

École polytechnique de Louvain

The optimal role of biomass in a low-carbon European energy system by 2035

Authors : **Antoine SEPULCHRE, Julien VIÉRIN**

Supervisor : **Hervé JEANMART**

Readers : **Julien BLONDEAU, Martin COLLA, Paolo THIRAN**

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Abstract

The world is currently facing one of its greatest challenges, global warming. To mitigate climate change, greenhouse gas emissions (GHG) from the energy system need to be reduced. A solution to this issue is to use biomass as source of energy. Therefore, in this study, the goal was to evaluate the optimal role of biomass in a low-carbon Europe by 2035. A data collection was realised for each country, including the energy potentials and the costs of the local biomass resources. This work presents a detailed overview of how biomass would be optimally used in the energy system and also focuses on the optimisation of biomass exchanges across Europe while respecting limited greenhouse gas emissions. The analyses were made with EnergyScope Multi-Cells, a model that optimises energy systems. The research has revealed that the optimal role of biomass would be to cover the local energy demands. Concerning the countries with insufficient renewable potential, imports of biomass can contribute to achieving greater energy neutrality. These exchanges are a more cost-effective solution when the resources are converted into a higher energy-dense commodity.

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Glossary

CCGT : Combined-cycle Gas Turbine. It is a power generation system that combines the principles of gas turbines to maximise efficiency and electricity generation.

CHP : Combined Heat and Power. It is a system that generates heat and electricity. Also known as "Cogeneration" or under the abbreviation "Cogen".

CNG : Compressed Natural Gas. It is a natural gas stored at high pressure.

CO_{2eq} : Carbon Dioxide Equivalent. This unit is used to express the impact on the climate of different greenhouse gases in terms of their global warming potential (GWP) relative to carbon dioxide (CO₂).

DEC : Decentralised. A decentralised energy system is characterised by the location of energy production facilities closer to the site of energy consumption.

DHN : District Heating Network. Distribution of heat from a centralised location to multiple buildings or customers through a network of insulated pipes.

EEA : European Environment Agency. It is an agency of the European Union that provides independent information on the environment to policy makers and the public. The EEA is responsible for collecting, analysing and disseminating environmental data and information from the EU and its member countries.

eHP : Electrical Heat Pump. This is a device that uses electricity to raise or lower the temperature from one place to another by compressing and expanding refrigerant gases.

EUD : End Use Demand. It refers to the different energy demands in the energy system. Electricity, mobility, heating, cooling and the non-energy demand are the five EUD's implemented in EnergyScope.

EUT : End Use Type. It refers to the different forms energy can take in order to respond to the EUD's.

GHG : Greenhouse Gases. These are gases that trap heat in the Earth's atmosphere, causing the greenhouse effect and climate change. Examples: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O).

GWP : Global Warming Potential. Generally expressed in $\text{ktCO}_2\text{eq/GWh}$, it represents the quantity of GHG emissions per unit of energy.

HVC : High Value Chemicals. All ethylene and associated by-products, other than hydrogen, that result from the ethylene production process, including propylene, butadiene and benzene [1]. These chemicals may be used in pharmaceuticals, specialty chemicals, agrochemicals, or other industrial applications.

IND : Industrial. It refers to technologies from the industry.

LFO : Light Fuel Oil. LFO is a type of liquid fuel that is typically used in industrial boilers, furnaces, and other heating applications. It is a relatively low-cost fuel compared to other liquid fuels such as diesel and gasoline.

NED : Non-Energy Demand. It refers to the use of energy for non-energy purposes such as the production of chemicals, fertilisers, and other industrial products.

PHS : Pumped Hydro Storage. It is a method for the storage of electricity. It works by pumping water during periods of low demand and releasing it to generate electricity during peak demand.

RCG : Reed Canary Grass. It is a perennial grass species native to temperate regions of Europe, Asia, and North America. It is commonly found in wetlands, along riverbanks and in other areas with moist soil.

RED II : Renewable Energy Directive II. It is a European Union directive that sets a framework for the production and promotion of energy from renewable sources in the EU. It is an update of the original Renewable Energy Directive (RED I) that was introduced in 2009.

SNG : Synthetic Natural Gas. A type of fuel gas that is chemically similar to natural gas, but is produced from non-renewable or renewable feedstocks through a gasification process.

THHP : Thermal Heat Pumps. These are heating systems that use gas as an energy source to transfer heat from a cool space to a warm space by transferring thermal energy using a refrigeration cycle, cooling the cool space and warming the warm space.

Introduction

Past and present human activities are responsible for an excessive amount of greenhouse gases. These gases have caused present day global warming on our planet. In order to address the issue of climate change, the countries of the European Union (EU) have set a target to achieve carbon neutrality by 2050 [2]. Since the energy sector is responsible for 75% of these emissions, it is essential to transform the energy system into a more sustainable one and implement radical changes in the way energy is generated [2]. As several renewable energy sources (RES) exist, each capable of impacting this transition, their optimal use becomes a necessity.

Multiple studies have already analysed the influence of renewables on the European energy system. In their master thesis, J.L. Tychon and J. Dommissie have modeled 26 European countries independently in order to know if they could be carbon-neutral in 2035 using their own renewable resources [3]. The conclusion was that five countries were unable to respond to their needs. Belgium, the Netherlands, Germany, Slovenia and Italy indeed still need to use other energy sources, like fossil or imported energy, in order to meet their demand, resulting in larger GHG emissions. This work was continued by N. Cornet and P. Eloy, who analysed energy exchanges between countries in Western Europe to see if it could help Europe reduce its GHG emissions at a lower cost [4]. The outputs showed that permitting energy exchanges allows countries lacking renewable potential to fulfill their demand in order to present a carbon-neutral energy system.

In these two master theses, the question is analysed considering every renewable source, without focusing on a specific one. Solar, wind, hydro, tidal, geothermal and biomass energy potentials are thus all studied. In this master thesis, the work of these two master theses is extended, and a focus is set on biomass and its role in the energy transition. The term ‘biomass’, used in the energy domain, covers all organic materials with the potential to be used in an energy production process to generate electricity, heat, biogas or biofuel. As bioenergy (biomass for energy) is currently the most used source of renewable energy in the EU [5], representing around 60% of the renewables consumption, knowing how it is produced, processed and used becomes very interesting.

This thesis will further assess how biomass will be used in the near future and to which demand it will respond. As some European countries will arguably not match their demand with their own renewable resources [3], biomass exchanges will also be addressed and discussed in detail. Trades indeed, may benefit the ones in need to solve their gaps in the most cost-effective and carbon-neutral way. As multiple energy targets have

already been set for 2030, and knowing that the aim of the European Union is to be carbon neutral by 2050, the chosen year of this study will be 2035. Indeed, this study has the objective to present the role of biomass in the energy transition of Europe. Therefore, 2035 represents a good midterm milestone between today and 2050 towards carbon neutrality. In this study, the greenhouse gas emission reduction target is set to 90%. While this is an optimistic scenario, it will highlight the potential role of biomass in contributing to a low carbon Europe. The objective of this study is thus to answer the following questions : **"What role will biomass play in a low-carbon European energy system by 2035 ?"** and **"Can biomass exchanges help countries to use more renewable energy by 2035 ?"**.

In order to meet these objectives, EnergyScope Multi-Cells was used. This model, which was created by P. Thiran and A. Hernandez during their master thesis in 2020 [6], is an extension of EnergyScope TD [7]. While EnergyScope TD could only focus on the energy system of one country, this improved version of EnergyScope allows for the analysis of multiple countries at the same time, grouping them in certain regions and, above all, it permits exchanges of resources between countries/regions. The main methods and functions of EnergyScope Multi-Cells will be detailed in Chapter 1. For the analysis produced in this master thesis, some European countries are merged together, creating what is called macro-cells. The macro-cells used for this study are also introduced in the first chapter.

In the second chapter, the implementation of biomass in EnergyScope Multi-Cells is stated. The term "biomass" includes many different types of living plant and animal matter, all presenting their own attributes and characteristics. Considering all these types as a single resource would be a mistake, hence biomass is divided into several categories, each having its own features. Then, the biomass data of every European country will be addressed. For each resource, the global warming potential as well as their local potentials and costs are presented and discussed. This part will be linked with a section showing the distribution of each biomass category in Europe. Later on, the implementation of the conversion to energy is presented and the transport of biomass, including the modes of locomotion and the types of feedstocks traded, is introduced.

Chapter 3 will present the main results of a low-carbon European energy system. This system refers to a case study on Western Europe with a -90% GHG emissions limit. How is the biomass potential of each region used, which technologies convert the biomass into energy, which demand sectors are covered by the different categories, what are the different biomass exchanges, etc.. are all reflections addressed in this chapter.

In Chapter 4, three alternative scenarios are analysed in order to discuss the results of the low-carbon Western Europe optimisation of the third chapter. Therefore, an energy system without non-energy demand, an optimisation with free exchanges by freight and a case study prohibiting gas exchanges between regions are studied.

Finally, some results will be challenged in Chapter 5. The sensitivity to certain parameters of the model will be examined in this chapter. A section will also deal with the

instability of the current energy system since the start of the political conflict between Ukraine and Russia.

Chapter 1

Model description

In this Chapter, the aim is to explain the main methods and functions of EnergyScope Multi-Cells, which is the model used for this study. In order to correctly understand how it works, it is useful to recall the basic principles of the EnergyScope TD model, from which EnergyScope Multi-Cells is an extension. This is explained in Section 1.1.

As this study focuses on Western Europe, which integrates a substantial amount of data concerning the energy sector, a method simplifying the size of the studied region will be used. This is done by grouping several countries into one large region, a macro-cell. Section 1.2 will develop this procedure.

1.1 EnergyScope Multi-Cells

EnergyScope TD, elaborated by G. Limpens in his PhD thesis with the help of S. Moret from the EPFL, is an open-source model for the strategic energy planning of urban and regional energy systems [7]. This linear programming model has the objective to optimise the investment, design and operation of an energy system for a future target year, under a certain greenhouse gas emissions constraint. This is done with an hourly resolution. The model has the particularity to be computationally effective as this hourly resolution is resumed by a set of typical days, ranging from 6 to 20 units, that represent the characteristics of an entire year in much less days. In this study, a number of 14 typical days will be used in order to reduce the computational time of the model, while keeping enough data to get meaningful results.

The functioning of EnergyScope TD is quite simple. An example is represented in Figure 1.1. It turns a large set of resources into End Use Types (EUT) in order to respond to the different End Use Demands (EUD), which are electricity, heating, cooling, mobility and non-energy demand. To do so, several technologies are implemented. The main ones, technologies of EUTs, directly convert resources into energy, like windmills that convert wind into electricity. There are also storage technologies that can store energy from a certain layer and give it back to the same layer later on. Finally, infrastructure technologies are also implemented in EnergyScope. This conversion process, presenting thousands of possibilities, is optimised in order to minimise the total cost of the energy system and often while respecting a specific GHG limit.

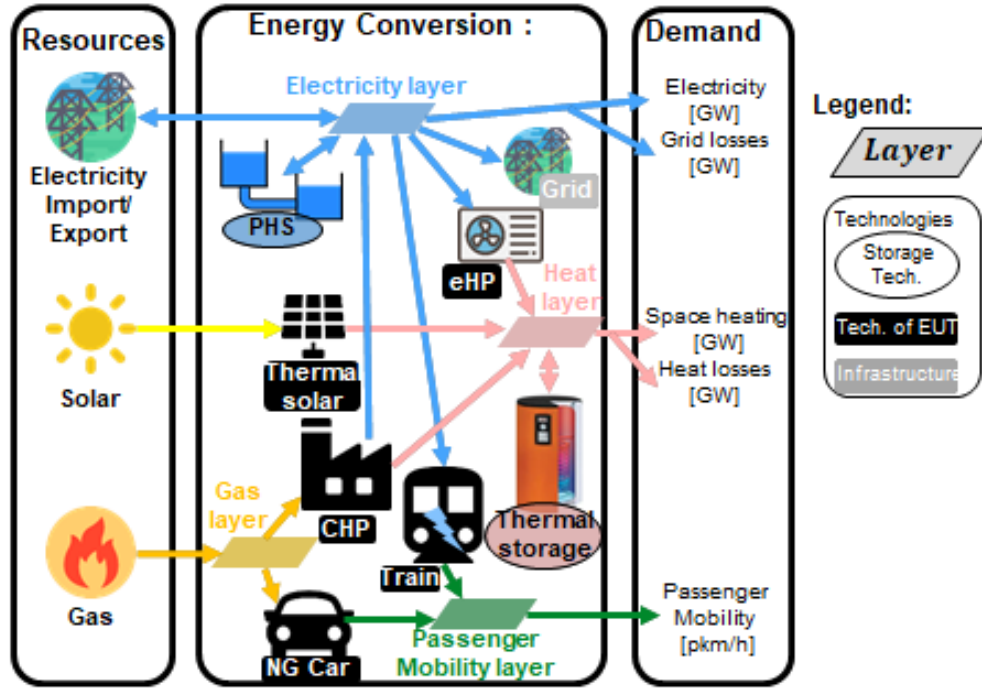


Figure 1.1: Representation of an EnergyScope TD energy system, as created by G. Limpens [7].

In EnergyScope TD, only one cell, which can be a country or a region, can be analysed at a time. By creating EnergyScope Multi-Cells, and thus expanding the work of G. Limpens ; A. Hernandez and P. Thiran allowed for the analysis of multiple cells simultaneously and most especially unlocked the ability to exchange either resources or already converted energy between cells [6]. Since the cells are linked, resources can have multiple origins. They can be produced on the cell's ground, be imported from another cell or be imported from the outside of the system (the "exterior"). A specific variable, named "Exchanges", has been added to the model in order to represent these exchanges. Refer to the thesis of A. Hernandez and P. Thiran to obtain the mathematical explanations of the implementation of these exchanges [6]. Exchanges of some resources or energy commodities evidently present some losses, which are also implemented in the model. These are specific to the type of exchange. Indeed, there exists two different exchange possibilities, depending on what is traded : by network or by freight.

The first possible exchanges are done through networks. This is the case, for example, of electricity which is transmitted through transmission lines, or natural gas which is traded through pipelines. The resources exchanged through networks are limited by the size of the installed interconnections. Moreover, these types of exchanges are characterised by a specific parameter, the transfer capacity (T_c), which corresponds to the maximum power that can be imported from a first cell to a second cell. The value of this parameter can vary depending on the direction of the flow, as certain asymmetries can exist between cells. Losses during the exchange, like the grid losses of electricity

passing through transmission lines, are inevitable. In order to compensate for these losses, the country or region importing the resource needs to multiply the desired imported quantity by $(1 + \text{exchange_losses})$, with the variable *exchange_losses* representing the losses in the network.

Secondly, exchanges can happen by freight. The concerned resources encompass all solid and liquid fuels like methanol, wood or waste. For the purpose of achieving interesting optimisations, freight exchanges present an unlimited transfer capacity in the model. Additionally, each country participating in the exchange of resources by freight contributes to the price of the freight. The exporting cell covers the freight of the exchange up to its frontiers and the importing cell takes the freight over after it crosses the border. Concerning the losses, they correspond to the energy expended in transporting the energy carrier via freight from one country to another. Additional freight needs to be included in the exchange in order to fix these losses.

1.2 Use of macro-cells

In order to optimise the runtime of EnergyScope and minimise the quantity of generated outputs, it is always good to limit the amount of input data provided to the model. Therefore, the 14 countries located in Western Europe are reduced to 6 regions in EnergyScope. This not only reduces the volume of the output data, but also speeds up the optimisation process. The creation of macro-cells, which groups together countries presenting similarities, was made by N. Cornet and P. Eloy in their master thesis [4]. They used it to analyse electricity and gas exchanges across Western Europe. Six macro-cells were created, as represented in Figure 1.2.

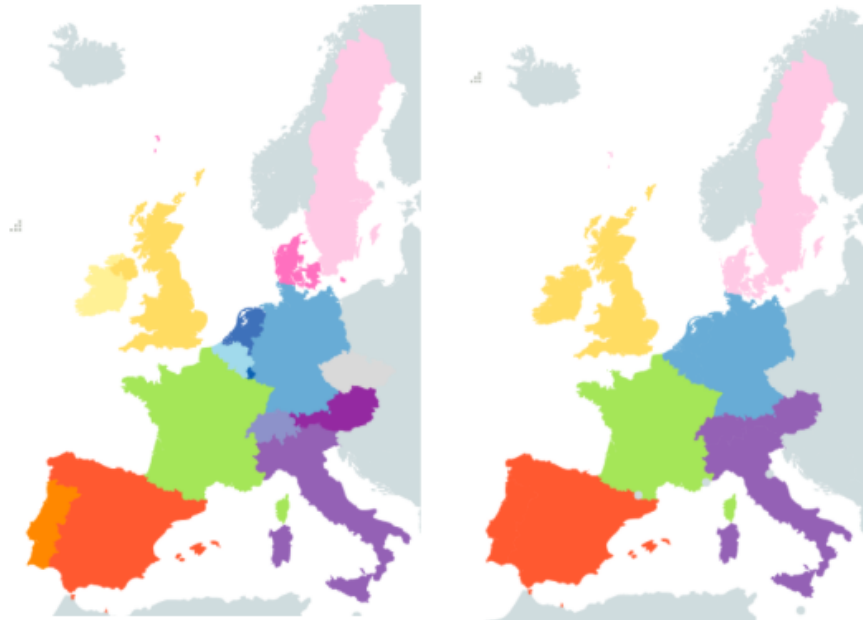


Figure 1.2: Merging of Western European countries into macro-cells, as realised in the master thesis of N. Cornet and P. Eloy [4].

For the advantages explained above, these macro-cells will also be used in this study to analyse the optimal role of biomass in Western Europe. The composition of the different regions is detailed in Table 1.1.

Table 1.1: Macro-cells composition.

Macro-cell name	Composition of the region
The Iberian Peninsula	ES-PT
The British Isles	IE-UK
France	FR
Italy & Alpine states	AT-CH-IT
Germany & Benelux	BE-DE-LU-NL
Scandinavia	DK-SE

Chapter 2

Biomass implementation

This chapter focuses on the implementation of biomass in EnergyScope Multi-Cells. Initially, the model had only two biomass categories: wood and wet biomass. However, this categorisation lacked the necessary precision for this analysis. Therefore, the first part of this chapter will cover the new categorisation of biomass and the creation of new EnergyScope resources. To correctly integrate this local resource into the model, specific information is required, such as its local energy potential, its operational global warming potential and its local cost, which are needed for each region. Detailed information will be provided on all the data that has been updated. Additionally, in the last part of this chapter, the current methods of biomass transportation in Europe are reviewed. This literature review will allow for the effective implementation of biomass exchanges with the EnergyScope model.

2.1 Biomass categories

Bioenergy can have a variety of origins and can take several forms. There is a diversity in the inherent characteristics of each type of biomass, which leads to differences in terms of potential, cost and features for final uses. To map all these types of biomass, the ENSPRESO database [8], which is an open data, EU-27 wide, transparent and coherent database of wind, solar and biomass energy potentials, has been chosen. Within this database, there are 16 different types of biomass, each presenting their own characteristics.

As said previously, before this work, EnergyScope Multi-Cells contained only two biomass resources : wood and wet biomass. Wet biomass accounted for all digestible biomass, while the wood category accounted for all the non-digestible biomass. By doing so, this categorisation grouped together biomass types presenting different potentials, costs, final uses, etc.. It was thus not precise enough for this analysis and an update was needed in order to perform correct optimisations with biomass resources on the energy system. On the one hand, as the EnergyScope model already comprises a significant number of resources, the addition of the 16 different ENSPRESO biomass types would overburden the model. On the other hand, it would also be inadequate to treat all the biomass as a single resource when analysing its optimal role. Consequently, the biomass types have been divided into categories to enhance the accuracy of our re-

sults. This approach will allow for the gaining of a more comprehensive understanding of the use of various biomass sources.

Six biomass categories have thus been created in order to group resources having common characteristics. These categories regroup resources that share the same origin, present similar GHG emissions, use common technologies or have an identical final use. Among these categories, five of them have been implemented in Energyscope : woody biomass, energy-dedicated lignocellulosic biomass crops, wet biomass, other biomass residues and biowaste. A sixth category, edible energy crops, is discussed in this chapter, but has not been selected for implementation in EnergyScope.

2.1.1 Woody biomass

The woody biomass is the first part of the lignocellulosic biomass, which consists of dry plant-based materials rich in cellulose, hemicellulose, and lignin. Woody biomass includes almost all types of biomass resources coming from forestry. This category contains five types of biomass coming from the ENSPRESO database, which are shown in Table 2.1.

Table 2.1: Woody biomass resources.

ENSPRESO code	Resource
MINBIOFRSR1	Forest residues (logging residues)
MINBIOWOO	Stemwood (sustainable extracted forest biomass)
MINBIOWOOa	Additional harvestable stemwood (woodchips and pellets)
MINBIOWOOW1	Secondary forest residues from industry (but not saw dust)
MINBIOWOOW1a	Saw dust

The major similitude of these different types of biomass is their origin, i.e. forestry. The category indeed presents biomass coming from stemwood production (MINBIOWOO and MINBIOWOOa), primary forestry residues (MINBIOFRSR1) and secondary forestry residues (MINBIOWOOW1 and MINBIOWOOW1a). Many technologies can convert wood into energy. Firstly, wood can fill the non-energy demand by being transformed into methanol or HVC [9]. Woody biomass can also be used in cogenerations or boilers to respond to the heat demand. It can be gasified in order to obtain hydrogen or gas [10]. Finally, pyrolysis can convert woody biomass into gasoline or Light Fuel Oil (LFO) [11]. With all these possibilities, these biomass resources can respond to multiple demand sectors such as agricultural, commercial, electricity production, industrial and residential. Concerning their price, it varies between 7 and 36 €/MWh₂₀₁₀. Saw dust and secondary residues are the cheapest options for this category, while the harvestable stemwood formed of woodchips and pellets is the type presenting the highest price.

2.1.2 Energy-dedicated lignocellulosic biomass crops

This category contains the lignocellulosic biomass types that are specifically cultivated for the production of energy. Three resources are included in this category, as shown

in Table 2.2.

Table 2.2: Energy-dedicated lignocellulosic biomass crops resources.

ENSPRESO code	Resource
MINBIOCRP31	Miscanthus, RCG and switchgrass
MINBIOCRP41	Willow
MINBIOCRP41a	Poplar

Other than the fact that these biomass types are destined to produce energy, they are also linked together with their origin in agriculture. As regards the technologies that convert these resources into EUT's, they are the same as their lignocellulosic counterpart, woody biomass. Energy-dedicated crops can indeed be used to cover the non-energy demand [12], to produce heat by combustion [13], to form hydrogen or gas by gasification [14] and to make fuels with a pyrolysis processus [15]. However, they present a price range that is quite superior than woody biomass. It varies between 18 and 65 €₂₀₁₀/MWh, with miscanthus, RCG and switchgrass corresponding to the lower price and poplar presenting prices of up to 65 €₂₀₁₀/MWh.

2.1.3 Wet biomass

The resources included in this category differ from the lignocellulosic biomass because of their composition and their moisture content. Indeed, wet biomass is characterised by its high moisture content, which can range from 60% to 90% or even higher. There are two biomass types considered in this category, represented in Table 2.3.

Table 2.3: Wet biomass resources.

ENSPRESO code	Resource
MINBIOGAS1	Dry and wet manure
MINBIOSLU1	Sewage sludge, paper and cardbroad waste, dredging spoils

The first resource, dry and wet manure (MINBIOGAS1), regroups all the agricultural primary residues. The second resource (MINBIOSLU1) corresponds to biomass coming from waste that is not biodegradable, such as sewage sludge or dredging spoils. Both resources are mainly converted to biogas by anaerobic digestion/biomethanation [16]. There exist other technologies to convert wet biomass into energy, such as hydrolysis [17]. However, these various conversion methods are often mentioned only once or twice in the literature, while anaerobic digestion is the dominant documented process. Biomethanation is therefore the only technology considered for the transformation of wet biomass in this study. The price of the category oscillates between 4 and 7 €₂₀₁₀/MWh. This price is quite low compared to the two previous categories.

Concerning the potential of dry and wet manure (MINBIOGAS1), it is important to note that it is already given in terms of biogas in the ENSPRESO database. This is a difference from all the other biomass types, for which potentials are given in terms of

raw biomass. In order to stay coherent throughout the entire analysis, this potential is put back in terms of dry and wet manure. To do so, as the conversion of manure to biogas, using the biomethanation technology, has a ratio of 29.9% [18], the potential given in biogas is simply multiplied by the inverse of this ratio. As biomethanation is the main converting technology of wet biomass, taking its conversion ratio to get the potential in terms of dry and wet manure is a proper assumption.

2.1.4 Other biomass residues

The resources considered in this category are the last types classified as lignocellulosic biomass. Two biomass types are considered in this category as shown in Table 2.4.

Table 2.4: Other biomass residues resources.

ENSPRESO code	Resource
MINBIOARGW1	Agricultural residues and prunings
MINBIOFRSR1a	Landscape care

The two resources present different origins. The first type (MINBIOARGW1) originates from agriculture, while landscape care (MINBIOFRSR1a) corresponds to primary forest residues. These two biomass types are separated from the other lignocellulosic resources as their use is more limited. Indeed, they are used to produce heat [19] and can be transformed into oil by pyrolysis [20], but they are rarely used to produce methanol or HVC's. Moreover, these residues can be converted with biomethanation to gas [21], which the rest of the lignocellulosic biomass cannot. The two resources also share a relatively low price compared to the price of woody biomass or energy-dedicated crops presented above. Their price varies between 7 and 21 $\text{€}_{2010}/\text{MWh}$.

2.1.5 Biowaste

This biomass category represents all solid biofuels created by biodegradable waste like public greens, municipal renewable waste, abandoned grass cuttings, vegetable waste, husks, shells, etc.. It has been created to separate renewable waste from another waste category, already implemented in EnergyScope, containing only non-renewable waste. Biowaste can be treated with the same technologies as the biomass residues of the previous category. It can be used in boilers [22], which produces heat, and for the production of gas [23]. It can also be used for pyrolysis [24] in order to produce oil. Concerning its price, it is the lowest one of all the categories as it never goes above 0.5 $\text{€}_{2010}/\text{MWh}$, which makes it an interesting resource to use.

Table 2.5: Biowaste resources.

ENSPRESO code	Resource
MINBIOMUN1	Solid biofuels and biodegradable waste

2.1.6 Edible energy crops

As introduced above, the last category of biomass resources is presented as the first generation energy crops for liquid biofuels. Based on the ENSPRESO database, there are three resources that are considered here, which are given in Table 2.6.

Table 2.6: Edible energy crops resources.

ENSPRESO code	Resource
MINBIOCRP11	Starchy crops
MINBIOCRP21	Bioethanol sugar beet
MINBIORPS1	Rape seed

This category groups the energy crops from the first generation, such as rape seed, sugar beet and other oil crops. Currently, these resources represent about 10% of the whole energy production from biomass [25]. First-generation biofuels, which are produced from edible energy crops, have been criticised for their negative environmental impact and competition with food production [26]. Now that multiple limitations concerning these crops take place, e.g. the interdiction of selling combustion engines in 2035 in Europe [27], the use of energy crops from the second generation will increase. Second-generation biofuels, which are produced from energy-dedicated lignocellulosic biomass crops, indeed present a lower environmental impact and their use limits the competition with food production [28]. Moreover, as first-generation energy crops can be used as food or feed, making biofuels on the basis of energy-dedicated lignocellulosic biomass crops values the whole biomass in the production of energy.

As the use of the first generation of energy crops will surely diminish, making the hypothesis not to analyse its impact is a correct assumption. This biomass category is thus left out of this study, which could be expanded by deepening the subject and taking into account the edible energy crops.

2.2 Biomass data in Europe

Now that biomass has been divided into multiple categories, it is time to update and detail the data linked to these categories for each European country. In order to analyse the optimal role of biomass in the energy transition and to implement it correctly into the EnergyScope model, several pieces of information are required :

- Energy potential (GWh) : For each country, the five implemented biomass categories have their own potential.
- Local cost of the resource (M€/GWh) : It takes into account the price of cultivation, production and transport.
- GWP of the resource (ktCO_{2eq}/GWh) : It corresponds to the contribution to global warming of the resource. It is specific to each resource.

2.2.1 Energy potentials

The energy potentials have been computed based on the ENSPRESO database. It gives the energy potential of each resource, for each European country, for the years 2010, 2020, 2030, 2040 and 2050. The target year being 2035, the total energy potential for each biomass category was computed by adding potentials of all resources of each category and making a linear interpolation of the data from 2030 and 2040. A distribution of the total biomass potentials of each category in Europe is represented on the bar chart hereunder 2.1.

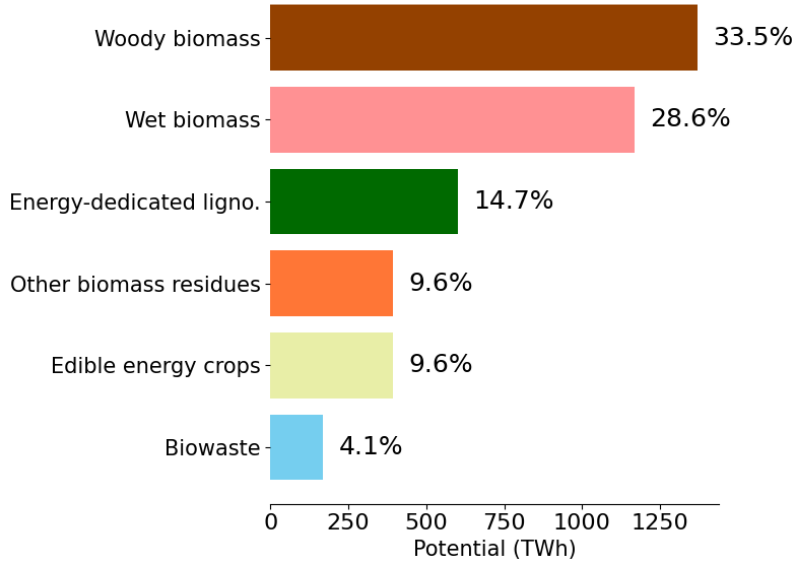


Figure 2.1: Total potential of the different biomass categories in Europe for the year 2035. "Energy-dedicated ligno." here defines "Energy-dedicated lignocellulosic biomass crops".

The lignocellulosic biomass, which includes woody biomass, energy-dedicated lignocellulosic biomass crops and other biomass residues, represents the most important source of bioenergy. Amongst them, the woody biomass stands out as the most important potential, representing a third of the total potential. Wet biomass also presents a significant potential, accounting for one quarter of the potential of 2035. Concerning the edible energy crops, as enunciated earlier, they represent about 10% of the biomass resources. Still, they will not be taken into consideration in this study. Finally, the biowaste category finds itself at the bottom of the chart, exhibiting only 4% of the total biomass energy potential.

To find out where the biomass is more precisely located in Europe, a more in-depth analysis is performed. For each category, a map shows the distribution of the resources in each country and a bar chart highlights the potential of all the European countries. The potentials of each category and for each country can be found in Appendix A.1. The maps are made using the NUTS classification, which is a hierarchical system dividing countries of the EU into multiple regions to collect regional statistics [29]. Concerning

the biowaste category, as data is lacking in the ENSPRESO database, the map is made using the NUTS0 scale, which means countries are not separated in several regions. For the other biomass categories, the zones are made using the NUTS2 scale, meaning the countries are divided in a certain number of regions that match the application of regional policies. For these maps, data is given in MWh per km². On the other side, biowaste data are represented in MWh per inhabitant, which is more representative because biowaste is mostly generated by humans. There are indeed regions in Europe, like the North of Scandinavia, that are not inhabited, thus generating no biowaste.

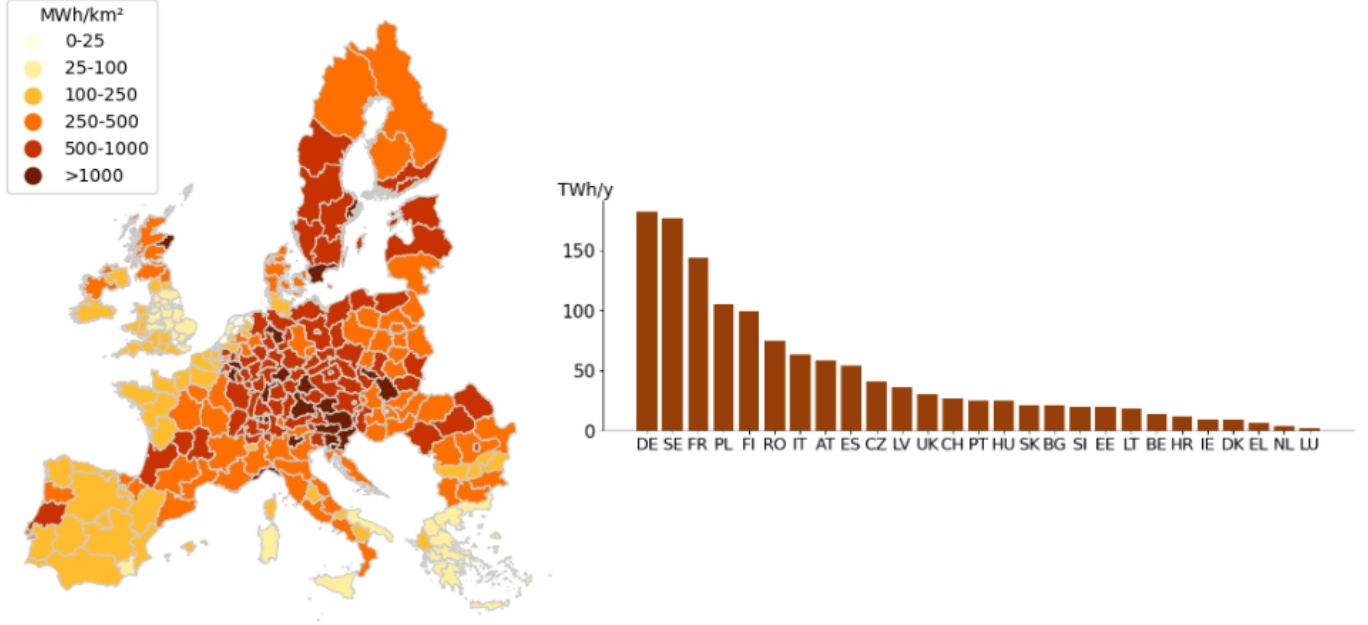


Figure 2.2: On the left, NUTS2 distribution of woody biomass in Europe for the year 2035. On the right, woody biomass potentials, expressed in TWh/y, of the 27 countries of the EU, excluding Cyprus and Malta, and including the United Kingdom (UK) and Switzerland (CH), for the year 2035.

Woody biomass is the most represented biomass category across Europe. Multiple countries exceed a potential of 100 TWh per year, as we can see on the right part of Figure 2.2. Germany is the country presenting the largest potential. The whole country displays a significant energy density coming from wood, which can be explained by the presence of the many forests in its territory, like the Black Forest located in the South-West of the country. Sweden and Finland also find themselves at the top as they are the second and fifth largest woody biomass potentials in Europe for 2035. The two neighbours are the European states with the largest proportion of their territory being covered by forests [30], which explains the considerable amount of wood they possess. France completes the podium. Even if the energy density in the North-West of the country is lower than the average of the continent, the large territory France possesses makes up for it and allows the country to be within the top spots. Some smaller countries, like Austria or the Czech Republic, also present a large woody biomass potential. With some regions surpassing 1000 MWh/km², the energy density of woody biomass

in the center of Europe is indeed quite massive.

Looking at countries or regions which have a smaller quantity of wood, the Netherlands comes quickly to mind. As we can see on the map, the energy density in the country is very low, which is explained by the fact that there are no considerable forests near the coast as the region is covered with a dune environment and a lot of plains. The bar chart supports this idea, with the state presenting the second worst potential of Europe. Amongst other notable countries presenting a low woody biomass potential, there is Greece and the United Kingdom. Greece is a special case as we will see that its energy potential is low for each biomass category. The country's renewable energy is indeed primarily composed of wind power, representing 85%, and solar power, representing 10% [31]. Concerning the United Kingdom, its potential is fairly low for a quite large territory. The South of the region displays a low energy density in woody biomass, but this can be explained by the fact that the region presents an important agricultural sector and thus large potentials in wet biomass and other biomass residues, as shown on the following maps.

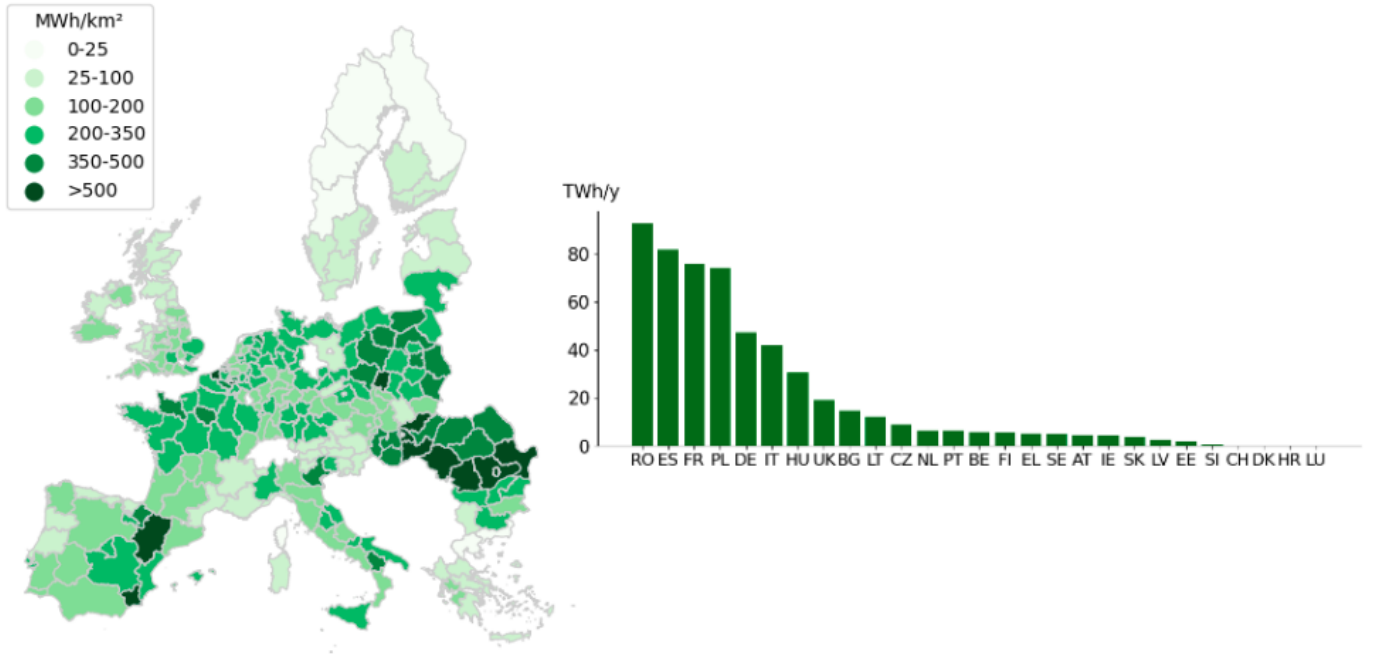


Figure 2.3: On the left, NUTS2 distribution of energy-dedicated lignocellulosic biomass crops in Europe for the year 2035. On the right, energy-dedicated lignocellulosic biomass crops potentials, expressed in TWh/y, of the 27 countries of the EU, excluding Cyprus and Malta, and including the United Kingdom (UK) and Switzerland (CH), for the year 2035.

Before analysing the potentials of the energy-dedicated lignocellulosic biomass crops in Europe, it is important to state that miscanthus/RCG/switchgrass contributes to the vast majority of the total potential. Willow and poplar are indeed poorly represented according to the ENSPRESO database. The energy potentials of the category and their distribution in Europe are shown in Figure 2.3. Romania emerges as the largest

producer in Europe, which is also shown on the map, as the South of the country is the region presenting the largest energy density on the whole continent. The potential of the country is mainly coming from agriculture [32], explaining why its potential is high for this category. Overall, Eastern Europe possesses large amounts of these biomass resources, with Poland and Hungary also having high energy potential densities. It is interesting to note that Romania is the only Eastern European country to feature in the top three of any biomass category potential. Spain and France also show a large potential of energy-dedicated lignocellulosic biomass crops.

Within the countries presenting a low energy density for this category, Sweden, Finland and Greece are the ones standing out. The two Scandinavian neighbours are more focused on the production of woody biomass, while Greece produces the majority of its renewable energy from wind, as explained above. A lot of the smallest European countries also show a low potential in energy-dedicated crops. Belgium, Austria, Slovakia, Lithuania, Estonia, etc.. all display a potential that is lower than 10 TWh per year. When looking closely on the bar chart, some countries seem to have no potential for this biomass category. The concerned countries are Switzerland, Denmark, Croatia and Luxembourg. This is verified on the map as these countries present no energy density at all on their territory. The ENSPRESO database indeed presents no values for the potential of the biomass types of this category for the four concerned countries. Therefore, their "energy-dedicated lignocellulosic biomass crops" potential is set to zero in the optimisations.

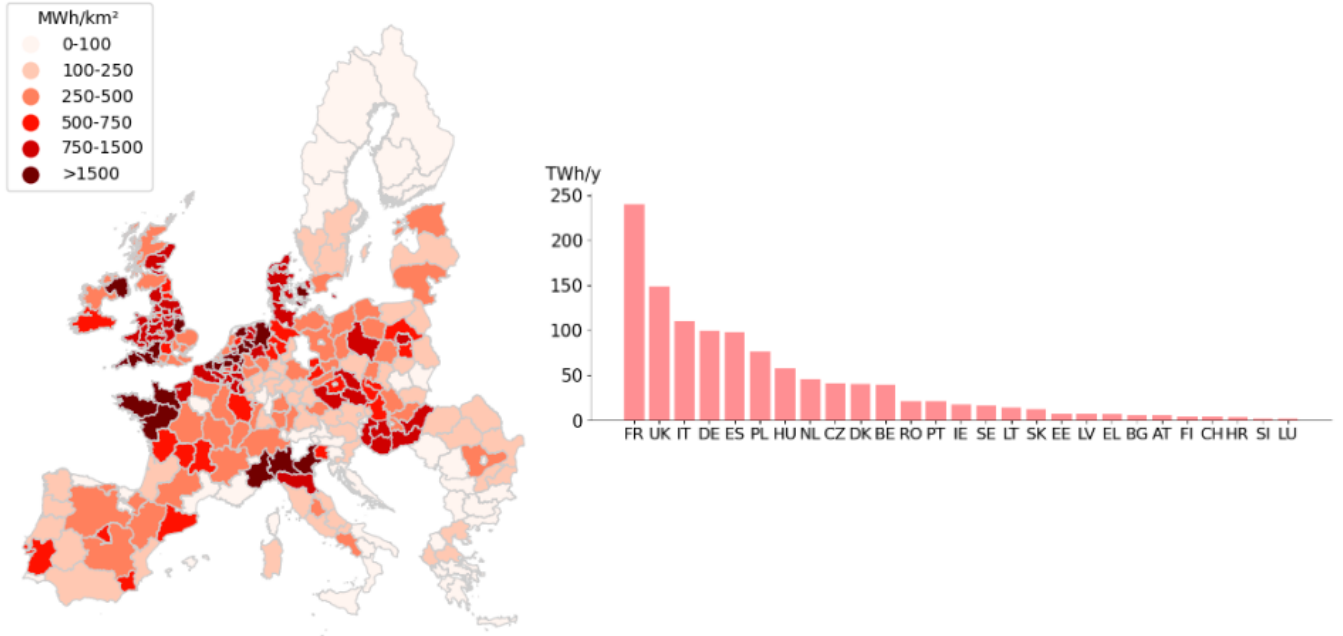


Figure 2.4: On the left, NUTS2 distribution of wet biomass in Europe for the year 2035. On the right, wet biomass potentials, expressed in TWh/y, of the 27 countries of the EU, excluding Cyprus and Malta, and including the United Kingdom (UK) and Switzerland (CH), for the year 2035.

Wet biomass stands as the second most significant energy source derived from biomass. The bar chart of Figure 2.4 highlights that France, with its important agricultural sector, is the leading producer in this category, producing over 200 TWh annually. The region of Brittany shows a dense potential of wet biomass and participates a lot in the potential of the country. The United Kingdom also displays a large potential of wet biomass, with Northern Ireland and the South of the state being the zones with the highest energy density. The regions of Piedmont, Lombardy and Veneto, situated in the North of Italy, present a potential higher than 1500 MWh/km² and explain why Italy is a big producer of wet biomass as well. Among other countries or regions showing a dense production of manure and sludge, there is the Netherlands, the North of Belgium, Denmark or Hungary. These regions are mainly covered by plains, fields and grasslands that are partly filled with cattle, which leads to the formation of dry and wet manure.

Multiple countries exhibit a low potential in wet biomass. Sweden, Finland, Austria, i.e. countries presenting a large woody biomass potential, are all part of this list. These territories are indeed mainly covered by forests, therefore there are less plains and fields, resulting in a lower potential of wet biomass. Looking at the bar chart of Figure 2.4, the Baltic States and The South-East of Europe are also characterised by low potentials in manure and sludge. As exposed on the map, Croatia, Greece and Bulgaria possess regions with an energy density lower than 100 MWh/km². The livestock population in these countries is indeed very low compared to the majority of the European countries [33].

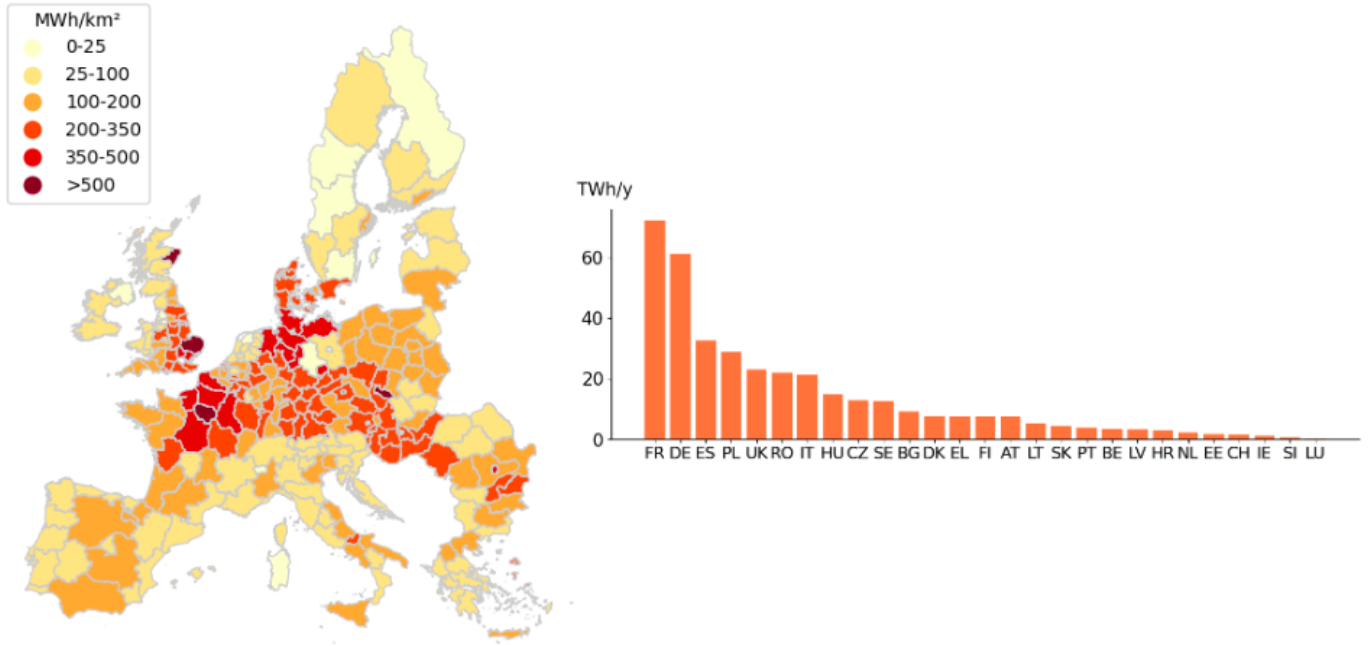


Figure 2.5: On the left, NUTS2 distribution of other biomass residues in Europe for the year 2035. On the right, other biomass residues potentials, expressed in TWh/y, of the 27 countries of the EU, excluding Cyprus and Malta, and including the United Kingdom (UK) and Switzerland (CH), for the year 2035.

Among the various forms of lignocellulosic biomass, these biomass residues represent the smallest potential. They are mainly composed of agricultural residues (straw, pruning, etc.), with landscape care only being a small part of the potential of the category. France and Germany, with a potential double as large as the potential of every other country considered in the study, are the dominant players here. As we can see on the left part of Figure 2.5, in France, the energy density is high in the North of the country, especially around the capital. With France as the largest potential, it once again highlights its important role in Europe's energy system. Concerning Germany, almost the whole country presents a dense production in biomass residues of the category. Some other regions or countries have a high productivity. It is the case for the South-East of the United Kingdom, Denmark or Hungary, each with a density higher than 200 MWh/km². Spain and Poland, despite not showing a dense production on their territories, are in the top five of the largest producers of these types of residues.

Being part of the countries or regions with a small potential of biomass residues, there is the North of Sweden and Finland. There are indeed no agricultural activities in these territories as the temperatures are very low. Portugal, the Netherlands, Switzerland, Belgium and Ireland are all in the lower ranked potentials in Europe for these biomass residues. Luxembourg is once again the country presenting the lowest potential. As its size is very small by comparison to the other European countries, seeing it in the last place is no surprise.

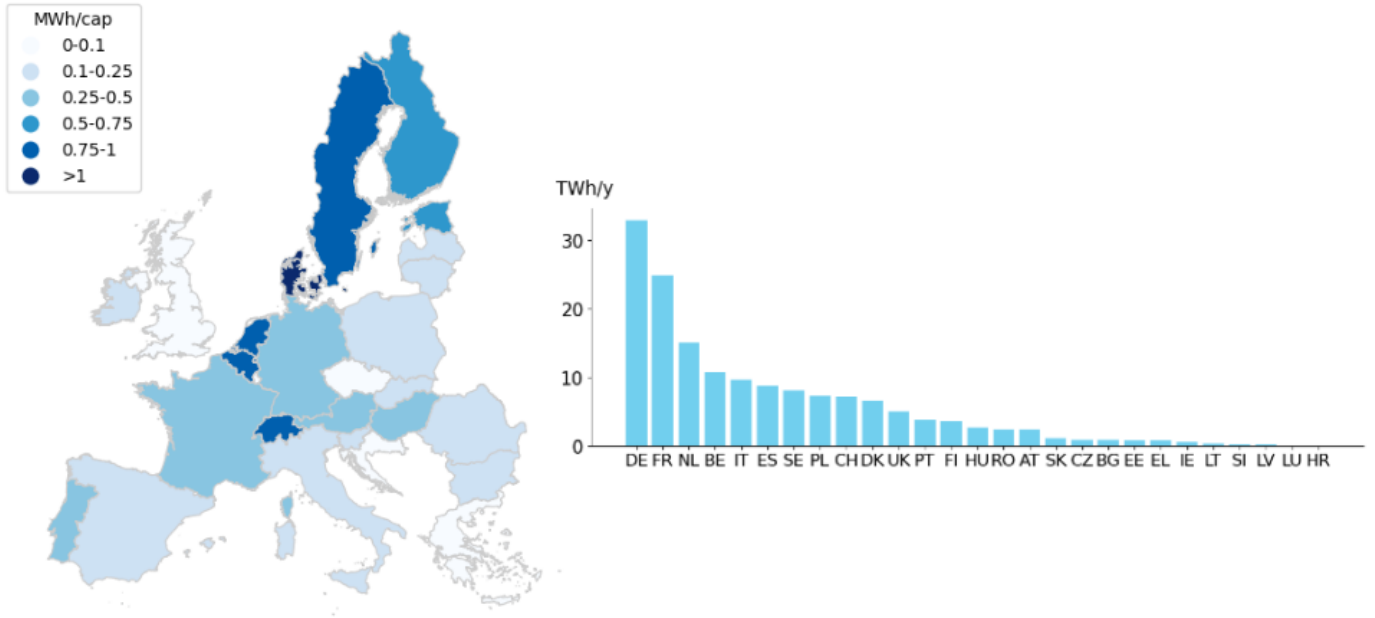


Figure 2.6: On the left, NUTS0 distribution of biowaste in Europe for the year 2035. On the right, biowaste potentials, expressed in TWh/y, of the 27 countries of the EU, excluding Cyprus and Malta, and including the United Kingdom (UK) and Switzerland (CH), for the year 2035.

As explained earlier, the map of the biowaste category is made using the NUTS0 classification because data for the creation of regions with the NUTS2 scale is lacking. As

some countries are very large, using MWh/km² units is not relevant anymore, hence why the energy density is now calculated with the amount of energy produced per inhabitant. Biowaste is the least prominent resource among the different types of biomass as its total potential is the lowest one. The right side of Figure 2.6 shows that Western Europe possesses the highest potentials of the continent. Indeed, in the last ten countries, only Ireland and Luxembourg are part of Western Europe. Germany and France are still the countries presenting the greatest potential. Summing up the potentials of the five categories, the two powerhouses are way ahead of the other European countries. On the map, it is Denmark that stands out as it is the only country with a potential higher than 1 MWh/cap. Other countries presenting a significant potential per inhabitant are Sweden, the Netherlands, Belgium, Switzerland, Finland and Estonia.

Many countries show a potential lower than 10 TWh per year, explaining why this biomass resource is the least represented in Europe. The United Kingdom, Luxembourg, the Czech Republic, Croatia and Greece are the countries with the smallest productivity per inhabitant, which translates in a small biowaste potential, as represented on the bar chart of Figure 2.6. In general, countries having a low GDP per inhabitant will tend to have a low potential in biowaste. The Eastern countries, several of which present a GDP per inhabitant below the average [34], are indeed the ones standing on the right side of the bar chart.

Biomass potential in the energy model

Now that the potential of biomass has been detailed in Europe, it is valuable to examine its relative importance in the energy system by comparing it with the total renewable source potential and the total energy demand of each region for 2035. To determine the demand, data was gathered from the "EU reference scenario 2020" [35]. The renewable potentials were solely obtained from the ENSPRESO database, which is a new approach. The data shown on Figure 2.7 may thus differ slightly from the ones used in previous theses based on EnergyScope optimisations. The renewable potentials considered in this analysis include biomass, wind onshore and offshore, solar PV, and hydro (from dams and rivers). To avoid presenting too much data at once, the analysis focuses on the six macro-cells of Western Europe defined in Chapter 1.

The renewable potential is substantial enough to cover the total demand in all macro-cells, except for Germany & Benelux. In each region, the biomass potential is relatively small compared to the total renewable potential and the end-use demand. Nevertheless, there are major differences between regions. For example, the biomass potential of the Scandinavian countries is approximatively half of its total demand, while the demand for Germany & Benelux is almost eight times larger than its biomass potential. Even if biomass is only the third largest renewable potential, it can play an important role in the energy transition. Solar PV and wind onshore are the two leading renewable technologies in terms of potential, but biomass has its own advantages as it is storable, tradable and not intermittent. It is also versatile as it can respond to the demand in heat, electricity, mobility and the non-energy demand.

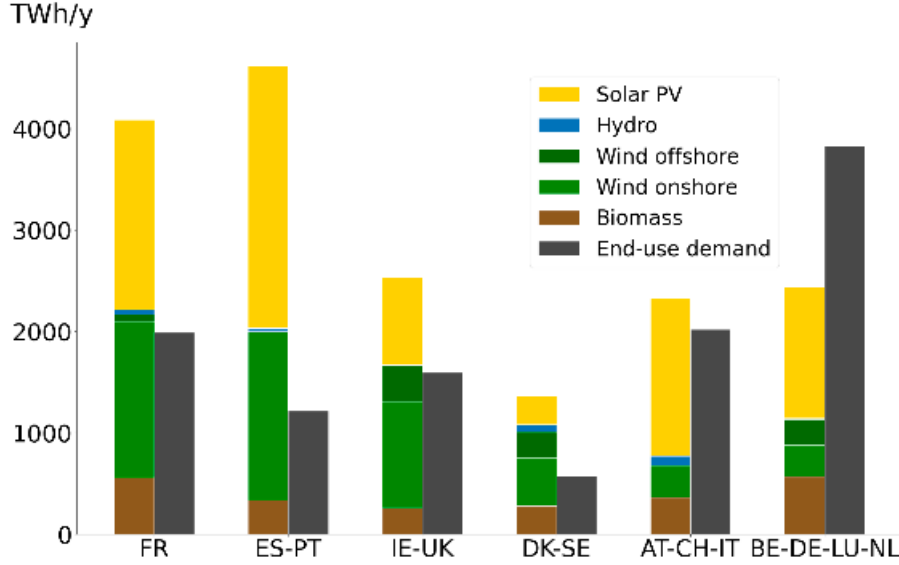


Figure 2.7: Renewable potential vs Total end-use demand of each Western European macro-cell for the year 2035.

2.2.2 Local cost of resources

To update the local cost of each biomass category, a weighted mean of the local costs of all resources within a category is computed. To be consistent, the local costs of the resources are weighted by their energy potential. Considering that the ENSPRESO database only gives data for the years 2030 and 2040, costs for 2035 are computed by averaging the costs of the two years. It is to be noted that the ENSPRESO costs are given in euro₂₀₁₀. As all prices are actualised in euro₂₀₁₅ in the EnergyScope model, an inflation of 7.2% is considered [36]. Equation 2.1 displays the formula used to compute the local costs. The costs of each category and for each country can be found in Appendix A.2.

$$c_{\text{biomass category}}^{2035} = \sum_{\text{resources}} \frac{(c_{\text{op}}^{2030} \times \text{pot}_{\text{resource}}^{2030} + c_{\text{op}}^{2040} \times \text{pot}_{\text{resource}}^{2040})}{2 \times \text{pot}_{\text{biomass category}}^{2035}} \times 1.072 \quad (2.1)$$

2.2.3 Global warming potentials

Next to the potential and the cost of the different biomass resources, each biomass category has its own global warming potential (GWP). This parameter is a measure of the contribution to global warming of energy production based of a specific resource. It is expressed in (ktCO_{2eq}/GWh), which means it is a quantity of CO₂ emitted per quantity of energy produced. It can depend on various factors : the mode of cultivation, production, the transport of the resource, etc.. Table 2.7 hereunder shows the operational GWP of each category. To compute it, for most of the categories, the European directives of 2018 are used [37]. An exception is made for the category of energy-dedicated lignocelulosic biomass crops as there are no values given for the biomass types of this category. The missing value is then calculated based on the emissions linked to the

energy production from miscanthus, which is the main part of the potential of the category [38]. The details of the calculations of each GWP are given in Appendix C.

Table 2.7: Operational global warming potentials (gwp_{op}) of each biomass category.

Resource	GWP operational (ktCO _{2eq} /GWh)
Woody biomass	0.025
Wet biomass	0.011
Biowaste	0.015
Other biomass residues	0.003
Energy-dedicated lignocellulosic biomass crops	0.008

In EnergyScope, there is a specific way GHG emissions limits are set. Indeed, there is, in the model, a CO₂-NET parameter, which represents the quantity of CO_{2eq} emitted by the production of a resource minus the CO_{2eq} captured by that resource. Since biomass undergoes processes like photosynthesis, we make the hypothesis that it captures all greenhouse gas emissions produced during its production. Therefore, for all biomass resources, the CO₂-NET parameter is set to 0. As EnergyScope’s GHG emissions limits are set in terms of CO₂-NET, biomass is considered as a 100% green source of energy in this study.

2.3 Biomass conversion to energy

In order for biomass to be converted to energy, it needs to be treated by specific technologies, depending on the EUT desired. Many technologies already existed in EnergyScope, turning the previous categories of wood and wet biomass into energy. As some biomass resources have been reworked and others have been added to the model, the technologies must be fixed in order for all the biomass categories to be converted to energy using the adapted technologies. The entire process of resources turned into energy is explained in this section.

The whole biomass has been divided into five categories according to multiple criteria, such as the origin, the internal composition, the price, etc.. Each category can respond to one or several specific demands, and the conversion to energy is done with the associated technologies. In order to clarify all the possibilities, the table illustrated in Figure 2.8 synthesises the whole process of biomass conversion to energy. The table is split into three parts. The first one resumes the five biomass resources which have been described in a previous section. The second part focuses on the energy conversion itself, which includes the possible technologies used to treat the biomass in order to produce energy. The third part contains the different EUT’s that can be produced from the treated biomass resources. The resources and the energy commodities are put in the form of ”layers”, which are made to ease the model in EnergyScope.

The table illustrates how technologies connect resource layers to EUT layers. In the previous version of EnergyScope, only the Wood and Wet biomass layers existed. Since

the number of biomass categories has increased, an update regarding the layers in the model is needed. As we can see in Figure 2.8, two major modifications take place. The first one is the fact that some categories have been joined into a single layer. It is the case for the woody biomass and the energy-dedicated lignocellulosic biomass crops categories. This choice is justified by the fact that the biomass types share similar conversion technologies. However, even if they are joined together, each category maintains its unique potential, operational GWP and local resource cost as outlined in the subsequent section. The consolidation only means that both categories will be treated by identical technologies and with the same conversion rates. The second update is the addition of a new resource layer, the Biowaste layer. The categories of other biomass residues and biowaste are both grouped into this layer which includes the conversion technologies that can transform these specific biomass resources into energy.

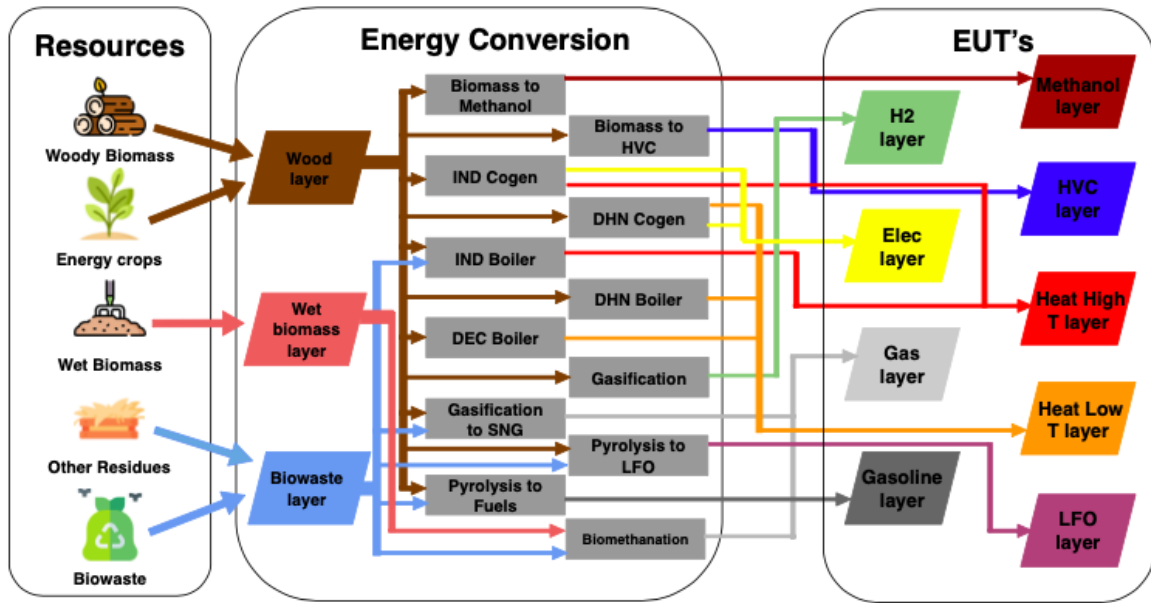


Figure 2.8: Conversion routes of the biomass resources to the EUT layers, including all the possible technologies. "Energy crops" here defines "Energy-dedicated lignocellulosic biomass crops" and "Other residues" defines "Other biomass residues".

Each resource layer is then linked to the different technologies that can transform the biomass into any form of energy. The possible conversion routes of each category have already been detailed in the section describing the resources. For the new Biowaste layer, the technologies capable of converting the biomass resources to energy have been added to the model. Concerning the other two layers, no modifications in the existing technologies were needed. Every technology obviously has its own energy conversion ratio and its own cost. The conversion ratios are directly taken from the Danish Energy Agency [39].

Finally, the possible EUT's are shown on the right side of Figure 2.8. They respond to the different demands of electricity, heat, mobility and to the non-energy demand. Concerning the electricity layer, while not being the main energy commodity of a specific treatment method, it is still produced during the transformation of the biomass in

cogenerations. In these cases, the production of electricity is minor, but not negligible, hence why the electricity layer is still illustrated.

2.4 Transport of biomass

The primary added value of the Multi-Cells extension of EnergyScope is the possibility of regional exchanges, which can occur by two distinct ways : network or freight. On one side, the exchange of gas and electricity, which has been previously analysed in the master thesis of N. Cornet and P. Eloy [4], occurs through networks. On the other side, other resources, such as biomass, may be transported by freight. This section will focus on the second option, thus analysing the transportation possibilities of biomass and identifying commonly transported biomass types.

2.4.1 Types of transport

As several countries cannot produce enough renewable energy from their own resources, the import of biomass is a solution to meet their demands while limiting CO₂ emissions. There are multiple ways to transport biomass in its natural form from one country to another [40]. Each method has its advantages and drawbacks [41]. The different possibilities are discussed hereunder.

The most common way to exchange biomass between countries is by road transport. The main advantages of this mean of locomotion are its practicability and its flexibility. Trucks are indeed the most straightforward mean of transportation of goods from Point A to Point B. The extensive road network enables trades from places only the truck can access, making it the most interesting solution in many cases. Trucks are also adapted if the demanded quantities vary somewhat. A trade can easily be adjusted by adding or removing a truck or two. Moreover, for a short trip, trucks are the quickest to deliver the demanded quantity of biomass at destination. The loading of the goods is indeed the fastest for a truck than for any other means of transport. Even if it is the most used exchange mode, road transport presents some drawbacks. Firstly, trucks contribute a lot to air pollution. They are indeed the second most polluting mode of transport, after the plane [42]. Trucks also have to deal with the traffic, which is not a problem for other means. Thirdly, the exchange of large biomass quantities requires many vehicles, which inevitably increases the transport costs and the emissions.

A second possibility for the transport of biomass is the train. A first advantage is the large capacity of goods that they can transport. Trains can be composed of tens of wagons, meaning there is a considerable volume available for the merchandise. For long distance trades, as the transported quantities can be very large, the ratio of the cost on the transported quantity is quite low, making it also a cost-effective solution. Moreover, rail transport is quick for large distances as, unlike trucks, it has no traffic to deal with. Finally, the biggest asset of trains is their low impact on the environment. They usually work on electricity, which causes barely any emissions. In fact, a freight train emits, on average, 9 times less CO₂ per kilometer than a truck for the same amount of goods transported [43]. Trains, however, present a major problem, which is the lack of infras-

structure. The starting and end points of an exchange are indeed rarely situated next to rail infrastructures. For the majority of the trades, trucks are needed to bring the biomass to a station and, at the end of a line, deliver the biomass to its final destination.

Biomass can also be transported by boat. Like trains, boats are mostly used for transport over large distances, but on a larger scale that can go up to exchanges between continents. As large quantities can be transported, maritime transport is also an economical solution. Their cost of transport is indeed often lower than that of trains. Boats also tend to pay attention to their impact on climate and try to produce as little CO₂ emissions as possible [44]. Like the trains, the major downside of using boats as a means of transport is the fact that boats are infrastructure-dependent. In most of the cases, trucks bring biomass to the boat for transport, after which, trucks bring biomass to its destination. Additionally, transport by maritime ways is usually very slow in comparison to the truck or the train.

To resume, road transport is the best solution for the import and export of biomass on short to average distances. Its practical side and its flexibility indeed makes it the go-to plan for exchanges on a standard scale. On the other hand, trains and boats offer the best characteristics for large distance exchanges. Depending on the starting and end points of the biomass, one mean will be chosen over the other.

Next to these modes of transport, it should not be forgotten that biomass can be exported in a different form than its original nature. Indeed, as seen in our conversion chain, the treatment of biomass can produce multiple forms of energy, and some of them are exchangeable. Among these energy commodities, we can find gas, fuels and electricity. For electricity, large networks, made of land-based and sub-marine cables, exist and it is an easy way to export this resource from one country to another. Concerning gas, the use of pipelines is widespread and often the chosen path for exchanges. Biomass can also be transformed into solid or liquid fuels and then be transported by freight. These forms of transfers are thus considered and also implemented in EnergyScope.

2.4.2 Types of feedstocks in transport

As the different types of transport used for the trading of biomass have been introduced, it is then interesting to develop which types of feedstocks can actually be exchanged between countries. Some biomass types are actually transported, while it is more difficult for others, as explained below.

Traditionally, all biomass fuels are used in the same geographical area where they are produced. In recent decades, this pattern has changed because of the large-scale use of wood, which is processed into pellets and briquettes. Wood pellets and chips are now traded internationally, particularly in Europe and North America [45]. Pellets are biofuels made from compressed wood particles and they present many advantages over other feedstocks, especially in terms of transportation. The main benefit of wood pellets in international trades are their standardisation. As woody biomass can have different forms, it is advantageous to have a standardised fuel format for commercial purposes. Secondly, they are small, making them easy to transport. They also present a high

energy density compared to other forms of wood. Finally, wood pellets have a very high efficiency of around 95%, compared to 70-80% for wood logs [46]. In addition to wood pellets, woody biomass can also be transported in the form of wood chips or even wood logs. However, these forms of transportation are often limited to short distances and are not commonly used for international trade.

Given the existence of wood exchanges, they have been implemented in the EnergyScope Multi-Cells model. As mentioned above, the most efficient method for the transport of woody biomass is to transform it into pellets. However, ENSPRESO resources included in the woody biomass category have each their specific form. Some are given in the form of wood chips, briquettes or even sawdust, while others are already considered as pellets. Implementing a consistent pelletization technology capable of converting all types of woody biomass into pellets is thus a difficult task. Therefore, this study will consider that all forms of woody biomass are exchangeable as they are provided within ENSPRESO.

Concerning biomass coming from the categories of energy-dedicated lignocellulosic biomass crops and other biomass residues, exchanges can happen. These types of biomass can be transported over short distances within a country, but as these feedstocks are less used than wood, international trade is not developed. Moreover, for these categories, there is not a standardised type of feedstock like wood pellets for the woody biomass category. It is possible to make pellets having an agricultural origin [47], coming from agricultural residues or perennial grasses, but these are less common than the ones made from wood. In addition, the mean of locomotion of these biomass types are sometimes first filled in terms of volume rather than in terms of mass. In EnergyScope, a vehicle is said to be filled when a certain mass of merchandise is attained. However, in reality, sometimes the volume of a vehicle is filled before it attains the weight limit. It is the case for perennial grasses and straw for example, as their density, which are respectively 130 kg/m^3 [48] and around 100 kg/m^3 [49], are much smaller than the one of wood pellets, which varies between 600 and 750 kg/m^3 [50]. A vehicle transporting wood pellets possesses thus more energy to be converted than a vehicle of perennial grasses or straw. To match that, several vehicles of these resources are needed, which leads to increased costs and emissions. The transport of these biomass types is thus not an optimal solution. For these reasons, these two biomass types are not considered as exchangeable between regions in the EnergyScope model.

Biowaste is also an uncommon resource to exchange. The transport of municipal waste over long distances is not practical. It must also be registered and meet complex regulatory standards [51]. In addition, the lack of a standardised feedstock makes international trade difficult. Exchanges of biowaste are thus not implemented in the EnergyScope model.

Finally, wet biomass is also a resource not traded between countries. One of the problems is the transport logistics, as manure or sludge are cumbersome and odorous, making them pretty difficult to handle and transport. Wet biomass also contains a lot of water and has therefore a very low energy density. Moreover, multiple regulations and limitations exist in certain countries concerning the treatment of wet biomass. Among

these restrictions, we find environmental regulations encompassing concerns on, for example, possible soil contaminations or nutrient pollutions as well as biosecurity issues linked to the bacteria and pathogens that manure can contain [52]. For these reasons, exchanges of wet biomass are not implemented in the model.

To summarise, the only type of biomass feedstock implemented as exchangeable in the model is woody biomass. In order to model it accurately within the EnergyScope Multi-Cells model, it is essential to determine the quantity of each type of biomass that is transported per unit of energy potential. This is known as the lower heating value (LHV) and is defined as the amount of heat released by combusting one kg of fuel. The LHV of woody biomass has been computed based on the Phyllis2 database [53]. Considering woody biomass at an original state of moisture content, it gives a LHV of 15,07 MJ/kg.

Chapter 3

Case study : Western Europe

In the previous chapter, the European biomass potentials were analysed in detail. The objective of this chapter is to determine how these biomass potentials could be optimally used by 2035. In order to investigate their role, an optimisation of the Western European energy system, which is chosen as a case study in this work, is realised with the EnergyScope Multi-Cells model. Indeed, as we have seen from the data presented in Chapter 2, this region possesses a significant share of Europe's biomass potential. The studied region is divided in six macro-cells, as explained in Chapter 1.

The analysis will explore the results obtained by the EnergyScope optimisation for a low-carbon energy system. Indeed, the latter has been optimised with an objective set to a 90% reduction of the 1990 level of GHG emissions in each macro-cell. This chapter will focus on the optimal use of the biomass potentials and their transformations into EUT's, thus exploring the technologies chosen by the model for the conversion of biomass to energy and the reasons for their use. Biomass exchanges will also be examined to determine if they can help the different regions to stay within their emissions limit.

3.1 Results introduction

The objective of this section is to provide an overview of the use of biomass in the energy system. It is a main introduction to the results obtained from the EnergyScope Multi-Cells optimisation.

Before going into details about biomass, it is important to recall the role and implications of fossil fuels in the current European energy system. Presently, these fuels are the most used energy source in the world, representing around 82% of the total energy consumption [54]. These energies are well known under three forms, which are oil, natural gas and coal. In our society, oil, or petroleum, is the most used one out of the three, since multiple sectors, such as mobility and the non-energy demand, are dependent of this resource. In the context of a 90% reduction in greenhouse gas emissions, fossil fuels have a relatively limited role. However, we will see that natural gas is widely used. It is important to emphasise that coal is the cheapest fossil energy source, but it is excluded from the model as it would be unrealistic to import a significant quantity of coal from the exterior in 2035 given the actual European context [55]. There is therefore a large

place for renewable energies, and thus biomass energy potentials.

In the optimisation on Western Europe, EnergyScope uses almost entirely all biomass potentials. Indeed, all the regions rely on this renewable resource to meet their energy needs. The exact potential of biomass used in each region will be discussed later on. Figure 3.1 illustrates the different applications of biomass in Western Europe and resumes all the conversion pathways used by the model to produce energy. Some of them are used by every macro-cell, while other paths are only employed by one or two regions. As a reminder, the resources positioned on the left side of the figure correspond to the three biomass layers implemented in EnergyScope. The different EUT's produced and the demands to which they respond are shown on the right side of the figure.

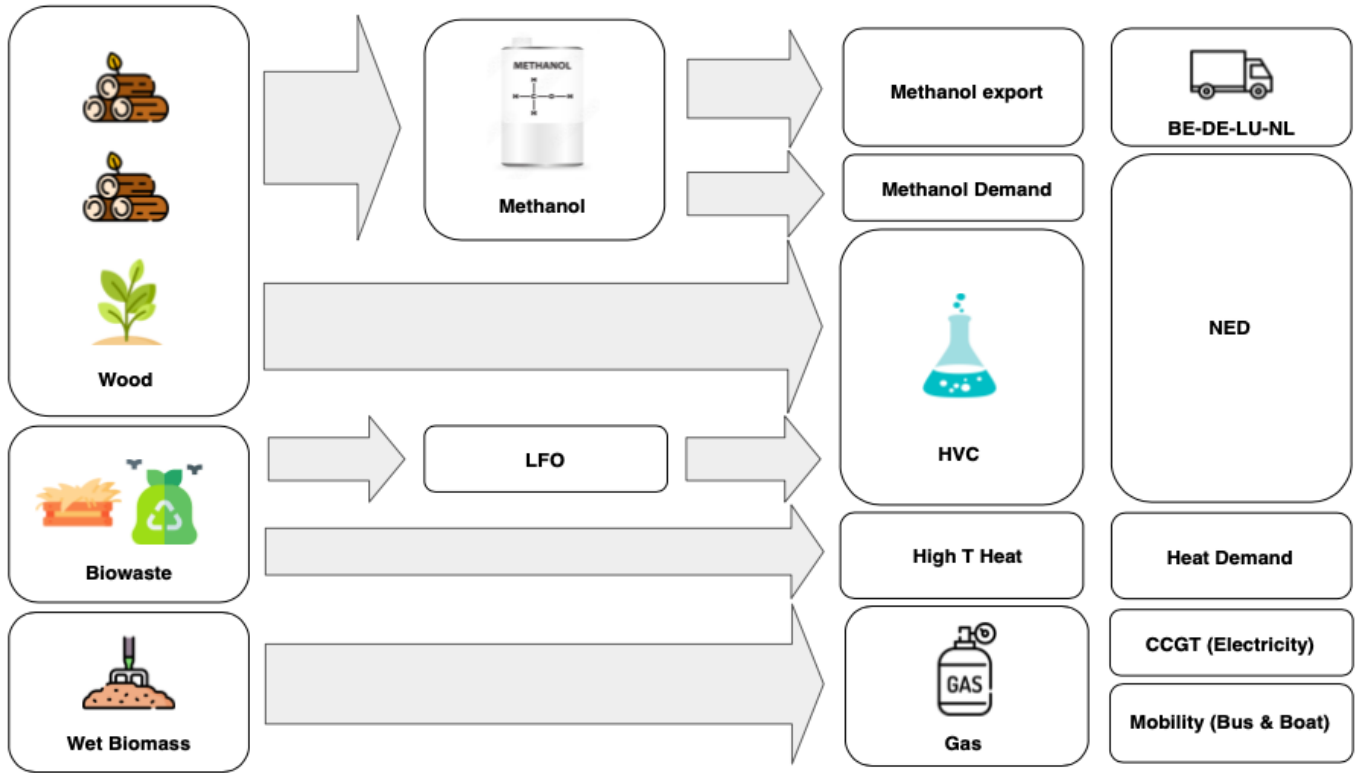


Figure 3.1: Optimal pathways for the conversion of biomass into energy in Western Europe by 2035, considering an objective of a 90% reduction of the 1990 level of GHG emissions.

The first role EnergyScope gives to biomass resources coming from the Wood layer is to cover the NED. There is indeed a small demand in methanol, that the resources easily fill in each region, and a larger one in HVC's for which a large potential is often needed. For the regions presenting a remainder of woody biomass or energy-dedicated crops potential after responding to these two local demands, the resources left are transformed into methanol and exported to the region of Germany & Benelux. As seen in Chapter 2, this region presents an important gap between its renewable potential and its total energy demand. Therefore, any help coming from its neighbours is quickly accepted. The optimisation of the NED in Western Europe as well as the exchanges aimed at

covering this demand for the region of Germany & Benelux are explored in Section 3.2.

Concerning the resources coming from the Biowaste layer, there are two paths used in Western Europe. They can either help to cover the NED if the woody biomass and the energy-dedicated lignocellulosic biomass crops are not able to do it on their own. This is done by transforming the resources into LFO, which in turn is converted to HVC's. Biowaste can also be used to participate in the production of high temperature heat. The coverage of this specific demand is detailed in Section 3.3.

About wet biomass, its potential is entirely transformed into biogas, which is done by anaerobic digestion, also called biomethanation. The importance of the biogas made from wet biomass is debated and contrasted to the use of fossil natural gas in the European energy system in Section 3.4.

Finally, the role of biomass will be compared to the role of other renewable energy sources in Western Europe. Among others, the technologies linked to wind and solar energy are developed. This comparison is conducted in Section 3.5.

3.2 The importance of the Non-Energy Demand

In general, according to EnergyScope, the first role of biomass is to cover the NED. As a reminder, the non-energy demand includes energy products used as raw materials in different sectors, not consumed as a fuel or transformed into another fuel [56]. It is primarily linked to the chemical sector and is composed of HVCs, methanol, ammonia, and other products. In EnergyScope, only the three prominent products are implemented in the NED, i.e. HVC's, methanol and ammonia. In all the regions, EnergyScope produces ammonia by electrolysis using hydrogen. As it cannot be produced from biomass, this demand will not be analysed in this study. On the other hand, the methanol demand is always filled with either woody biomass or energy-dedicated lignocellulosic biomass crops. As it is a small demand, of around 2 TWh per year, in every macro-cell, it is directly covered with the local biomass. The most interesting demand to detail is the HVC demand, which is the largest one of the three products. Figure 3.2 presents how every region produces its HVC to fill its demand.

To cover the HVC demand, biomass is always the first choice for Western European countries. More precisely, it is the categories of woody biomass and energy-dedicated lignocellulosic biomass crops that present the most cost-effective solution for the production of HVC's. It depends on the price, whether countries prefer to use biomass from the first or second category. For France, energy-dedicated crops are the cheaper solution. For the five other macro-cells, woody biomass is the most profitable choice.

It is notable that four regions are able to cover this demand by using 100% local biomass resources. The two other regions, i.e. the British Isles and Germany & Benelux, do not have enough biomass available to cover the entirety of their HVC demand.

For the British Isles, synthetic methanolation using hydrogen helps fill the part of the

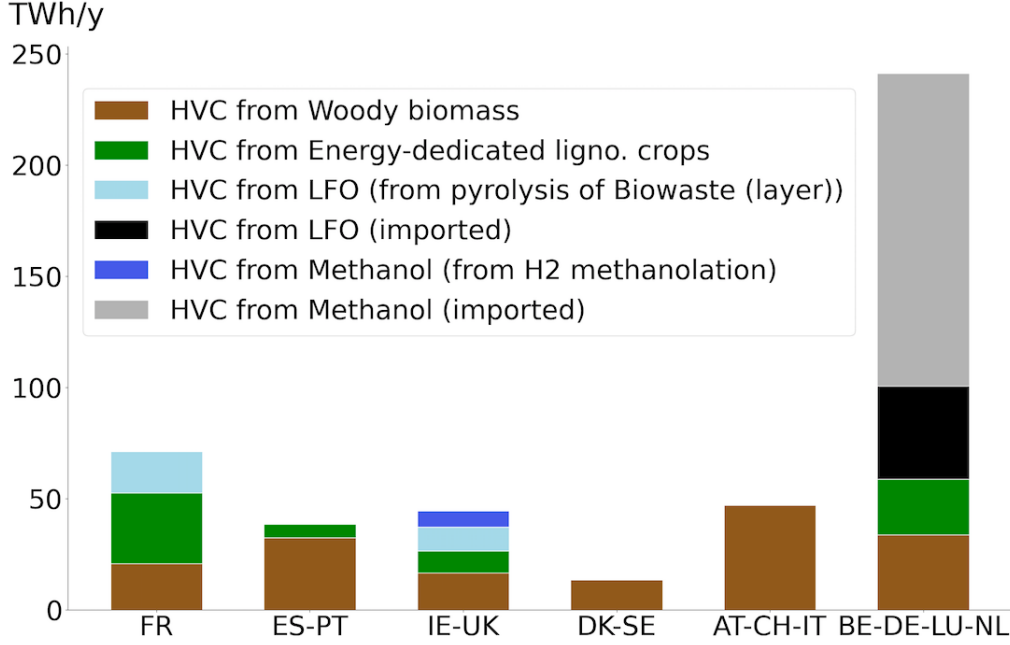


Figure 3.2: Detailed breakdown of the HVC demand coverage by Western European region for the year 2035.

demand that biomass cannot. It is also noticeable that the region uses all its biowaste and other biomass residues potentials to produce HVC's. Covering the NED with biomass is indeed very important in order to limit GHG emissions, hence why the region uses all its biomass resources to fill it. In this case, these resources are first treated by pyrolysis to produce LFO's, which are then turned into HVC's.

The region of Germany & Benelux is a more particular case. Indeed, as this region has a significant HVC demand, which is more than three times that of every other region, there is an important gap between its biomass potential and its demand. Moreover, as will be detailed in the next section, a part of the biomass potential is used to cover the heat demand, meaning that the region cannot use all its potential to produce HVC's. To complete it, a first solution is to import LFO from the exterior of the system and to transform it into HVC's. It is a cheap alternative, but it emits a non negligible amount of GHG, which thus limits its use. The second solution, and the most important one, that helps Germany & Benelux meeting its HVC demand is the import of renewable methanol. Indeed, as illustrated on Figure 3.2, the region imports a lot of methanol from its neighbours, more precisely 183.2 TWh per year, making it the most exchanged freight resource across Western Europe. Figure 3.3 can therefore be analysed as it resumes the exchanges made by freight across Western Europe.

As the map shows, the region of Germany & Benelux is the only one importing resources from its neighbours. France, Italy & Alpine States and Scandinavia all export methanol to this region. The three regions indeed possess enough biomass potential to meet their own energy demand. Therefore, they produce a surplus of renewable methanol and send it to Germany & Benelux. Concerning the British Isles, they do

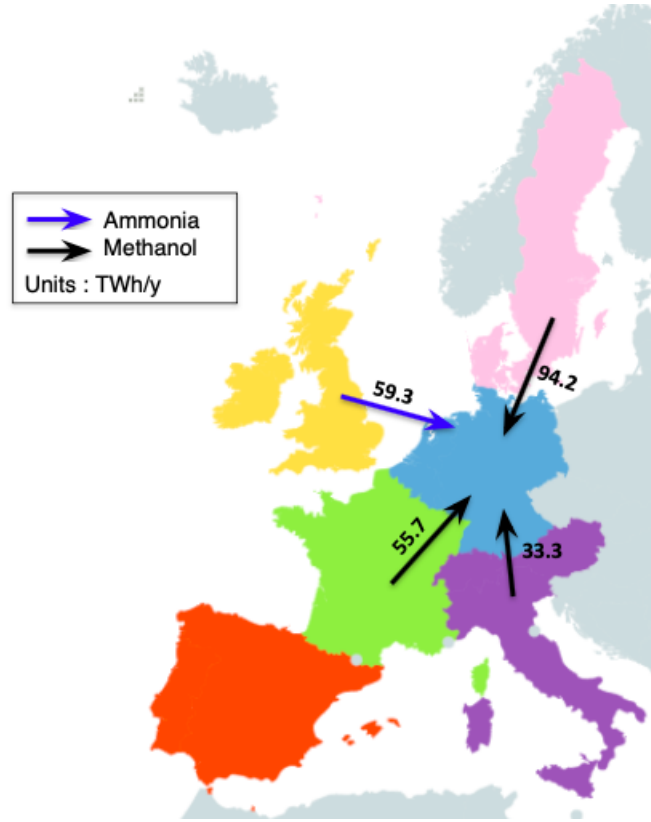


Figure 3.3: Yearly freight exchanges, expressed in TWh/y, across Western Europe for the year 2035.

not participate in the exchanges of methanol as they need their local resources to fill their own HVC demand. However, they still participate in the yearly exchanges as they export ammonia to the region of Germany & Benelux. The British isles indeed have enough renewable electricity, which allows them to produce a surplus of hydrogen by electrolysis. Ammonia is then produced from this hydrogen and exported to Germany & Benelux, which has less available renewable electricity, to fill its demand for ammonia.

Renewable methanol is thus exported by the regions of France, Italy & Alpine States and Scandinavia. The region of Germany & Benelux chooses the region from which they import methanol according to the price. The latter depends on the cost of the biomass resource, the price of the conversion into methanol and the freight cost of the import. To recall, renewable methanol can be produced from woody biomass as well as from energy-dedicated lignocellulosic biomass crops. The prices of the different possibilities of methanol importation are assembled in Table 3.1. The development of the computations leading to these costs can be found in Appendix D.

The first choice for the region of Germany & Benelux is to import methanol produced from wood in France, as it is the cheapest. All the remaining woody biomass that France does not use is thus exported to their Northern neighbours. After that, the region imports methanol produced from Italian woody biomass. Once again, the rest of the local woody biomass is exported. As the HVC demand of Germany & Benelux

Table 3.1: Comparison in the cost of production of biomass-based methanol and its exportation to the region of Germany & Benelux. All costs are given in $\text{Meuro}_{2015}/\text{GWh}$.

Resource	Freight Cost	Total cost
Methanol from french woody biomass	0.0066	0.064
Methanol from italian woody biomass	0.0094	0.067
Methanol from scandinavian woody biomass	0.0102	0.076
Methanol from italian energy crops	0.0094	0.080
Methanol from scandinavian energy crops	0.0102	0.087

is still not completed with both imports, it also imports methanol made from the available woody biomass of Scandinavia. To reach the 183.2 TWh needed per year, only a part of the energy-dedicated lignocellulosic biomass crops potential of Italy & Alpine States is imported in the form of renewable methanol. The HVC demand of Germany & Benelux is then finally filled.

In Table 3.1, there is no mention of the energy-dedicated crops of France. Indeed, as the price of the resource is relatively low, the country uses it entirely to complete its own energy demand. Germany & Benelux thus cannot import energy-dedicated crops-based methanol coming from France. For the other regions though, the price of the resource is higher, and sometimes too high. In fact, some macro-cells do not even use their potential of energy-dedicated crops, as it can be seen on Figure 3.4.

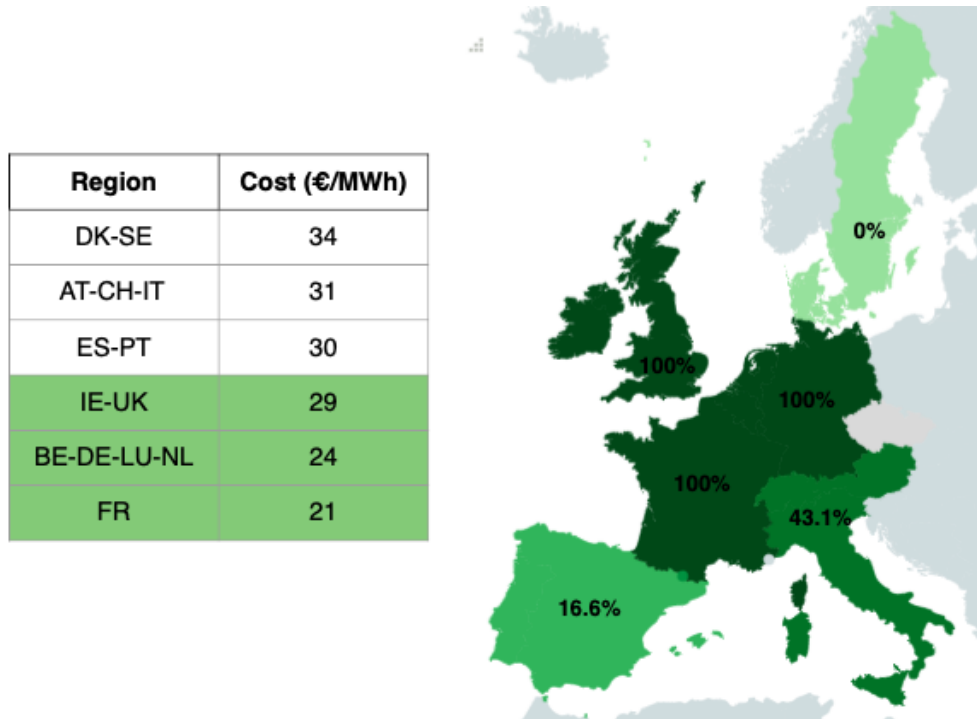


Figure 3.4: On the left, cost of the energy-dedicated lignocellulosic biomass crops, expressed in $\text{euro}_{2015}/\text{MWh}$, for each region. On the right, proportion of the category's potential used in the energy system per region.

A link is quickly made between the price of the resource and its use. Scandinavia presents the highest cost, which translates into a potential that is not used at all. In Italy & Alpine States, as woody biomass is sufficient to cover the NED, energy crops are thus only partially used for export to Germany & Benelux in the form of methanol. It is an expensive solution, but it is needed in order for the region to respect the -90% GHG emissions objective. The Iberian Peninsula also prefers to use its woody biomass to cover their NED as the price of energy-dedicated crops is too onerous. Only a part of the energy crops potential is used to complete this NED. For the British Isles and Germany & Benelux, all the local potential is used as it is needed to cover the NED.

It is also interesting to compare imported renewable methanol produced in Western Europe to methanol coming from the exterior of the system. As Table 3.2 shows, even the most expensive methanol of the six macro-cells, which is the methanol based of energy-dedicated lignocellulosic biomass crops coming from Scandinavia, is cheaper than renewable methanol originated from the exterior. The price of fossil methanol is higher as well, while also being responsible for a large amount of GHG emissions during its production. The prices presented here include the cost of the resource, the cost of the transformation to methanol and the freight cost, as it is the case for the prices presented above.

Table 3.2: Price comparison for different types of methanol.

Resource	Cost (Meuro2015/GWh)
Fossil methanol (from exterior)	0.102
Renewable methanol (from exterior)	0.111
Renewable methanol (from DK-SE energy crops)	0.087

Finally, as introduced in the previous chapter, biomass can be transported in its raw form, and especially woody biomass. Germany & Benelux could thus import this raw resource to fill its lack of HVC's. In fact, it is more profitable for the region to import already transformed wood, in the form of methanol, than to import original woody biomass. This is proved with Table 3.3, which shows the difference in costs between the production of HVC's with imported wood and the production of HVC's with imported methanol made from wood.

Table 3.3: Costs comparison, expressed in Meuro₂₀₁₅/GWh, between two processes to produce 1 GWh of HVC's in the region of Germany & Benelux. The first process consists in importing Scandinavian woody biomass and to transform it into HVC's. The second process is based on the import of Scandinavian renewable methanol, which is produced from woody biomass, and to transform it into HVC's.

Resource	Resource cost	Freight cost	HVC conversion cost	Total Cost
Woody biomass	0.065	0.036	0.018	0.119
Renewable methanol	0.081	0.013	0.012	0.105

We can see that the costs of the freight for the import of woody biomass is three times

higher than the cost linked to the importation of renewable methanol. The difference lies in the exported quantity needed to produce HVC's. It indeed needs more wood than methanol to produce 1 GWh of HVC, respectively 2.38 GWh against 1.24 GWh. Moreover, as the LHV of methanol is higher than the one of woody biomass, respectively 23 against 15,07 MJ/kg, more trucks are needed to transport 1 GWh of wood than 1 GWh of methanol. These reasons explain the difference in the cost of the freight for the importation of the two resources. The prices of the table are calculated for imports coming from Scandinavia, but the conclusions are the same for importations coming from other regions. The computational development of the costs linked to methanol exchanges can be found in Appendix D. A similar development is made to compute the cost of imported wood.

3.3 High temperature heat demand coverage

Next to the NED, EnergyScope also gives an important role to biomass in the filling of the heat demand. For multiple macro-cells, part of the demand is indeed covered by biomass resources. This is illustrated in Figure 3.5, which shows how regions meet their high temperature heat demand. To recall, heat at high temperature is obtained by using industrial cogenerations or industrial boilers.

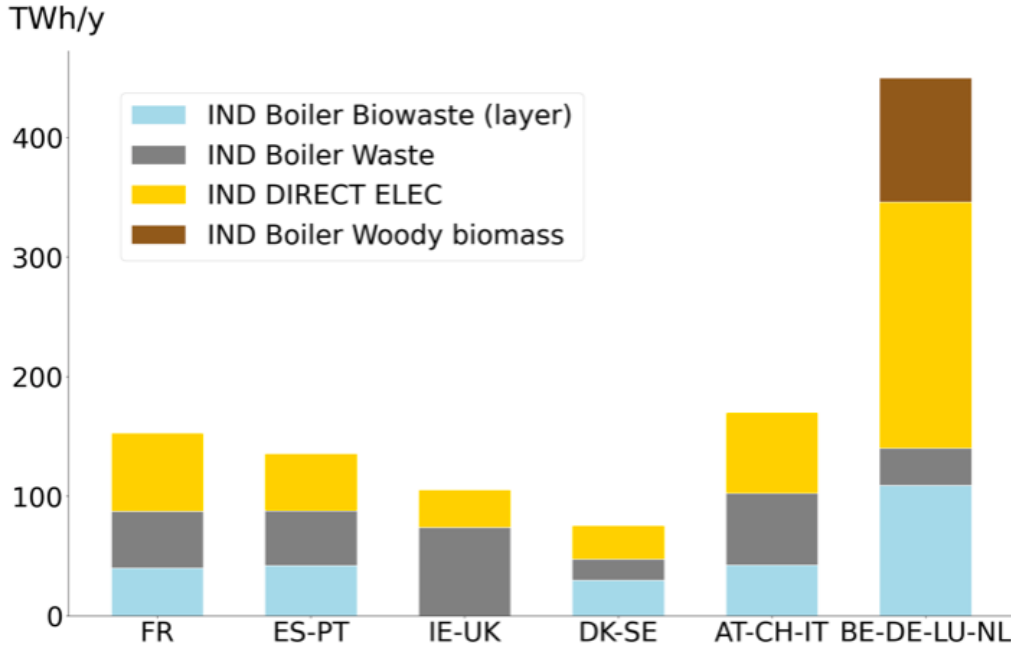


Figure 3.5: Detailed breakdown of the high temperature heat demand coverage by Western European region for the year 2035.

By analysing the graph, we can see that every macro-cell, except the British Isles, transforms its potential in biowaste and other biomass residues in high heat temperature. These two resources are totally used as they present the lowest cost of all the local biomass types. Moreover, they emit no GHG emissions. With these qualities, there is

no reason for the regions not to use the full potential of these biomass types.

The British Isles are the only region not using their potential in biowaste and other biomass residues in heat generation. As seen in the previous section, the region lacks resources to cover its NED. The potentials of these two categories are therefore completely used to produce LFO, meaning they cannot be transformed into heat. On the other hand, all the other macro-cells, except France, use the entirety of their biowaste and other biomass residues potentials to produce high temperature heat. The reasons presented above justify this choice. Finally, France, who used part of its potential in biowaste and other biomass residues to meet its NED, uses the rest of these resources to fill the demand in high temperature heat. The country can use part of its potential to cover the NED as it can count on a considerable amount of electricity generation potential.

Electricity is indeed also an important source for the production of high temperature heat. In fact, every macro-cell produces part of its high temperature heat with electricity. For Germany & Benelux, it is even the largest contribution to its demand. A part of this electricity is directly imported from the other macro-cells. Figure 3.6 shows the exchanges of electricity that happen in Western Europe, with the trades mainly being destined for Germany & Benelux. In order to cover its demands, 135 TWh of electricity is imported yearly by the region.

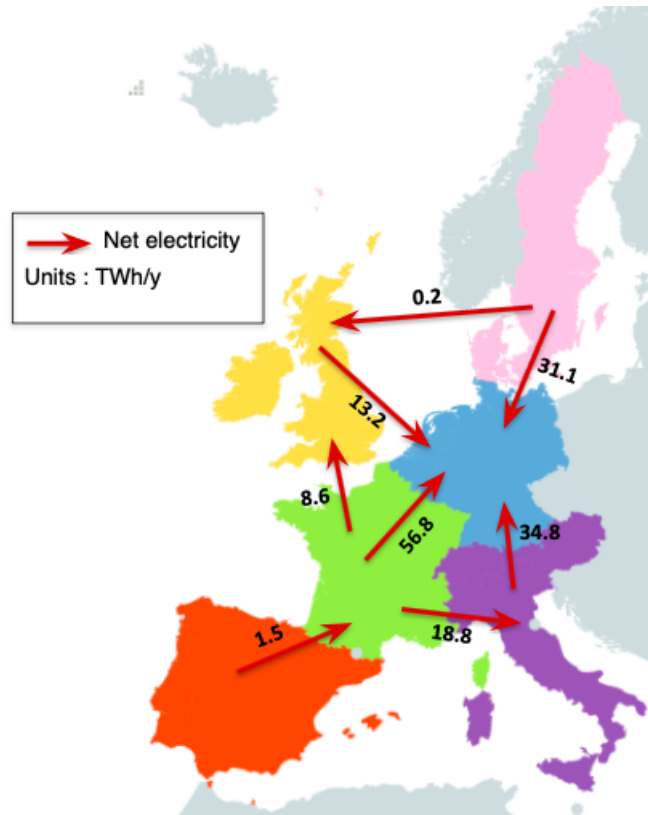


Figure 3.6: Yearly net electricity exchanges, expressed in TWh/y, across Western Europe for the year 2035.

Another solution employed by Germany & Benelux is to use part of its woody biomass in industrial boilers to produce heat. The resource indeed presents very good heat yields and, as it is a renewable source of energy, no emissions are produced during the conversion process. This explains why the region can afford to use woody biomass for this purpose, otherwise the resource would be used to cover the NED.

Finally, Figure 3.5 also shows that each macro-cell uses non-renewable waste to cover a part of its heat demand. The process of boiling these wastes inevitably generates GHG emissions. However, the cost-effectiveness and the high energy yield, equal to 82%, of the waste boiler technology make up for it and ensure that this resource is always used at its maximum capacity.

Whether it is for biowaste, other biomass residues, non-renewable waste or woody biomass, the industrial boiler technology is always preferred over industrial cogenerations. Despite the fact that cogenerations also produce electricity, the technology is much more expensive, making it less attractive to use. Moreover, as indicated in Table 3.4, an industrial boiler presents a far better yield when producing heat, regardless of the resource.

Table 3.4: Comparison in the costs of industrial cogeneration and boiler technologies (investment costs expressed in Meuro₂₀₁₅/GW ; maintenance costs expressed in Meuro₂₀₁₅/GWh) and their respective yields to high temperature heat.

Resource	COGEN costs	BOILER costs	COGEN yield	BOILER yield
Gas	(1408 ; 92.6)	(59 ; 1.2)	0.46	0.93
Wood	(1081 ; 40.5)	(115 ; 2.3)	0.53	0.86
Waste	(2928 ; 111.3)	(115 ; 2.3)	0.45	0.82

3.4 Analysis of the role of gas

Wet biomass is the only biomass resource left to analyse, and it also plays a role in the energy transition. Due to its low cost, the entire potential of wet biomass is always used locally. The main technology that converts this resource into an energy commodity is biomethanation. It is indeed a cheap technology, which explains why wet biomass is always transformed by anaerobic digestion. The final energy commodity is thus in the form of biogas. Biomethanation is also a possibility for the conversion of biowaste and other biomass residues, but as industrial boilers present a much higher efficiency, equal to 86.4%, as well as a low cost, it is more advantageous to burn them rather to convert them into biogas.

Each region thus uses its own resources locally to produce biogas. Unfortunately, the amount of biogas produced is not enough to replace all the natural gas used in the energy system. Figure 3.7 proves this as it shows the proportion of gas based of wet biomass compared to the total amount of gas consumed yearly in each macro-cell. When analysing the map of Figure 3.7, the main result is the fact that the biogas produced from wet biomass contributes to less than half the total used gas for each

Region	Wet biomass potential
BE-DE-LU-NL	185 530
FR	240 333
AT-CH-IT	119 654
ES-PT	118 546
IE-UK	165 403
DK-SE	56 892

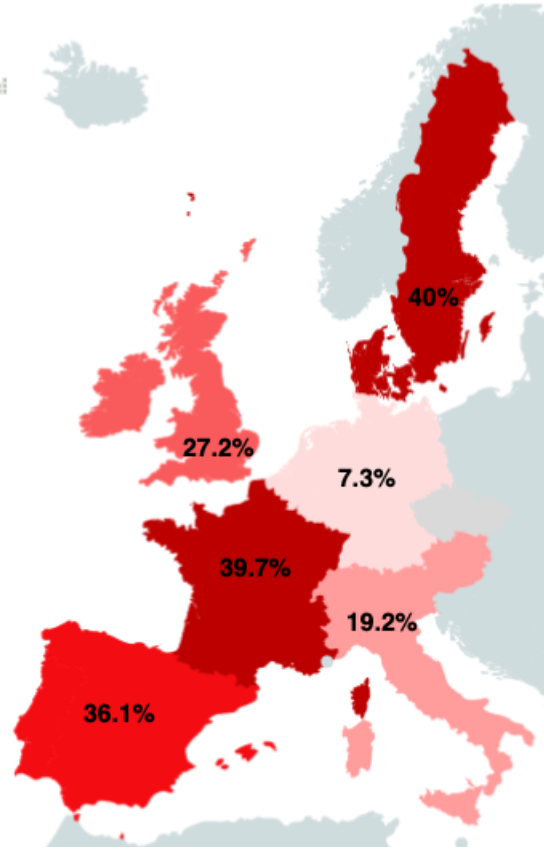


Figure 3.7: On the left, wet biomass potentials, expressed in GWh/y, of each region for 2035. On the right, proportion of wet biomass-based gas in the total gas consumption for each region.

region. It helps France and Scandinavia the most, as it represents around 40% of their gas consumption. This is an interesting result as France and Scandinavia present the largest and the smallest potential of all the regions respectively. The biogas production has thus the same impact for both macro-cells. Germany & Benelux is the region where the conversion of wet biomass presents the smallest impact, covering only 7.3% of its gas consumption. Once again, this region presents a severe lack of resources.

To compensate for this shortage in gas, natural gas is imported from the exterior of the system. It is indeed the cheapest solution in order for the regions to fill their energy demands. For some regions, the amount of natural gas imported is considerable. This is the case for Germany & Benelux, which imports a total of 701 TWh yearly. While being the most cost-effective solution, it should not be forgotten that natural gas is a fossil resource which participates a lot to GHG emissions. It is thus possible that the import of natural gas from the exterior is limited to a certain amount, in order to respect the objective of -90% GHG emissions. In fact, this is the case for Germany & Benelux. The import of 701 TWh from the exterior of the system indeed causes the region to surpass the GHG limit. In order to avoid this scenario, Germany & Benelux imports part of their total gas demand from the other regions of Western Europe. Figure 3.8 shows the different imports that take place in order to help the region in need.

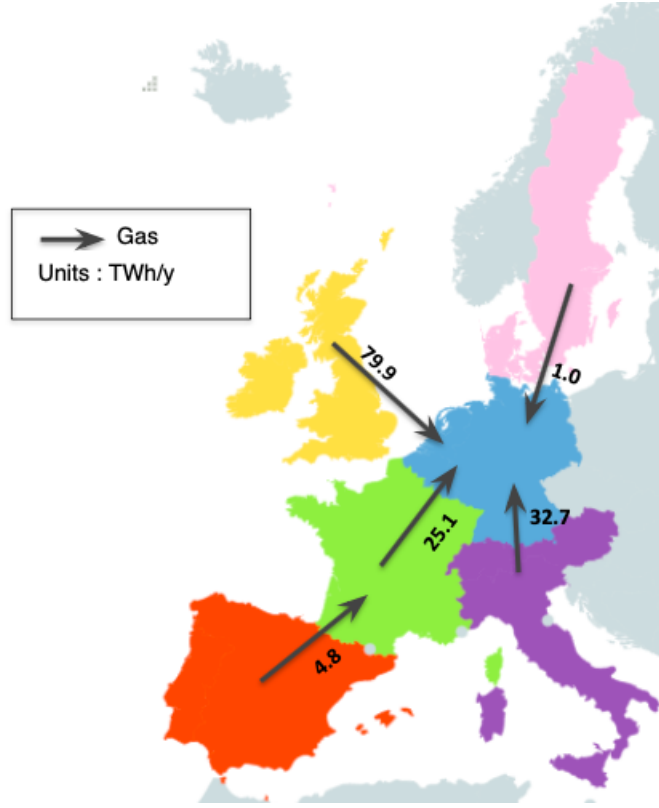


Figure 3.8: Yearly gas exchanges, expressed in TWh/y, across Western Europe for the year 2035.

The quantities that each macro-cell sends to Germany & Benelux is an extra importation of fossil natural gas coming from the exterior of the system. By doing so, it is the other regions that account for the emissions linked to this import, not the region of Germany & Benelux. This is an assumption made by the EnergyScope model, which permits the region to stay under the limit of GHG emissions. It is evident that this solution has an important impact in the optimisation of the energy systems of other regions. Table 3.5 shows the emissions limit per macro-cell and how these emissions are made. Without surprise, the vast majority takes origin from the import and the use of fossil natural gas.

Table 3.5: Distribution of the GHG emissions, expressed in $ktonCO_{2eq}$, of each region compared to their limit.

Region	Natural gas	Waste	LFO	GHG emissions limit
AT-CH-IT	36839	19074	0	55920
BE-DE-LU-NL	112294	8413	21307	142020
DK-SE	5586	5585	0	11177
ES-PT	13543	14454	0	28004
FR	25973	15022	0	41003
IE-UK	42776	25091	0	67877

Figure 3.9 provides an illustration of the different uses of gas. Each region presents an almost similar use of the biogas they produce and the natural gas imported. The mobility demands are the first one to be covered by the regions, with buses for public mobility and freight boats being the main vehicles using the gas. A little part of the gas is then used in CCGT technologies to produce electricity at a low cost. Finally, concerning Germany & Benelux, the region also needs to cover an important part of its low temperature heat demand. It is indeed a major reason of the enormous import of natural gas as this demand, equal to 454 TWh yearly, is quite significant. The other regions manage to fill this demand with electricity coming from renewable resources, while only a small part is covered by electricity for Germany & Benelux.

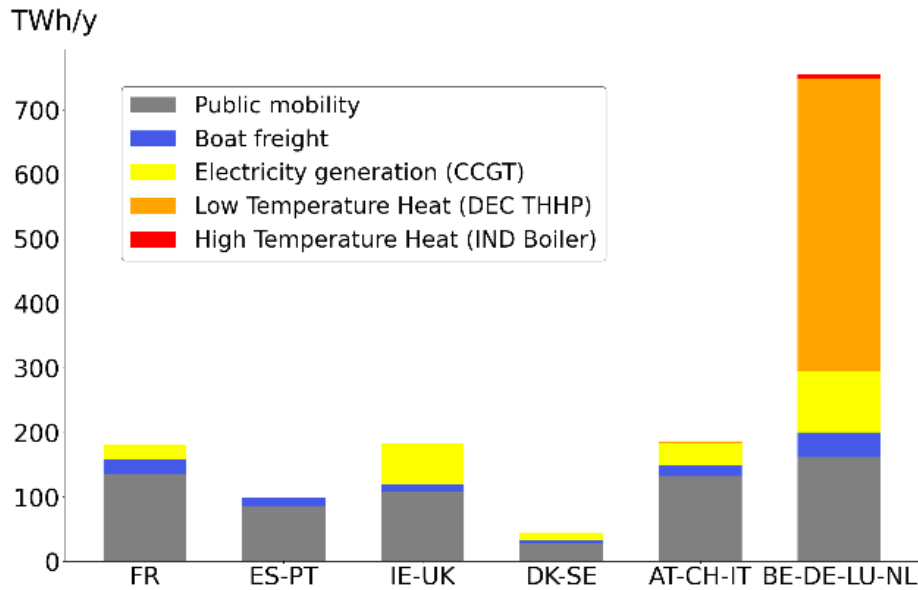


Figure 3.9: Detailed breakdown of the gas use by Western European region for the year 2035.

3.5 Comparison with the other renewable sources

As mentioned in Chapter 2, except for the region of Germany & Benelux, the renewable energy potential of each macro-cell is larger than its total end-use demand. This does not mean that the regions use only renewable energy sources to cover their demand. Figure 3.10 shows the renewable potential used by each macro-cell and compares it to the total renewable potential and the total end-use demand for each region.

Concerning the amount of renewable potentials used in the energy system, biomass represents around one third for every macro-cell. Solar and onshore wind power also represent the same proportion of the renewable sources used, meaning that biomass is just as important in the energy system. Moreover, biomass is the renewable resource that is the most used compared to its potential. Indeed, as can be seen on the left side of Figure 3.10, it is almost entirely consumed by all macro-cells. The few small quantities that are not used by certain regions, like France or Scandinavia, are exported to Germany & Benelux. This is represented on the bar chart of the latter region as a

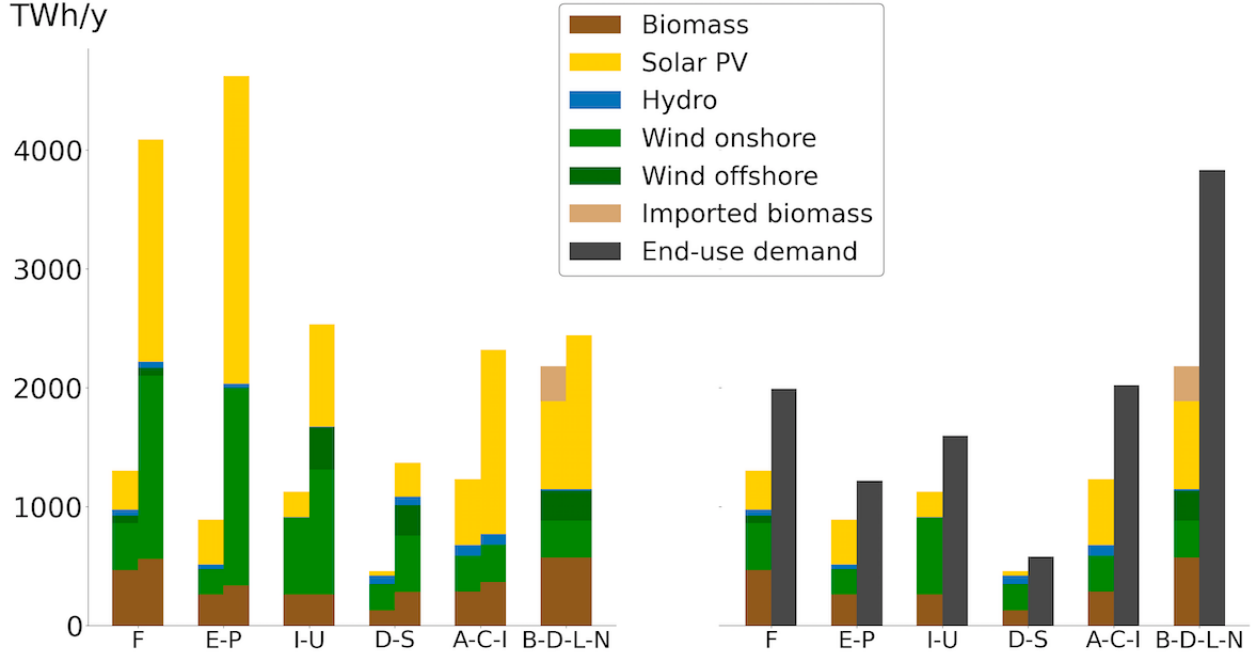


Figure 3.10: On the left, renewable energy used in EnergyScope vs total renewable energy potential by region. On the right, renewable energy used in EnergyScope vs total end-use demand by region. Regions are denoted with the first letter of their code (e.g. DK-SE is here D-S).

part of its used potential. Unlike biomass, only a small fraction of the solar power and the onshore wind potentials, which are much larger than the potential of biomass, is used. This highlights the important role of biomass in a low-carbon Western Europe.

When looking at the right side of Figure 3.10, it is noticeable that about three quarters of the total end-use demand is covered by the renewable energy potential in each region. The remaining part of the end-use demand is mostly supplemented by the import of natural gas from the exterior, depending on the gap each region has to fill. It is therefore not surprising to see Germany & Benelux importing more than 700 TWh of gas, as discussed earlier. Additionally, other local potentials, such as non-renewable waste, are used to produce energy. They are not represented in this graph as they are not renewable sources of energy. Finally, regions can also import a small amount of hydrogen or LFO from the exterior to complete any remaining gap in the coverage of their demands.

It is interesting to address the particular case of France, as it is the only region that possesses nuclear resources. This translates in a slightly different demand coverage because a large quantity of electricity, around 240 TWh per year, is produced from this source. Unlike the other macro-cells, France therefore does not need to import large quantities of fossil natural gas to cover its demands. Moreover, the production of electricity from nuclear resources does not emit any GHG emissions, meaning that France can use this resource and convert it without getting closer to the emissions limit. It is important to mention that France is the only country for which a potential in nuclear is implemented

in EnergyScope. This decision was taken in order to reflect the reality, considering the current energy context of France. The country is indeed known for its high reliance on nuclear power compared to other European countries [57]. Moreover, France intends to continue its production of nuclear power in order to reach carbon neutrality by 2050. This approach differs from the positions of other European countries like Germany [58].

Wind and solar energy are also two primordial sources of power in the optimisation of the European energy system. Concerning solar power, there are two types of PV installations capable of converting sun into EUT's : public installations (utility) and private installations (rooftop). The second type is more expensive and therefore rarely used by EnergyScope. Table 3.6 details the costs of the different wind and solar technologies implemented in the model.

Table 3.6: Costs of the different wind and solar renewable technologies implemented in EnergyScope. Investment costs are given in Meuro₂₀₁₅/GW, maintenance costs are given in Meuro₂₀₁₅/GWh.

Technology	Investment cost	Maintenance cost
Wind onshore	1010	16.8
Wind offshore	1667	51.9
PV Rooftop	738	9.7
PV Utility	335	8.4

At first glance, the installation of maximum capacity solar utility PV may seem to be the obvious choice in order to produce energy at the lowest cost. However, it should not be forgotten that wind and solar power are intermittent renewable energy sources, meaning that they cannot be produced at every hour of the day. Therefore, the technologies converting these sources possess a capacity factor. As EnergyScope optimises the energy system according to an hourly resolution, the capacity factor varies according to the hour of the day and the region in which the technology is installed. Solar energy will, for example, have a higher capacity factor at midday in the Iberian Peninsula than in the morning in Scandinavia. This parameter is thus as important as the investment and the maintenance costs of the technologies when the optimal conversion path needs to be chosen.

In general, wind offshore presents the highest average yearly capacity factor, between 0.35 and 0.5, among the four technologies of Table 3.6. The capacity factor helps wind technologies to be competitive in relation to solar technologies. Indeed, the wind onshore technology possesses an average yearly capacity factor that varies from 0.2 to 0.3 depending on the region it is placed in, whereas technologies producing solar power present an average capacity factor that fluctuates between 0.1 and 0.2, with the higher value corresponding to the average capacity factor in the Iberian Peninsula. Nevertheless, offshore wind requires much more maintenance, hence why it is rarely used as a priority. Onshore wind and solar PV are therefore the most used technologies.

Chapter 4

Alternative scenarios

In this chapter, the results obtained from the case study on Western Europe are discussed and nuanced. EnergyScope Multi-Cells has optimised the use of biomass resources in the six macro-cells in order to meet their various demands. The main result is that a large part of the biomass is used to cover the non-energy demand. The first section of this chapter will challenge this result by considering an alternative scenario in which the NED no longer exists in Western Europe. The model has also optimised the exchanges of biomass between regions, resulting in an important amount of biomass exchanges in the form of methanol. In order to investigate the role of the freight cost in the exchanges between regions, the second section examines a case in which the distances between macro-cells are assumed to be zero, meaning there is no cost taken into account for the freight. Finally, a third scenario is realised in which the implementation of gas exchanges between macro-cells in EnergyScope Multi-Cells is removed, in order to assess their importance in the energy system of Western Europe in 2035.

4.1 Discussion on the NED

For this first alternative scenario, the non-energy demand of the six regions is set to zero. Even if this may not be realistic, the objective is to explore if the woody biomass and the energy-dedicated lignocellulosic biomass crops are still used in the absence of the NED, and in the case they are, for what purpose. This is the first point of discussion of the section. To recall, the limit of GHG emissions is set in relation to the total actual emissions of each region. As the NED is removed from the energy system, a corresponding reduction in the emissions limit of each region is applied. The results obtained from this alternative scenario and from the case study of Chapter 3 are then discussed with the actual way to cover the NED.

4.1.1 Biomass use in the absence of NED

One of the key results from the optimisation realised in the previous chapter is the crucial role of biomass in the coverage of the non-energy demand. Indeed, in all the regions, woody biomass and energy-dedicated lignocellulosic biomass crops are used as the primary source for the production of HVC's and methanol. However, for this analysis, the NED is no longer taken into account. Figure 4.1 illustrates the difference between the used potential and the total potential of the two resources when the NED

is removed.

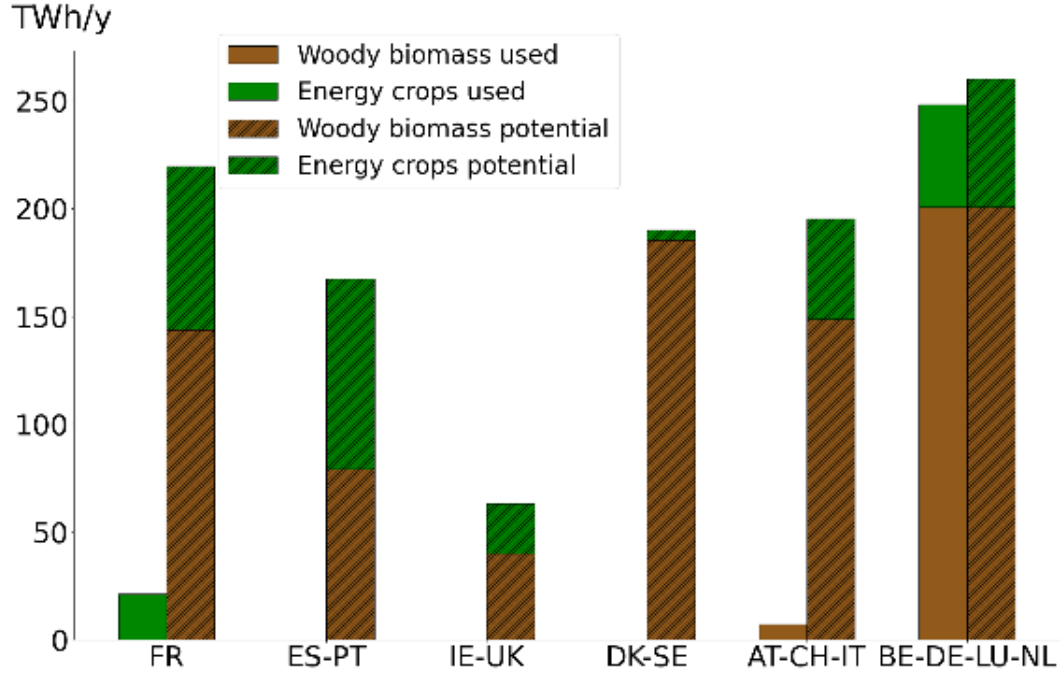


Figure 4.1: Used woody biomass and energy-dedicated lignocellulosic biomass crops potentials in EnergyScope vs total resource potentials by region.

It is easily remarked that the proportion of used potential of the two categories has drastically decreased in comparison to the base scenario. Indeed, the British Isles, the Iberian Peninsula and Scandinavia do not use their woody biomass or energy-dedicated crops potentials anymore.

Concerning the three other regions, part of the biomass potentials are used, and each macro-cell has its own way. France only exploits around 20% of its potential of energy-dedicated crops. As mentioned earlier, the resources from this category are cheaper than the ones of woody biomass, hence why this potential is prioritised by the country. This small quantity, representing between 20 and 25 TWh yearly, is converted into methanol and covers half of the boat freight demand.

Unlike France, the region of Italy & Alpine States prioritises the potential of woody biomass over energy-dedicated crops and converts a small amount into energy. This potential is used to complete multiple heat demands. The resources are either transformed into low temperature heat or into high temperature heat by being burned in different types of boilers. Nevertheless, the proportion of the demand covered is minimal compared to the impacts of biowaste, other biomass residues and electricity on these demands, making it in fact a negligible contribution.

As previously analysed, Germany & Benelux faces a significant gap between its renewable energy potential and its total end-use demand. In the case study presented in

Chapter 3, this had a significant impact on the management of the renewable resources of the other regions as they exported part of their potentials, mainly transformed into methanol, to the region in need. In this alternative scenario, no freight exchanges happen between macro-cells anymore. While being a strong result, it is a logical one as these exchanges were made in order to help Germany & Benelux cover its NED. When looking at the graph of Figure 4.1, Germany & Benelux stands out as, unlike the other regions, almost all the biomass potential of woody biomass and energy-dedicated crops is used. In this case, the potential is essentially used for the production of heat at high temperature. Given the energy challenges faced by the region, it is not surprising to see Germany & Benelux using the resources they possess. However, as can be seen on the graph, it is interesting to note that a small part of the energy-dedicated crops potential is not converted. Indeed, the demands in heat, electricity and mobility are already filled with electricity or gas conversion, meaning the remainder of energy-dedicated crops is left unused.

When analysing the three other demands, there are only little changes in comparison to the case study of the third chapter. This is easily explained by the fact that, except for Germany & Benelux, all the regions cover their NED using mainly woody biomass and energy-dedicated lignocellulosic biomass crops, which are not used anymore in this case. For example, the heat demand is still filled with transformed biowaste, transformed other biomass residues, transformed non-renewable waste and electricity. Wet biomass is still at the basis of the production of biogas. The only notable modification is found in the heat demand of Germany & Benelux, which now uses its woody biomass and energy-dedicated crops to produce heat. This permits the region to produce less electricity from solar panels, which is an expensive technology presenting a low yearly average capacity factor due to the lack of sun in the region.

To conclude, except for the particular case of Germany & Benelux, woody biomass and energy-dedicated lignocellulosic biomass crops have limited usefulness for the demands other than NED. In most cases, EnergyScope prioritises the use of other renewable energy sources, such as solar or wind, for the generation of green electricity. However, to produce methanol or HVC, biomass stays the most optimal resource. It is indeed the only direct renewable option to cover these demands, as the other possibilities are oil or gas-based production technologies.

4.1.2 The actual context of the NED

The optimisations made in Chapters 3 and 4 were based on the data processed by the EnergyScope model. It is important to note that the model does not consider the existing reality and the potential willingness associated to a transition to bioenergy. As the target year of the study is 2035, which is already around the corner, the results obtained need to be nuanced with the actual reality. The woody biomass, for example, currently possesses a different role in comparison to its role accorded by the model for the year 2035. Presently, approximately 85% of the solid biomass in Europe is used in boilers to generate renewable heat [59]. A lot of the woody biomass potential is considered in this production. EnergyScope presents a totally different use of the resource, as it is specifically used to cover the NED. Moreover, even if the NED is not considered, the

majority of the regions do not use the woody biomass to produce heat. Indeed, only Germany & Benelux uses part of its woody biomass to fill the heat demand. The same can be said for the use of energy-dedicated lignocellulosic biomass crops.

Concerning the actual fabrication of the NED in Europe, and more precisely the HVC's, an important portion of their production still relies on petroleum and natural gas [60]. These resources are indeed cost-effective and present a high efficiency in the process of HVC production. While bioenergy offers many advantages, and especially the fact it diminishes the environmental impact of the energy industry on the planet, its adoption is blocked due to financial issues. Indeed, in the absence of mandatory GHG emissions limits, many European countries prefer to use cheaper resources rather than renewable ones. It is therefore a question of both cost effectiveness and willingness to prioritise sustainable alternatives.

4.2 Discussion considering free exchanges by freight

In this second alternative scenario, distances between macro-cells are assumed to be 0 km. In other words, this means that the exchanges realised by freight are costless. Only the price of the transported resource is taken into account for the price used in trading. The objective of this discussion is to analyse the importance of the freight cost in the exchanges of biomass. In the case study on Western Europe, methanol produced from woody biomass or energy-dedicated lignocellulosic biomass crops is the most exchanged renewable freight resource, with all the exchanges being destined to the region of Germany & Benelux. By modifying the distances between regions to zero in the model, it is hoped to see the apparition of new freight exchanges as well as an evolution of the trades happening in the base scenario.

As explained in Chapter 2, woody biomass is the only biomass resource allowed to be exchanged by freight between macro-cells in EnergyScope. This resource can either be exported after being transformed to methanol, as it is the case for the exchanges in the case study of Chapter 3, or be exported as raw woody biomass. Both options are available for this scenario as well. The exchanges happening for an optimisation presenting zero distances between regions, meaning there are no freight costs included in the price of the exchanges, are showed on Figure 4.2.

A first observation is the high number of exchanges occurring in this scenario. Indeed, whether the countries are exporting woody biomass or methanol, there are more exchanges compared to the optimisation of the previous chapter. When analysing the maps, it is also easy to see that the exchanges of woody biomass are significantly larger than the ones of methanol. Indeed, more than 300 TWh of woody biomass is sent to Germany & Benelux, while the largest exchange of methanol is under 10 TWh. In fact, the exchanges of woody biomass replace the exchanges of renewable methanol obtained in Chapter 3 for the production of HVC's. These results already underline the importance of the freight cost. In the case study of Chapter 3, the higher LHV of methanol is the key factor that explains why exchanges in the form of methanol are preferred over trades of raw woody biomass.

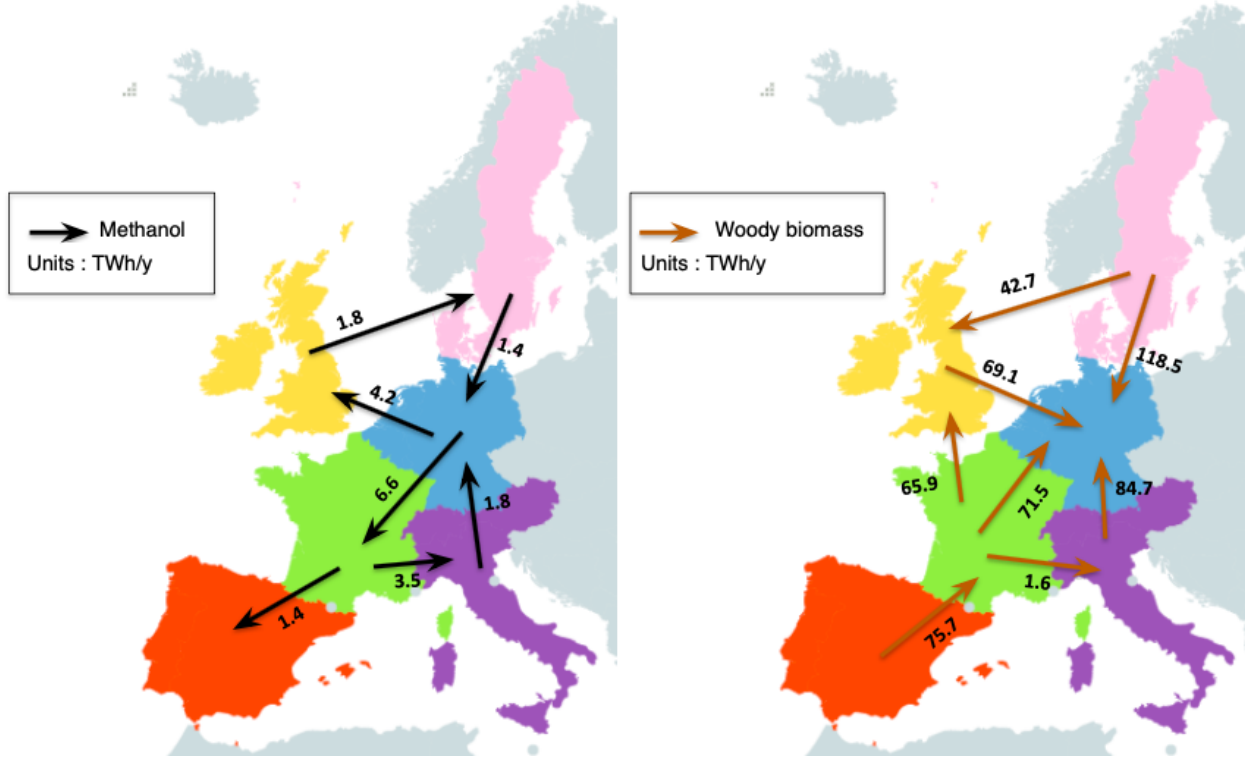


Figure 4.2: Yearly methanol and woody biomass exchanges, expressed in TWh/y, across Western Europe for the year 2035 when the distance parameters between macro-cells are set to 0 km.

When analysing the exchanges themselves, major differences appear between the two maps. Looking at the exchanges of woody biomass, the majority is destined to Germany & Benelux. This is logical as the region presents a local renewable potential lower than its demand. The region encompassing the British Isles also imports woody biomass, but the amount is smaller than for its neighbour. Concerning the trades of methanol, it is interesting to notice that Germany & Benelux is the only region presenting a positive balance. Indeed, all the other macro-cells import methanol, which is originally from Germany & Benelux, in order to cover their corresponding demand. This result may seem special, but it is simply explained by the fact that EnergyScope optimises the system for a cooperative Europe. Indeed, the technology transforming the woody biomass to methanol produces a small amount of heat as well. For each GWh of methanol produced, 0.35 GWh of low temperature heat is generated. As seen in the previous chapter, the region of Germany & Benelux uses a large amount of gas to produce heat at low temperature. Letting the region produce the methanol of the six macro-cells helps it cover its low temperature heat demand, while also benefiting the whole system as Germany & Benelux can import a little less natural gas.

Nevertheless, since these exchanges of methanol are quite small and not very realistic, the rest of the analysis will focus on the use and the exchanges of raw woody biomass. As the freight cost is not considered anymore in EnergyScope, the exchangeable resources are redistributed across regions. Figure 4.3 resumes the new distribution of

woody biomass in each macro-cell after the imports have taken place.

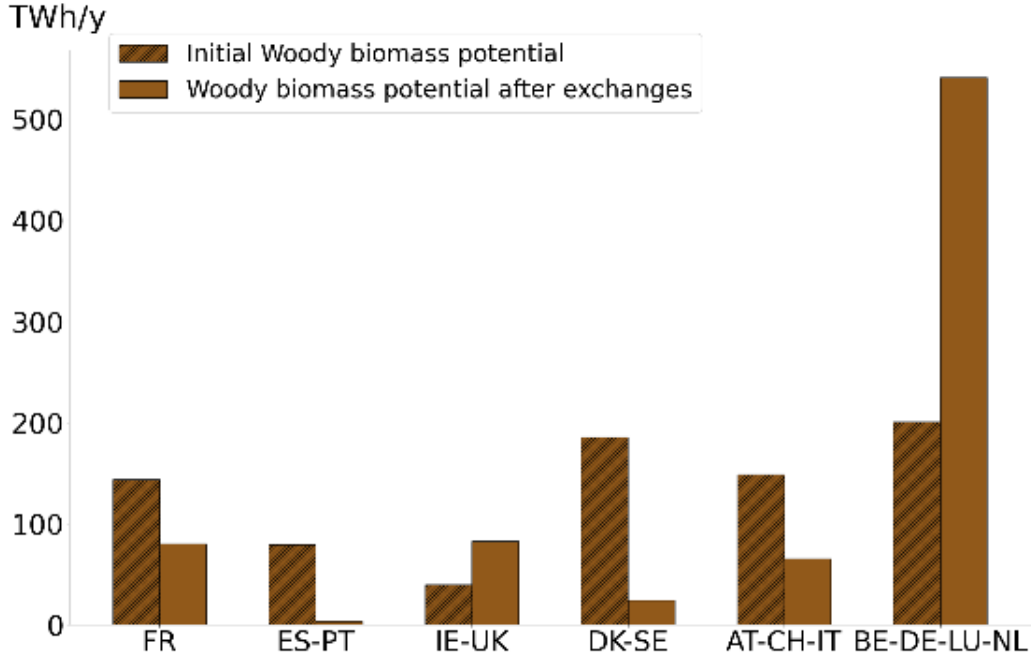


Figure 4.3: Woody biomass potential of each region before the exchanges vs woody biomass potential of each region after the exchanges.

Two regions possess a larger quantity of woody biomass after the exchanges have occurred, i.e. Germany & Benelux and the British Isles. These two regions correspond to the same ones that have difficulties covering their NED with local resources in the base scenario. The most optimal role of woody biomass is thus to meet the NED, hence why EnergyScope redistributes the resource between macro-cells. Within the constituents of the NED, methanol is only taking up a small part of the woody biomass potential. Each macro-cell imports its methanol from Germany & Benelux, as explained above. As ammonia is not made from biomass, the production of HVC's is thus the main purpose of the woody biomass and its exchanges. The detailed distribution of biomass for the fabrication of HVC's is displayed on Figure 4.4.

The wood redistribution allows Western European regions to cover their HVC demand only with European biomass and without emitting any GHG emissions. For the majority of the macro-cells, woody biomass is the most used resource to produce HVC's. However, it is interesting to note that each region uses the entirety of its energy-dedicated lignocellulosic biomass crops potential, which is not the case in the base scenario. Moreover, certain regions, like the Iberian Peninsula, use this potential before employing their woody biomass, even if the prices of the resources are higher. This result seems contradictory, but the explanation lies in the optimisation of EnergyScope. The model indeed optimises the whole system before optimising the energy system of each macro-cell. The Iberian Peninsula thus pays more to cover its HVC demand, but it helps other regions, especially Germany & Benelux, in terms of costs and

emissions by exporting its woody biomass, hence benefiting Western Europe as a whole.

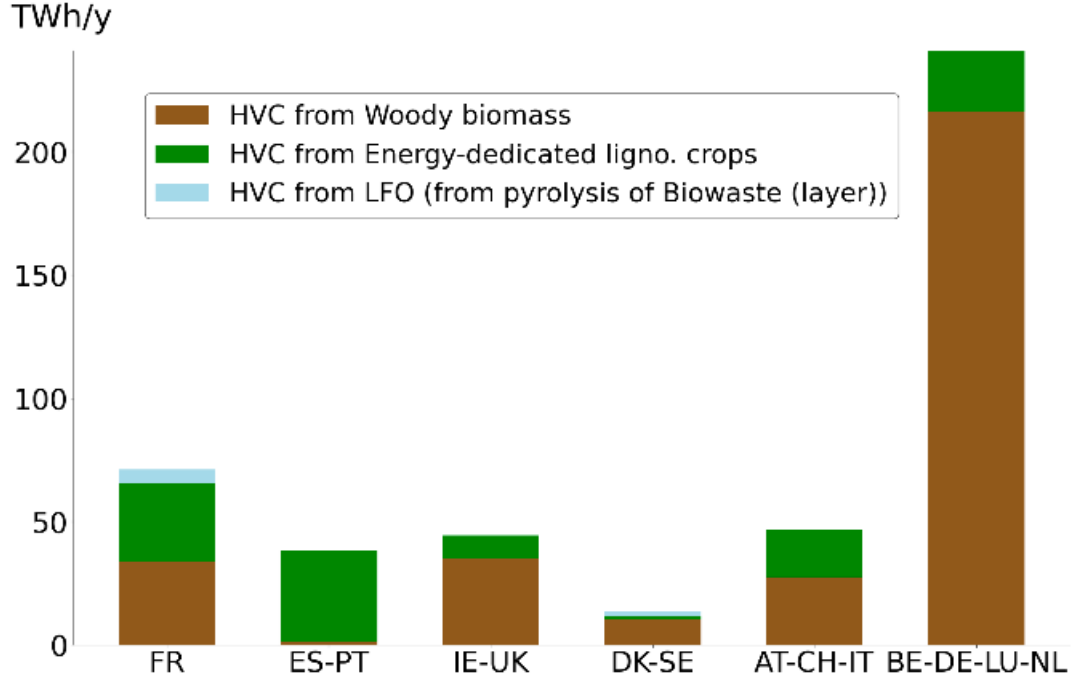


Figure 4.4: Detailed breakdown of the HVC demand coverage by Western European region for the year 2035 when the distance parameters between macro-cells are set to 0km.

This same methodology is used to cover the high temperature heat demand. Indeed, EnergyScope redistributes the non-renewable waste across regions in order to optimise their utility. This is a simple consequence of the removal of the freight cost and will not be further analysed.

Concerning the exchanges through networks, regarding gas or electricity exchanges, there are no real changes compared to the case considering normal freight. Western Europe still imports a lot of natural gas from the exterior, especially Germany & Benelux, and the other five macro-cells send an extra amount of fossil natural gas to this region so that it can cover its demands. For electricity, the trades also stay the same, with Germany & Benelux being the sole net importer. Removing the cost of the freight does not have a real influence on the exchanges by networks.

To conclude, the optimal use of woody biomass and energy-dedicated lignocellulosic biomass crops is still to cover the demands in methanol and HVC, as it is the case in the base scenario of Chapter 3. To optimise the energy system of each macro-cell, EnergyScope reallocates woody biomass across Western Europe. Indeed, the biomass energy potential of the six macro-cells is sufficient to meet the demands of each region. The region of Germany & Benelux is once again far ahead in terms of import, with the resources being only woody biomass. A small part of this woody biomass is then transformed and exported to the other regions in order for them to cover their demand

in methanol. In an ideal scenario, the best way to address this challenge is thus to redistribute the woody biomass in proportion to the NED of each region. In a realistic scenario though, it is preferable to convert raw biomass into resources with higher energy density, such as methanol, before exporting it. The cost of the freight is indeed the main obstacle for the export of raw biomass.

4.3 Discussion on gas exchanges

As detailed in Chapter 3, the region of Germany & Benelux imports a large amount of natural gas from the exterior of the system to meet its needs. Since it is still not enough, an additional amount of natural gas is imported via the five other regions, which have imported these extra amounts to help Germany & Benelux to cover its demands. Even if it is the latter region that uses the resource, it is the five other regions that account for the GHG emissions of these imports. This allows Germany & Benelux to avoid exceeding its limit. While this is how it is implemented in EnergyScope Multi-cells, it would be interesting to know how the region of Germany & Benelux operates on its own, i.e. without receiving the needed quantities of gas from its neighbours. In this section, the possibility of exchanging gas between regions is therefore removed from the model.

When gas exchanges between macro-cells are allowed, Germany & Benelux imports a total of 701 TWh of natural gas. 561 TWh come directly from the exterior of the system, and the remaining 140 TWh are exported from the five other regions, as illustrated on Figure 3.8 in the third chapter. Now that these exchanges are not permitted anymore, the region of Germany & Benelux has to replace them without surpassing the GHG emissions limit.

In this new scenario, Germany & Benelux imports a total of 603 TWh of natural gas from the exterior of the system. As this is a little more than for the base scenario, the quantity of imported LFO is thus reduced in order to respect the emissions limit. This LFO was primarily used to cover the NED of the region, so to fill the gap left by this resource, more renewable methanol from Italy & Alpine States is imported. Compared to the 701 TWh of the optimisation realised in Chapter 3, Germany & Benelux has now less gas available. The distribution of its use is therefore slightly different from the base scenario, as illustrated in Figure 4.5. It should not be forgotten that the biogas produced by the wet biomass is included in this distribution.

Regarding the demands in public mobility and boat freight, nothing changes. As it is the most optimal use for natural gas, they are still completely covered by this resource. The difference compared to the base scenario lies principally in the coverage of the low temperature heat. Natural gas is indeed replaced by electricity, which is produced thanks to the installation of new PV panels. To recall, as shown on Figure 3.10, solar PV is the only technology not used to its maximum potential by the region of Germany & Benelux.

Concerning the five other regions, since they no longer have to import natural gas from

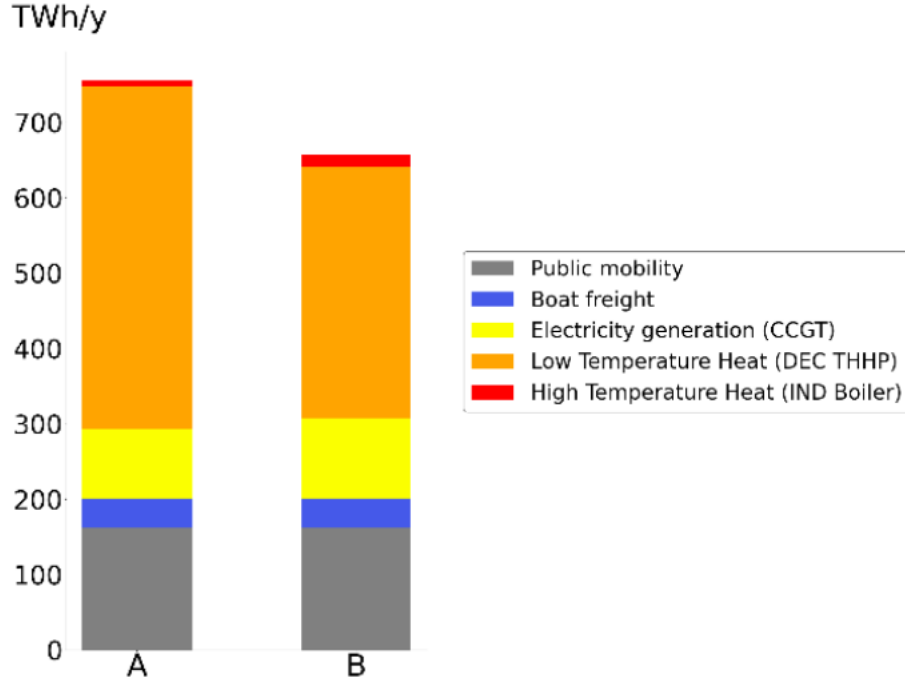


Figure 4.5: Scenario A presents the gas use distribution when gas exchanges are allowed between macro-cells. Scenario B presents the distribution in the case gas exchanges are prohibited.

the exterior of the system for the region of Germany & Benelux, they can emit more GHG for their own energy production. Not surprisingly, the regions choose to locally use the natural gas previously exported. Its low cost is the factor that plays in favour of the resource. This extra amount of gas replaces part of the electricity used to produce low temperature heat. As this electricity is generated with the solar PV technology, which is one of the most onerous ones, reducing its use is a cost-effective solution.

In fact, the scenario studied in this section is potentially more realistic than the base scenario. Indeed, by prohibiting gas exchanges between macro-cells, each region is constrained to respect its own emission limit, meaning that Germany & Benelux cannot use the other regions to take over a fraction of its GHG emissions. An analysis of this minor issue in the modelling of EnergyScope Multi-Cells could be an interesting study for future research.

Chapter 5

Sensitivity analyses

In the two previous chapters, the Western European energy system was optimised and the results were discussed by realising alternative scenarios. In this chapter, the objective is to challenge some results obtained before. First, the optimisation of the system has led to significant exchanges of renewable methanol in Europe. A sensitivity study on the biomass-to-methanol conversion technology is therefore carried out in order to assess the impact of its price on the results. A second study is realised, challenging the role of fossil natural gas and its influence on the energy system by modifying its price according to recent trends.

5.1 In-depth study on the renewable methanol exchanges

The EnergyScope optimisations suggest that a significant part of the NED of Germany & Benelux will be covered by renewable energy imported from border countries in a low-carbon energy system by 2035. This is indeed the result obtained in the base scenario, where half of the NED of Germany & Benelux is covered by imports of renewable methanol. Although this result is the most optimal to ensure the sustainability of the European energy system, having renewable methanol exchanges of this order of magnitude in 2035 does not correspond to the actual reality.

In reality, most of the methanol production comes from coal or natural gas. In the world, less than 1% of the global methanol production is attributed to biomass [61]. Observing large renewable methanol trades in Europe in 2035 is therefore hard to believe. However, it is known that methanol could potentially have a role in the energy transition. According to the Methanol Institute, due to the increasing number of renewable methanol projects, it is clear that production sales for bio-methanol facilities will increase in the whole world over the next few years [62]. Renewable methanol exchanges are thus a highly viable option and will certainly have a role to play in the European energy transition.

In this section, the plausibility of the exchanges of renewable methanol obtained in the case study on Western Europe is challenged. This is done by modifying the cost of the technology that converts biomass into methanol. Figure 5.1 shows the results obtained

for multiple prices of the biomass-to-methanol technology.

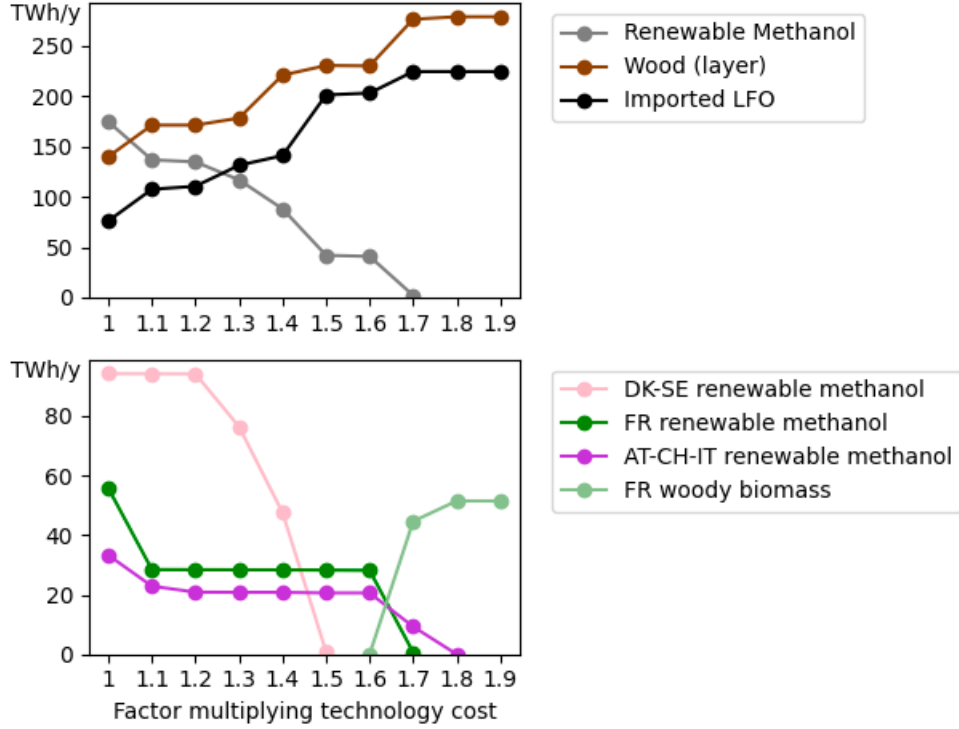


Figure 5.1: On the top, Germany & Benelux HVC's production in function of the biomass-to-methanol technology cost. On the bottom, the quantity of resources imported by Germany & Benelux in function of the biomass-to-methanol technology cost.

When considering a 10% increase in the price of the conversion technology, there is a significant reduction in the quantity of renewable methanol exported from France. As France was covering part of its NED with LFO's produced from biowaste, a slight increase in price leads indeed the model to find a more optimal solution than to burn resources from the Biowaste layer by pyrolysis. The country uses more woody biomass to cover its NED, which results in less renewable methanol available for the region of Germany & Benelux. This shows how sensitive the model is to the use of pyrolysis technologies. The amount of renewable methanol exported from Italy & Alpines States has also fallen, which is explained by the fact that the model no longer transforms Italian energy-dedicated crops into methanol. As seen in Chapter 3, the methanol produced from these resources is the most expensive. It is thus not surprising to see that the model reduces its use in the European energy system when increasing the price of its conversion technology.

However, it is interesting to note that the base price of the biomass-to-methanol technology can be increased up to 30% without causing another significant drop in the quantities of renewable methanol exchanged. Moreover, for methanol coming from the regions of France and Italy & Alpines States, only an increase of 70% in the price of the technology sees the quantities of imported methanol decrease. Indeed, at this point, exporting methanol based of woody biomass is still the most optimal solution. How-

ever, this is not the case for Scandinavian methanol as the woody biomass of the region is the most expensive one in Europe and the distance between Germany & Benelux and Scandinavia is quite large. The quantity of imported methanol from this region starts decreasing, as the costs of the technology increases by 30%, and ceases when the increase reaches 50%, i.e. when this resource is not exchanged anymore.

From an increase of 80% in the price of the biomass-to-methanol technology, renewable methanol exchanges are no longer an optimal solution. It is indeed partly replaced by woody biomass exports coming from France. As this is the closest region to Germany & Benelux, the cost of the freight is the lowest one in this case. The amount of woody biomass exchanges increases as the price of the technology rises, but in general, the cost of the biomass-to-methanol technology has to increase considerably before exchanges of raw biomass happen.

Regarding the production of HVC's in the region of Germany & Benelux, the proportion of renewable methanol is gradually replaced by woody biomass, which was used in boilers to produce heat in the base scenario, and by LFO's imported from the exterior. As the latter are responsible for GHG emissions, the gas consumption of the region needs to be reduced in order to avoid surpassing the emissions limit. The importation of renewable methanol has thus an important role in maintaining the equilibrium of the Western European energy system.

To conclude, the model is not particularly sensitive to the price of the technology converting biomass into methanol. In fact, renewable methanol exchanges remain important with a price of the technology that increases up to 50% of its base price. Biomass exchanges only appear when the cost of the technology reaches high levels. Methanol exchanges stay therefore more optimal than raw biomass exchanges and play a significant role in the energy system.

5.2 Solutions to gas dependency

As introduced in the case study on Western Europe, fossil fuels are the most common source of energy in the world, with oil being the most used resource. However, according to EnergyScope, and without forgetting that coal is not implemented in this study, natural gas is the fossil fuel on which the system relies on the most for the year 2035. Indeed, as observed in the optimisations realised on Western Europe, natural gas is preferred over oil in order to cover the demand sectors, with in particular Germany & Benelux needing a significant amount. As the society is heading towards carbon neutrality, it is thus interesting to see how the European energy system reacts to a modification in the price of natural gas.

In the optimisation of Chapter 3, the price of natural gas is set at 44 €/MWh. This price corresponds to the months of March and April of 2023, meaning it is a recent price which is up to date. However, as the energy world is currently very volatile, prices can increase in a short period of time. This was the case at the end of 2021 when, due to the political conflict between Ukraine and Russia, the prices started rising at a very

high rate. During the month of August 2022, the price even reached the value of 340 €/MWh, which has never happened before. Since then, as shown in Figure 5.2, the price slowly dropped until it reached its actual value, which is approximately equal to the price before October 2021.



Figure 5.2: Evolution of the European natural gas prices from mid-2021 to the end of April 2023. Figure from Trading Economics [63].

As the prices of natural gas have varied a lot recently, and since they can still vary significantly in the next months or years, conducting a sensitivity analysis by modifying this parameter is a legitimate choice. A new optimisation using EnergyScope is therefore realised, with the price of the fossil natural gas set to 137.73 €/MWh, which corresponds to the average price of the year 2022. As it was the year knowing the most variation, taking its average is a good assumption.

The main result of this EnergyScope optimisation is the elimination of any use of fossil natural gas. Indeed, all regions have stopped importing natural gas from the exterior of the system, the main reason being obviously its price, which is far too expensive. The role that natural gas played in the previous optimisations is thus left empty, and each region has its own way to fill the void.

A first positive consequence of this analysis is the fact that all regions, except Germany & Benelux, do not pollute anymore. Indeed, each macro-cell covers its demands with the renewable potential it possesses, which leads to the absence of GHG emissions. Concerning the region of Germany & Benelux, as it is the only region presenting a higher total end-use demand than its renewable potential, it needs to fill the void left by the natural gas. Part of the solution lies in increasing the quantity of imported LFO, as the region imports a total of 366 TWh in this scenario, which corresponds to around 18 times the amount imported in the optimisation of Chapter 3. Indeed, since the use of natural gas contributed to an important part of the accepted GHG emis-

sions, a significant amount of LFO can be used by the region of Germany & Benelux to optimise its energy system. The choice is put on an increased amount of imported LFO because it is the most profitable way for the macro-cell to cover its demands while complying with the emissions limit. This LFO is thus transformed into HVC's and, with the woody biomass and the energy-dedicated lignocellulosic biomass crops potentials, it covers the NED of the region. Concerning the other regions, the local biomass resources are sufficient to cover the NED.

As a result of a new way to cover its NED, the region of Germany & Benelux is no longer interested in the importation of renewable methanol from its neighbours. Its NED is indeed completely covered by imported LFO and part of its own biomass. For the three macro-cells that are exporting renewable methanol in the base scenario, i.e. France, Italy & Alpine States and Scandinavia, the use of biomass declines considerably. Renewable methanol is only used here as fuel for freight boats. The rest of the mobility demand will be detailed later on.

Since natural gas covered a large part of the energy demands of the regions, and especially for Germany & Benelux, it must be replaced by an equivalent resource capable of producing the same EUT's. To compensate the absence of natural gas, some regions start producing gas by synthetic methanation, which is a technology transforming hydrogen into gas. A small quantity of this production is used to cover local demands, while the majority is exported to other macro-cells. The exchanges that take place are illustrated on Figure 5.3.

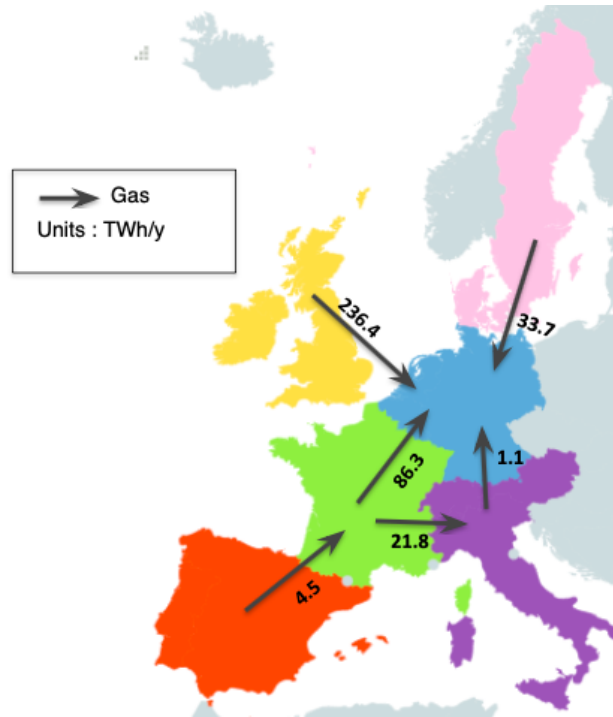


Figure 5.3: Yearly gas exchanges, expressed in TWh/y, across Western Europe for the year 2035 when considering a higher price for the natural gas coming from the exterior of the system.

Once again, Germany & Benelux is the region presenting the most importations in Western Europe since it does not possess enough resources to produce gas. Italy & Alpine States also imports a small quantity of gas, while the other macro-cells are all exporters. It is interesting to note that France is the only country exporting part of its gas produced from wet biomass. The other regions only send gas produced of synthetic methanation. Among the exporting regions, the British Isles are far ahead of the other macro-cells, as they send 236.4 TWh of gas to Germany & Benelux. This result seems improbable, but it is easily explained by the expansion of the production of electricity. Indeed, with the removal of natural gas, Western European countries also increase their electricity production substantially. This is shown in Figure 5.4, which resumes the extra quantities of electricity that are produced when the price of natural gas is too high. This increased electricity production is the basis of almost all the gas exchanges since it is mainly used to produce hydrogen by electrolysis, which in turn permits the production of gas. The huge amount of electricity produced by the region of the British Isles is thus converted to hydrogen before being transformed to gas by synthetic methanation, which explains the large export from this region to Germany & Benelux.

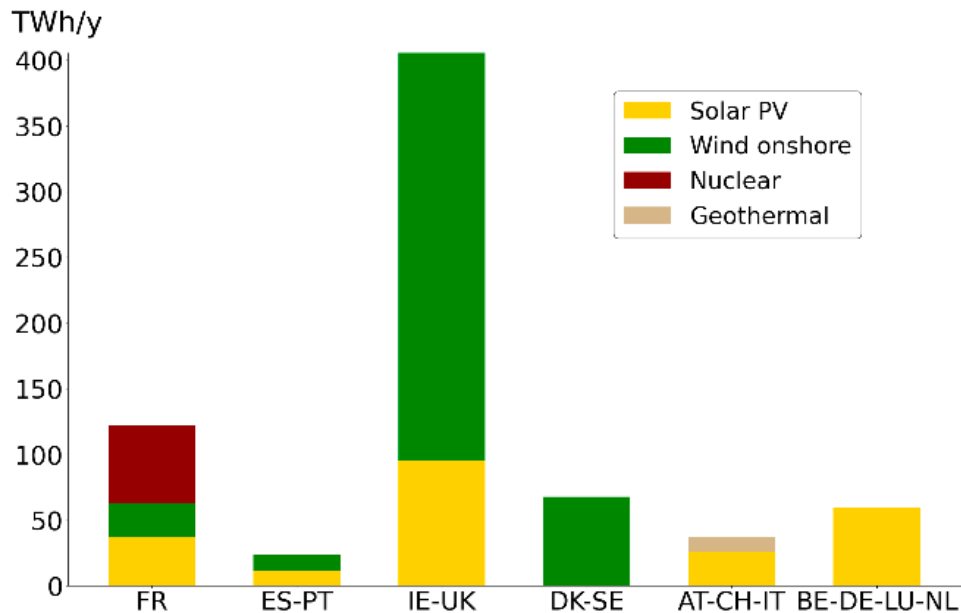


Figure 5.4: Additional amount of electricity produced by each region in 2035 due to higher natural gas prices.

The majority of the electricity production comes from onshore wind and solar PV, which shows that regions tend to use their renewable sources of energy. Only France derogates from the rule as it uses part of its nuclear potential to produce electricity, which is also the case in the base scenario.

Concerning the gas produced by synthetic methanation, as explained above, the majority is exported to the region of Germany & Benelux. The rest fills a small part of

the local mobility demand, which is now mainly covered by electricity. Indeed, in this optimisation, the use of CNG buses diminishes heavily in favour of public trains working on electricity in order to meet the public mobility demand. On the other hand, in Germany & Benelux, the coverage of this demand is still done by using 100% of imported gas. As the region has less gas available than in the base scenario, it is the low temperature heat demand that it is not able to cover with gas anymore.

To cover the low temperature heat demand, EnergyScope has found an unusual, but optimal, solution. Indeed, the model converts the rest of the imported gas into electricity by CCGT and then transforms this electricity into low temperature heat. The overall efficiency of this process, which is equal to 1.89, is in fact higher than the efficiency of converting gas directly into heat at low temperature, equal to 1.5. Although this process is more expensive, it is the most optimal solution for this scenario. It may seem inefficient to convert gas into electricity when it is originally produced from electricity, but the model does it in this way because the maximum amount of gas that can be exchanged between regions is much higher than the maximum exchange capacity of electricity. For example, taking the trade happening between the British Isles and Germany & Benelux, the maximum amount of gas that can be exchanged is equal to 237.9 TWh, while the maximum capacity is equal to 29.7 TWh if there are electricity exchanges. Since Germany & Benelux has to import a considerable amount of resources from other regions, EnergyScope chooses to transport these resources in the form of gas. Next to the electricity produced from gas, the region also invests in additional solar PV installations in order to complete its low temperature heat demand with local electricity.

In conclusion, the higher natural gas prices lead to a greater use of renewable energy sources, which is realised by installing new wind and solar energy technologies. Although biomass is a good solution to increase the share of renewable energies, its potential remains limited compared to the solar and wind potentials, which can enable a complete transition away from fossil fuels. Paradoxically, the rise in gas prices has even reduced the use of biomass. Indeed, while it plays the same role in the regions as in the base scenario, it is no longer exchanged between macro-cells. Regions prefer to exchange gas that is produced from hydrogen. This highlights the limits of biomass, which can be used in an optimal scenario for the coverage of the NED and part of the high temperature heat demand. If the price used in this analysis was the actual price for the year 2022, the use of renewable technologies would theoretically have been more advantageous in terms of cost than gas. In fact, maybe the instability of fossil fuels will accelerate the transition to renewable energies in the future.

Conclusion

Accounting for 75% of the carbon emissions, the energy system is the main cause of global warming in Europe [2]. To reduce its impact on the environment, the continent has entered a transition phase, with as final goal a carbon-neutral Europe in 2050 [2]. In order to reach this target, renewable energy sources will play an important role in the years to come. As bioenergy currently accounts for 60% of Europe's renewable energy consumption, biomass is one of the most promising resources for the energy transition [5]. Therefore, the first research question of this master thesis was : **"What role will biomass play in a low-carbon European energy system by 2035 ?"**. Since some European countries do not have enough renewable potential to cover their energy demand [3], a second question was added to this study, that is : **"Can biomass exchanges help countries to use more renewable energy by 2035 ?"**.

In order to assess correctly the impact of biomass resources on the environment, a comprehensive dataset was created. Biomass was divided into six categories, i.e. woody biomass, energy-dedicated lignocellulosic biomass crops, wet biomass, other biomass residues, biowaste and edible energy crops. Due to a surely reduced use in the future, resources from the last category were not taken into account in this study. Each category was given a local potential and cost based on the ENSPRESO database [8], as well as a specific GWP. Research on the different conversion technologies of biomass to energy and on the transport of biomass was also carried out.

The five considered biomass categories and their conversion technologies were then implemented in EnergyScope Multi-Cells, which is an open-source model optimising an energy system under certain constraints for a future target year. With this implementation, the model optimised the energy system of Western Europe for 2035 while applying a 90% reduction of GHG emissions compared to the 1990 level. The main result is that the Western European countries use their biomass potentials almost entirely. Indeed, while presenting a much smaller potential than wind and solar energy, bioenergy is used at the same proportion than the other renewable sources. Biomass is therefore an important source of green energy for a future low-carbon Europe.

Covering the non-energy demand is always the first role of biomass, and more particularly of woody biomass and energy-dedicated lignocellulosic biomass crops. These resources are mainly transformed into methanol or HVC's and, as Germany & Benelux presents a severe lack of renewable potential to cover its demands, considerable amounts of renewable methanol are exported to this region. Concerning biowaste and other biomass residues, even if they can be used to produce HVC's by the intermediate of

LFO's, they are mostly converted locally into high temperature heat. Finally, regarding wet biomass, its potential is used most optimally when transformed into biogas through biomethanation. This is the case in every Western European macro-cell, which are, to recall, regions regrouping countries located in the same area and presenting similarities.

According to the optimisation, despite a 90% GHG emissions reduction imposed to the model, fossil natural gas will still represent an important part of the sources needed in the energy system in 2035. Indeed, every region imports a certain quantity from the exterior of the system to meet its public mobility demand and, for Germany & Benelux, this resource will help cover a large part of its low heat temperature. While covering up to 40% of the gas consumption in certain Western European regions, wet biomass does not have sufficient sustainable potential to completely replace fossil gas.

In order to nuance the results of the optimisation realised on Western Europe, some alternative scenarios have been studied. The first scenario, in which the NED of each macro-cell is put to 0, showed that biomass has a limited usefulness when the NED is not considered. Other renewable sources are indeed preferred in the energy system in that case. When considering free freight exchanges, due to the price of the resource, trades of woody biomass appear to be the better solution, replacing the exchanges of renewable methanol from the global optimisation. In this second alternative scenario, covering the NED is still the priority in each region. Since the region of Germany & Benelux imports fossil gas from its neighbours, a third case, in which gas exchanges between macro-cells are prohibited, was studied. Germany & Benelux imports then a lot of natural gas from the exterior of the system, while installing more solar PV installations to fill the demands that are normally covered by the exchanged gas.

Moreover, sensitivity analyses were made to discuss and check if the results hold up. Increasing the price of the biomass-to-methanol technology does not change the fact that methanol exchanges are the most optimal solution to help the region of Germany & Benelux cover its demands. On the other hand, increasing the price of fossil natural gas has a significant impact on the energy system of Western European countries, as renewable energy sources replace the previously considerable amounts of natural gas used.

The work performed in this master thesis evidently presents some limitations. Firstly, the results obtained are based on the linear programming model EnergyScope, meaning it only takes the cheapest option without considering all the possibilities. The model will therefore rarely spread the use of a resource over different energy production options. Secondly, EnergyScope does not possess all the already existing energy infrastructures. The results provide an idea of the most cost-effective energy system for the year 2035 without taking into account the transitional steps needed to reach this objective. The model might thus be disconnected from the reality, as some of the solutions proposed might be difficult to apply for 2035. Moreover, the objective of this study was to highlight the potential role of biomass in a low-carbon Europe. Given that fossil fuels are still widely used today, a 90% reduction in GHG emissions by 2035 stays an optimistic scenario. Finally, as examined with the fossil natural gas, the price of a resource or a technology might vary considerably in the years to come, which could cause a radical change in the proposed energy system.

To conclude, this study has shown the optimal use of biomass in the European energy transition, and more precisely for the year 2035. The optimisations also determined that biomass exchanges, mostly in the form of renewable methanol, can enable a cooperative Europe to use more renewable potential. While giving a solid basis to the role of biomass in the energy system, this master thesis can be extended by future studies. The work could be extended to the whole of Europe in order to see if the obtained results are verified on a larger scale. Moreover, it might be interesting to add countries located outside of Europe, such as Canada or China, to the study. Indeed, these two countries are the largest exporters of wood in the world, holding more than 25% of this market [64]. Finally, an in-depth study on the methanolation of biomass and methanol exchanges could be carried out to see whether this solution is sustainable and feasible in the actual world or whether it is only theoretical.

Appendices

A Biomass data

A.1 Biomass potentials

Table 5.1: Biomass potentials, expressed in GWh, per country for the year 2035. "Energy crops" here defines "Energy-dedicated lignocellulosic biomass crops".

Region	Woody biomass	Energy crops	Wet biomass	Other biomass residues	Biowaste
AT	58657.97	4539.83	5365.43	7301.95	2321.69
BE	13413.16	5717.92	39614.42	3517.94	10823.64
BG	20940.41	14555.69	5476.79	9237.62	863.50
CH	26835.85	0	4359.70	1523.46	7237.61
CZ	40776.57	9023.72	41372.58	914.83	12744.36
DE	182263.42	47166.37	98974.47	61272.29	33019.78
DK	8686.62	0	40527.90	7738.50	6603.52
EE	19941.44	2009.04	7629.97	1668.24	797.92
EL	6520.37	4958.20	6850.88	7435.94	793.99
ES	54088.71	81766.74	97450.45	32629.24	8769.30
FI	99220.07	5387.81	4393.86	7383.56	3650.37
FR	143761.29	75834.76	240333.57	72342.04	24921.10
HR	11528.38	0	3033.66	2904.63	26.42
HU	24829.22	30321.76	57761.40	14800.73	2707.17
IE	9631.56	4201.62	17062.94	1295.40	532.65
IT	63239.16	41991.39	109929.23	21204.68	9651.44
LT	17998.15	12056.23	13886.66	5063.56	371.58
LU	1622.79	0	1414.64	131.04	36.12
LV	36053.00	2615.30	7504.72	3084.38	204.74
NL	3486.19	6378.61	45526.66	2258.83	15105.33
PL	104722.74	74331.83	76591.71	28906.67	7299.88
PT	25164.97	6267.78	21095.65	3786.35	3868.63
RO	74617.68	93086.56	21397.84	22067.29	2412.56
SE	176715.24	4641.59	16364.72	12535.83	8058.36
SI	19954.97	735.68	1438.36	436.70	280.44
SK	21397.61	3614.71	12222	4555.05	1162.71
UK	30407.68	18900.64	148340.36	23012.75	5026.11

A.2 Biomass costs

Table 5.2: Biomass costs, expressed in $\text{Meuro}_{2015}/\text{GWh}$, per country for the year 2035. Costs of the wet biomass category are given in terms of biogas, but without taking into account the technology cost. "Energy crops" here defines "Energy-dedicated lignocellulosic biomass crops".

Region	Woody biomass	Energy crops	Wet biomass	Other biomass residues	Biowaste
AT	0.02358	0.02111	0.02369	0.02089	0.0005800
BE	0.01953	0.02336	0.02399	0.01324	0.0001700
BG	0.01099	0.01353	0.01356	0.00946	0.0000002
CH	0.02135	//	0.02359	0.00058	0.0005800
CZ	0.02235	0.01395	0.01365	0.01397	0.0000010
DE	0.02328	0.02259	0.02303	0.01569	0.0002400
DK	0.01893	//	0.02708	0.01576	0.0000147
EE	0.01187	0.01897	0.01471	0.00997	0.0000200
EL	0.02228	0.03791	0.01643	0.01533	0.0003000
ES	0.02424	0.03097	0.01794	0.01343	0.0000058
FI	0.02707	0.02587	0.02417	0.01508	0.0001600
FR	0.02260	0.02121	0.02429	0.00987	0.0002680
HR	0.01059	//	0.01535	0.01087	0.0001100
HU	0.00987	0.01347	0.01347	0.01347	0.0134700
IE	0.02317	0.02685	0.02317	0.01047	0.0104700
IT	0.01047	0.03181	0.03181	0.01356	0.000300
LT	0.01206	0.01512	0.01501	0.00960	0.0001500
LU	0.02478	//	0.02328	0.01820	0.0000026
LV	0.01114	0.01482	0.01450	0.00975	0.0000006
NL	0.02319	0.03135	0.02389	0.01364	0.0001900
PL	0.01252	0.01902	0.01491	0.00991	0.0000106
PT	0.02508	0.01999	0.01549	0.01232	0.0000174
RO	0.00970	0.01286	0.01261	0.00977	0.0004460
SE	0.02787	0.03432	0.02516	0.01392	0.0000133
SI	0.01131	0.01298	0.01616	0.01163	0.0004833
SK	0.01053	0.01374	0.01437	0.01477	0.0000673
UK	0.02522	0.03018	0.02517	0.01477	0.0001400

B EnergyScope Multi-Cells tutorials

B.1 How to add a ressource to EnergyScope Multi-Cells

General rules :

1. The name of the resource must always be written in capital letters.
2. The typical units in the data are GW, GWh, ktCO_{2eq}, Meuro, Mpkm and Mtkm.
3. The region-specific data is structured as follows :
 - (a) A reference region (ref_region, here FR) contains the entire data that needs to be defined for 1 region.
 - (b) For the other regions, only the data that are different from the ref_region are defined.

Open the Data/ref_year/ref_region and in each region folder

1. Open the Resources.csv file.
2. Add a line with :
 - (a) The resource name in capital letters.
 - (b) The category and subcategory of the resource (!! be accurate as they can be used to generate sets of the optimisation problem).
 - (c) The local and exterior potentials (avail_local and avail_exterior in [GWh/y]).
 - (d) The operational global warming potential (gwp_op in [ktCO_{2eq}/GWh]).
 - (e) The local cost of the resource (c_op_local [M€/GWh]).
3. If some parameters of the ressource (e.g. c_op_local) changes from one region to another, specify it in each Resources.csv file of each region.

Open the Data/ref_year/00_INDEP folder

1. Open the Resources_indep.csv file and add a new resource line with all required informations.
2. Open Layers_in_out.csv.
 - (a) Add a line with :
 - i. The technologies param in the first column.
 - ii. Put a 1 in the main output column/layer (this is important as it will be used to build some sets of the optimisation problem).
 - (b) If the resource is a layer :
 - i. Add a column with the new layer.
 - ii. Open Storage_eff_in.csv and add the new layer column.
 - iii. Open Storage_eff_out.csv and add the new layer column.

- (c) If the resource is not a layer, open Misc_indep.json and add the resource in the set “NOT_LAYERS”.

If the resource can be exchanged between regions, open the Data/ref_year/01_EXCH folder

1. Open Misc_exch.json and define the type of exchange in the correct set :
 - (a) If it is exchanged by freight (e.g. woody biomass) add it in EXCHANGE_FREIGHT, then :
 - i. Define a low heating value in Lhv.csv (in [GWh/kt]).
 - (b) If it is exchanged through a network (e.g electricity, gas), add it into EXCHANGE_NETWORK, and if the network is bidirectional, add it also into EXCHANGE_NETWORK_BIDIRECTIONAL, then :
 - i. Add the losses in the network in Exchange_losses.csv.
 - ii. Add the actual installed transfer capacity between regions (tc_min in [GW]), the maximum transfer capacity that could be installed for the ref_year (tc_max in GW) and the specific cost of adding transfer capacity (c_exch_network in [M€/GW/y]) in Network_exchanges.csv. For c_exch_network, the investment cost is annualized assuming an interest rate of 3.22% and a lifetime (e.g. 40 years for electrical lines). Then it is summed with the O&M cost to get the total cost per year. A typical line length is also assumed to convert cost per km in the literature.

B.2 How to add a technology to EnergyScope Multi-Cells

General rules :

1. The name of the technology (i.e. technologies param) must always be written in capital letters.
2. The typical units in the data are GW, GWh, ktCO_{2eq}, M€, Mpkm and Mtkm.
3. The region-specific data is structured as follows :
 - (a) A reference region (ref_region, here FR) contains the entire data that needs to be defined for 1 region.
 - (b) For the other regions, only the data that are different from the ref_region are defined.

Open the Data/ref_year/ref_region/Technologies.csv file and add :

1. The category and subcategory of the new technologies (e.g Mobility; Freight).
2. The technologies name and then the technologies param written in capital letters.
3. The costs of investment and maintenance (c_inv and c_maint) [M€/GWh].
4. Gwp_constr : The technology construction specific GHG emissions [ktCO_{2eq}/GW].

5. The lifetime of the technologies in years.
6. The capacity factor c_p of the technologies.
7. The parameters f_{min_perc} and f_{max_perc} , f_{min} and f_{max} , which are the minimum and maximum relative installed share for this technology in a layer (%) and the minimum and maximum installed size ([GW]).

Open the folder Data/ref_year/00_INDEP/Layers_in_out.csv file :

1. Add the technologies param in the first column.
2. Put a 1 in the main output column/layer (this is important as it will be used to build some sets of the optimisation problem).
3. Put the equivalent conversion efficiency in the other input and output columns/layers, e.g. an industrial gas cogeneration (IND_COGEN_GAS) is installed firstly to produce industrial heat (put a 1 in the HEAT_HIGH_T column), electricity is a "byproduct" (put the equivalent ratio (here, 0.9565) into the ELECTRICITY layer), gas is consumed put the equivalent amount consumed (i0) per unit of heat produced (here, -2.1739).
4. If your technology consumes a fuel, you should also add the amount of CO2 emitted and that could be captured into the CO2_INDUSTRIY layer.
5. If the technology needs a time series, it needs specific tutorial not detailed in this study.
6. Some technologies might need to have additional changes such as adding specific parameters and equations into the model. For this, refer to the optimisation model formulation and to the python preprocessing functions.

For storage technologies, other data need to be added in Data/ref_year/00_INDEP folder

1. In Storage_characteristics.csv, add the storage_availability (the storage output for 1 unit of storage input) and the storage_losses (% of losses per hour).
2. In Storage_eff_in.csv and Storage_eff_out.csv, add the efficiency of input and output for this type of storage.
3. If storage characteristics change from one region to another, specify it in each Technologies.csv file of each region.

C Development of the GWP of each biomass category

The values chosen for this study come from the table C of Annex VI of the European directives [37].

Woody biomass

To compute the GWP of woody biomass, four of the five biomass types of the category are considered. Only the emissions linked to cultivation and production (first two columns of the table) are taken into account.

The four types are :

- Wood chips from forest residues (MINBIOFRSR1)
- Wood chips from stemwood (MINBIOWOO)
- Wood chips from wood industry residues (MINBIOWOOW1)
- Wood briquettes or pellets from stemwood (MINBIOWOOa). For this type, three cases are given in the tables. The value taken is the mean of the three cases

For the woody biomass type "sawdust" (MINBIOWOOW1a), no values are given in the tables. As its potential is very low compared to the potentials of the other types, the loss is negligible.

The GWP is found by doing a weighted average with the total potentials of the four biomass types in Europe. Finally, as the target year is 2035 and since the ENSPRESO database only has values for 2030 and 2040, the final GWP is found by taking the mean between the two years.

Energy-dedicated lignocellulosic biomass crops

For this category, looking at the potentials of the biomass types, miscanthus/RCG/switchgrass (MINBIOCRP31) presents a far bigger potential than the ones of poplar (MINBIOCRP41a) and willow (MINBIOCRP41). As the value of the emissions linked to the cultivation and the production of poplar are very low, and as no values are given for willow in the tables of the European directives, only the values of emissions of miscanthus/RCG/switchgrass are considered. Unfortunately, there are no values given in European directives for this type of biomass.

It has been found that the energy inputs per 1 GJ of produced miscanthus reach 2.1 kgCO_{2eq} [38]. Considering that switchgrass and RCG present similar GHG emissions as miscanthus, the converted value of 2.1 kgCO_{2eq}/GJ is taken as GWP for the energy-dedicated lignocellulosic biomass crops category.

Wet biomass

In the European directives, there are no emissions described for the biomass type composed of sludge, waste and spoils (MINBIOSLU1). As its potential is minimal compared to the one of its fellow wet biomass type (MINBIOGAS1), the GWP of the category is equal to the one of dry & wet manure (MINBIOGAS1).

Concerning the different possibilities in the tables, the chosen value come from the "Disaggregated default values for biogas for the production of electricity" section as the biomass type is described with "possible combustion and electricity production downstream" in the report of the ENSPRESO database [65]. The case of "close storage" is considered because the "open storage" case takes into account additional emissions, whereas only emissions for the production and the cultivation of the resources are taken into account.

The GWP of the category is computed by taking the mean of the three cases present in the table since none of them describes the wanted situation. The final value is found by converting the calculated value into (ktCO₂_{eq}/GWh).

Other biomass residues

In the European directives, there are no emissions described for the biomass type named landscape care (MINBIFRSR1a). As its potential is a very small part of the energy potential of the category, only the emissions linked to the other biomass type of the category, which are agricultural residues (MINBIOAGRW1), are taken into account. As there are two categories of agricultural residues in the table, the GWP of the category is calculated by taking the mean of the two values, which is then converted to the same units as the other categories to get the final GWP.

Biowaste

To get the GWP of this category, the same method as for wet biomass is used. The chosen value come from the "Disaggregated default values for biogas for the production of electricity" section as the biomass type is described with "possible combustion and electricity production downstream" in the report of the ENSPRESO database [65]. The case of "close storage" is considered because the "open storage" case takes into account additional emissions, whereas only emissions for the production and the cultivation of the resources are taken into account.

The GWP of the category is computed by taking the mean of the three cases present in the table since none of them describes the wanted situation. The final value is found by converting the calculated value into (ktCO₂_{eq}/GWh).

D Computations of imported renewable methanol cost

Renewable methanol cost = $a + b$

- a = Wood conversion into methanol technology cost
- b = Transport cost to the importing region

Computation of a

- x = Wood cost in the exporting region ($\text{Meuro}_{2015}/\text{GWh}$). It is given in the data files.
- y = Technology cost to produce 1 GWh of methanol.

To compute y , the EnergyScope optimization output of methanol produced in a region is divided by the output total cost in the same region. In every region, the result is the same :

$$y = 0.02115 \text{ Meuro}_{2015}/\text{GWh}.$$

As the conversion ratio of the technology converting wood into methanol is 0.62, $\frac{1}{0.62} = 1.6129$ GWh of wood are needed to produce 1 GWh of methanol.

$$a = 1.6129 * x + y$$

Computation of b

The total transport cost is equal to the addition of the infrastructure investment and maintenance costs and the consumed fuel cost. We will consider that the transport is always realized with trucks. The optimal truck type to cover national freight demand according to EnergyScope in a low-carbon energy system is the fuel cell truck in all region. This truck works with hydrogen fuel and is considered for transport in computations hereunder.

The following data can be found in the documentation of EnergyScope TD [18] :

Table 5.3: Truck Fuel Cell data. Investment cost is given in $\text{keuro}_{2015}/\text{veh}$. Maintenance cost is given in $\text{keuro}_{2015}/\text{veh}/\text{y}$.

Inv. cost	Maint. cost	Tonnage (t)	Lifetime (y)
181	5.4	10	15

- n = Number of trucks needed.

According to EnergyScope TD, methanol LHV is equal to 6380 GWh/kt. As a truck can transport 10 tons, the amount of trucks needed for an exchange can be computed.

$$n = \frac{\text{Energy transported (GWh)}}{10t * \text{LHV (GWh/t)}}.$$

- k = Yearly infrastructure costs.

In EnergyScope TD, all costs are annualised with a discount rate of 1.5%. As trucks lifetime is 15 years, the yearly cost of one truck can be computed as here below.

$$k = \frac{181000}{\sum_{i=1}^{15} (1/1+r)} + 5400 = 17\,647.5 \text{ euro}_{2015}/\text{veh/y}$$

$$k = 0.0176475 \text{ Meuro}_{2015}/\text{veh/y}$$

- h = Hydrogen consumed (GWh).

A fuel cell truck consumes in average 440 Wh/km-t of H2 [18].

$$h = \frac{440 * \text{Distance covered (km)} * n * 10}{10^6} \text{ GWh}$$

As the price of hydrogen can vary according to the production process and the region, the exterior price of H2 (0.088 Meuro₂₀₁₅/Wh) is considered here as approximation.

$$b = \frac{n*k + 0.088*h}{\text{Energy transported (GWh)}} \text{ Meuro}_{2015}/\text{GWh}$$

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UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain

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