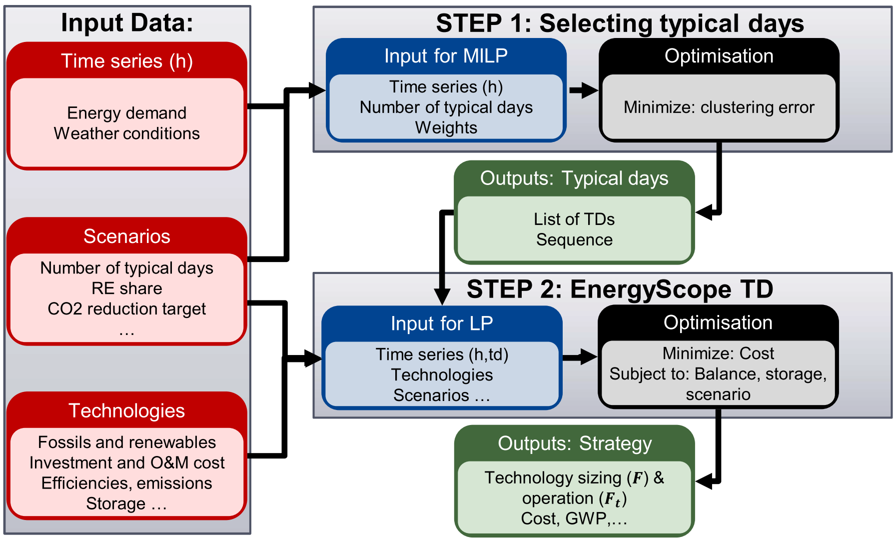


Figure 1.1: Overview of EnergyScope's two-step methodology. STEP 1: optimal selection of typical days. STEP 2: Energy system model. Abbreviations: typical day (TD), mixed-integer linear programming (MILP), linear programming (LP), global warming potential (GWP). Figure from [3].

Input data There are many different types of input data and not all of them are presented here. Therefore only the ones needed to understand the current work are detailed in the sections that make use of them.

A focus should however be made on time series, which are used all along this work. Some quantities are not constant over the year:

- the capacity factors of iRES: onshore and offshore wind, photovoltaic (PV) and thermal solar, hydro run-of-river and dams, tidal energy;
- part of the EUD: electricity, space heating and cooling, passenger and freight mobility.

Those varying quantities were thus collected[1] for the 8760 hours of the year and treated to obtain the time series (TS) used by the model. For the production, a TS simply represents the capacity factor i.e. the maximum energy that can be produced at each hour, per installed capacity unit of the associated technology. For the demand, each TS is computed as the hourly consumption over its total yearly EUD.

STEP 1: Typical Days selection The first step pre-processes all the hourly data and selects the representative TDs of the year. The usage of TDs can reduce the computational time by several orders of magnitude while only introducing a small error in the designed system; and it was determined that using 12 TDs is a good trade-off for one cell [3].

The input data are the TS of demand types and of iRES hourly capacity factors for each cell, as well as the wanted number of TDs and the *Weights* that represent the importance of each TS for each cell in the process that selects the typical days (see Figure 1.1).

STEP 2: Energy System optimisation The second step performs the global optimisation based on the selected TDs. The mathematical formulation of the model includes a set of linear constraints and a linear objective function. The main objective is to minimise the total annualised cost of the system (C_{tot} [M€/y]). The general expression of this objective function is the following:

$$\min \sum_{c \in CELLS} C_{tot}(c) \tag{1.1}$$

$$\begin{aligned} \text{with} \qquad C_{tot}(c) = & \sum_{j \in TECHS} \left(\tau_j C_{inv}(c,j) + C_{maint}(c,j)\right) \\ & + \sum_{r \in RES} \big(C_{op}(c,r) + C_{exch\_network}(c,r)\big) \end{aligned} \tag{1.2}$$

where:

$\tau_j = \frac{i(i+1)^{n_j}}{(i+1)^{n_j}-1}$ is the investment cost annualisation factor of technology j,

$C_{inv}(c,j) = c_{inv}(c,j)\, F(c,j)$ is the investment cost of technologies [M€],

$C_{maint}(c,j) = c_{maint}(c,j)\, F(c,j)$ is the maintenance cost of technologies [M€/y],

[1] For the collection procedures, see the Supplementary Materials of EnergyScope TD [10, 11] for detailed description over Switzerland and Belgium, and the work of J.-L. Tychon and J. Dommisse [5] for general description over all EU countries.

$C_{op}(c,r) = \sum_{t \in T} c_{op}(c,r)\, F_t(c,r,h_{(t)},td_{(t)})\, t_{op}(c,h_{(t)},td_{(t)})$ is the operating cost due to resource utilisation [M€/y],

$C_{exch\_network}(c,r)$ is the cost of networks for energy exchanges between cells (expression detailed below) [M€/y],

with:

n_j: the expected lifetime of technology j, in years;

i: the interest rate;

$F(j)$: installed capacity of technology j, in [GW];

$F_t(r,h,td)$: consumption of resource r during hour h of typical day td [GW];

$c_{inv}(j)$: specific investment cost of technology j, in [M€/GW];

$c_{maint}(j)$: specific yearly maintenance cost of technology j, in [M€/GW/y];

$c_{op}(r)$: specific cost of resource r, in [M€/GWh];

T: set of all the periods of the year (8760 hours). The $_{(t)}$ subscripts indicate the hours and TDs corresponding to the period t.

The optimal energy system design of a region is computed from its resources, energy conversion technologies and EUD. Figure 1.2 shows an example: resources (external, or available locally) are converted by technologies in different types of energy layers to meet the EUD. The optimisation of the system depends thus of the 3 following main inputs and their characteristics:

- the local and imported resources: availability, cost and GWP;
- the EUD, split in different end use types (EUTs): heat (high temperature, low temperature for space heating and low temperature for hot water), electricity (constant and variable), mobility (passenger mobility and freight), cooling (process and space cooling) and non-energy;
- the energy conversion technologies: the optimal installed capacity of a technology is constrained between an upper bound (f_{max}) and a lower bound (f_{min}). This allows to take into account the minimal capacity already installed and the maximal potential deployment of a technology. The investment and maintenance costs as well as the construction GWP are also taken into account.

These technologies convert energy between two layers of the system. A layer is a resource or an EUT, and has to be balanced at all time. For example, the production of electricity must balance at each hour the consumption and losses of electricity, including storage input and output. There are different types of technologies that connect different types of layers:

- technologies of end-use type: convert energy from a layer to an EUT layer, for example heat or electricity. Note that energy in an EUT layer is not necessarily consumed immediately, it can also be transformed again (*e.g.* electricity to heat) or stored;

- storage technologies: store energy from a layer, and restore it to the same layer, at a different time;
- infrastructure technologies: other type of technologies.

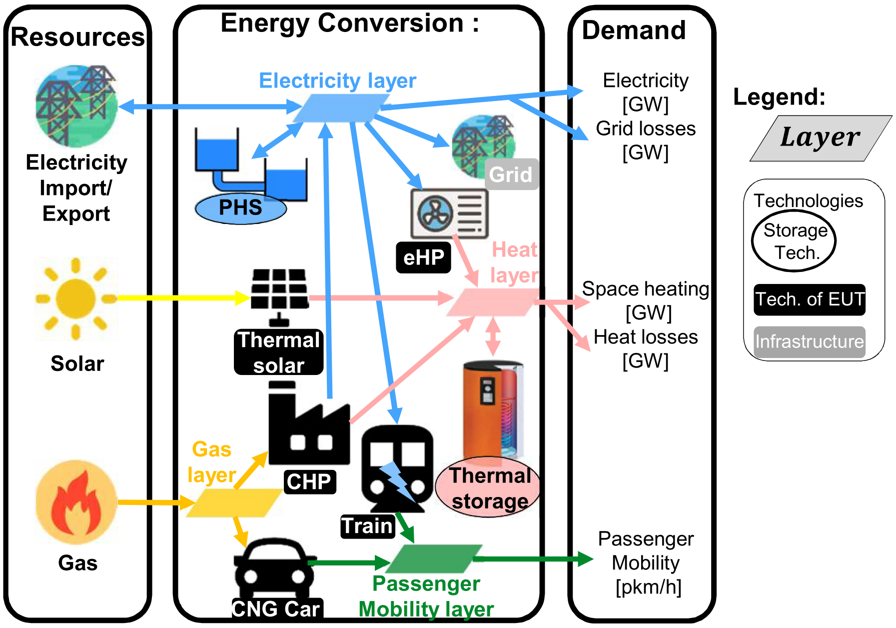


Figure 1.2: Conceptual example of an energy system with 3 resources, 8 technologies (of which 2 storage and 1 infrastructure) and 4 end use demands (of which 1 losses). Abbreviations: pumped hydroelectric storage (PHS), electrical heat pump (eHP), combined heat and power (CHP), compressed natural gas (CNG). Figure from [3].

This approach allows to take into account different energy sectors and to model interactions between them. Finally, the optimal solution is given by the quantity of resources used, the installed capacity of each technology and their operation at each time period. The performances of this energy system can be assessed in terms of cost and GWP associated with infrastructure installation and resources use.

1.1.2 Exchanges

A cell interacts with its neighbours through the variables $Exch_{imp}(c_1, c_2, r, h, td)$ and $Exch_{exp}(c_1, c_2, r, h, td)$ that represent the amount of resource r imported by cell c_1 from cell c_2, or exported from c_1 to c_2, at each time step (each hour of each TD). The link is made between these exchange variables and the inner cell by summing the imports and the exports (separately) from all countries and make them increase and decrease the layer corresponding to resource r:

$$\sum_{c_2 \in COUNTRIES} Exch_{imp}(c_1, c_2, r, h, td) = R_{t,import}(c_1, r, h, td) \tag{1.3}$$

$$\sum_{c_2 \in COUNTRIES} Exch_{exp}(c_1, c_2, r, h, td) = R_{t,export}(c_1, r, h, td). \tag{1.4}$$

What c_1 imports from c_2 is imposed to be equal to what c_2 exports to c_1. The losses occurring in the exchange process are proportional to $R_{t,export}$ and depend on the resource.

Exchanges are limited by the variable $Tc(c_1, c_2, r)$ that represents the transfer capacity: the maximum power that can be imported by c_1 from c_2 for resource r. This value is forced to 0 between cells that cannot exchange directly. Some resources can be exchanged by freight (*e.g.* woody biomass), while other are exchanged through dedicated networks (*e.g.* electricity). The transfer capacity is unlimited for freight exchanges; but for network exchanges, Tc is optimised. This value does not take into account security margins or redundancy, therefore it represents the net transfer capacity (NTC) of the transmission lines.

For networks of exchanges, the price is defined per unit of NTC in the parameter $c_{exch\_network}(c_1, c_2, r)$ [M€/GW/y]. For a same resource r, a different price can be set for different borders, to account for differences in length or in technology requirement (*e.g.* to cross a sea). Moreover, some networks are defined as bidirectional. For those networks, Tc is the same in both directions, and the price is only accounted once for both directions. For other networks, $Tc(c_1, c_2)$ is independent of $Tc(c_2, c_1)$.

1.1.3 Contributions to the model

Some parts of model presented here have been implemented as part of the present work. These contributions are listed below. The model is open-source, and the version used here is available in a GitHub repository [12] that contains documentation and some tools of analysis and results.

Loops and transit The previous implementation used one variable that could be positive or negative for exchanges, instead of $Exch_{imp}$ and $Exch_{exp}$. This led cells that were importing and exporting at the same time to only account for the net balance of import-export regarding the losses. Two problems arose from this:

- formation of loops, in which an amount of resources went round three (or more) cells and came back to the first one at the same time step. This led to quite unrealistic values, but it was only a virtual offset that could be removed during post-processing;
- when a resource transited trough a cell, the losses were not accounted for during the transit. So whatever the number of cells that were crossed, the losses only occurred in the source and destination cells.

Summing the positive and negative parts of a variable is not possible directly in linear programming. A solution is to split the initial variable into two separate variables that are both non-negative. One can then replace every occurrence of the initial variable by the difference of the new ones, and use the two of them separately for separated positive and negative sums, as proposed above.

Optimal transfer capacities In previous version of EnergyScope MC, the net transfer capacity of each interconnection was fixed. One could already choose the value, and perform a parametric analysis. The possibility to optimise the NTCs has been added to the model in this work, and does not impact much the computational cost.

This feature is implemented by introducing the variable Tc. It replaces the parameter tc (fixed value) in the model. The latter is set to the current NTC value and becomes the lower bound of the new Tc variable. Also, the cost related to the transfer capacities,

$C_{exch\_network}$, is added as a variable. Before that the cost was fixed and therefore not involved in the optimisation process.

Different price for each interconnection In the previous version, the price of interconnections was the same for each border, for a given resource. As the area covered by this study includes more geographical diversity, the need for a different price according to the border appeared. The geographical diversity includes seas to be crossed and connecting grids that are not synchronous with each other. More details are given in the case study description (Chapter 2).

This feature is implemented by adding the dimensions c_1 and c_2 to the parameter $c_{exch\_network}$, and setting a specific value for each pair of cells. It also appeared to be more relevant for some exchange networks to be defined as bidirectional (*e.g.* electricity), therefore what concerns 'bidirectional networks' as also been introduced in this version.

1.2 Merge methodology

As the model detailed above is costly to apply to a high number of cells, the merging of cells is introduced in order to lower the spatial resolution. The aim being to significantly reduce the complexity, while maintaining as much as possible the precision of the results.

1.2.1 Overview and detailed objectives

The general idea is to consider a region of several countries that have similarities as a single cell, called a macro-cell. This macro-cell will be considered exactly the same way as a cell by EnergyScope TD. An illustration of a system before and after merging is shown in Figure 1.3.

To do so, the data of all the cells-to-be-merged (cells$_{\mathrm{tbm}}$) have to be pre-processed in order to fit into one cell. This merging procedure is described in Section 1.2.3. The resulting system has to capture as well as possible the behaviour of each cell$_{\mathrm{tbm}}$. However, a loss of information is unavoidable.

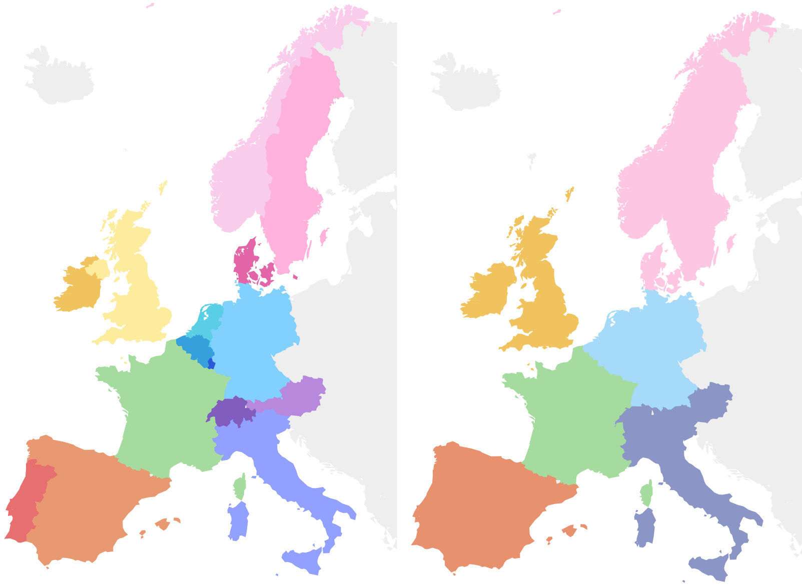
As this study analyses the exchanges between countries, those exchanges are wanted to be with an error, compared to the system with non-merged cells, that is small. This would furthermore allow to perform the optimisation again on each region that was represented by a macro-cell, while imposing the exchanges with the exterior of that macro-cell: giving results close to the original (non-merged) system, but with a fragmented computation.

To merge cells together, part of the data can simply be added up (*e.g.* the EUDs), but other parts have to be averaged (*e.g.* the time series or costs). This requires to define weights to account for the importance of each cell.

1.2.2 Selection of the right weights

A clarification has to be made first, because there are two types of weights that are used. They have similarities, but are not used exactly the same way.

- The first type covers the weights for the TDs selection (STEP 1), written w_{TS}: they were already used in EnergyScope TD. For one cell, those w_{TS} give the relative



(a) *Cells before merging.* (b) *Macro-cells.*

Figure 1.3: Illustration of the merging principle, as it is applied in [7] for the study area of Western Europe.

importance of different types of TS (Electricity EUD, Space Heating, PV availability, ...) in the process of selecting the typical days. When using multiple cells, each cell has its own set of w_{TS}.

- The other type of weights is introduced in this work in order to merge several cells. They give the relative importance of each cell_{tbm} for the resulting macro-cell. They are written w_{cell}. Those weights are also applied to the TS, to obtain one TS of each type for each macro-cell. The w_{cell} weights are defined for the merging procedure, but they can also be used to redefine the w_{TS} for TDs selection, as explained hereafter.

When using multiple cells, the w_{TS} for TDs selection should in addition account for the importance of each cell, and not only the importance of the different types of TS. To this end, w_{cell} are used to redefine the w_{TS} for TDs selection, that originally only represented the importance of types of TS. Therefore, w_{TD} is defined to replace w_{TS} in the TDs selection:

$$w_{TD}(c,ts) = \frac{w_{cell}(c,ts)}{\sum_{c_2 \in cells} w_{cell}(c_2,ts)} \cdot w_{TS}(c,ts) \qquad \forall\, c \in \text{cells},\ ts \in \text{types of TS}. \tag{1.5}$$

For what follows, the weights that are mentioned are the ones representing the cells importance (w_{cell}), unless explicitly stated otherwise. They are used to perform weighted averages over the different $\text{cells}_{\text{tbm}}$ of one macro-cell. Therefore, the input data coming from the $\text{cells}_{\text{tbm}}$ are multiplied by the corresponding weight, and divided by the sum of the corresponding weights of all cell_{tbm} of that macro-cell, to normalise the weight.

1.2.3 Procedure for input data of merged countries

The procedure to merge each type of input data is presented here. For a detailed description regarding specific implementation, the reader is referred to Appendix A.

Time Series They can be divided in two groups: the EUD TS, and the intermittent renewable energies TS. To merge the TS of the different $\text{cells}_{\text{tbm}}$, a weighted **average** is performed. For the EUD TS, the total EUD of the related demand types of each cell_{tbm} are used as weights. For the iRES TS, the weight definition is less obvious and a selection was performed (see Appendix B). In the end, the maximum energy production over a year of the related technologies of each cell_{tbm} are used as weights: for most of the TS, it is computed as f_{max} of the related technologies multiplied by the mean capacity factor over the year (*i.e.* the mean of that TS). An exception is made for the *Solar* TS, which is used by several technologies, and for which the maximum capacities are not always defined. The weight used for this TS is the total solar energy potential of the country, computed as the mean direct normal irradiance (DNI) multiplied by the surface-area of the cell, which are taken from the Global Solar Atlas [13]:

$$Solar\,potential_c = \overline{DNI}_c \cdot Area_c. \tag{1.6}$$

Resources In EnergyScope MC, the resources can be considered as coming from the exterior, or as produced in the country (local). Exterior resources have, by default, an availability set to 0, or unlimited: the merged cell will thus have the same limit (either 0 or unlimited). The local resources have a non-zero availability limit: they are thus **added up** through each cell-to-be-merged (cell_{tbm}).

Concerning their cost and GWP, only the cost of local resources are defined per country. The **average** of those costs is then taken, with the local availability as weight. This does not introduce any approximation in the low-carbon scenario presented in this study, because every country tends to use those local resources at their maximum.

End-Use Demand The demand is simply **added up** through each cell_{tbm}, for each end use type and each sector.

Technologies The minimum and maximum capacities (f_{min} and f_{max}) are **added up** through each cell_{tbm} (if f_{max} is unlimited for at least one cell_{tbm}, it is unlimited for the macro-cell).

If investment or maintenance costs (c_{inv} or c_{maint}) of technologies vary between the cell_{tbm}, the **average** is taken, using f_{max} as weight.

In the data used in this study, only the cost of *Efficiency* and *Grid* vary between countries while having a non-limited f_{max}. Both are **added up**: *Efficiency* because it represents a fixed cost for each cell; and *Grid* because it depends on the electricity EUD of each cell [5], which are added up.

Storage Technologies of storage have additional characteristics, and most of them are set globally (*i.e.* they do not depend on the cell). Only the storage charge and discharge times of the pumped hydroelectric storage (PHS) are defined per country, because this technology highly depends on the geography. Their values account for the currently installed PHS capacity in each country [5, 11], and the model therefore assumes that the charge and discharge times will stay similar even if the PHS capacity increases a lot. For the merging, those values are **averaged** using the currently installed capacities as weights. As a result, the charge and discharge time values for the macro-cell captures well the behaviour of the individual cells if the model keep the PHS capacities at their current value; however the values can be quite different than with non-merged cells if the PHS capacities increase, due to the above assumption made in the model[2].

Exchanges The minimum transfer capacities between two macro-cells are simply obtained as the **sum** of the minimum transfer capacities that cross their borders. The electricity import capacities from the exterior of the system can also be added up, if the user wants to allow interconnections with the exterior in his analysis[3].

The distances for freight transport have to be obtained **manually** for the macro-cell: as proposed in [9] for a cell, this value is taken as the half distance between the two big cities furthest apart within the macro-cell.

Miscellaneous Among the other parameters, several are independent of the cell and have one global value, at least in the current implementation of EnergyScope MC. Their values are thus left unmodified when merging: the interest-rate, the specificities of vehicles battery storage, the network losses, and the grid reinforcement costs due to renewable intermittency.

The GWP limit and the limit in land surface for solar production can be **added up**. The weights representing the importance of each cell_{tbm} −used to compute the new w_{TD} for TDs selection− are also added up. Re-computing them based on the data of the new macro-cell give the same values.

Other parameters have to be **averaged**: the minimum renewable share uses the total EUD as weight; the minimum and maximum share of public transportation use the passenger mobility EUD, the shares of boat, train and truck use the freight mobility EUD; and the share of district heating network (DHN) use the total low temperature heating EUDs (space heating and hot water). If the weights w_{TS} for TDs selection differ between cells, they are averaged with the corresponding weights w_{cell} representing the cells importance.

1.3 Method of analysis

The analyses made in Chapters 4 and 5 are conduced with the same general structure, in order to specifically analyse the exchanges between cells.

Firstly, the focus is made on the exchanges themselves. The energy carriers that are used in the system design are listed, and a global analysis is performed to present general results. The yearly energy exchanged and the transfer capacities installed are given and commented. The role of each cell towards the rest of the system is outlined. Then, specific analyses are performed on the utilisation of the different interconnections over the year.

Next, the energy system design −within the cells− is analysed. The main installed technologies are presented and strategies of energy production inside the cells are highlighted. The coupling of sectors is also assessed, all of this in view of supporting the observations made about the exchanges, and give explanation on phenomena that were observed for exchanges.

[2]If the PHS capacities increase compared to the current capacities, the mean charge and discharge times will be different in the merged and non-merged cases. However it is assumed here that the values resulting from the merge case are as valid as the ones from the non-merged case, because they all fall under the same assumption of the original model.

[3]In this study, no electricity import from the exterior is considered. If the user sums the import capacities, he has to make sure that their values only account for interconnections with the exterior.

Finally, a sensitivity analysis is performed on some parameters if it is found to be appropriate.

1.3.1 Metrics definition

In order to analyse some results about the exchanges, some specific metrics are used. They are defined in this section.

Transit factor

When exchanges are made between several interconnected cells, it is possible that a cell serves as link to transfer energy between two other cells. In this case, the energy exchanged with this intermediate cell is only transiting through it. It is interesting to introduce a transit factor (TF) to underline the share of the total energy exchanged with a cell that transits.

To define this indicator, the total amounts of import and export of resource r are computed for each hour of the year. The minimum between these two values is set to be the hourly amount of energy transiting and the maximal one is the net hourly total exchange. The TF of a cell, for a given resource, is defined as the sum of all the energy transiting through it over a year compared to the sum of all the net energy exchanged with this region:

$$\begin{gathered}
Transit(c,r,t) = \min\left\{R_{t,import}(c,r,t);\ R_{t,export}(c,r,t)\right\} \\
Net_energy(c,r,t) = \max\left\{R_{t,import}(c,r,t);\ R_{t,export}(c,r,t)\right\} \\
\forall\, c \in \text{cells},\ r \in \text{exchanged resources},\ t \in time^4
\end{gathered}$$

$$\begin{gathered}
TF_{c,r} = \frac{\sum_{t \in time} Transit(c,r,t)}{\sum_{t \in time} Net_energy(c,r,t)} \\
\forall\, c \in \text{cells},\ r \in \text{exchanged resources.}
\end{gathered} \tag{1.7}$$

Import share

To analyse the amount of energy imported in each cell for a given resource, this quantity can be reported to the total consumption of that resource in the same cell. The import share therefore highlights the proportion of the resource usage that is covered by imports.

For this study, its value is computed as the total amount of resource r imported into cell c (excluding the part that is transiting), divided by the total amount of the resource that is consumed within the cell:

$$\begin{gathered}
\text{Import share}(c,r) = \frac{\sum_{t \in time} \max\left\{R_{t,import}(c,r,t) - R_{t,export}(c,r,t);\ 0\right\}}{\sum_{t \in time} -\left(\sum_j \min\left\{prod_cons(c,r,j,t);\ 0\right\}\right)} \\
\forall\, c \in \text{cells},\ r \in \text{exchanged resources}
\end{gathered} \tag{1.8}$$

where j represents all the resources, technologies, storage and end use that can produce or use the resource, while excluding the imports and exports; and $prod\_cons(c,r,j,t)$ is

[4] The writing of hours (h) and typical days (td) is simplified here in profit of t, which is comprised in $time$: the 8760 hours of the year.

the amount of resource r produced or used by j at time step t. The interesting part of $prod\_cons$ is the consumption (not including exports), hence the min{} that leaves out the production.

Interconnection utilisation factors

In the context of the hourly utilisation of the interconnections, it is useful to define global metrics. These metrics are taken from [9].

The **utilisation factor (UF)** is the ratio describing how much the interconnection is used in a given direction, compared to the maximum power that could be transferred if the lines were used at full power in that direction during the whole year. It can be assimilated to the full-load-hours −used in some studies− of the lines in that given direction, over the 8760 hours of the year. For the a resource r imported in c_1 from c_2, it is expressed as:

$$\mathbf{UF}_{c_1,c_2,r} = \frac{\sum_{t \in time} Exch_{imp}(c_1, c_2, r, t)}{8760 \cdot Tc(c_1, c_2, r)}. \tag{1.9}$$

The **Full** factor is the ratio of the number of hours during which an interconnection is used at its maximum transfer capacity, over the 8760 hours of the year. This factor should not be confused with the full-load-hours.

The **Null** factor is the ratio of the number of hours during which an interconnection is not used, over the 8760 hours of the year. This factor does not depend on the direction of the line.

Chapter 2

Definition of the studied system and scenarios

This study focuses on Western Europe energy system. A representation of the studied area is given on Figure 2.1. Indeed, due to the size of the territory and the specificity of geography, this area is a good representation of diversified weather conditions and renewable energy potentials; but also of diversified end use demand (EUD) and consumption profiles. The interconnections between cells are therefore interesting, to take advantage of this diversity. In addition, this part of Europe represents 80 % of total European EUD, and 74 % of its renewable potential[1]. This diversity is highlighted by the fact that 4 out of the 5 countries that lack of renewable potential to meet their demand according to [5] are in this area, and that countries with the largest energy surplus are also located in Western Europe.

Figure 2.1: Map of the studied area. Countries studied are coloured.

[1]Based on data from [5], which comprises the countries of EU28. Switzerland is added in this study, but not included in the above shares.

Furthermore, countries in Western Europe already have interconnections with most of their neighbours, and the number of links projects planned is increasing [14, 15], which means that energy exchanges are operational and that countries are investing in it.

In this chapter, the different countries are first presented. The data origin is detailed, and characteristics of the countries are described, including the renewable potentials. Then, the grouping into macro-cells is presented. Finally details about the studied scenario are given.

2.1 Countries description

The countries modelled in this study are the following: Austria (AT), Belgium (BE), Switzerland (CH), Germany (DE), Denmark (DK), Spain (ES), France (FR), Ireland (IE), Italy (IT), Luxembourg (LU), the Netherlands (NL), Portugal (PT), Sweden (SE) and the United Kingdom (UK).

2.1.1 Data collection

Most of the country-by-country data have been collected by J-L. Tychon and J. Dommisse [5], who modelled all the countries of European Union separately. In addition, Switzerland data come from the work of A. Hernandez and P. Thiran [9] which adapted them from [3] to fit with the data from the other countries.

Data concerning energy exchanges are also taken from [9]. In order to have more coherence between the data of all the countries, modifications performed in the latter work have also been applied to the data of [5], along with some more up-to-date values taken from more recent versions of the EnergyScope MC model [16]. This includes modifications to have multi-cell compatible data. A detailed description of the origin and adaptation of the data can be found in Appendix C.

Some changes have been made to the data above-mentioned:

- when several countries are optimised altogether, their hourly data must be synced, especially if they are allowed to exchange energy fluxes. In [5] most of the time series (TS) were expressed in the local time zone of the country. Therefore, the TS have been manually shifted to the Coordinated Universal Time (UTC);

- as mentioned in Chapter 1, the model has been slightly modified to allow a different price for each interconnection between cells, for the network exchange infrastructure. The prices of electrical interconnection have been specifically assessed, and they are given later for the relevant connections.

These modifications are also further described in Appendix C.

2.1.2 Countries potentials

A detailed description of the energy potentials and demand of each country of the European Union has been made in [5] for the same data. Here only a brief overview is presented, for the 14 countries of interest.

Figure 2.2 shows the potential in renewable resources of each country. Except for the biomass resources, it is computed as the maximum potential that can be installed in the cell multiplied by the number of full load hours −which is the average capacity factor times the number of hours in a year. The total EUD of each country is also shown, in order to have an idea of the ability for the cells to meet their demand with renewable energy alone. Note that if the values of potential and EUD are close, the ability of the cell to meet its demand can hardly be determined *a priori*, because there are losses in the system that will lower useful potential, and because there are technologies such as heat pumps and cooling devices with a COP > 1 that lower the energy needed to meet the demand.

It can be highlighted that Spain, Portugal, Denmark and Sweden should play a great role in the production of energy for the whole system, given the excess and the diversity of their potential. The United Kingdom and Ireland also have a big excess of potential, but mostly constituted of one resource. France proportionally has less potential excess. The other countries have a demand greater or of the same order as their potential.

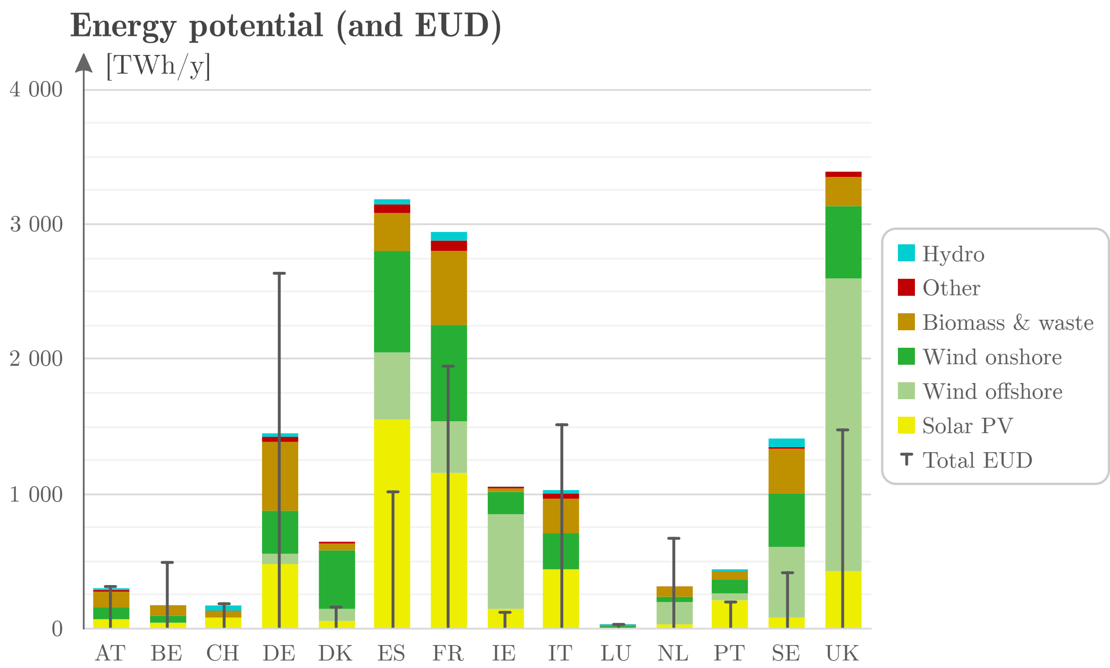


Figure 2.2: Renewable potential of the 14 countries studied, and comparison with the EUD [5]. 'Other' accounts for thermal solar (including CSP), tidal and geothermal potentials. Luxembourg has 26 TWh/y of potential and 29 of EUD. Abbreviations: Countries code in list of abbreviations, end use demand (EUD), concentrated solar power (CSP), photovoltaic (PV).

2.2 Macro-cells constitution

The studied system is made-up of 14 countries. However a 14-cell system is quite large to be run with the model: using 12 TDs, the memory usage is too large to run on most personal computers (16 GB of memory is far too low); and it takes several hours to run on a server dedicated to that purpose[2], which makes it difficult to perform parametric analyses.

The system used in this study thus resorts to 6 cells for the main scenario. First, a

[2]Using ®AMPL and the CPLEX 12.9 solver on a cluster of 18 double-threaded Intel© cores (i9-10980XE).

6-cell system seems to be the limit for a 16 GB personal computer, and it takes between 30 min and 1 h to run. Moreover, a division of Western Europe in 6 cells is performed and used in [7].

2.2.1 Distribution of countries in macro-cells

The distribution of countries into macro-cells considered here is the same as in the latter work, exception made for Norway which is not included in the present work. Indeed its data have not yet been collected for a use in EnergyScope. The macro-cells are thus defined as follows:

- Iberian Peninsula (Ib. Peninsula): Spain and Portugal;
- France: France;
- British Isles (Br. Isles): Ireland and the United Kingdom;
- Germany & Benelux (DE & Benelux): Belgium, Germany, Luxembourg and the Netherlands;
- Italy & Alpine States (IT & Alpines): Austria, Switzerland and Italy;
- Scandinavia: Denmark and Sweden.

In [7], the choice of the cells is mainly based on the prevalent type of intermittent renewable energy source in the countries, and the bottlenecks in electricity transmission lines between them. However, it focused only on the electricity sector, and it used fixed values for transmission and renewable capacities. Therefore, the country distribution needs to be motivated for the whole-energy system optimisation performed in the present work.

Overall cell size Smaller countries are grouped to bigger ones so that the macro-cells are globally of the same order of magnitude regarding their total EUD or renewable potential. Some cells have a bigger potential and less demand, such as the Iberian Peninsula; and Germany & Benelux are in the opposite situation. This is however not a problem, and it is even better to group together countries that have the same imbalance and other similar characteristics, in order to not over-simplify the system. And of course, the countries that are merged together must be located next to each other.

Renewable potential As observed in [7], the prevalent type of iRES is respected. In addition to that, the share of biomass and waste is of the same order for the different countries of a macro-cell (see Fig. 2.2). The biggest differences are for Switzerland that can rely less on wind but more on hydro-power, and for Austria that has less PV potential but more biomass than their neighbours; also, the Netherlands proportionally has more offshore and less PV potentials than its neighbours.

In general, the macro-cells can be classified according to the following main characteristics: Germany & Benelux all have much more demand than potential[3]; Italy & Alpine States have a bit more demand than potential; Ireland and the United Kingdom have a big renewable potential surplus, and the shares of resources in their potential are very alike

[3] Only 10 % more demand than potential in Luxembourg, which is not considered as being a problem due to the size of the country.

and are mostly based on offshore wind; the same observations can be drawn for Spain and Portugal, except that their primary potential lies in solar PV; Denmark and Sweden both have a pretty low demand compared to their potential; and France is more balanced.

Demand The shares of the types of end use demand are shown in Figure 2.3 for each country, grouped by macro-cell. It can be seen that those shares are alike for all countries, and especially for countries of a same macro-cell. The only country that stands out is Luxembourg, which has the highest share of electricity EUD of the system. It is again not considered as being an issue, given the size of the country.

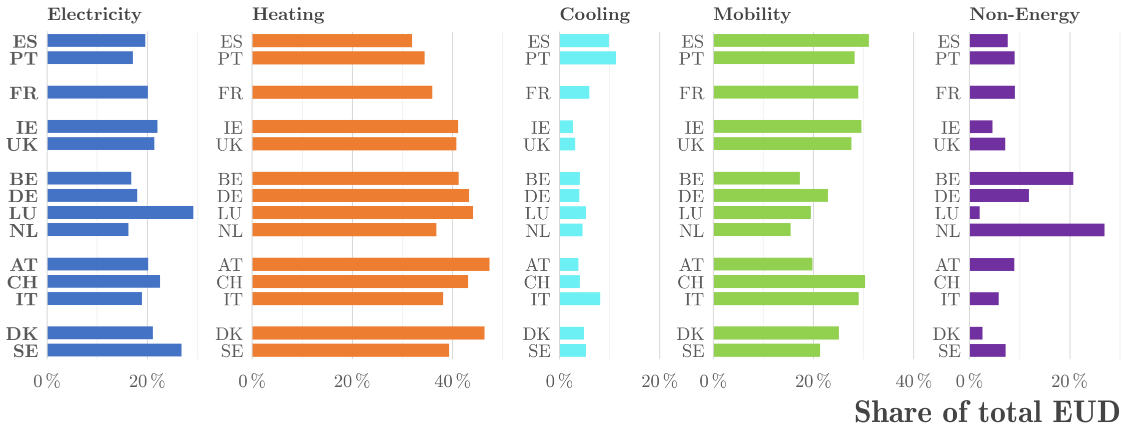


Figure 2.3: Share of the total end use demand (EUD) of each country, grouped by macro-cell, countries code are in list of abbreviations.

2.2.2 Adaptation of the data to the macro-cells

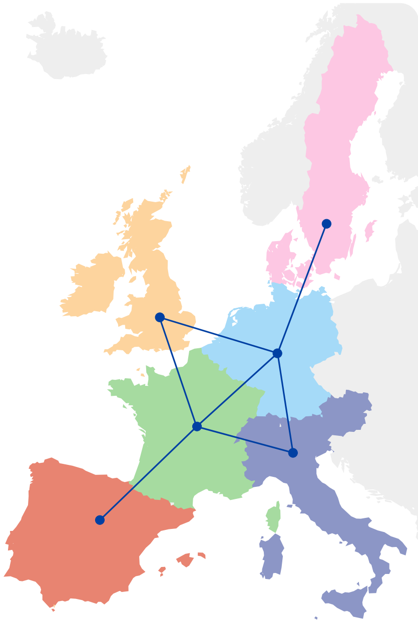
As explained in the merging procedure (Sec. 1.2.3), some data cannot be simply merged, but have to be determined for the macro-cell directly.

Borders subject to exchanges Resources exchanges are allowed through all inland borders. In addition, the British Isles can exchange energy with France and Germany & Benelux; and Scandinavia can exchange energy with Germany & Benelux. The representation of exchange routes is given in Figure 2.4a.

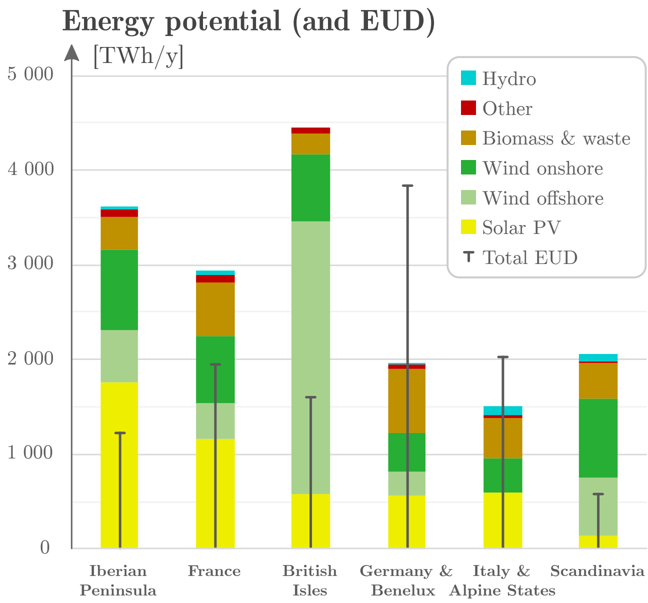
Distance for freight exchanges This value has been chosen to be the half distance between the two furthest big cities of each cell, calculated with Google Maps [9]. The values used in for the studied system are given in Table 2.1.

Interconnections cost In Section 1.1.3 the ability to set a different price for each interconnection was introduced. Indeed, prices of electrical connection can be much higher when crossing a sea, especially because British Isles and the majority of Scandinavia are on grids that are not synchronous with the continent[4], and that therefore have to be connected using high voltage DC (HVDC) links. The price used in EnergyScope MC up until now

[4]Ireland, including Northern Ireland, and Great Britain are in two separate synchronous areas. The Eastern part of Denmark is connected to the Nordic synchronous area that includes Sweden, while the Western part is connected to the Continental European synchronous area [17].



(a) Map of the macro-cells and their allowed exchange routes.



(b) Renewable potential and EUD of the macro-cells. Abbreviations: end use demand (EUD), photovoltaic (PV).

Figure 2.4: Summary of system with merged countries.

Table 2.1: Definition of the freight distance parameter and cities chosen to compute its value (half the real distance by road between the two cities).

Cell name	City 1	City 2	Freight distance parameter [km]
Iberian Peninsula	Faro	Girona	644
France	Calais	Marseille	540
British Isles	Plymouth	Thurso	605
Germany & Benelux	Flensburg	Rosenheim	500
Italy & Alpine States	Palermo	Vienna	1000
Scandinavia	Abisko	Esbjerg	1110

comes from [7], which considers a unique cost per MW, despite the fact that it covers the same region as the present work. With EnergyScope, different prices can be set without increasing the complexity of the model, by using the proposed implementation.

The new prices are computed based on a book of the IEA [18] that gives ranges of values, typical of OECD member countries, for AC lines, DC lines, and DC submarine cables separately. To obtain a value per GW of transfer capacity, the cost of a station has been considered for 1 station at each end per 1 GW line because most interconnections have a capacity of this order [19]; furthermore, the maintenance cost depending on the utilisation of the link has been considered with its maximum of 8760 full-load hours per year.

The inland connections are considered to all have the same properties, which are taken to be the same as in [7]: 50 % of AC lines, 80 km long; and 50 % of DC lines, 130 km long. The lengths of the DC sea-cables vary with the length of the sea to be crossed. Lengths of existing and planned links [19] have been used to determine an approximate mean value for links that EnergyScope would propose to install.

The length and price per GW used for each interconnection are given in Table 2.2

Table 2.2: Type, length and price of electrical interconnections considered in the model. Inland connection are 50 % *AC,* 50 % *DC overhead lines.*

Interconnection	Type	**Length** [km]	**Price** [M€/GW/y]	
Inland	AC (50 %)	80	10.17	15.33
	DC (50 %)	130	20.49	
France – Br. Isles	DC sub-sea	200	27.66	
DE & Benelux – Br. Isles	DC sub-sea	300	35.24	
DE & Benelux – Scandinavia	DC sub-sea	300	35.24	

2.3 Scenarios

A scenario is defined as a set of specific values for each parameter, which will result in a specific system design after running the model. Those parameters include the country-specific energy potential and demand, and interconnections detailed above, but also other parameters that have to be defined. They are described in the next subsection, in order to define a first scenario: the Baseline. Then, variations around the Baseline scenario are detailed, to perform further analyses.

2.3.1 Baseline: existing vectors for energy exchanges

The Baseline is defined to allow the use of energy vectors and technologies that have already been studied in EnergyScope TD [3, 5, 9], with emission target for 2030.

Technologies and resources With some exceptions, all the technologies and resources that are implemented in EnergyScope are allowed, if they can technically be installed or used on the given territories, as determined in [5].

In contrast to [5], the use of nuclear technology is not allowed. This is a strong assumption, but the purpose of this work is to study how the system deals with the intermittency of renewable production in the different cells. Forbidding the use of nuclear challenges further the system as it induces a higher integration of RES and less baseload to compensate for their fluctuations. Moreover, the countries that have the largest lack of renewable resources (in DE & Benelux macro-cell) are phasing out of nuclear power, and they must therefore import a similar amount of power, which means that the transfer capacities will be of the same order. This was verified *a posteriori*: with nuclear power allowed, the largest connection is less than 10 % smaller.

The electricity imports from the exterior of the system are also forbidden. In fact, the purpose is to study the ability of the system to use its renewable resources, and not to import energy for which the primary sources of production are not known. Furthermore, an external electricity production that can supply the system at any time implies that the exterior is probably not supplied at the same level with renewable sources. Other resources such as coal and natural gas (NG) can be imported from the exterior of the system to each cell within the system. Synthetic fuels (SLF, SNG, H_2) can also be imported from the exterior at a fixed cost and GWP, usually superior than if it were produced in the system.

Exchanges The implemented vectors for energy exchanges are the same as in [9], which are commonly used vectors: electricity and gas through their respective network; synthetic liquid fuel (SLF), wood, waste and captured CO_2 through freight. The parameters that were not explicitly redefined above in this chapter are kept the same as in [9]:

- the losses for network exchanges are the same at every border. For electricity, 6.12 % of the energy exchanged, which is the loss considered for the internal grids of the cells [10]. This value is kept even for long-distance connections because the losses in the internal grid are more important than the one occurring directly in the interconnection lines [18]. For (synthetic) natural gas pipes, the considered losses are 2 % of the energy exchanged, even if they might be lower[5];

- the losses for freight exchanges account for the distance between the two centres of the two cells, defined in the previous section, and the lower heating value of each fuel [9].

Note that NG can be exchanged within the system and imported from the exterior. It would be more accurate to only allow this import for cells that have a direct supply from the exterior of the system, but at present most of the macro-cells have such supply, so it is approximated that it is the case for all cells in order for them to be on the same footing in this regard. The network for gas exchanges within the system is therefore useful only for synthetic natural gas (SNG), produced within the system.

A sensitivity analysis on the price of electrical interconnections will also be performed. Indeed, the electricity exchanges were found to be a key element of the system, unlike the other vectors for energy exchanges. It is therefore important to see if the costs of the connections have a significant impact on the system design, given the uncertainty on these parameters. The uncertainty ranges are taken from [18]. For example, the prices for inland interconnections range from 11.97 to 18.68 M€/GW/y, and for a 200 km-long HVDC sea cable they range from 22.95 to 32.36 M€/GW/y.

GWP reduction target It was chosen for this study to consider a new target from an European Commission proposal: cut the greenhouse gas emissions by at least 55 % by 2030 [20] compared to 1990. The proposal is currently being reviewed and is therefore not yet in force, but this target was chosen because it is more ambitious and to anticipate likely future decisions. Even if (a new version of) the Effort Sharing Regulation will still be in force with the new proposal, it was decided for this study to impose only a global reduction and let EnergyScope choose how to split the emissions between the cells.

To compute the limit, the emissions of the 14 countries from 1990 have been taken from the European Environment Agency [21], for the *Energy* and *Industrial processes and product use* sectors. Their total emissions were of 3597 $\mathrm{Mt_{CO_2eq}}$ in 1990, therefore the limit for the model is of 1619 $\mathrm{Mt_{CO_2eq}\,y^{-1}}$.

Those emissions are the direct operational part of fuel usage: they therefore do not include the emissions due to transport and production of the fuels, nor the emissions due to construction of technologies. Also, the biomass resources are assumed to have a net-zero GWP, because their production has to be renewed each year, capturing the emissions released by combustion. Therefore, the limit on the GWP in EnergyScope is set on direct emissions of combustion, whose values for each resource are given in Table 2.3.

[5] [9] computed that the losses in the Belgian transmission network are around 0.08 %. It was not found important to update the parameter to this new value, because the model never chooses to use gas interconnections in the scenarios of this study. Moreover no specific value was found for H_2 connections (detailed below), but it should be larger than 0.08 %.

Table 2.3: Global warming potential of combustion (GWP_{comb}) for the different resources with non-zero value. Abbreviations: liquid fuel oil (LFO), natural gas (NG).

Resource	**Gasoline**	**Diesel**	**LFO**	**NG**	**Coal**
$\mathbf{GWP_{comb}}$ [$t_{CO_2eq}\,GWh^{-1}$]	250	270	280	200	340

2.3.2 Adding hydrogen exchanges

By 2030, hydrogen is expected to play a significant role in Europe in several sectors, including transport and electricity production [22]. It should back up the electrical grid and therefore facilitate the penetration of renewable technologies to decarbonate the energy system. In addition, a large number of projects aimed at the massive deployment of hydrogen are expected to receive public support [23]. The European Hydrogen Backbone (EHB) initiative [23], grouping several European gas Transmission System Operators, drafted a proposal for a dedicated hydrogen pipeline infrastructure, largely based on repurposed existing natural gas pipelines. The EHB presents a possible scenario on how hydrogen infrastructure in Europe may be created that would be technically viable and achievable for 2030, 2035 and 2040. Except Portugal, all countries studied in the present work have planed to invest in hydrogen networks. It does not mean, however, that Portugal does not project to invest in hydrogen: in fact, some pipelines are planed to be built in Spain up to the border with Portugal.

Given the interest in hydrogen as energy vector, it is added to the energy vectors of the Baseline to obtain a new scenario. This scenario will be analysed and compared to the Baseline, to see the benefits of hydrogen exchanges with EnergyScope.

According to the EHB [23], H_2 pipelines are projected to be rapidly in place partly by conversion of existing pipelines. Furthermore, their estimations predict that establishment of a hydrogen infrastructure is possible with limited economic effort. As no large-scale project has yet been implemented, it is difficult to assess precisely the cost of hydrogen interconnections in the same terms as what is used in EnergyScope MC. The present work therefore considers first the cost to be the same as for NG lines from [9]: 0.54 M€/GW/y. This is motivated by the fact that most of the H_2 infrastructure should come from repurposed gas infrastructure with a limited cost for conversion [24]; but also because it is expected that a different cost will not have much impact in this work, given that it should remain much lower than the cost of electrical interconnections. In fact, the considered cost corresponds with some assumptions[6] to the low range prediction of the EHB [23]. It will then be verified that this cost does not have a large impact on the system design, by making a sensitivity analysis and introducing a cost twice higher.

2.3.3 Additional interconnections lines

The European electrical grid is in expansion, and there are several projects planning long-distance interconnections [19, 25]. It is therefore relevant to consider an additional scenario that allows long-distance electrical interconnections.

In this scenario, supplementary lines are allowed between Scandinavia and British Isles; British Isles and the Iberian Peninsula; the Iberian Peninsula and Italy & Alpine States. All are HVDC subsea cables for which projects attest of the feasibility. The distances of interconnection, to compute the costs, have been taken from these projects: respectively,

[6]Same pipelines length as AC interconnections, highest lifetime and lowest maintenance cost from [23].

760 km (70 M€/GW/y) for the *Viking DKW-GB* link which is under construction [19]; 1330 km (117 M€/GW/y) for the *Britib* link which is still under consideration [19]; approximately 1200 km (111 M€/GW/y) for a link between Spain and Italy which is however no longer planned to be built [26].

Those interconnections are not taken into account in the Baseline scenario because they are not currently in service. Furthermore, they are not on an equal level with other interconnections. In fact, some assumptions made for multi-cell exchanges make them more or less interesting than they should be, compared to interconnections between neighbouring cells:

- less losses, because the losses are fixed per GW transferred, therefore energy transferred over one long line will have twice less losses as the one transiting through one cell;
- more costly, because only the cross-border lines are considered and therefore connecting, *e.g.*, the Iberian Peninsula and British Isles through France only requires two short connections (43 M€/GW/y in total), while a direct subsea connection costs more (117 M€/GW/y).

This highlights limitations of the current model which can hardly be solved by only changing how interconnections are implemented. In fact, the model already accounts for a cost for grid reinforcement due to renewable production, therefore reinforcement due to exchanges should be implemented while excluding the part due to renewable production that is already taken into account. This would require a deeper investigation of those costs.

2.3.4 Stricter emission limits

According to the objectives of the Green Deal, the European Union wants Europe to become the world's first climate-neutral continent by 2050 [1]. After the 2030 target set in this work, the GWP emissions must be further reduced to achieve carbon neutrality. In this view, it can be interesting to perform some analysis with stricter emission limits to predict the evolution of the total cost. It also allows to highlight the importance of energy exchanges during the decarbonization.

Different scenarios will be compared while reducing the limit of operational GWP allowed: a scenario without exchanges, and two scenarios with exchanges allowed, with and without hydrogen exchanges.

Chapter 3

Verification and impacts of the merge methodology

In this chapter, the validity of the merge methodology introduced in this work is assessed. First, a simple case composed of 2 cells will be analysed to verify if the results of the EnergyScope MC model are well represented using the merging method. Secondly, a more complex case of 14 cells is studied to see if the observations are different with an increased number of cells, and to see how exchanges between macro-cells are impacted by the merging.

3.1 Verification on a simpler 2-cell system: Spain and Portugal

In this analysis, the systems of Spain and Portugal are modelled in two cases, that are analysed and compared:

- non-merged case: the 2 cells are modelled separately and are allowed to exchange energy fluxes (electricity, gas, and resources transportable by freight);
- merged case: the 2 cells are merged in one macro-cell.

A 2-cell system merged into 1 macro-cell is analysed first because of the higher sensitivity of such a system. Therefore, a part of the limits of the merging procedure will be more easily highlighted than in a system composed of more cells and more resulting macro-cells.

Their similarities are assessed based on several criteria, which are detailed in turn in the following sections.

3.1.1 Impact on resources availability

It is first important to verify that the merging does not lead to significant changes in the input data of the optimisation process. As mentioned in Section 1.2.2, a loss of information is introduced in the time series of resources availability. A selection for suitable weights has been performed in Appendix B; here the final results are detailed for the selected weight.

To measure the impact on resources availability, the duration curves errors are compared. They represent the RMS errors between the duration curves of each case and a reference case. This reference case uses the non-simplified data, thus for all the hours of the year (*i.e.* without TDs) and without merging. An error of 100 % corresponds to a constant time series. Other details and mathematical formulation are given in Appendix B.2.

It was determined in [3] that using 12 TDs is a good trade-off between representativeness of the system and computational time. The simplification in TDs introduces some error in the results. Consequently, it must be kept in mind that a part of the error observed in the merged case computed with 12 TDs is due to the introduction of TDs and not only to the merging itself. A more detailed analysis could be performed in a further work to verify that the optimal number of TDs for multi-cells remains 12.

The errors on each resource used in the resulting system −after optimisation− are shown in Table 3.1. For both the reference and the non-merged cases, the TS of the two cells have been combined using the installed capacities of the related technologies, in their respective resulting system, as weights for the average. The additional error in the merged case corresponds approximately to the error introduced by the merging process.

For most of the resources, the additional error seems acceptable. More specifically, the additional error is small for onshore wind, which has the largest potential (385 GW). The error is however much bigger for river hydro-power, but this resource has a negligible potential[1] (4 GW).

The global duration curve error, also shown in Table 3.1, is computed by multiplying the squared error by the installed capacities of the related technologies from the reference case results. This is detailed in Appendix B.2. The additional error of the merged case is less than 2 %, which suggests that the availability of resources is fairly represented in the merging process.

Table 3.1: Error on duration curves of renewable resources availability of non-merged and merged cases compared to reference case. Global error and aggregated values of the non-merged case are weighted by installed capacity of reference case.

Resources	$\boldsymbol{\epsilon_{dc}}(resource)$ [%]	
	Non-merged case	Merged case
Solar PV	5.92	8.34
Wind onshore	20.81	21.66
Hydro dam	13.02	9.51
Hydro river	29.11	90.53
Solar DHN	3.32	3.86
Global error	9.26	11.15

3.1.2 Impact on the resulting system

The role of the merging methodology is to simplify a system modelled with EnergyScope MC by lowering the number of cells while providing a system design as close as possible to the original one. To assess this condition, the optimal installed capacities and the energy flows obtained in the merged case can be compared to the ones obtained in the non-merged case.

The resulting systems of the merged and non-merged cases are similar in many ways. Figure 3.1 shows the global Sankey diagrams of the yearly energy flows for both cases.

[1]With the selected parameters, the time series of this resource does not play any role in the selection of typical days (STEP 1), therefore the STEP 1 does not try to minimise this error.

Although some differences −which are discussed below− can be observed, it shows that the two systems have the same general behaviour.

Regarding the resources used, both cases use the local resources at their maximum availability, and as external resources they only use natural gas up to the GWP_{op} limit. The yearly utilisation of renewable resources is slightly different, but proportional to the technologies installed capacities, which are detailed below.

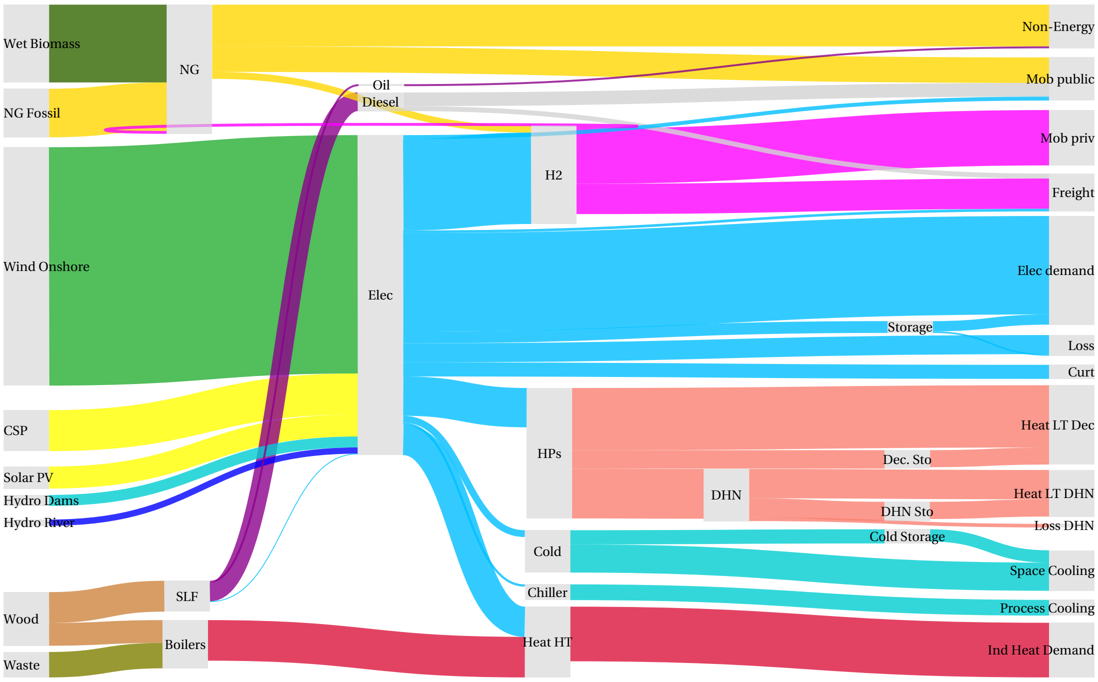
The mobility sector and the industrial heat supply are pretty much the same in both cases. The main changes occur in the electricity and low temperature heat supply, and in the storage capacities. The technologies for which a difference of more than 1 % is observed in installed capacity are presented in Table 3.2.

Table 3.2: Comparison between merged and non-merged cases for 2-cell scenario: main differences in technologies installed capacities (> 1 %) and cost. Constrained case in addition, with constrained values in bold.

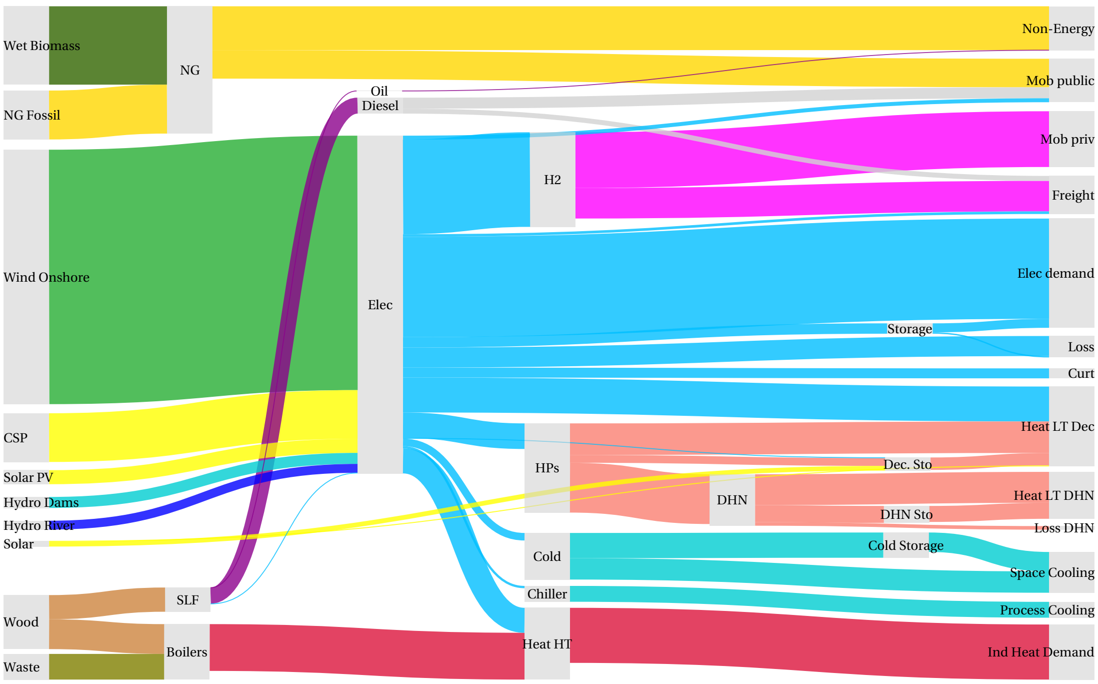
	Exchange case	Merged case	Constrained merged
Production technologies capacities [GW]			
Solar PV	27.70	17.66	**27.70**
Wind onshore	231.33	246.62	226.32
Dec. HP	72.19	37.43	76.78
Dec. solar	0	7.34	0
Dec. direct electricity	0	42.57	**0**
DHN HP	29.50	22.72	22.96
Ind. wood boiler	8.86	10.01	9.37
Ind. waste boiler	9.22	8.19	8.74
Bus diesel [Mpkm/h]	43.24	34.51	41.78
Bus gas [Mpkm/h]	80.06	88.79	81.51
Infrastructures [GW]			
DHN	29.50	22.72	22.96
Solar tower collector	213.55	245.11	**213.55**
H_2 electrolysis	23.54	24.18	23.71
H_2 from gas	4.33	0	0.89
Pyrolysis	6.02	4.69	5.37
Methanation	1.17	0	0
Storage capacities [GWh]			
Th. storage HP	112.96	48.28	99.03
Th. storage direct electricity	0	28.66	0
Seasonal th. storage DHN	16 661.60	11 204.44	9 849.00
Th. storage cold	453.70	592.33	592.33
Seasonal H_2	115.75	875.61	343.12
SLF storage	996.33	1 691.54	1 878.96
Solar tower storage	416.86	610.14	434.14
System cost [b€/y]	126.9	125.5	125.9

The differences that are observed can be due mainly by two phenomena, one linked to the merging, the other not specifically.

Differences not merge-specific Even though the two resulting systems cannot be considered to be equivalent, it does not mean that one is less valid than the other. Indeed, when using linear programming, it is typical that the optimiser switches to a solution that can be different on several points, but that is similar in terms of objective value, for only a small perturbation in the input data. To verify that the two systems could be almost equivalently chosen, one can constrain a system to be like the other and check that they



(a) Non-merged Spain and Portugal.



(b) Merged Spain and Portugal.

Figure 3.1: Comparison of Sankey diagrams of energy flows in Spain and Portugal: energy flows in the overall system from primary energies (left side) to end-use demand (right side). CSP only shows useful part of electricity produced; mobility only show energy consumption and not the end use demand. Abbreviations: see list of abbreviations.

are equivalent in terms of objective values.

This was done by constraining the merged case to have some identical installed capacities as the non-merged case. Because the main changes occur in the electricity and decentralised heat supplies, only some technologies of these sectors have been constrained in order to still let the system adapt to the exact input conditions: *Solar PV*, *Decentralised direct electricity* and *Solar tower collectors* capacities are imposed. It results that the constrained (merged) system is much closer to the non-merged system, for most of the technologies that had a large difference. As expected, despite these changes, the objective value is still close to the case that is not constrained: an increase of 1.22 % is observed in total for all the costs that have changed between the initial and constrained merged cases. This amounts to a difference of only 0.39 % in the total system cost.

Differences due to merging Some differences between non-merged and merged systems are not entirely due to similar objective values. Although it is difficult to tell exactly which part of the changes are due to merging itself, some tendencies can be highlighted.

First, the total cost of the system (end of Tab. 3.2) decreases by 1.2 % in the merged case. Such a diminution could be expected because some costs disappear. In fact, the exchange networks between the two cells are not represented anymore, and this neglected cost amounts for 15 % of the total cost reduction.

The storage technologies also decrease globally, inducing a cost reduction. This is due to the fact that the storage capacities of the two cells are pooled, thus leading to economies of scale, because the two cells might not have their utilisation peaks at the same time. The same behaviour is observed for the *Pyrolysis* infrastructure, which is pooled among the two cells.

In general, it can be concluded that the merged system can be slightly different from the non-merged one, but most of its features will be conserved. A cost diminution is to be expected, therefore the user should know that the price can be somewhat higher than in his merged system. The small differences observed within the system do not make the result much less accurate than the non-merged system.

3.2 Global verification on 14 cells: Western Europe

To be used for a system containing several macro-cells, as in this work, the merging methodology must be verified on a more diversified system, in which there are several macro-cells that can exchange energy. As it is feasible to perform the optimisation on the non-merged system of the area of interest on this study, it is even better to perform the verification on this area directly[2]. The two systems that are compared are therefore the ones detailed in Chapter 2:

- non-merged case: the 14 cells are modelled separately and are allowed to exchange energy fluxes. The additional data concerning exchanges are given in Appendix D.1
- merged case: the 14 countries are merged in 6 macro-cells that are allowed to exchange energy fluxes, as the Baseline scenario described in Chapter 2.

[2]As explained in Section 2.2, the computational cost for 14 cells is high, and it would be most likely not possible to perform all the analyses of the following chapters without merging.

In this chapter, only the verification of the merging methodology on the final system is performed. The final results of this case will be presented and detailed in Chapter 4. In the following subsections, the reader should focus on the comparison and not on the absolute values of the results obtained.

3.2.1 Resulting system within macro-cells

This section aims at confirming that the observation made on the 2-cell system are still valid for a larger system with several macro-cells. It highlights the observations that differ.

Installed capacities The technologies installed capacities are very similar between the two cases. The major change lies in the storage sector, which is undersized as it has been noted in the previous section for two cells. Also, as in the previous analysis, the model chooses a slightly different solution which tends to install less PV but more coal power plants. This is possible because the GWP limit is not reached. The installed capacity of PV decreases by 281 GW (−41 %), and that of coal plants increases by 107 GW (+28 %). However, these differences are not major for a system of this size, and represent a change of only 6 % in the total electricity mix installed. To be convinced of the similarities of both systems, their installed capacities are given in Appendix D.2.

Yearly electricity produced To further compare the two cases, the yearly amount of electricity produced per type of technology is assessed for each macro-cells. Figure 3.2 shows that the total electricity produced is fairly similar in both cases. There are no significant differences in energy produced from wind and hydraulic sources. However in the merged case, the production of electricity with solar energy is slightly lower especially in the Iberian Peninsula and Italy & Alpine States where the solar potential is more important. Figure 3.2 highlights that these differences are not significant compared to the total amount of electricity generated. The share of electricity produced by PV panels decreases from 7.2 % in the non-merged case to 3.9 % in the merged case. The share of electricity produced from solar tower changes of only 1 %. In return, the amount of electricity generated from coal is more important in the merged case in Italy & Alpine States. Therefore, the share of electricity produced from coal power plant increases from 13.8 % to 16.5 %.

The two main changes observed represent approximately + and −3 % of the share of electricity production. As already mentioned, these differences should not significantly impact the results for a system of this size.

Cost The cost optimum is very similar in both cases. The merged system is slightly more expensive by 0.27 %. In fact, the investment costs are reduced in the merged case because less costly solar technologies are installed and because less interconnections are built, as explained with the 2-cell system. However, the operation costs are increasing in the merged case because of the more important consumption of fossil fuel resources, most likely due to weather conditions that are worse in the merged case. The costs of the two systems are the following:

$$\begin{aligned}\text{Total cost}_{non-merged} &= 1024.29\,\text{b€/y}\\ \text{Total cost}_{merged} &= 1027.15\,\text{b€/y}.\end{aligned}$$

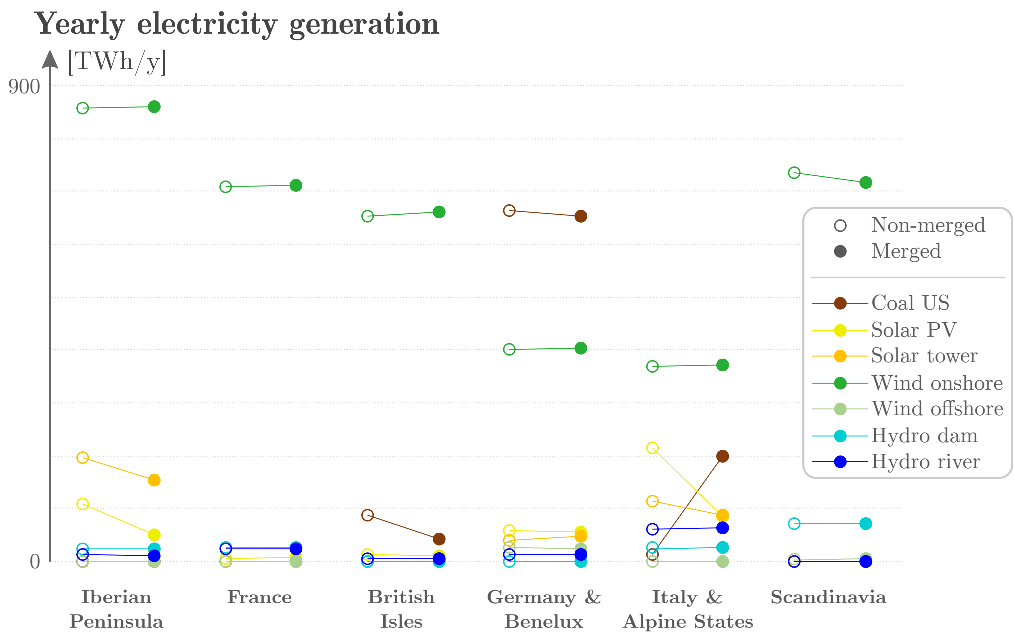


Figure 3.2: Comparison of the annual electricity generated in each macro-cell per type of technology between the non-merged and the merged cases.

Global warming potential In both cases, the GWP limit constraint in the optimisation is not reached. In the merged case, the emissions are higher by 6 %. According to the observation made above, the merged case has a lower GWP_{constr} mostly due to the reduced amount of solar technologies installed. However its GWP_{op} is higher because of the greater amount of fossil fuel used:

	Non-merged	Merged	
GWP_{op}	1419	1563	Mt_{CO_2eq}/y
GWP_{constr}	680	671	Mt_{CO_2eq}/y

3.2.2 Yearly energy exchanged

As interconnections are one of the main purpose of this study, the energy exchanges between countries need to be truly captured by the merging methodology. The yearly quantities of energy exchanged between each macro-cell are given in Tables 3.3 and 3.4. It can be highlighted that the major fluxes remain the same. The tendencies are then well captured by the merging methodology.

Table 3.3: Electricity exchanged over the year [TWh/y] between macro-cells for the ***non-merged case*** *(sum of exchanges of the cells$_{tbm}$ with the cells$_{tbm}$ of the neighbouring macro-cell).*

To \ From	Ib. Peninsula	France	Br. Isles	DE & Benelux	IT & Alpines	Scandinavia
Ib. Peninsula	0	14.46	0	0	0	0
France	535.09	0	81.34	44.25	25.21	0
Br. Isles	0	136.62	0	6.91	0	0
DE & Benelux	0	84.43	13.65	0	11.62	432.95
IT & Alpines	0	156.56	0	47.00	0	0
Scandinavia	0	0	0	0.56	0	0
Total	535.09	392.07	94.99	98.71	36.83	432.95

Table 3.4: Electricity exchanged over the year [TWh/y] between macro-cells for the ***merged case****.*

To \ From	Ib. Peninsula	France	Br. Isles	DE & Benelux	IT & Alpines	Scandinavia
Ib. Peninsula	0	0	0	0	0	0
France	443.13	0	43.97	7.25	4.84	0
Br. Isles	0	79.07	0	55.56	0	0
DE & Benelux	0	34.25	50.24	0	29.12	420.34
IT & Alpines	0	121.33	0	45.26	0	0
Scandinavia	0	0	0	0.92	0	0
Total	443.13	234.65	94.21	108.99	33.97	420.34

The major differences are due to the fact that a lot of energy fluxes transit through DE & Benelux instead of France in the merged case. In fact, if countries are not merged, it is more profitable to exchange energy via one big cell like France rather than exchanging through several smaller cells. It highlights the need of improving how the losses and reinforcement costs due to transit are accounted for in the model. Without these improvements, it is better to have cells of the same scale.

In the merged case, exchanges with Br. Isles are distributed more evenly between France and DE & Benelux, partly for the same reason as above.

In the end, even if some TWh are transferred through different countries between the two cases, the global amount of energy exchanged from and to each macro-cell remains similar (end of Tables 3.3 and 3.4). Only the Iberian Peninsula exports less in the merged case, as its PV production is compensated by coal in Italy & Alpine States, which therefore needs to import less. The difference observed in France is due to the reduced transits explained above.

To sum up, the amount of energy exchanged over the year between macro-cells seems to be fairly represented in the merged case. The global amount of energy is a bit under-estimated but the tendencies are well captured. It is also noted that the total cost might be a bit higher, and not necessarily lower. Obviously, small differences are due to the different strategies chosen by the optimiser that can be equivalent, but the final results seem consistent.

Chapter 4

Baseline scenario results: traditional energy vectors

In this chapter, the main scenario presented in Chapter 2 is analysed. It allows exchanges of conventional energy carriers: electricity, gas, SLF, wood, waste and captured CO_2. This chapter assesses the benefits of those exchanges to help reaching a low-emissions system.

First, the optimal interconnections capacities and energy exchanges are studied. Then, the characteristics of the energy system, within the cells, are outlined. A sensitivity analysis on the price of electricity interconnection is performed to further assess the validity of this analysis. Finally, a general discussion is conduced over the results and observations made in this chapter, and the most important messages are outlined.

4.1 Energy exchanges

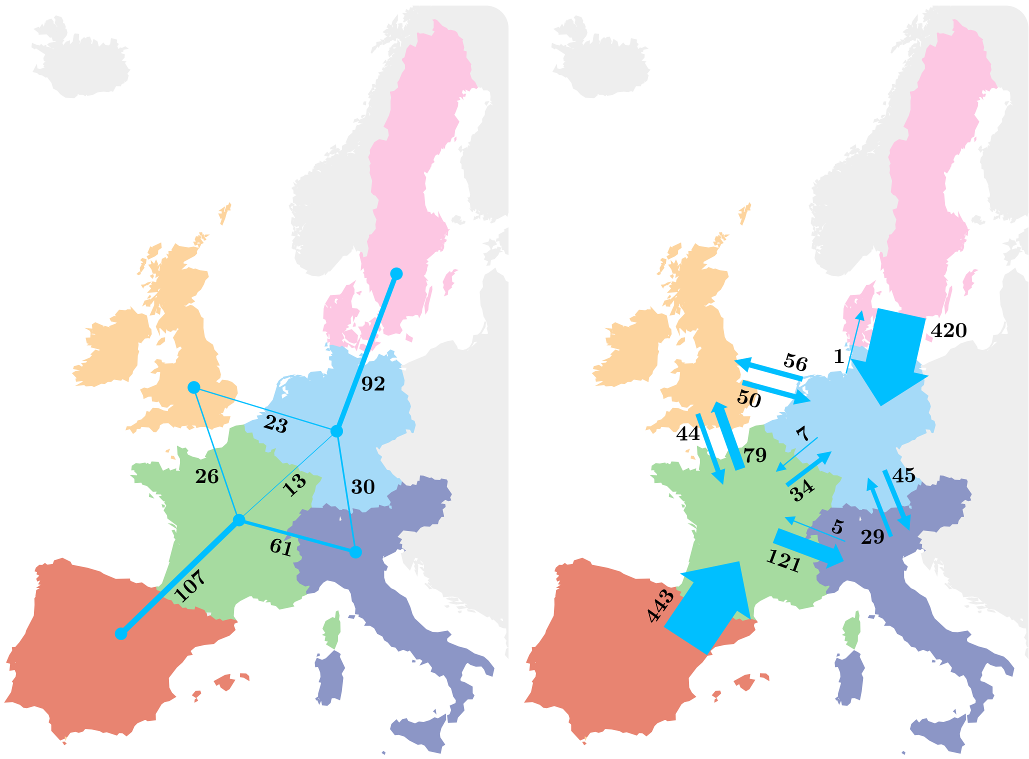
Among the five exchangeable energy vectors −*i.e.* electricity, synthetic gas, SLF, wood, waste and captured CO_2− only electricity is exchanged in this case.

4.1.1 Global fluxes and interconnections

The optimal sizes of all the cross-border electrical interconnections are given in Figure 4.1a. As a reminder, these interconnections are bi-directional and have therefore the same capacity in both directions. In addition, the total electricity exchanges over the year are given in Figure 4.1b.

The first main observation concerns the macro-cells that are net exporter of electricity. Indeed, the largest transfer capacities are across the borders of the Iberian Peninsula and of Scandinavia as they are the biggest exporters. The other regions are all net importers. The Iberian Peninsula and Scandinavia therefore produce more electricity than their needs, to export to France and DE & Benelux, which in turn supply the rest of the system.

Due to the geographical layout, a substantial amount of energy transits through France and DE & Benelux to reach other areas of the system. Therefore, the values of energy imported by these two cells might seem high in Figure 4.1b, but a non-negligible part is only transiting through them. To have a better idea of the amount of electricity that is actively used by each cell −either the amount consumed from the imports or produced for the exports− the transit factor (TF) and then the import share of the cells are computed.



(a) Net transfer capacities [GW] of cross-border electricity lines between macro-cells.

(b) Yearly electricity exchanged [TWh/y] between macro-cells.

Figure 4.1: Maps of the exchanges of electricity for the main scenario (only electricity is exchanged).

As defined in Section 1.3.1, the TF represents the quantity of a resource that transits through a country compared to the total amount of energy it imports or exports for this resource. The electricity TF are the following:

$$\begin{aligned}
\text{TF}_{France} &= 27.9\,\% \\
\text{TF}_{Br.Isles} &= 2.5\,\% \\
\text{TF}_{DE\&Benelux} &= 20\,\% \\
\text{TF}_{IT\&Alpines} &= 12.7\,\%.
\end{aligned}$$

More than a quarter of the energy exchanged with France and a fifth for DE & Benelux are only transiting through them. Furthermore, in view of the TF for Italy & Alpine States, a certain amount of energy is exchanged between France and DE & Benelux by the intermediate of it. This takes place when the interconnection between these two last cells is saturated, which happens 25 % of the time. In this case, the lines with IT & Alpines are preferred compared to those with Br. Isles because those lines are more expensive, sub-sea DC cables, and therefore tend to be used more often at full load as they are less oversized.

To assess how much each cell depends on the others, the average shares of import are shown in Figure 4.2. As detailed in Section 1.3.1, it represents the total amount of electricity imported (excluding transits) over the total energy consumed in the cell. The two major energy exporters have no import or nearly none in their electricity mix.

France and DE & Benelux have respectively a third and a quarter of their electricity mix covered by imports. They are therefore highly dependants on other regions. For DE & Benelux, it is mostly explained by the lack of local resources. France do not lack

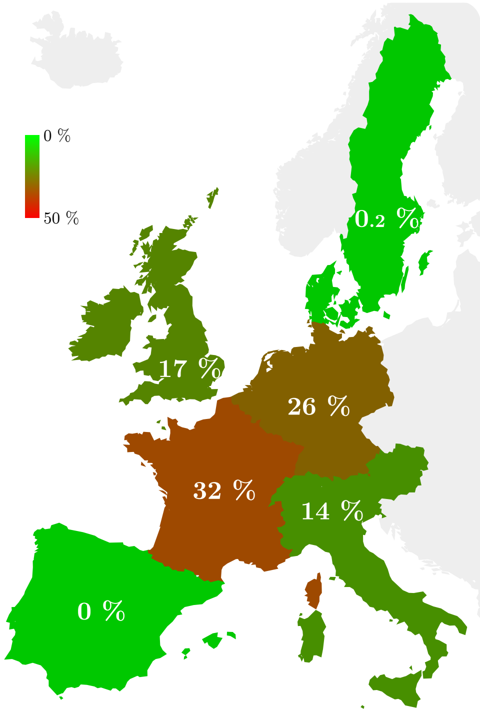


Figure 4.2: Yearly share of the electricity imports for each regions in its total electricity mix for the Baseline scenario (only electricity is exchanged).

of potential, but a part of its import share is explained by the lower efficiency of solar technologies compared to the Iberian Peninsula. This share is also partly due to the large incoming transfer capacity. The connection with the Iberian Peninsula is large because this cell supplies more other cells than France; but France can take advantage of the available capacity of the interconnection when other cells do not require to use it at full potential for them. At other moments, France exports a lot of energy. Therefore, its import share is so high because of the differed imports and exports. This is similar for British Isles which have a significant import share, but a negligible net import-export balance.

The largest interconnections are around 100 GW which is much larger than what currently exists. These results can be challenged and the feasibility of such a network may be questioned. As a general idea, the average interconnection size proposed here is 50 GW, while currently it is only 4.6 GW for the same borders. The interconnection with the Iberian Peninsula is the most challenging, because it is currently among the smallest (only 2.8 GW in 2020) [27]. In comparison, the European Climate Foundation predicted in their Roadmap 2050 [28] that this interconnection should have a 53 GW capacity in their scenario with the higher share of energy coming from RES. Even if the results presented here are quite large, the main tendencies that are observed can be retained. It furthermore highlights the need for a potential new energy vector, such as hydrogen as presented in the next chapter.

4.1.2 Lines utilisation

To have an overview of the utilisation of transmission lines over the year, the load duration curves of all interconnections are shown in Figure 4.3. It represents the number of hours during which an interconnection is used at least at a given power. The negative values are associated to the utilisation of the line in the opposite direction.

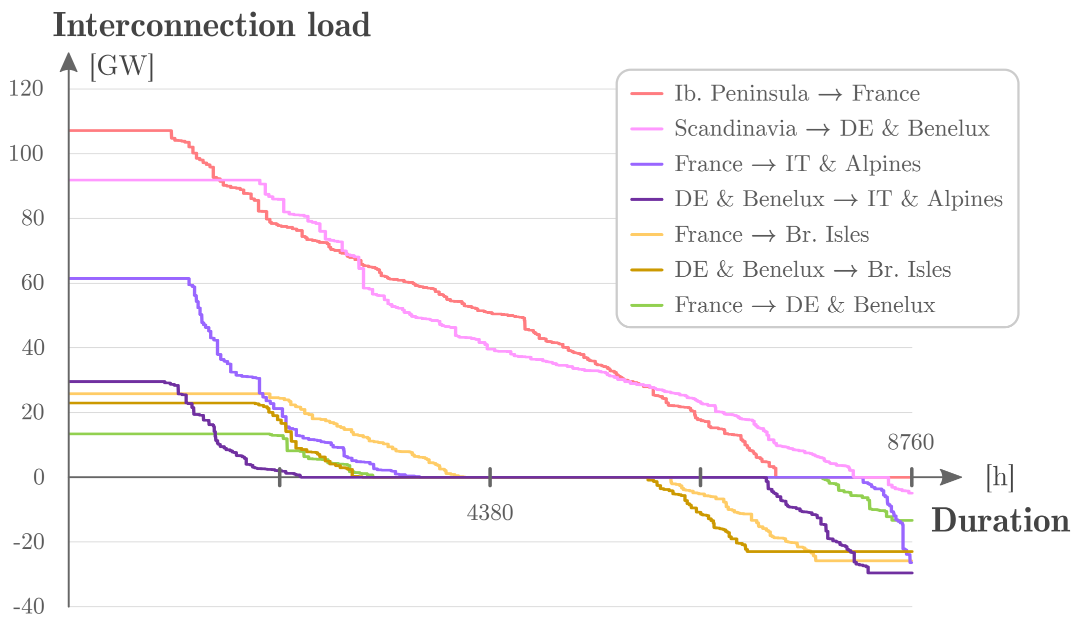


Figure 4.3: Load duration curves over the year of all electricity interconnections for the Baseline scenario (only electricity is exchanged): number of hours at which an interconnection is used at least at a given power. Negative values represent the line utilisation in the opposite direction.

Interconnections from the Iberian Peninsula and Scandinavia are more often used and at a higher power. The utilisation of these two lines in the reverse directions is negligible or null. Other lines are used in both directions, but have a preferential direction. They are more often unused. It can be seen that most of the time the interconnections are not used at full load.

Numerical values are given in Table 4.1 to further analyse the utilisation of cross-border lines. It includes the share of time at which a line is unused (Null), the share of time when it is used at full load for a specific direction (Full) and its utilisation factor (UF), as introduced in Section 1.3.1.

*Table 4.1: Utilisation of cross-border electricity lines for the Baseline scenario: share of time in a year spent at null (**Null**) power, at full (**Full**) capacity, and utilisation factor (**UF**). All in %.*

Interconnection	**Null**	Direction	**Full**	**UF**
France ↔ Ib. Peninsula	16.1	←	12.1	47.2
France ↔ Br. Isles	24.4	→	23.8	34.9
		←	11.3	19.4
France ↔ DE & Benelux	53.3	→	23.2	29.2
		←	2.3	6.2
France ↔ IT & Alpines	52.6	→	14.2	22.5
		←	0	0.9
DE & Benelux ↔ Br. Isles	33.8	→	22.1	27.6
		←	19.5	24.9
DE & Benelux ↔ IT & Alpines	54.9	→	11.3	17.4
		←	5.2	11.2
DE & Benelux ↔ Scandinavia	4.0	→	0	0.1
		←	22.6	52.2

First, as already noted, the lines connected to Scandinavia and the Iberian Peninsula are almost exclusively used in one direction. These two lines, in addition with the interconnections with Br. Isles, have a total UF around 50 %. This occurs mainly because Scandinavia and the Iberian Peninsula are the main exporters, and for British Isles because its interconnections tend to be less oversized due to their cost, as explained above. These four connections have the lowest unused time factors. The other lines are unused for more than half of the year. The connections to British Isles and Italy & Alpine States all have an UF and full factor bigger in the direction coming from the central cells.

4.2 Energy system

To understand the reasons that drive these exchanges, the energy system within the cells is analysed. The Sankey diagram with the energy flows of the system is shown in Figure 4.4. It gives an overview of the results and helps to understand the key elements.

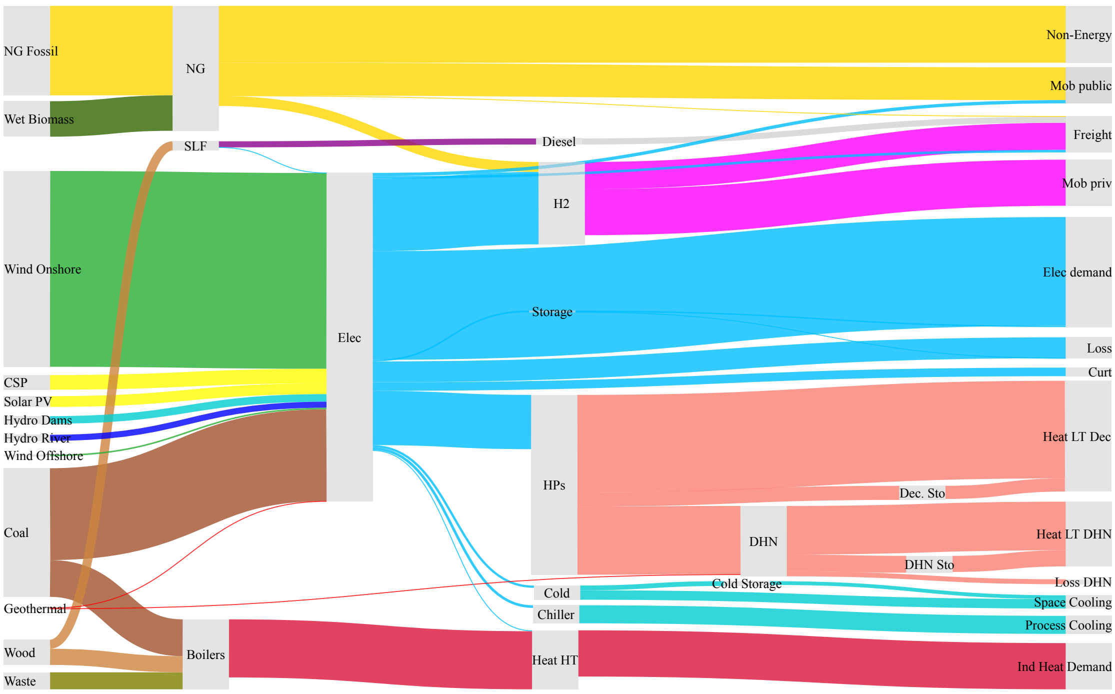


Figure 4.4: Sankey diagram of the main scenario: energy flows in the overall system from primary energies (left side) to end-use demand (right side). CSP only shows useful part of electricity produced; mobility only show energy consumption and not the end use demand. Abbreviations: see list of abbreviations.

One of the most important results to point out is that the system is highly electrified. Except a tiny amount produced by geothermal, all the demand of sectors *heat low temperature* and *cooling* is provided by electricity. It is also used to produce most of the hydrogen that powers the private mobility and part of the freight transport. 72 % of the total EUD is hence provided by electricity. As this energy vector is a key element of this system, a focus is made on it to study it more in depth.

It can furthermore be highlighted that there is a high penetration of renewable resources, which is mostly made possible thanks to the electrification. However the system is still supplied by a substantial amount of fossil resources. Before starting to study the electricity sector in detail, the usage of 'consumable' resources is first analysed.

4.2.1 Resources consumed

The Sankey diagram (Fig. 4.4) shows that part of the coal is used for electricity generation and all the remaining local and exterior resources are used to supply *mobility*, *heat high temperature* and *non energy* sectors.

It is then interesting to understand in which cells these resources are consumed. Figure 4.5 shows that most of the fossil resources are used in DE & Benelux. As seen in Chapter 2, the potential of this macro-cell is very low compared to its demand[1]. This highlights one of the main challenges of the decarbonisation of Europe: if the GWP_{op} is limited, most of the emissions will be produced in DE & Benelux which is the most difficult macro-cell to decarbonise. The second main consumer of fossil resources is Italy & Alpine States, as Italy also faces problems in independently meeting its demand with local renewable resources.

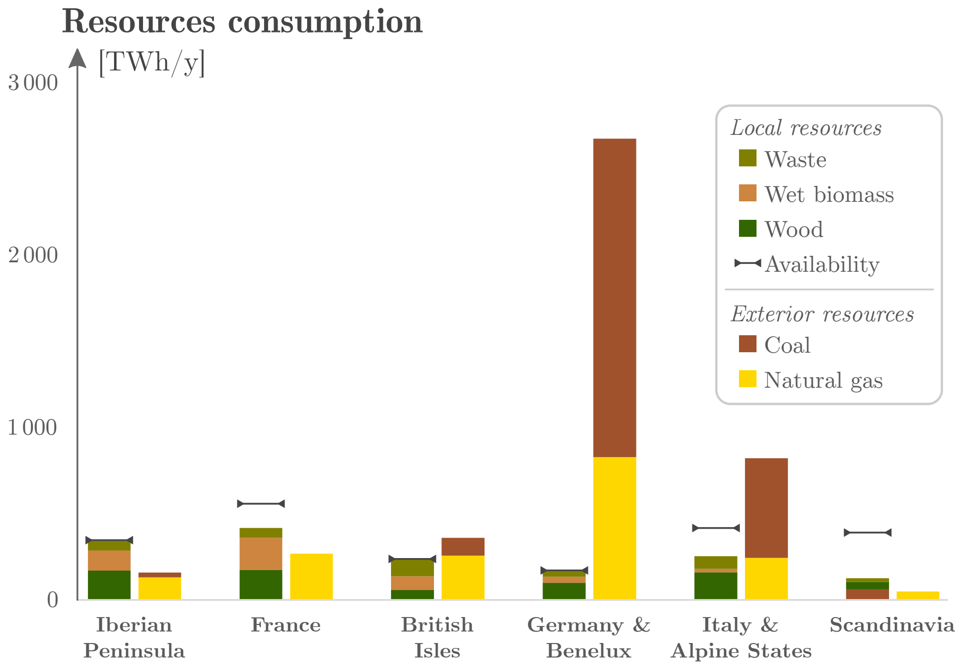


Figure 4.5: Local and exterior resources used in each macro-cell for the Baseline scenario, with the maximum availability of local resources.

In addition, Figure 4.5 highlights that the potential of resources produced locally is not reached for each macro-cell, but the unused quantity is very low. Again, the potential of these resources is poor in DE & Benelux and they are used at their maximum. To further decarbonate the global system, exchanges will be even more important to provide the *electricity* and *heat high temperature* sectors of DE & Benelux and Italy & Alpine States, that have a non negligible usage of coal.

The unused local potential only consist of wood. Therefore, wet biomass and waste are fully consumed locally, which explains why no exchange of synthetic gas (from wet biomass) nor waste are exchanged between cells. Note that synthetic gas can be produced

[1] Due to an error while merging the 4 cells, the local resources potential of DE & Benelux is undersized in the results: only 10 % of wood, 34 % of waste, and 44 % of wet biomass are accounted. However, the impact is limited in this scenario, because wood would not replace coal in this cell. A small decrease in coal and NG consumption would occur, with change of less than 0.2 % in total system cost. The validation of Chapter 3 is not less accurate: results are even slightly better. At stricter emission limits, the impact of the error would be higher, but the tendencies and conclusion remain the same.

from hydrogen, in turn produced by electricity. However, the conversion process induces many losses, which makes it too costly compared to fossil NG. Italy & Alpine States does not use all its wood, because it is more costly than coal. Moreover, wood is not exchanged because the energy losses due to transportation range from 32 % to 49 % due to the long distances between the cells. With these losses, it becomes more costly than coal (for boilers) and H_2 production or NG (for freight transport) in all the cells.

4.2.2 Electricity mix

A focus is made on the electricity sector because of its key role in the system, as it supplies the other sectors. Indeed, the need of electricity as an end use demand represents less than half of the electricity consumed, which means that the production is twice higher than what is required for electricity EUD. 27 % of the electricity produced is used for mobility, and 22 % for low temperature heating. The few other percents include some cooling and high temperature heating, as well as the losses.

Electricity also has a key role in the system given the high amount that is exchanged, which impacts the design strategy for its production. To understand the strategies observed in the exchanges, Table 4.2 shows the share of electricity that each cell consumes and produces, with respect to the total electricity of the system. The difference between those values furthermore allows to grasp the share that exchanges represent in the total electricity used.

Table 4.2: Shares of each macro-cell to the total electricity consumption or production and differences between production and consumption, for the Baseline scenario.

Share to total electricity:	consumed [%]	produced [%]	excess produced [%]
Ib. Peninsula	11.8	20.3	+8.5
France	19.2	14.2	−5.0
Br. Isles	14.1	13.3	−0.8
DE & Benelux	30.2	22.1	−8.1
IT & Alpines	18.1	15.4	−2.7
Scandinavia	6.6	14.7	+8.1

It highlights that DE & Benelux and France are importing a substantial share of the energy produced system-wide. It can also be seen that Br. Isles has a net difference much lower than Italy & Alpine States, even though the share of import in their total electricity mix (Fig. 4.2) is similar. Br. Isles therefore has a more balanced role in the system, importing and exporting a significant amount of electricity, with a net balance almost null. This table also shows that the Iberian Peninsula and Scandinavia produce approximately twice as much electricity as what they consume locally. Exchanges therefore allow to increase significantly the production in some regions.

Resources for electricity production

To understand how exchanges allow a change of strategy, the yearly amount of electricity generated per macro-cell is shown in Figure 4.6, compared to a case where exchanges are not allowed. The reader interested in the installed capacities of technologies for the Baseline is referred to Appendix D.2.

It can be seen that the increase of production in the Iberian Peninsula and Scandinavia is mainly due to an increase of onshore wind generation. Indeed, this technology is already

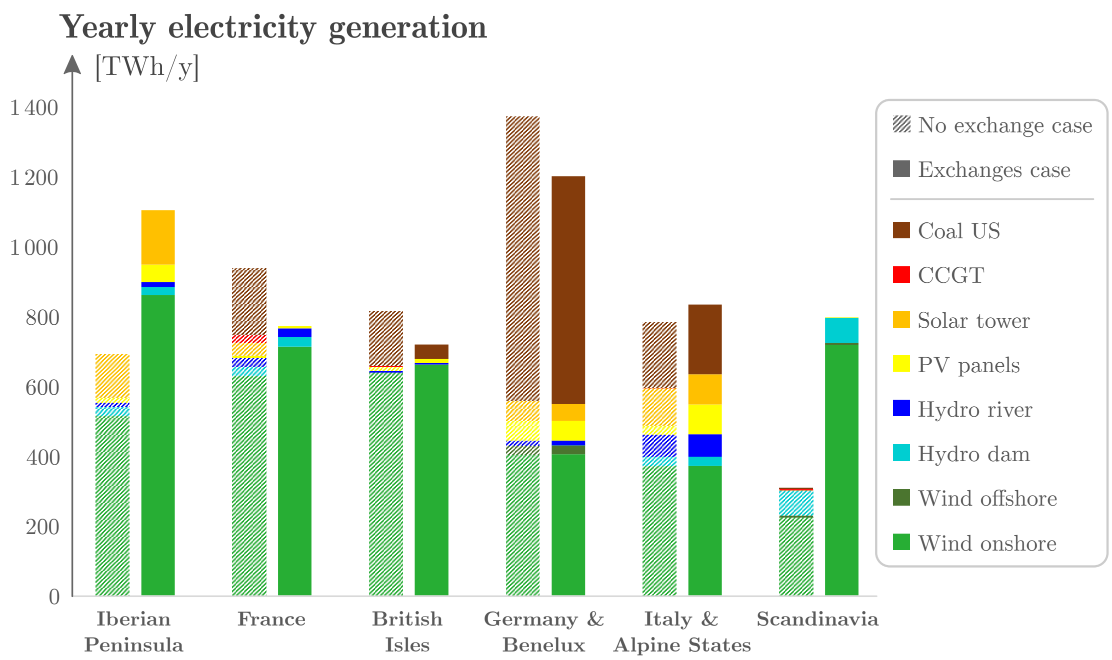


Figure 4.6: Annual electricity generated in each macro-cell per type of technology. Comparison between case without exchanges allowed (left) and the Baseline with electricity exchanges (right). The no-exchange case reaches the GWP_{op} limit, but the Baseline is 24 % below the limit.

used at full potential in the other four cells when there is no exchange, but in the Iberian Peninsula and Scandinavia its potential is higher than the total electricity consumption. With exchanges, onshore wind is installed at maximum capacity in all cells, due to its low cost. Increasing cheaper electricity production in some regions allows the system to reduce more costly production in other macro-cells, and especially electricity produced from fossil resources. In the end, 16.5 % of the electricity is produced from fossil fuel, against 28 % without exchanges. This is in accordance with objectives of the European Commission: achieving a share lower than 20 % by 2030 [29]. One can note that the amount of fossil fuel used decrease, even though the limit of emissions is the same in both cases: this is because the cost-optimum is below the −55 % limit when exchanges are allowed (*i.e.* in this case, the limit is not restrictive). This scenario emits 24 % less greenhouse gases from resources utilisation than the case without exchanges.

It can also be noted that the exchanges allow a better use of installed technologies. In fact, France and the British Isles have the same onshore wind installed capacity with and without exchanges, but their production is higher with exchanges. Cells can therefore curtail less energy and reduce the required installed capacity for a given amount of production. Something similar is observed for Scandinavia which can stop its small use of gas and coal power plants thanks to exchanges. It has enough potential locally, but without exchanges it was more costly to store energy or oversize wind turbines capacity for the production dips.

Furthermore, when exchanges are allowed, the total amount of electricity produced is higher. Exchanges therefore allow to reduce emissions not only by decarbonising the electricity production, but also by letting parts of the EUD that were supplied by fossil fuels switch to electricity that has a cleaner production mix. This can be noted directly from Figure 4.6 for Italy & Alpine States which produces more electricity, in addition to being a net-importer (Table 4.2).

Verifying the main resources

From Figure 4.6 it can be seen that onshore wind turbines are the main producer of electricity: they cover 73 % of the total production. They are installed at maximum potential in every cell, which represents 1780 GW of installed capacity globally. This is more than 10 times what is currently installed. The consistency of input data related to this resource should therefore be verified. The maximum installable capacities of this work −which come from [5]− are compared to other sources [30],[8]. It results that the capacities of this work do not seem overestimated, and are even much lower than in [30]. The capacities comparison is shown in Appendix E.

The levelized cost of electricity (LCOE) is also assessed for onshore wind, because it is mainly this value that makes EnergyScope choose a technology rather than another, and it covers both the technology price and the availability. Figure 4.7 shows the LCOE for each cell, which reflects their load factor, as the price per GW installed is considered the same here. They are compared to values from an expert elicitation survey on projections, conduced in 2020 [31]. The range shown on the graph corresponds to the average between 2025 and 2035 predictions. The values from [31], presented here, are the median of values collected over several continents, but the values specific to Europe tend to be slightly higher (≈ 1.5 €/MWh).

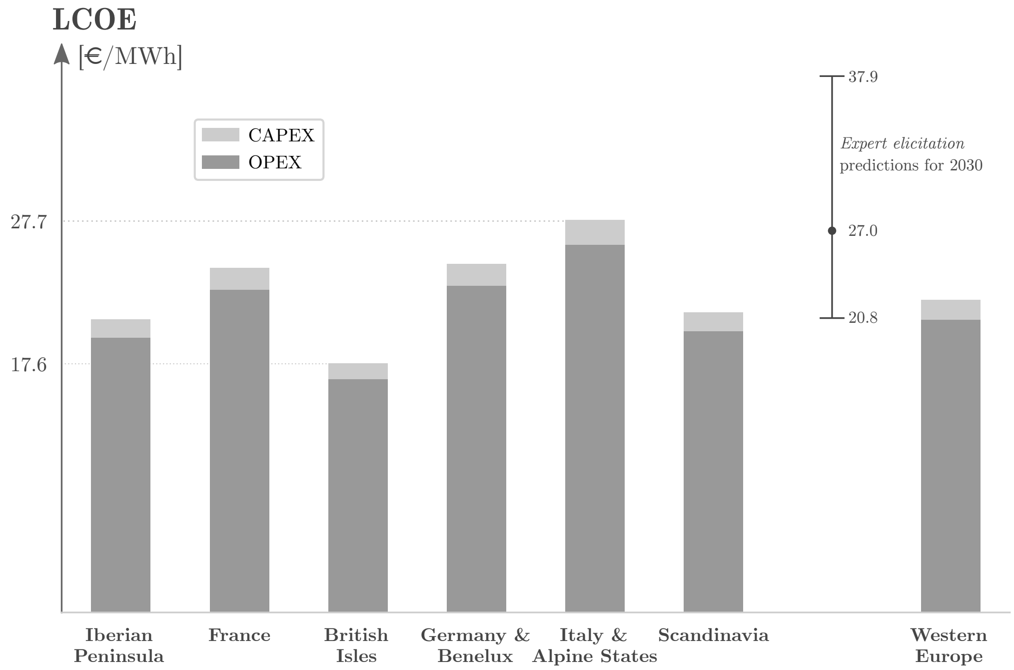


Figure 4.7: Levelized cost of electricity for installed onshore wind turbines in each macro-cell and for the whole system compared to prediction range from 2020 expert elicitation [31]. LCOE computed as the annualised cost of the technology over the yearly energy produced. The range from [31] is averaged between ranges for 2025 and 2035, and is converted from $ 2019 to € 2015.

It results that the average LCOE of Western Europe corresponds to the lower range of predictions. Values are thus optimistic, but might still be considered as acceptable. Having lower values in British Isles is not necessarily an issue because outliers are possible [31] and this cell has a large capacity factor. The main differences lie in the O&M costs (around 30 M€/GW/y in [31] for 2035 median predictions for Europe, and around 2.9 M€/GW/y for the current value in EnergyScope) and in the capacity factors (around 38 % in [31] for

Europe, and 24 % as output of the model for Western Europe). The capacity factor of the expert elicitation might be too high [32], but the O&M costs might need refinement in EnergyScope: modifying those parameters would result in higher LCOE for both the model used and for the range to which it is compared.

Even with an increase in its LCOE, onshore wind should remain the preferred resource for electricity generation up to a certain point. In fact, the next three technologies that have the lowest LCOE are PV, coal US and offshore wind turbines, with 41.3, 50.7 and 66.8 €/MWh respectively for the whole system. Locally, PV goes down to 32 €/MWh in Iberian Peninsula: it would require an increase of at least 54 % in the onshore wind LCOE in order to switch to PV as preferred technology, and this is without considering the additional costs for storage required by more PV penetration.

Solar towers also have a low LCOE in regions with good solar irradiation and are therefore installed at maximum capacity in those cells. Its global LCOE is of 35.9 €/MWh, but it was found lately that the investment costs considered for this technology might be too low and need reviewing.

4.2.3 Supply of the end use demand sectors

The other EUD sectors can also be analysed. Firstly, the following sectors can be briefly described: **low temperature heat** is provided by electrical heat pumps, either decentralised or through DHN, and with geothermal for less than 1 %; the **cooling** sector is also running with electricity; the **non energy** sector is entirely provided by gas, either imported NG (89 %) or produced from wet biomass (11 %). The other sectors require a more detailed description.

Industrial high temperature heat As seen in the Sankey diagram (Fig. 4.4), this sector is covered by boilers provided by coal, waste, wood, and some direct electricity. In every cell, local waste is preferred because it is cheaper than the other fuels, for an equivalent boiler price. Then, some cells use wood because it is cheaper than coal for them (Ib. Peninsula, France, Br. Isles and Scandinavia). They complete with coal if necessary. In DE & Benelux and Italy & Alpine States, wood is more costly and not used in boilers. Industrial heat produced directly by electricity is only used in Scandinavia. It covers 25 % of the demand, and is used to compensate part of the curtailment. The EUD of industrial heat is covered at the following level by the different energy carriers:

$$\begin{aligned} \text{Wood} &= 23.5\,\% \\ \text{Coal} &= 51.5\,\% \\ \text{Waste} &= 23.5\,\% \\ \text{Electricity} &= 1.5\,\%. \end{aligned}$$

Mobility In the passenger mobility, there is a high usage of public transports: their share has reached its limit value, imposed as an arbitrary social limit of acceptability. Passenger mobility is then served half by private and half by public vehicles in in every region of the system. **Public mobility** is covered in each cell at 70 % with natural gas buses and at 30 % with tramway. This is the maximal share of tramway, which reflects that this limit value might need to be better defined and to account for the different reality of each cell. On the other hand, **private mobility** only accounts for fuel cell cars, powered by hydrogen. In fact, each type of car considered in the model have the same order of investment cost, but fuel cell vehicles have a lower maintenance cost. Furthermore, the yearly cost of hydrogen as fuel represents only 15 % of the annualised cost of the vehicle, therefore the higher cost of the hydrogen compared to other fuels is not as important as the lower cost of the vehicle itself. Fuel cell cars are then cheaper but do not have the vehicle-to-grid advantage of the electric vehicle that can help support the grid.

For **freight transport**, hydrogen is also the most used fuel. Indeed, the road freight is used at its minimal share of 45 % and it is composed of fuel cell trucks, except in Br. Isles where half are diesel trucks. Next come boats which have reached their maximal share of 30 %. They are powered by synthetic diesel and completed at one tenth with gas, all of the gas boats being in DE & Benelux. The diesel is entirely produced from wood. Finally electric trains are covering the last 25 %, which is their maximal allowed share.

Hydrogen is mainly produced from electricity (90 %) through electrolysis, and the remaining is produced from gas. The production from gas occurs in cell that rely more on import of electricity: British Isles produces 22 % of its H_2 from gas, 15 % for DE & Benelux, 11 % for IT & Alpines and 2 % for France.

To sum up, the EUD of transport sector is covered at the following level by the energy vectors:

$$\begin{aligned} \text{Hydrogen} &= 48\,\% \\ \text{Gas} &= 26\,\% \\ \text{Electricity} &= 18\,\% \\ \text{Synthetic diesel} &= 8\,\%. \end{aligned}$$

It means that this sector relies mostly on electricity as it covers approximately 62 %. Synthetic gas and fossil NG play a secondary role as they provide 30 % of this EUD.

Storage The quantity of energy stored is low compared to the EUD. However, this sector is essential to ensure the flexibility needed in the system, in order to correctly meet the demand while integrating iRES. The reader interested in storage capacities is referred to Appendix D.2.

In general, the system tries to avoid storing electricity, and prefers storing energy before electricity production or after conversion to other energy vector. There are 2397 TWh of pumped hydroelectric storage (PHS) capacity to store electricity, but this is the currently installed capacity (*i.e.* the minimum that the system can install).

Some flexibility is brought to electricity production thanks to dam storage and solar towers molten salt storage. Over a year, 46 % of hydroelectric dams energy is stored in dam storage. 44 % of the heat produced by solar towers is stored before producing electricity.

After conversion, 16 % of H_2 is stored in seasonal storage. Some SLF is also stored, so that its production can be synced with iRES technologies to decrease curtailment, as pyrolysis generates electricity. The biggest part of the storage is in form of heat. Indeed, it is much cheaper to first produce heat from electricity *via* heat pumps and then store it, mainly in DHNs as seasonal storage. In consequence, it is prioritised to export electricity when it is produced and then to store it after conversion in the cell that will make use of the energy. This implies that storage capacities are not necessarily greater in countries that exploit more iRES if they exchange their excess of electricity. However, exchanging energy allows to reduce the need for storage options as excess energy can be exported and used in other areas of the system.

4.3 Sensitivity analysis on the price of electricity interconnections

As the electricity interconnections are a key element of the system, it should be verified that the observed results are still valid even with a change in their price, especially because these prices are computed based on values given with a range of uncertainty. The Baseline scenario uses the mid-range values, which are compared to the low-range and high-range values, and intermediate values at 25 % and 75 % in-between.

In addition, the length for the connections are somewhat arbitrary, and to relieve the local grids, some interconnections could be longer. To assess the potential impact of such change, the above cases are also compared to a case with interconnections 900 km long[2], which corresponds approximately to the center-to-center distance of the connected macro-cells. This represents an upper-limit for the length, and therefore the price, of electricity interconnections.

The changes induced in the system design of each case is assessed in terms of: change in system cost; change in NTC installed; and change in electricity transferred.

The change in system cost is shown in Figure 4.8, along with the change in cost of electricity interconnections only. Within the low-high range, the total system cost increase linearly with the price of interconnections. This change in total price is at most 0.1 % compared to the Baseline scenario, which can be considered as a small impact. Moreover, the change in the interconnection cost represents most of the change in total cost, which means that the rest of the system is only slightly affected. However, the more the prices increase, the lower is the share of interconnections additional cost in the the total additional cost. The Centre-to-centre result highlights that, even if lines are longer than in the Baseline scenario, the total cost increase should remain below +1 %. In this upper-limit case, the additional cost for interconnections represents half of the total additional cost.

Table 4.3 shows the numerical values of the net transfer capacities and the total electricity transferred through these interconnections for the whole system combined. Within the low-high range, the NTC change non-linearly: a price decrease leads to a small additional 3 GW, which tends to stabilise, while a price increase leads to a bigger −11 GW decrease (−4 %). On the other hand, the change in electricity transferred is almost linear, and the change stays below 2 %. The Centre-to-centre result highlights that the amount of electricity transferred should not decrease by more than 28 % even if lines are longer. As a reminder, this value is an upper-bound that the system will in principle not reach.

Table 4.3: Total cost, net transfer capacity and electricity transferred over a year for different interconnections prices.

Case	Total cost [b€/y]	NTC [GW]	Electricity transferred [TWh/y]
Low	1025.7	263.6	1360
	1026.4	263.0	1348
Baseline	1027.2	260.4	1334
	1027.9	253.9	1320
High	1028.6	249.3	1309
Centre-to-centre	1038.0	157.8	954

[2]Inland connections are still fully represented by 50 % AC and 50 % DC lines; but interconnections that cross a sea keep their original length for DC sea-cables, which is completed by the same mix of AC and DC overhead lines for the remaining length.

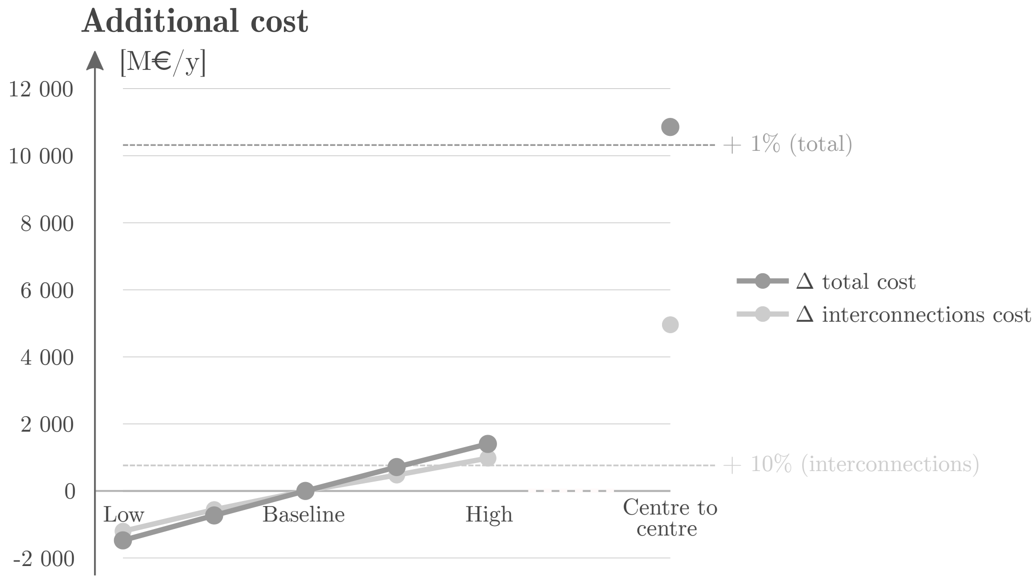


Figure 4.8: Change in the total cost and electricity interconnections cost due to change in the price per unit of electricity interconnections. From the bottom (Low) to the top (High) of the range on which the prices are based. Centre-to-centre represents the maximum additional cost if interconnections had to cross the cells entirely. Dashed lines represent the relative change in total and interconnection costs compared to the Baseline.

4.4 Discussion

Analyses of this chapter were conduced to study the benefits of energy exchanges, and more specifically under a constrain of greenhouse gas (GHG) emissions. With this scenario, only electricity is exchanged, and the emission limit is not reached.

Electricity exchanges allow to reduce the total cost of the system while lowering the global emissions. Compared to the case without exchanges with the operational GWP limit presented before, the total cost of the system is reduced by 2.5 % (−27 b€/y). Furthermore, the global emissions are also reduced as the cost-optimum solution with exchanges emits less GHG than what is required by the limit. As less fossil fuels are needed, the operational GWP (direct + indirect) is reduced by 23 %. The total GWP decreases by 17 % ($-462.5\,\mathrm{Mt}_{\mathrm{CO_2eq}}$/y). The benefits of exchanges can become even more important as the emission target becomes more restrictive. This point will be briefly studied in the next chapter.

In this analysis, some results can be discussed in more detail and possibilities to further investigate them open.

First, in the system design proposed here, the total iRES generation in the electricity sector is covering 60 % of the overall EUD. It is in accordance with Europe expecting to cover from 45 % up to 60 % of its demand with RES in 2030 [33]. The share presented in this work might be optimistic, but is in the range of the previsions. In addition, wind onshore is identified as the main source of energy used in the system. A short analysis was conduced to conclude that the large wind potential seems to be plausible, but the observed results could still be challenged as it is a determining parameter. Indeed, the social acceptance could be a sticking point to the installation of such quantity of wind turbines.

Secondly, to provide green energy to Western Europe, two main regions have been identified as the main exporters of energy because of their surplus of cheaper RES. This project could face social constraints in accepting the installation of a large number of technologies in some countries as well as political and economical constraints. In contrast to this, France imports up to a third of the electricity it consumes, and such a dependence to neighbouring countries could be questioned, especially for a country that has a large amount of RES (including the installed potential).

Also, the size of the electrical interconnections that need to be built is much more important that what currently exists: on average the current capacities represent 10 % of the optimum presented here. This point could be challenged and the feasibility of such a network of electricity with all the reinforcement of the grid needed can be questioned, including about the social acceptance of extra-high voltage lines. To face these problems by reducing the size of required electrical interconnections, one can try to extend the exchanges to other energy carriers and new interconnections. This point will be studied in the next chapter.

To assess the importance of building these *new* interconnections, the model can be run while limiting the NTCs to the existing capacities. It results that the system behaves almost the same way as when there is no exchanges, in terms of total cost and installed technologies per cell. The importance of new lines is also highlighted by the sensitivity analysis results: even with changes in the interconnection prices, the NTCs and the strategy of the system do not change much. Moreover, the EU Expert Group asks to have an interconnection level of at least 30 % in each country by 2030, and recommends to search for opportunities increase this level if it is below 60 % [33]. The present work seems to be within these goals, as the only cell above 60 % is France (with 97 %), for which transits increase the required capacities.

Finally, one of the main limitations of this work is that the system presented here is a snapshot of an optimal future system: it does not account for the pathway to 2030. The final solution is thus not optimal with regard to the current energy system installed. However, the main tendencies can still be captured.

Chapter 5

Scenario variations analyses

This chapter focuses on the study of additional options of energy exchanges that could be implemented in the future and the benefits associated. Specifically, two secondary scenarios presented in Chapter 2 are analysed, based on possible future solutions for which similar projects are already being developed.

First, a scenario allowing hydrogen exchanges is studied and the main differences with the Baseline scenario are outlined in Section 5.1. Secondly, in Section 5.2, the benefits of adding long-distance interconnection lines and the changes associated are assessed. Then, different scenarios are compared while imposing stricter emission limits in Section 5.3, to see if major changes occur and complement the observations made in other sections. Finally, the benefits of those scenarios are summed up, and a general discussion over the feasibility of their implementation in the future energy system is given in Section 5.4.

5.1 Adding hydrogen exchanges

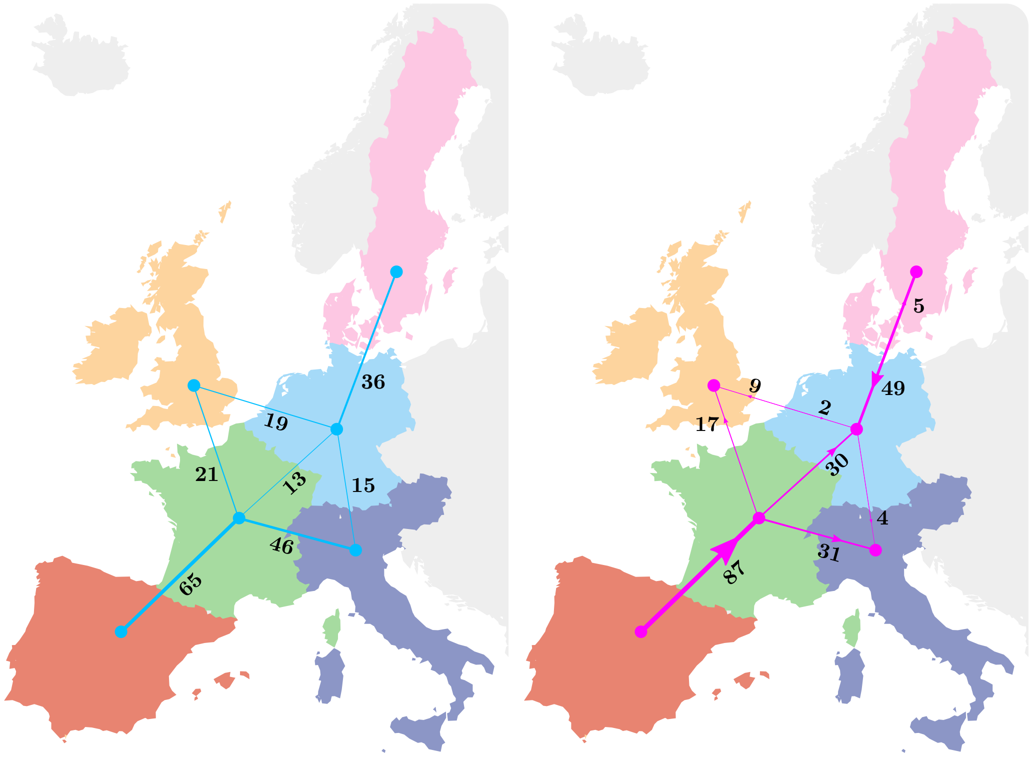
As detailed in Section 2.3.2, hydrogen is a promising energy vectors that could be used in tomorrow's energy system. The ability to exchange hydrogen (H_2) between cells is therefore added to the model, and this new scenario is compared to the Baseline scenario of the previous chapter. This section assesses the benefits of hydrogen as energy carrier to help reaching a low-emissions system.

5.1.1 Energy exchanges

Global fluxes and interconnections

The system now exchanges hydrogen and electricity. Synthetic gas, SLF, wood and waste can still be exchanged, but the system does not use these energy vectors for exchanges. The interconnection capacities for electricity and hydrogen are shown in Figure 5.1.

First, it can be noted that hydrogen connections take over part of the electricity connections. Therefore, hydrogen exchanges allow to reduce transfer capacities required for electricity exchanges, and have values closer to other predictions [28]. The reductions in



(a) Electricity interconnections (bi-directional).

(b) Hydrogen interconnections. Those interconnections are not bi-directional, therefore the capacity is not the same in both directions.

Figure 5.1: Net transfer capacities of interconnections [GW] between macro-cells for the scenario allowing hydrogen exchanges in addition.

size compared to the Baseline are as follows:

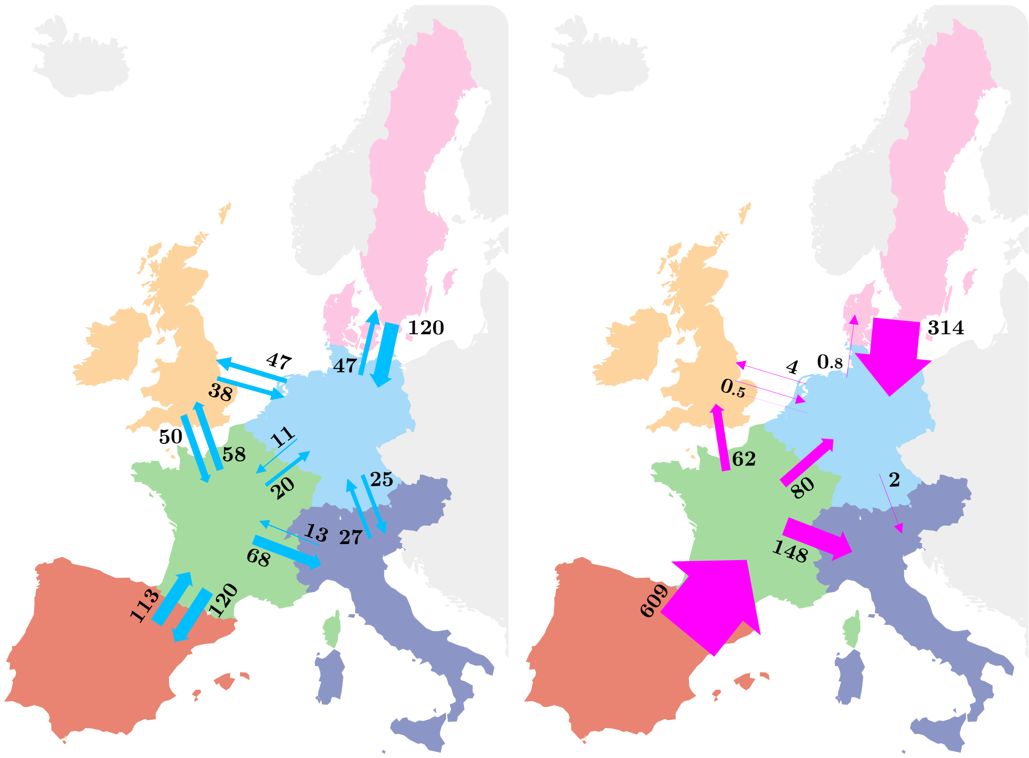
$$\begin{aligned}
&\textbf{Reduction in electricity NTC}\\
\text{Ib. Peninsula} - \text{France} &= -40\,\%\\
\text{Br. Isles} - \text{France} &= -20\,\%\\
\text{DE \& Benelux} - \text{France} &= -0\,\%\\
\text{IT \& Alpines} - \text{France} &= -25\,\%\\
\text{Br. Isles} - \text{DE \& Benelux} &= -18\,\%\\
\text{IT \& Alpines} - \text{DE \& Benelux} &= -50\,\%\\
\text{Scandinavia} - \text{DE \& Benelux} &= -60\,\%.
\end{aligned}$$

The lines connecting the Iberian Peninsula and Scandinavia with their respective neighbour were the largest connections and are the ones that have been reduced the most. These two connections remain important, and are now of the same order as the connection between France and Italy & Alpine States. The largest connection, still between the Iberian Peninsula and France, is now 65 GW which is closer to the 53 GW that the European Climate Foundation [28] planned for its maximal renewable case for the same border.

In return, the hydrogen connections can be pretty large. Specifically, the connections with the Iberian Peninsula and Scandinavia, that were the largest for electricity, are now the largest for hydrogen. It can be noted that, as hydrogen connections are not bi-directional by default, they are mostly designed to be used in one direction. Only two interconnections are designed to allow bi-directional flows, even though the secondary direction is much smaller.

For both energy vectors, all the possible lines are built, even if some are small and not all of them are bi-directional. For both hydrogen and electricity also, the connections between the Iberian Peninsula and France are much larger than in the rest of the system, which makes these connections a key element of the system.

To better understand the fluxes that drive this system, the yearly exchanges of energy are represented in Figure 5.2. The hydrogen fluxes are very large from Scandinavia and especially from the Iberian Peninsula. The main exporting cells thus remain the same, but the form and sometimes the amount of energy changes. It can be seen that the amount of exported energy from Scandinavia is still of the same order, but the Iberian Peninsula exports approximately 33 % more than in the Baseline.



(a) Electricity exchanged. *(b) Hydrogen exchanged.*

Figure 5.2: Yearly energy exchanged [TWh/y] between macro-cells for the scenario allowing hydrogen exchanges in addition.

Figure 5.2a confirms that hydrogen exchanges allow to reduce significantly the amount of electricity exchanged. The differences in the amount of electricity exchanged are summarised in Table 5.1. It can be seen that the exchanged electricity decreases at every border, except for the directions towards big exporters: that is, from France to the Iberian Peninsula and from DE & Benelux to Scandinavia, but also from the other cells to France, because they send electricity back to the Iberian Peninsula through France.

Table 5.1: Change in total electricity exchanged over the year [%] when hydrogen exchanges are allowed compared to when they are not allowed.

To \ From	Ib. Peninsula	France	Br. Isles	DE & Benelux	IT & Alpines	Scandinavia
Ib. Peninsula	-	$\gg 0^{1a}$	-	-	-	-
France	-74	-	+12	+45	+162	-
Br. Isles	-	-27	-	-16	-	-
DE & Benelux	-	-42	-24	-	-7	-72
IT & Alpines	-	-44	-	-46	-	-
Scandinavia	-	-	-	$\gg 0^{1b}$	-	-

[1] Those electricity exchanges were small or non-existing before adding hydrogen exchanges.
[a] +120 TWh/y; [b] +46 TWh/y.

The transit factors of both vectors are the following:

Electricity lines

$$\mathrm{TF}_{France} = 15\,\%$$
$$\mathrm{TF}_{DE\&Benelux} = 27\,\%$$
$$\mathrm{TF}_{IT\&Alpines} = 6\,\%$$
$$\mathrm{TF}_{Br.Isles} = 4\,\%$$

Hydrogen lines

$$\mathrm{TF}_{France} = 48\,\%$$
$$\mathrm{TF}_{DE\&Benelux} = 2\,\%.$$

The share of transiting electricity in France is nearly divided by two compared to the Baseline. The TF of DE & Benelux and British Isles are a bit higher, but the global TF of the system is reduced.

Regarding hydrogen, half of the energy exchanged with France is only transiting to supply other regions of the system. In view of the low TF of DE & Benelux, most of the hydrogen exported from Scandinavia is used to provide this cell directly. For all the other macro-cells the TF is null or negligible which means that hydrogen coming from France −in which it transits− is nearly entirely used in the region importing it.

Lines utilisation

To deeper understand what happens during exchanges, the utilisation of the lines is further analysed. In the same way as for the Baseline scenario, load duration curves of hydrogen interconnections are presented in Figure 5.3. These connections are more often used compared to the electrical interconnections of the Baseline scenario. For a given amount of energy exchanged, it allows to have smaller transfer capacities. The major hydrogen interconnection is between France and the Iberian Peninsula: this interconnection is used all the time during the year which explains the high quantity exchanged through it. Because the interconnections are not bi-directional, the reverse direction is only used for a few hours, and for two connections only.

Electrical lines can be studied through the indicators given in Table 5.2. Compared to the Baseline, the interconnections with the main exporters are less used. Indeed, respectively for the Iberian Peninsula and Scandinavia, the Null factors increase from 16 % to 22 % and from 4 % to 26 %. The UFs decrease by a half and a quarter for those lines. This is compensated by a high utilisation level for hydrogen lines, with UFs above 70 %. Moreover, the utilisation of electrical interconnections are more symmetric in this case: in fact, the Iberian Peninsula exports more energy in the form H_2 than it was exporting electricity in the Baseline, but in return some electricity is sent back to this cell. This is

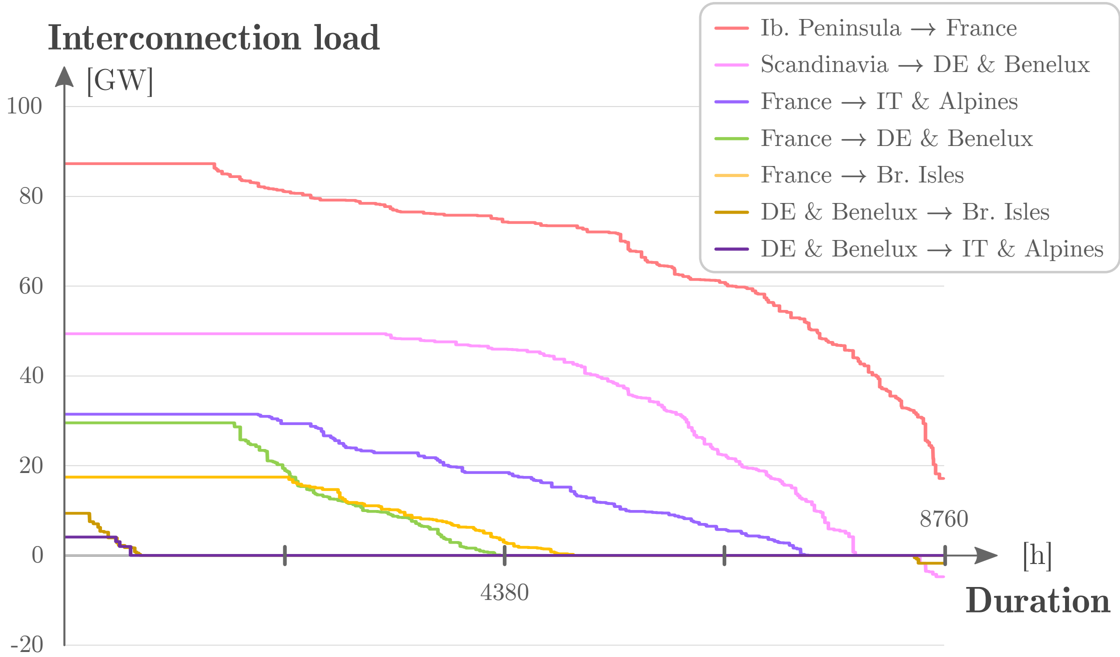


Figure 5.3: Load duration curves of all hydrogen interconnections for the scenario with hydrogen and electricity exchanges: number of hours at which an interconnection is used at least at a given power. Negative values represent the pipe utilisation in the opposite direction.

in part possible because the hydrogen exchanges relieve the electricity interconnections, which can be used with more flexibility.

*Table 5.2: Utilisation of cross-border electricity and hydrogen interconnections: share of time in a year spent at null power (**Null**), at full capacity (**Full**), direction of utilisation of the lines and utilisation factor (**UF**). All in %.*

Line	Electricity				Hydrogen			
	Null	Dir.	**Full**	**UF**	**Null**	Dir.	**Full**	**UF**
France ↔ Ib. Peninsula	22.7	←	8.2	19.8	0	←	17.0	79.6
		→	4.0	21.0		→	0.4	0
France ↔ Br. Isles	26.1	←	17.7	26.5	39.6			
		→	23.4	31.1		→	25.6	40.3
France ↔ DE & Benelux	62.7	←	5.8	9.5	48.2			
		→	15.3	18.0		→	19.3	30.9
France ↔ IT & Alpines	52.5	←	0.2	4.5	14.7			
		→	11.0	16.8		→	22.0	53.8
DE & Benelux ↔ Br. Isles	36.4	←	20.6	23.0	88.1	←	2.9	3.0
		→	19.1	28.3		→	2.9	5.2
DE & Benelux ↔ IT & Alpines	45.3	←	13.0	20.6	91.4			
		→	16.0	18.8		→	5.9	6.8
DE & Benelux ↔ Scandinavia	26.6	←	22.3	38.4	7.4	←	36.6	72.6
		→	5.4	15.0		→	0.8	1.2

As regards hydrogen interconnections, those with the two major exporters are very highly used. The others, connected to France, are often used with a UF between 30 % and 50 %. The remaining, connected to DE & Benelux, are rarely used with a Null factor around 90 % in accordance with the low TF of this macro-cell.

5.1.2 Changes in the energy system

Compared to the Baseline scenario, the Iberian Peninsula generates more electricity: PV panels produce 177 TWh/y in addition, and solar towers produce 40 TWh/y in addition. In return, the amount generated in other macro-cells decreases. DE & Benelux produces 74 TWh/y less electricity by coal (−6 % of total cell electricity production). Moreover, Italy & Alpine States produces 122 TWh/y less electricity with coal (−15 %) and 70 TWh less with PV panels (−8 %). Finally, the total amount of electricity produced is lowered by 1 %. This difference is explained by less electricity losses and a small amount of electricity replaced by natural gas for hydrogen production.

Allowing hydrogen exchanges lets the system shift part of the electricity production from some cells to others with limited additional costs −smaller than the cost benefits. This allows to generate more electricity in a region where the renewable potential is higher. In this case, the Iberian Peninsula has the best sunlight conditions: more solar technologies are installed in this cell to reduce fossil-based technologies globally, and replace some solar in macro-cells that have poorer availability.

In addition, the strategy to produce H_2 changes if exchanges of hydrogen are allowed. Figure 5.4 shows the hydrogen production in each cell, with and without hydrogen exchanges. The two main energy exporters −Ib. Peninsula and Scandinavia− are producing most of the hydrogen, and only from electrolysis. Indeed, electricity is partially transformed in hydrogen before exporting it to the rest of the system. The Iberian Peninsula generates 54 % of the total hydrogen. France, that receives from the latter cell a big amount over the year, does not produce any H_2 anymore. Scandinavia generates 26 % of the hydrogen, which allows to strongly reduce the production in DE & Benelux. Finally, some hydrogen is produced from natural gas to complete the consumption in some cells. Even if 87.5 % of H_2 is generated from electricity, the yearly amount of natural gas consumption is increased compared to the Baseline scenario: its share in the total hydrogen production has increased from 10 % to 12.5 %.

The overall consumption of natural gas in the system therefore increases by 3.3 % to produce the remaining H_2 in IT & Alpines that do not receive enough electricity. In terms of fossil resources used, this increase is compensated by 16.4 % less coal used for electricity production. At the end, the amount of fossil resources consumed is lower by 8.4 %. Consequently, the GWP_{op} decreases by 10 %. However, the GWP_{constr} is a bit higher which leads to a final reduction of 6.7 % of the global emissions. Hydrogen exchanges help thus to further decarbonate the system. It also allows to save money as the total cost of the system decreases by 0.6 % with a decrease 4 % in operational costs.

The hydrogen production strategy explains why electricity is flowing back to the Iberian Peninsula (Fig. 5.2a) while it was not the case in the Baseline: most of the electrolysis plants are located in this macro-cell. It is found to be cheaper to centralise the production there, even if the Ib. Peninsula sometimes needs to import electricity to produce and export hydrogen. A similar behaviour is observed for Scandinavia, but at a smaller magnitude.

To sum up, exchanged hydrogen allows to reduce the amount of electricity exchanged and the size of electrical interconnections. In return, hydrogen exchanges are large from the main exporting macro-cells and the system is still relying on electricity produced in Scandinavia and especially in Iberian Peninsula. It allows to reduce the global fossil fuel consumption and to install more solar technologies. Total emissions are thus reduced and the total cost is a bit decreasing. No specific changes occur in other sectors, strategies and technologies used remain the same.

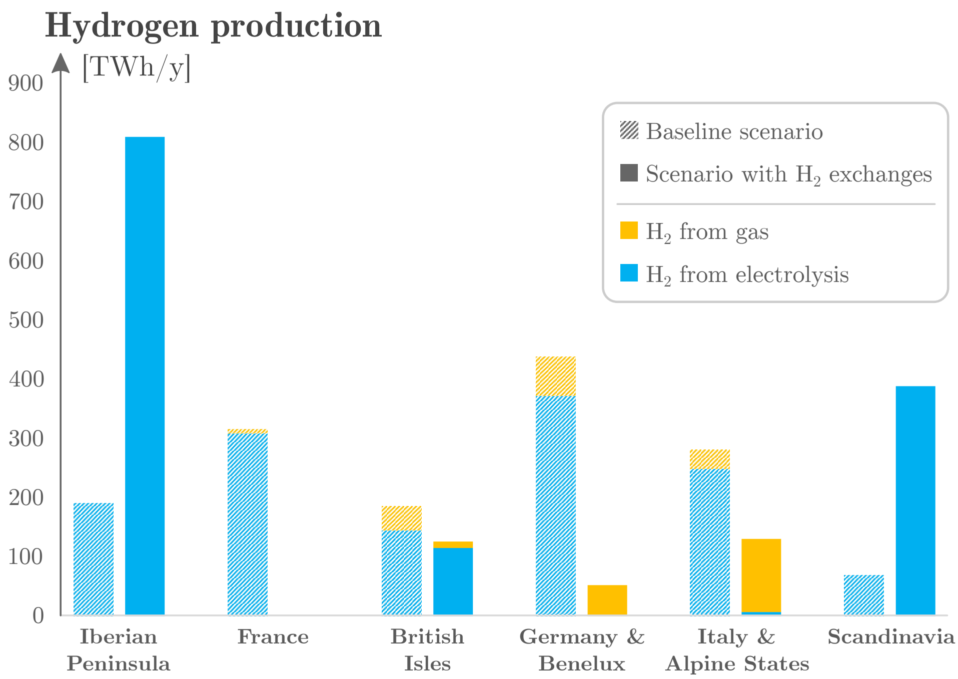


Figure 5.4: Hydrogen production in each macro-cell per production type. Comparison between the Baseline scenario with electricity exchanges only and the scenario with both electricity and hydrogen exchanges.

5.1.3 Impact of higher price of the hydrogen pipes

In Chapter 2, the definition of price of hydrogen interconnections was presented. However, due to the lack of knowledge on this topic because it is not yet well deployed, the impact of a change in the price of hydrogen pipes is assessed. The cost of hydrogen cross-border lines is then multiplied by two and reaches a value of 1.08 M€/GW/y. The differences in yearly energy exchanged per line for each direction are given in Tables 5.3 and 5.4.

Table 5.3: Differences of yearly ***electricity exchanged*** *[TWh/y] when the price of hydrogen interconnections double.*

To \ From	Ib. Peninsula	France	Br. Isles	DE & Benelux	IT & Alpines	Scandinavia
Ib. Peninsula	-	+0.04	-	-	-	-
France	+0.79	-	+0.96	+0.25	−0.69	-
Br. Isles	-	+0.03	-	+0.38	0	-
DE & Benelux	-	+0.39	−0.23	-	−0.23	+1.73
IT & Alpines	-	+0.67	-	+0.16	-	-
Scandinavia	-	-	-	−0.86	-	-
Total	+0.79	+1.13	+0.73	−0.08	−0.92	+1.73

The changes noted for electricity exchanged in each interconnection are very small (less than 1 TWh and less than 2 for large interconnections). For hydrogen, the difference is a bit more important but it remains very small compared to the total exchanged energy. The highest value is for the connection from France to IT & Alpines but it is only 6.5 TWh/y out of a total energy of 148 TWh/y. For exchanges higher than 7 TWh/y, this change represents the highest relative change. For smaller interconnections, the relative difference is more important but is negligible in view of the low amount computed.

In general, as the cost of hydrogen lines increases, the amount of energy exchanged

Table 5.4: Differences of yearly ***hydrogen exchanged*** *[TWh/y] when the price of hydrogen interconnections double.*

To \ From	Ib. Peninsula	France	Br. Isles	DE & Benelux	IT & Alpines	Scandinavia
Ib. Peninsula	-	0	-	-	-	-
France	-3.83	-	0	0	0	-
Br. Isles	-	-0.16	-	-1.06	-	-
DE & Benelux	-	$+3.11$	-0.43	0	0	-2.43
IT & Alpines	-	-6.56	-	$+4.67$	-	-
Scandinavia	-	-	-	-0.10	-	-
Total	-3.83	-3.62	-0.43	$+3.51$	0	-2.43

decreases for this vector ($-0.55\,\%$) and increases for electricity ($+0.44\,\%$). These changes are nevertheless negligible and the system strategy remains the same. At the end, the total yearly energy exchanged is not really modified as there is only a decrease of 3.4 TWh/y which corresponds to less than 0.2 % of the total. Furthermore, unless for the storage sector, the installed capacities computed in both systems are exactly the same, except for PV panels that go from 214 GW to 216 GW.

Finally, if the price of hydrogen interconnections is twice the one used in this study, the optimal energy exchanges are not importantly impacted, and the system computed remains the same. A certain uncertainty on this parameter is then acceptable.

5.2 Additional interconnections lines

As detailed in Section 2.3.3, plans to build new electrical lines in Europe have already been studied in other works. Hence, the possibility of installing three long-distance sea cables was added to the model. This section assesses the benefits of long-distance electricity lines to help reaching a low-emissions system.

Among the three possible new interconnections, only the one between Br. Isles and Scandinavia is built in this case. It allows to reduce sizes of lines connected to DE & Benelux as electricity can go directly from Scandinavia to Br. Isles. Figure 5.5 shows the new transfer capacities, along with the differences with respect to the Baseline scenario.

The differences in yearly electricity exchanged are given in Table 5.5.

Table 5.5: Differences of yearly electricity exchanged [TWh/y] between case with additional interconnection and the Baseline scenario.

To \ From	Ib. Peninsula	France	Br. Isles	DE & Benelux	IT & Alpines	Scandinavia
Ib. Peninsula	-	$+0.9$	0	-	0	-
France	$+5.9$	-	$+2.3$	$+2.0$	-0.4	-
Br. Isles	0	-6.7	-	-16.8	-	$+35.5$
DE & Benelux	-	$+4.8$	-8.4	-	-1.1	-35.0
IT & Alpines	0	$+4.8$	-	-4.5	-	-
Scandinavia	-	-	$+7.4$	-0.9	-	-
Total	$+5.9$	$+3.8$	$+1.3$	-20.1	-1.5	$+0.5$

The additional line allows Scandinavia to export 35 TWh/y to Br. Isles instead of transiting through DE & Benelux. This allows to reduce the size of the connections from DE & Benelux to Br. Isles and to Scandinavia. The amount of energy transferred through

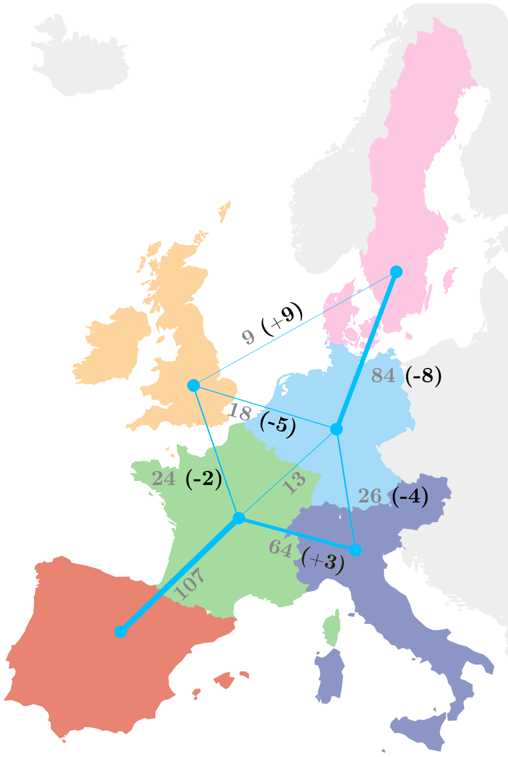


Figure 5.5: net transfer capacities of cross-border electrical lines [GW] between macro-cells with additional interconnections. Differences compare to the Baseline scenario in brackets.

those connections also decreases, and therefore the energy transiting through DE & Benelux decreases by 20 %.

Because Br. Isles is directly connected to Scandinavia which is one of the main exporters, this connection is favoured and it imports less energy coming from the Iberian Peninsula through France. In total, British Isles imports more energy over the year, and less energy transits through it. The connection between France and Br. Isles is therefore reduced, and more energy from Spain is available for France, Italy & Alpine States and DE & Benelux. The connection between DE & Benelux and Italy & Alpine States therefore decreases in profit to the one between France and Italy & Alpine States.

In general, the additional interconnection allows to have more flexibility in the production mix: therefore, the Iberian Peninsula is able to produce an additional 6.1 TWh/y from solar technologies (85 % PV, 15 % solar towers) and to export most of it without increasing the size of the interconnection. Italy & Alpine States can also increase its solar production by 4.6 TWh/y. This allows to produce more H_2 from hydrolysis in countries close to that solar production and to decrease the electricity production from coal in Italy & Alpine States (-17.3 TWh/y) and British Isles (-17.5 TWh/y). In return, some cells switch part of the H_2 production from electricity to NG. The only increase in coal use occurs in DE & Benelux (+14 TWh/y), to supply part of the consumption peaks that cannot be met with the reduced interconnections.

As a result, the global system increases its electricity production from solar technologies (+11.5 TWh/y) and reduce the amount produced from coal (-21.6 TWh/y). The yearly generation of electricity decreases by 0.2 %, which is compensated partly by more NG for H_2 production, and partly by more SLF usage for freight transport. The total emission decreases by 0.6 % ($-13.6\,\mathrm{Mt_{CO_{2eq}}}$/y) and the total price only decreases by 0.006 %

(−58 M€/y). Except for the technologies mentioned above and for storage, the global system remains the same: adding a connection only modified the electricity sector.

In the case where **hydrogen exchanges** are allowed, the tendencies are the same as detailed before but the changes are less important. Indeed, the differences in electricity generation for each macro-cell are less than 0.5 %, and 1.4 % for Br. Isles. The differences in energy exchanged follow the same trend except for the interconnection from France to Br. Isles for which exchanges are augmented instead of being decreased because less electricity is produced in the latter macro-cell. More changes are noticed in electricity instead of hydrogen exchanges because the new lines introduced are electrical one.

As explained in Chapter 2, introducing long-distance interconnections has some limitations with the current implementation of the model. Indeed, the cost to reinforce the local grid is not taken into account for regions that import electricity. The cost to connect two cells by the mean of one intermediate is then lower than building a long line between the two furthest cells. Consequently, the model considers that it is cheaper to connect the Iberian Peninsula with Br. Isles or IT & Alpines by the intermediate of France. However as in reality the cross-border capacities could be limited, those additional lines could also be useful to increase the exchanges capacity.

5.3 Stricter emission limits

It is interesting to analyse what happens if the emission target is more restrictive. Indeed, the benefits of the exchanges could evolve differently and become more or less important. To perform such analysis, three already presented cases are used: without energy exchanges; the Baseline scenario; and the scenario enabling hydrogen exchanges. The evolution of the optimal system cost of each scenario and the total GWP associated are shown in Figure 5.6. The different points are obtained with different targets of GWP_{op} reduction given in grey.

Firstly, it can be highlighted that the benefits of exchanges on the cost are more important if the GWP_{op} limit is more restrictive. For a target with no operational GWP, the system without exchanges is 9.8 % more expensive than the Baseline. The case with hydrogen exchanges is 1.3 % less expensive. Without exchanges, as DE & Benelux lack of potential, it needs to import resources from the exterior of the system, which come at a higher price. It imports SNG, H_2 and SLF for a total of 1153 TWh/y. Some other cells import a small amount of H_2, to compensate the deepest gaps in iRES availability. In contrast, exchanges allow to integrate more iRES and thus to electrify the system that will not import fuel from the outside. Indeed, it allows to produce all the hydrogen from electricity and avoid importing H_2 from the exterior. Hydrogen is also transformed in gas, which avoids importing synthetic gas and liquid fuel from the exterior. When no operational emissions are allowed, the system starts to exchange gas which is mainly required to cover a part of the non energy demand. Furthermore, without exchanges, more expensive and less efficient technologies need to be installed in countries which have a poor potential. The offshore wind yearly production is 75 % higher (273 TWh/y) compared to the case with hydrogen and electricity exchanges; and costly solar thermal technologies need to be used to produce heat (392 TWh/y) in regions that do not produce enough electricity. With exchanges, this is compensated by more onshore wind, PV panels and geothermal energy, made available by cells with a higher potential (+1851 TWh/y in total). It can be concluded that energy exchanges can be an important tool to decarbonise the system while inducing the lowest cost.

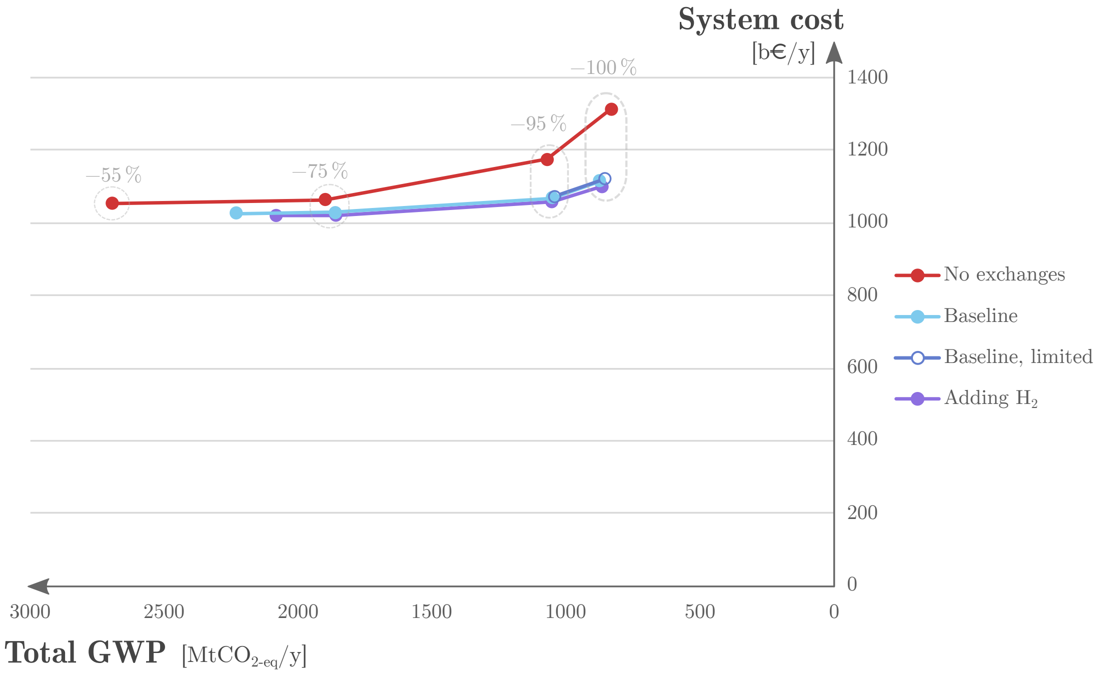


Figure 5.6: Evolution of the annualised system cost and the related total global warming potential, according to different targets of GWP_{op} reduction (mentioned in light grey), for different scenarios: without energy exchanges, Baseline scenario, Baseline scenario with sizes of electrical interconnections limited to 107 GW*, and scenario enabling hydrogen exchanges.*

Secondly, exchanging hydrogen in addition to existing fluxes induces only a small decrease in the total cost of the system. However, it allows to exchange energy in another way and it increases the interconnection possibilities if more constrains are added, *i.e.* political or social decisions.

In this analysis, the sizes of the interconnections between countries are not limited. It is then interesting to analyse how the cost would evolve if electrical transfer capacities were limited to lower values. In fact, the Baseline with reduction of 95 % and 100 % of emissions have respectively 312 GW and 479 GW of capacity for their biggest interconnection. The sizes of the interconnections are then limited to the maximal value obtained in the Baseline, −55 % emissions scenario: 107 GW. This new scenario is also represented in Figure 5.6. In view of the huge number of possible interconnections, the solutions found with and without limiting sizes have nearly the same total cost, with a difference of less than 0.5 %. It enforces the fact that this graph is a good approximation of the optimal cost that can be achieved for a system depending on the GWP_{op} target imposed even if no limitation are set on the size of the transfer capacities.

5.4 Discussion

These analyses were conduced to study the benefits, compared to the Baseline scenario, of different options of energy exchanges that could be implemented in the future: allowing hydrogen exchanges, and allowing new interconnections. Even if the cost reductions are small (respectively 0.6 % and 0.006 %) those scenarios allow to reduce the total GHG emissions of the Western Europe energy system (respectively −6.7 % and −0.6 %). The benefits and implementations of these solutions are discussed here to highlight their limits and open possibilities to study them more in depth.

Firstly, both strategies allow to integrate more iRES. Indeed, those additional options of exchanges increase the flexibility of the system. Specifically, this helps to integrate more solar energy. However, it increases the electricity production in the Iberian Peninsula, which has a high solar potential, and further increases the dependency of other countries to this region.

Secondly, thanks to hydrogen exchanges, the sizes of electrical interconnections are reduced and the sticking points linked to that also decrease. A much smaller reduction of some lines is noted for the second scenario. However, if cross-border capacities were limited in size, these two options could be even more useful to increase the exchange capacity.

As no H_2 exchanges exist nowadays, a deeper analysis on the feasibility and limits of this size of H_2 technologies and such a network could be performed. In particular, the cost of hydrogen exchanges should be reviewed, and given the high usage of H_2, a dedicated implementation of network within the cells might be needed. However, changing the costs should have a limited influence on the system strategy, as seen above.

In the scenario allowing long-distance lines, only the interconnection between British Isles and Scandinavia is built in the optimal solution. However, these observations should be taken with caution because they are partly due to limitations in the model. As explain above, the reinforcement cost of local grids due to additional cross-border connections is not taken into account which induces some bias in the solution. This could be improved by making an additional study over grid reinforcement costs, in particular when energy transits through a country.

In the end, although some aspects might need more investigation, hydrogen exchanges seem promising in terms of flexibility. Long-distance interconnections can also help, but the outcomes are less pronounced with the current implementation. As the role of exchanges increases when the emission reduction target increases, those options also become more advantageous through the decarbonisation as they raise the exchange capacity.

Conclusion

Europe wants to become carbon-neutral by 2050 to address climate change. An intermediate target of $-55\,\%$ compared to 1990 emissions level is set for 2030 [1]. To plan the energy transition, there is a need of models integrating properly intermittent renewable energy sources, and taking into account the different energy sectors and their coupling. To deal with countries lacking of renewable energies, and to reduce the costs, modelling interconnected regions is a necessity. A gap was identified in energy system modelling that do not take into account both interconnections and a whole-energy system approach.

In this master thesis, Western Europe was studied on an interconnected basis and with a whole-energy system approach. The aim was to analyse the role of energy exchanges in the transition to a carbon-neutral energy system. In addition to the case study analysis, this work developed a methodology to answer the needs. In fact, the open-source model EnergyScope Multi-Cell has been improved in order to be applicable to the studied area. To that purpose, some enhancements have been made to the model to suit the needs of the case study. A methodology has been developed to be able to process a large area while limiting the loss of information: merging several countries together to deal with macro-regions of the same scale. Consequently, large area can be modelled with a lower number of regions and thus a lower computational cost while limiting information loss. The validity of this methodology has been assessed, and it was found to be appropriated for the case study.

The case study was Western Europe, divided in 6 macro-regions. First, this area and the countries that compose it have been described in terms of energy demand and renewable potential. Then the different scenarios have been presented: a baseline scenario with the current commonly used energy vectors for exchanges; a similar scenario that allows exchanges of hydrogen in addition; and a scenario adding long-distance electricity interconnections. All have a limit in global warming potential (GWP) of $55\,\%$ below the emissions of 1990 for the main scenario. An additional analysis is conducted to see how these scenarios evolve when the operational GWP limit increases from $-55\,\%$ to $-100\,\%$, with comparison to a case without exchanges. The model used, the data gathered, along with some tools used to analyse the results can be found on the GitHub repository of this master thesis [12].

The results and their analyses were able to give answers to the question "How can energy exchanges help to reach a low-carbon Western Europe at least cost?". The following conclusions can be drawn:

- energy exchanges help to reduce the system cost, especially at very low operational emission targets ($-2.5\,\%$ for the 2030 target and $-16\,\%$ with no operational emissions), because:
  - the renewable resources that are the cheapest in some countries can be used

first for the whole system, especially onshore wind;
    - the different regions can complement each other depending on their weather conditions and demand peaks, so that the total installed capacity of technologies is reduced including some storage technologies;

- energy exchanges will allow countries that lack of renewable potential to have a carbon-neutral energy system;
- the Iberian Peninsula and Scandinavia are major exporters of energy, due to their high onshore wind resources and their low demand;
- the system is highly electrified (70 % of the demand covered by electricity), including with heat pumps and electrolysis to produce hydrogen for vehicles;
- the optimal transfer capacities required for electricity are quite large; up to 107 GW between France and the Iberian Peninsula:
    - compared to the current capacities, large construction projects are needed, which can raise societal barriers;
    - the investments required seem small (0.8 %) in comparison to the total system cost;
- without hydrogen exchanges, electricity is almost the only energy vector for exchanges, partly because each country can import fossil natural gas from abroad. Only some synthetic gas exchanges occur in addition in low-carbon scenarios;
- hydrogen exchanges can help reduce the size of electrical interconnections (-40 % in total) while not modifying much the rest of the system;
- the hydrogen exchanged covers only the demand in mobility that uses hydrogen: it is not converted back to electricity or another energy vector.

However, the model and the assumptions made to perform the analyses have some limitations. First, future data cannot be predicted with total certainty. Hence, the demand and prices forecasts might be wrong; and the time series data based on 2015 might not remain valid for the future, especially with climate change. Secondly, the optimum solution is based on the cost for the whole system, neglecting some political, societal, economical or even technical constraints. For example, the feasibility of such large interconnections can be verified: in terms of social acceptance of extra-high voltage lines, or in terms of cost for local network reinforcements starting from a certain level of interconnection. This last point could be directly implemented in the model, following a dedicated analysis. This could furthermore resolve the possible lack of consistency of long-distance interconnections. Also, the fact that some countries endorse a large energy production for others should be verified from a political point of view, and take into account social acceptance.

Finally, the scope of this work could be extended to an even larger scale, for example to take into account possible cooperation with North Africa for their solar resources [34, 35]. The model could also be used on smaller systems, to assess the roles of different regions at the scale of a country. In addition, other future works could develop a bridge between these two scales, and perform the optimisation on a small, local scale based on the exchanges resulting from the large scale optimisation. Ultimately, the transition pathway optimisation [36] could be integrated to such systems −if computational resources allow a sufficient accuracy− to take into account currently installed infrastructures and the step-by-step evolution towards carbon-neutrality.

Appendices

Appendix A

Detailed merge methodology

A.1 Time series

The new TS of each type i is defined as a weighted sum of the TS of all the countries that constitute the macro-cell.

$$TS_i(t) = \sum_c w_{i,c} TS_{i,c}(t).$$

Weather TS weights

The weight $w_{i,c}$ for a weather TS of type i is defined as:

$$w_{i,c} = \frac{f_{max\,i,c} \cdot c_{p\,i,c}}{\sum_{c_2} f_{max\,i,c_2} \cdot c_{p\,i,c_2}}$$

for i among: PV, Wind onshore, Wind offshore, Hydro dam, Hydro river, Tidal. $f_{max\,i,c}$ represents the maximum installable capacity of the technology that make use of i. $c_{p\,i,c}$ is the mean capacity factor of i over a year, thus the average of $TS_{i,c}$.

For the thermal solar TS (used also in CSP), the weight is defined as the total solar energy potential of the country, computed as the mean direct normal irradiance (DNI) multiplied by the surface-area of the cell, taken from the Global Solar Atlas [13]:

$$Solar\,potential_c = \overline{DNI}_c \cdot Area_c. \tag{A.1}$$

Demand TS weights

The weight $w_{i,c}$ for a demand TS is defined as:

$$w_{i,c} = \frac{EUD_{i,c}}{\sum_{c_2} EUD_{i,c_2}}$$

where $EUD_{i,c}$ is the sum, in all sectors, of the demand of end use type i for country c.

The end use type used for each TS are given in Tab. A.1.

Table A.1

Time series (i)	Demand of end use type (EUD_i)
Electricity	LIGHTING
Space Heating	HEAT_LOW_T_SH
Space Cooling	SPACE_COOLING
Passenger mobility	MOBILITY_PASSENGER
Freight mobility	MOBILITY_FREIGHT

A.2 Resources

Parameter avail_local

Sum the availability of the local[1] resources:

$$avail\_local_i = \sum_c avail\_local_{i,c}.$$

Parameter c_op_local

The new cost of local resources (c_op_local) is obtained by a weighted sum with the availability as weight:

$$c_{op,i} = \sum_c w_{i,c} c_{op,i,c}$$

$$w_{i,c} = \frac{avail\_local_{i,c}}{\sum_c avail\_local_{i,c}}.$$

A.3 Technologies

f_{min} and f_{max} are summed through the countries.

If another parameter of a technology i vary from one country to another, a weighted sum is performed with f_{max} as weight:

$$w_{i,c} = \frac{f_{max,i,c}}{\sum_c f_{max,i,c}}.$$

An exception is made for *EFFICIENCY* and *GRID* which are considered differently in the model: their costs are summed through the countries.

A.4 Storage

The parameters that are in common with other technologies are processed as for any technology (see Sec. A.3).

For parameters specific to storage, only the charge and discharge time of PHS vary between countries. They are averaged using the currently installed capacity as weight (by default, f_{min}).

[1]WOOD, WET_WASTE and BIOMASS

A.5 Exchanges

The *minimum transfer capacities* with neighbouring cells are summed. The *distance for freight* is obtained manually as the half distance by road (using Google Maps) between the two big cities the furthest apart in the cell.

If the user wants to enable electricity import from the exterior of the system, they can sum the *import capacities* of the countries. However, they should make sure that the import capacity parameter of each country before merge does not include the transfer capacity with other cells of the system. The per-border capacities can be found in [37].

Appendix B

Weight selection for merging

Section 1.2.2 presents the two types of weights used in this work, and introduces the need of selecting the right weights to represent the cells importance. This appendix first gives complements on the need of selecting weights; then it details the selection procedure and finally shows the results.

As a reminder, the weights that are selected here are the one that represent the importance of each cell, for each type of TS. They are defined in order to merge several cells together, but the same weights can be used in the process of selecting the TDs.

B.1 Why selecting weights

The choice of the weights is not always straightforward. In fact, for the TS of intermittent energy production, the best weights would be the final installed capacities of the corresponding technologies, but these installed capacities are not known. Other weights have thus to be selected, and they should give results as close as possible to the non-simplified case (without merging, and even without TDs).

On another hand, the weights for the TS accounting for EUDs is straightforward: the demands are simply summed up for the merging, therefore their TS should also be summed-up. As the TS are normalised, a weighted average is performed by using the total demand of the related EUT as weight.

In EnergyScope MC, when no cells are merged, there is no need of weights to merge them. But the weights for the TDs selection (written w_{TD}) could already account for the cell's importance. If such w_{TD} had already been defined in works over multi-cell, they could also be used to perform the weighted average for the merging procedure. However, no analysis has yet selected how the cells importance should be represented in those w_{TD} for TDs selection. A selection has thus to be performed here.

B.2 How the selection is made

As the purpose of this analysis is to have weights for the merging procedure, the selection is directly performed by comparing cases with merged cells to a reference case, without intermediate steps.

The best reference that one can get, in order to compare different cases, is a system that is not merged and that do not use typical days. It is thus a system optimised over 365 days that do not use weights: neither for TDs selection, nor for merging.

The main indicator used is the error on the duration curves of the resources availability, for the following reasons. First, the duration curves reflect properties of the TS that are fed to the optimisation model, which allows to compare the input data of the system, as the merging procedure affects those input data. Furthermore, the output results are less objective to compare, because of the high variety of solutions that can be selected by the model and that are similar in terms of cost. The resource usage are part of those results, but they are used as indicators as well to verify the tendencies observed with the duration curves error. The final cost of the system, however, cannot be easily compared to the reference, because the merging itself introduces some cost saving (due to some loss of information, see Chapter 3), and one cannot create a good reference case for the cost without using weights to merge the cells.

The error on the duration curves were also used in [3] to choose the clustering method. The relative errors ϵ_{dc} are compared, and they are defined as the absolute error E_{dc} (Eq. (B.2)) over the reference error $E_{dc,ref}$ (Eq. (B.3). The reference error is computed as the error made with a constant duration curve [3].

$$\epsilon_{dc} = \frac{E_{dc}}{E_{dc,ref}} \tag{B.1}$$

$$E_{dc} = \sqrt{\sum_{r \in TS, t \in hours} \omega(r) \cdot \left(dc_{ref}(r,t) - dc_{approx}(r,t)\right)^2} \tag{B.2}$$

$$E_{dc,ref} = \sqrt{\sum_{r \in TS, t \in hours} \omega(r) \cdot \left(dc_{ref}(r,t) - \frac{1}{8760} \sum_{t2 \in hours} dc_{ref}(r,t2)\right)^2} \tag{B.3}$$

$dc_{approx}(r,t)$ is the duration curve of resource r availability for the merged case, so the case whose performances are being investigated. $dc_{ref}(r,t)$ is the duration curve of resource r for the reference case. As this reference contains several cells, it has as many time series for each resource; they are combined into one TS per resource using the actual installed capacities of the related technologies, after running the model, to give a relative importance to each cell. $\omega(r)$ is also the actual installed capacities of technologies related to resource r in the reference case, but for the whole system at once (sum through all cells). This allows to obtain the error for what is relevant for the system, and this is a difference with how this value is computed in [3].

The analysis is performed on 2 cells that are merged. Spain and Portugal are used for this, because they have quite different size, but none of them are insignificant. Four cases will be analysed, and they use the following weights for the TS of intermittent energy production:

- f_{max}: the maximum installable capacities of the related technologies. This weight is a way to represent the potential of each cell in the related TS. Moreover, if the model decides to install those technologies at their maximum potential, the weights will be completely accurate; and if it decides to install far less than the maximum, the error introduced will not have a big impact;

- $f_{max} \cdot c_p$: the maximum capacities of technologies, multiplied by the capacity factor of the resource. This weight is a bit less accurate at full capacity, but it allows to give more importance to the cells that have a better resource availability;

- the surface-area of the cell. This is an intermediate weight that represents roughly the cell's importance. It allows to have a comparison point to see how well the first two cases fare against each other;
- uniform weights. This correspond to not applying weights, thus to have the same importance for each cell.

B.3 Results and choice

Table B.1 shows the results for the quantities presented above. It can be seen that the duration curve errors are not too different from each other. As a comparison, it is mentioned in Chapter 3 that ϵ_{dc} for non-merged cells with typical days is 9.26 %[1].

Table B.1: Results for the choice of the weights, compared to the reference. The duration curve error (ϵ_{dc}) is the quantity of main interest. The cost is only indicative, and resources usage are shown to confirm ϵ_{dc} tendency.

Case	Reference	f_{max}	$f_{max} \cdot c_p$	Surface	Uniform	Units
$\boldsymbol{\epsilon_{dc}}$	-	11.92	11.15	15.73	13.53	%
System cost	127 b€/y	−0.75	−1.29	−1.16	−0.63	%
Resources usage						
Wind	485.8	527.8	531.4	539.3	393.8	TWh/y
Solar	485.6	341.6	455.4	299.2	580.8	TWh/y
Hydro	37.5	37.5	43.1	48.5	41.1	TWh/y

It can be noticed that there is no big difference between the f_{max} and $f_{max} \cdot c_p$ cases: they increase by 2.66 % and 1.89 % respectively. The two less precise cases are not completely senseless, but their higher values highlight that the first two cases are indeed better. The total cost of the system is given in the table for information, but it can be seen that it decreases in all the cases, yet taking the price of the reference case as basis of comparison is not representative, as stated above.

The resources usage, also shown in Table B.1, confirms what is observed with the duration curve error: even though there are differences, the two first cases are much closer to the reference than the two less precise cases. Also, $f_{max} \cdot c_p$ shows a bit more differences for production by wind and hydro-power (+3.6 and +5.6 TWh/y respectively, compared to f_{max}), but it is much closer to the reference for the production by solar power (113.8 TWh/y closer than f_{max}).

In summary, both f_{max} and $f_{max} \cdot c_p$ could be used without causing too large differences in the system. However, $f_{max} \cdot c_p$ is slightly better and has therefore been selected for this study.

[1] This result was obtained with $f_{max} \cdot c_p$ to represent the cells importance on the w_{TD} for TDs selection, but this value is similar with other weights

Appendix C

Data origin and modifications

C.1 Data sources

The data used to characterise each country is gathered from different sources. The origins are detailed in Table C.1.

Table C.1: Origin of the data of each country used in this work.

Countries	Main data source	Other data sources
Austria	J.-L. Tychon and J. Dommisse [5]	
Belgium	[5]	**Wind offshore [38]**
Switzerland	P. Thiran and A. Hernandez [9]	
Germany	[5]	
Denmark	[5]	
Spain	[5]	
France	[5]	
Ireland	[5]	
Italy	[5]	
Luxembourg	[5]	
The Netherlands	[5]	**wind onshore [38]**
Portugal	[5]	
Sweden	[5]	**wind onshore [38]**
United Kingdom	[5]	**wind onshore [38]**

C.2 Data modifications of countries excels

As explained above, most of the data are taken from [5]. Consequently, some adaptations have to be made for the data excel of the countries. Indeed, they are principally defined for EnergyScope TD but they need to be used for EnergyScope MC in the current work. This section can be useful for a reader who would convert more EU countries from [5] in the EnergyScope MC format. All the additions, deletions and modifications made to the excel of [5] are listed below. Each subsection corresponds to one sheet of the excel file.

C.2.1 Time series

Most of the time series are collected in CET time zone. However, as countries have to be able to exchange energy fluxes, their data have to be selected in UTC time zone to correspond to the same hour simultaneously. Consequently, some TS had to be shifted of one hour to be correctly used in EnergyScope MC.

C.2.2 Resources

The following changes had to be performed:

- Remove the line *ELEC_EXPORT*.
- Set *ELECTRICITY* at zero (at least the availability).
- Change column name *c_op* to *c_op_local*.
- Set *c_op_local* of *SNG* to 0.197142857, of *BIOETHANOL* to 0.225714286, of *BIODIESEL* to 0.24, of *H_2* to 0.177142857 and of *SLF* to 0.211428571.

  Those are more up to date values used in EnergyScope TD.
- Add column *c_op_exterior* [M€/GWh] with same value of *c_op_local* for exterior resources and 0.02664 for *WOOD*, 0.004674 for *WET_BIOMASS* and 0.02664 for *WASTE*.
- Change column name *gwp_op* to *gwp_op_local*
- Add column *gwp_op_exterior* [ktCO2-eq./GWh] with same value of *gwp_op_local*.
- Change column name *available* to *avail_local* and put the local availability of all the exterior resources[1] at 0.
- Add column *avail_exterior* [GWh/y] with value 10 000 000 for all the exterior resources, and 0 for *ELECTRICITY*, local resources, *CO2_INDUSTRY*, *CO2_CAPTURED*, *PT_HEAT* and *ST_HEAT*.

C.2.3 User defined

- Change name *Electricity* into *Electricity (%_elec)* and *Space Heating* into *Space Heating (%_sh)*
- Add *Hydro_dam* in the table "TD input". Set a value that suits the dam potential of the country, or 0 by default.
- Add Solar characteristics [GW/km2]:
  power_density_pv at 0.2367 and
  power_density_solar_thermal at 0.2857.
- Change value of *%_truck,max* to 3.
- Remove *c_max* for max number of car [km-pass/h/veh] and add:
  vehicuke_capacity('PHEV') at 50.4, and *vehicuke_capacity('BEV')* at 50.4.
- Set values for *loss_network ELECTRICITY* to 0.061238988,
  loss_network HEAT_LOW_T_DHN to 0.07,
  and *cost to enforce power grid* to 367.8 M€/GW if no specific data for the country.

[1]all resources except *WOOD*, *WET_BIOMASS* and *WASTE*

C.2.4 EUD

No changes

C.2.5 Technologies

- Add *DHN_COGEN_BIO_HYDROLYSIS* in HEAT_LOW_T_DHN (not detailed here, see [16]).
- Add *TRUCK_ELEC* in FREIGHT (not detailed here, see [16]).
- Add *BIO_HYDROLYSIS* and *METHANE_TO_METHANOL* in INFRASTRUCTURE (not detailed here, see [16]).
- Add price and gwp to *transports* (not detailed here, see [16]).
- Set *NUCLEAR f_max* to 0 but could be change depending on the analysis made.
- Set *WIND_OFFSHORE c_inv* at 4974.633942.
- Set *H2_ELECTROLYSIS c_inv* to 696.2025316 and *H2_ELECTROLYSIS c_maint* at 19.14556962.
- Set *SYN_METHANOLATION c_inv* to 1679.651653 and *c_op* to 47.66486711, *SYN_METHANATION c_inv* to 262.1968349 and *c_op* to 66.99276316, *SYN_BIOMETHANATION c_inv* to 986.0473827 and *c_op* to 13.65909091.
- Rename *TS_MOLTEN_SALT* to *TS_HIGH_TEMP*.
- Change all *f_max* [GW] equal 100000 to 1000,
  except for MOBILITY, STORAGE, NON_ENERGY and *SLF_TO_...* (leave 100 000).
- Set *c_inv* to a low value ($1e^{-7}$) for *NON_ENERGY_OIL*, *NON_ENERGY_NG*, *SLF_TO_DIESEL*, *SLF_TO_GASOLINE*, and *SLF_TO_LFO*.

C.2.6 Storage

- Rename *TS_MOLTEN_SALT* to *TS_HIGH_TEMP*.

Appendix D

Verification of the merge methodology on a system with 14 cells

D.1 Input data for exchanges

Here are listed the chosen input data to perform the analysis with 14 cells.

Parameters freight distance

Table D.1: Definition of the freight distance parameter [km] and cities chosen to compute its value (half the real distance by road between the two cities).

Cell name	**City 1**	**City 2**	freight distance parameter [km]
Austria	Feldkirch	Vienne	370
Belgium	Arlon	Knokke	156
Switzerland	Genève	Zernez	222
Denmark	Hjørring	Copenhagen	225
Ireland	Cork	Letterkenny	215
Luxembourg	Weiswampach	Esch-sur-Alzette	50
Netherlands	Maastricht	Groningen	168
Portugal	Faro	Braganca	363
Spain	Gibraltar	Bilbao	412
France	Calais	Marseille	540
United-Kingdom	Plymouth	Thurso	605
Germany	Munich	Kiel	440
Italy	Bolzano	Marsala	829
Sweden	Lund	Abisko	963

Parameters interconnection cost

Table D.2: Length and price of electrical interconnections considered in the model. Inland connection are 50 % *AC,* 50 % *DC.*

Interconnection	Type	Length [km]	Price [M€/GW/y]	
Inland	AC	80	10.17	15.33
	DC	130	20.49	
United-Kingdom − France	DC sub-sea	200	27.66	
Netherlands − United-Kingdom	DC sub-sea	300	35.24	
Belgium − United-Kingdom	DC sub-sea	200	27.66	
Ireland − United-Kingdom	DC sub-sea	130	22.34	
Denmark − Netherlands	DC sub-sea	400	42.83	
Germany − Sweden	DC sub-sea	300	35.24	
Denmark − Sweden	DC sub-sea	200	27.66	

D.2 Resulting installed capacities

The used technologies and their installed capacities obtained for the 14-cell optimisation are given in Table D.3.

Table D.3: Comparison of installed capacities computed in non-merged and merged cases for the Western Europe system.

TECHNOLOGIES	non-merged	merged
Electricity [GW]		
Coal US	107.28	138.00
PV panels	281.65	164.86
Solar tower power block	69.85	78.70
Wind onshore	1780.36	1780.36
Wind offshore	9.33	9.33
Hydroelectric dam	67.27	67.28
Hydroelectric river	36.62	36.62
Geothermal	0.87	0.87
High temperature heat [GW]		
Wood boilers	36.65	36.12
Coal boilers	70.88	75.90
Waste boilers	40.93	35.50
Direct electricity	10.87	9.40
Low temperature heat through DHN [GW]		
Heat pumps	251.29	259.96
Deep geothermal	1.03	2.50
Low temperature decentralised heat [GW]		
Heat pumps	654.29	690.71
Cooling [GW]		
Big split	324.20	291.95
Chiller WC	40.80	40.80
Public mobility [GW]		
Tramways and trolleys	346.55	346.55
Buses diesel	11.56	0
Buses CNG	921.46	933.02
Private mobility [GW]		
Fuel cell cars	7701.16	7701.16
Freight [GW]		
Trains	245.24	245.24
Boats diesel	848.4	766.09
Boats NG	5.7	88.00
Trucks diesel	85.04	91.56
Trucks fuel cell	1514.23	1535.43
Storage [GWh]		
Dam storage	33 629	33 629
Pumped hydroelectric storage	2432	2397
Thermal storage: heat pumps	826	685
Thermal storage: DHN seasonal	63 368	50 612
Seasonal H_2	931	987
SLF storage	6581	7968
Solar tower storage	2270	1669
Thermal storage: cold	2412	2067
Infrastructure [GW]		
Solar tower collector	919.36	809.83
H_2 from electrolysis	178.57	176.00
H_2 from natural gas	19.62	30.84
Pyrolysis	18.00	16.12
Biomethanation	33.19	28.23

Appendix E

Verification of wind onshore potential data

Wind onshore is the major renewable resource used in the presented solution of Chapter 4. The data of its maximal installed capacities are then checked to support the consistency of the results and to verify if this huge potential is not overestimated. The data given in [5] are compared below to two other sources for each studied country.

Table E.1: Comparison between several works of the estimation of wind onshore potential in GW *for each country of the current study*

Countries	Installable capacity [GW] This study (from [5])	P. Enovoldsen [30]	PyPSA-Eur-Sec-30 [8]
Austria	40.86	48.97	52.48
Belgium	20.38	6.72	24.16
Switzerland	5.3[1]	45.10	40.01
Germany	176.40	501.69	219.45
Denmark	24.90	33.13	40.47
Spain	346.09	2187.18	214.40
France	375.07	300.37	316.69
British Isles[2]	251.94	876.35	249.49
Italy	176.41	369.96	129.42
Luxembourg	3.64	0.23	3.79
Netherlands	15.16	12.20	27.85
Portugal	39.69	290.37	48.25
Sweden	153.04	2445.57	302.41
TOTAL	1628.88	7117.83	1668.88

In Table E.1, it can be highlighted that the total potential of wind onshore installed capacity used in this work is lower compared to the one of the other studies. Thus the data used in the current work seems not to be overestimated. It may even be underestimated for Sweden which is defined as one of the major exporter in this study. A further analysis of this data could be performed in order to find more accurate values.

List of Abbreviations

AT Austria.

BE Belgium.

cell$_{\text{tbm}}$ cell-to-be-merged.

CH Switzerland.

CSP concentrated solar power.

DE Germany.

DHN district heating network.

DK Denmark.

DNI direct normal irradiance.

EnergyScope MC EnergyScope Multi-Cell.

EnergyScope TD EnergyScope Typical Days.

ES Spain.

EU European Union.

EUD end use demand.

EUT end use type.

FR France.

GHG greenhouse gas.

GWP global warming potential.

GWP$_{\text{constr}}$ construction global warming potential.

GWP$_{\text{op}}$ operational global warming potential.

HVDC high voltage DC.

HW hot water.

IE Ireland.

iRES intermittent renewable energy source.

IT Italy.

LCOE levelized cost of electricity.

LP linear programming.

LU Luxembourg.

NG natural gas.

NL the Netherlands.

NTC net transfer capacity.

O&M operation and maintenance.

PHS pumped hydroelectric storage.

PT Portugal.

PV photovoltaic.

RES renewable energy source.

RMS root mean square.

SE Sweden.

SH space heating.

SLF synthetic liquid fuel.

SNG synthetic natural gas.

tc transfer capacity.

TD typical day.

TF transit factor.

TS time series.

UF utilisation factor.

UK the United Kingdom.

UTC Coordinated Universal Time.

Glossary

British Isles Macro-cell containing the Ireland (IE) and United Kingdom (UK).

EnergyScope The open-source energy system model, for computing the least-cost optimum, which is used in this study.

Germany & Benelux Macro-cell containing Belgium (BE), Germany (DE), Luxembourg (LU) and The Netherlands (NL).

Iberian Peninsula Macro-cell containing Spain (ES) and Portugal (PT).

Italy & Alpine States Macro-cell containing Spain (ES) and Portugal (PT).

macro-cell A cell, as defined for its use in EnergyScope, with the specificity that it groups several smaller cells for which the data had already been gathered.

Scandinavia Macro-cell containing Denmark (DK) and Sweden (SE).

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