

École polytechnique de Louvain

Multi-Criteria Optimisation of an Energy System

and Application to the Belgian Case

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Abstract

The global warming issue with its resulting climate disturbances is a burning topic. The European Union is seeking, with its Climate Law, to drastically reduce greenhouse gas emissions by 2030 and to achieve climate neutrality by 2050. In this context, energy models are needed to study possible future energy systems that best meet these objectives.

Many models exist, but no model encompassing the different facets of the energy sector - electricity, heat and mobility - allows a multi-criteria optimisation of the studied energy system. However, given the challenges associated with the energy transition, it is crucial to be able to assess a system from different, sometimes contradictory, aspects: economic, environmental, technical and social.

The present work proposes the implementation of a multi-criteria approach in the *EnergyScope TD* model, which is currently single objective, but which has the following advantages: integration of all sectors of the energy system, open source, reasonable computation time and possibility of fine temporal resolution, which is necessary to take into account the fluctuating character of renewable energies.

In order to achieve a multi-criteria optimisation, key performance indicators were selected that allow for an economic, environmental and societal view and, in order to provide as global a perspective as possible on the energy system under consideration, additional criteria were introduced.

For data collection, we followed a "life cycle assessment" approach that takes into account the entire life cycle of the processes involved in the evaluation of the associated impacts. In this task, with the help of *SimaPro* software, we made extensive use of the *ecoinvent* database.

The application case selected is Belgium in the year 2035. The multi-criteria optimisation allows to obtain a mapping of the technologies to be implemented and the analysis highlights the environmental impacts of the energy system according to the weight associated to each criterion. Finally, a more targeted study of a low-carbon Belgian energy system is carried out. The findings of this case study are likely to be transposable to other countries.

La problématique du réchauffement climatique et des dérèglements engendrés est un sujet d'actualité brûlant. L'Union Européenne cherche, avec sa Loi Climat, à réduire drastiquement les émissions de gaz à effet de serre d'ici à 2030 jusqu'à atteindre la neutralité climatique en 2050. Dans ce contexte, des modèles énergétiques sont nécessaires afin d'étudier les futurs systèmes énergétiques possibles permettant de rencontrer au mieux ces objectifs.

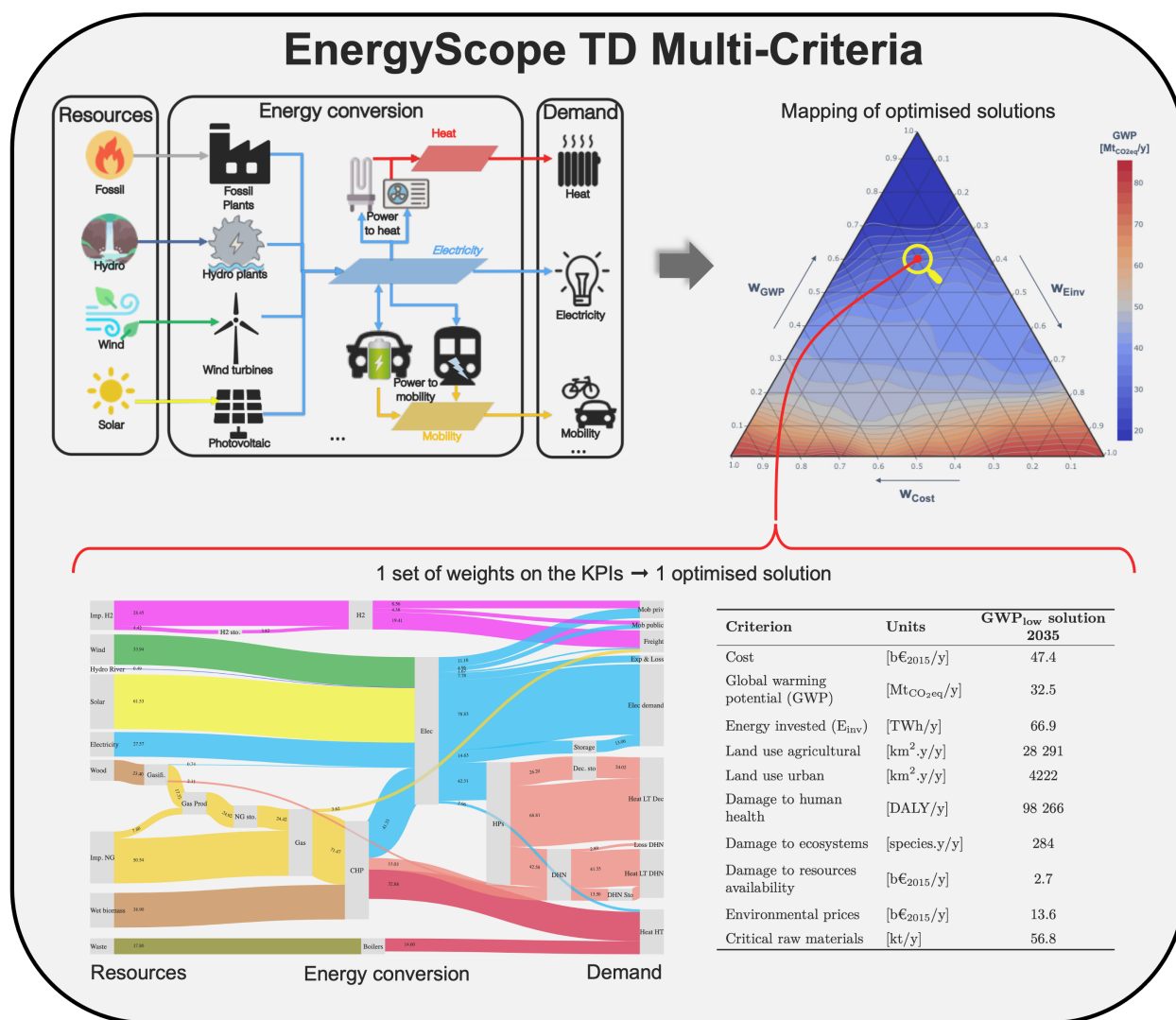
Beaucoup de modèles existent, mais aucun modèle englobant les différentes facettes du secteur énergétique - électricité, chaleur et mobilité - ne permet une optimisation multi-critères du système énergétique étudié. Or, étant donné les enjeux associés à la transition énergétique, il est crucial de pouvoir évaluer un système sous différents aspects, d'ailleurs parfois contradictoires: économique, environnemental, technique et social.

Le présent travail propose l'implémentation d'une approche multi-critères dans le modèle *EnergyScope TD* qui est actuellement à simple objectif, mais qui présente les avantages suivants: intégration de tous les secteurs du système énergétique, caractère "open source", temps de calcul raisonnable et possibilité de résolution temporelle fine, ce qui est nécessaire pour pouvoir tenir compte de la nature fluctuante des énergies renouvelables.

Dans l'optique d'une optimisation multi-critères, des indicateurs-clés de performance, permettant un regard tant économique qu'environnemental ou sociétal, ont été sélectionnés et, afin d'offrir une perspective aussi globale que possible sur le système énergétique étudié, des critères additionnels ont été introduits.

Pour la collecte des données, nous avons suivi une approche du type « analyse du cycle de vie » qui prend en compte l'entièreté du cycle de vie des processus impliqués dans l'évaluation des impacts associés. Dans cette tâche, aidés du logiciel *SimaPro*, nous avons fait extensivement usage de la base de données *ecoinvent*.

La mise en application a été faite sur la Belgique en 2035. L'optimisation multi-critères permet d'obtenir une cartographie des technologies à implémenter et l'analyse met en avant les impact environnementaux du système énergétique selon le poids associé à chaque critère. Enfin, une étude plus ciblée d'un système énergétique belge bas carbone est réalisée. Les conclusions de cette étude de cas sont certainement transposables à d'autres pays.



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List of Abbreviations

Notes:

- Besides the acronyms hereafter, some text abbreviations may also be used in figures and tables for clarity of presentation.
- Names for the variables are defined at the location of the equations where they are used.

BECPI	Belgian Consumer Price Index
BEV	Battery Electric Vehicle
CAPEX	Capital Expenditure
CCGT	Combine Cycle Gas Turbine
CED	Cumulative Energy Demand
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DALY	Disability Adjusted Life Year
DHN	District Heating Network
eHP	Electrical Heat Pump
E_{inv}	Energy Invested
<i>ELCD</i>	European reference Life Cycle Database
EROI	Energy Return On Investment
<i>ESTD</i>	<i>EnergyScope TD</i>
EU	European Union
EUD	End-Use Demand
EUT	End-Use Type
FC	Fuel Cell
FEC	Final Energy Consumption
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
HHV	Higher Heating Value
HP	Heat Pump
HT	High Temperature
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFO	Light Fuel Oil
LHV	Lower Heating Value
LI	Lithium-Ion
LP	Linear Programming
LT	Low Temperature
<i>NEEDS</i>	New Energy Externalities Development for Sustainability
NG	Natural Gas

NiMH	Nickel Metal Hybride
OPEX	Operational Expenditure
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydro Storage
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Source
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
SLF	Synthetic Liquid Fuel
SNG	Synthetic Natural Gas
SOUP	Single Output Unit Process
TD	Typical Day
TS	Time Series
V2G	Vehicle-To-Grid

Chapter 1

Introduction

Rising concerns regarding environmental impacts of human development, such as global warming, have led to the adoption of Kyoto Protocol in 1997 and Paris Agreement in 2015. In line with these pacts and as inscribed in its Climate Law, the European Union (EU) aims at reducing greenhouse gases (GHGs) emissions by at least 55% in 2030 compared to levels in 1990 and at reaching climate neutrality by 2050. Achieving these objectives requires efficient policies to direct the transition in all parts of society and economic sectors. To do so, policy makers call upon models, especially energy models to project future energy demand and supply for a given geographical area.

1 Energy system models

Energy system models are the mathematical models that are developed in order to represent as reliably as possible various energy-related problems. A wide variety of models exists depending upon the issue under consideration. Some models are made for design purposes and represent the behavior of an energy equipment whose energy efficiency must be optimised. Some others are used to forecast energy needs or to explore ways to balance energy supply and demand. The scale of the energy system under study may vary from a specific plant unit to a whole country. The amount of data required to build the model increases with the system complexity and, in any case, a number of simplifications and assumptions will be necessary when modeling the system, its boundary conditions and their transformations over time.

Many models have been developed over the years. As explained in [36], different types of models exist, each with its strengths and weaknesses. Macroeconomic models (or top-down models) are mostly used by policy makers because of their reliance on energy prices, economic and demographic developments, as well as their ability to apply feedback loops between welfare, employment and economic growth. However these models suffer from a lack of technological detail and are not suited to model substantial technological changes and show credible technology futures. Techno-economic models (or bottom-up models) on the other hand are more process-oriented and incorporate a high level of technological detail. Therefore they are deemed better able to capture the complexity in the transition towards a climate neutral energy system. But they are less complete from a macroeconomic perspective. In order to tackle these limitations, the trend is now towards hybrid models, combining bottom-up models with some macroeconomic prospect.

In order to address the energy transition and the integration of renewable resources that are required by the EU Climate Law, elected energy system models must meet certain criteria:

- **Multi-sector:** As mentioned previously, in order to achieve the EU climate goals, an energy transition is necessary in all economic sectors. A multi-sector modeling is therefore necessary to incorporate cross-sector interactions such as electricity storage as heat, or vehicle-to-grid interfaces.
- **Time resolution:** The integration of renewable to the energy system stresses the electricity grid and a minimum time resolution of one hour is necessary to model the eminently fluctuating renewable energy sources and deal with electricity supply security.
- **Optimisation:** In order to enable the exploration of the numerous available options of energy systems for the transition, an optimisation capability (as opposed to a simple simulation) is mandatory.

COMPOSE [25], *Oemof* [37] [30], *TIMES* [15] [2] and *EnergyScope TD* [52] are examples of energy system models that comply with these criteria. Amongst those models, *EnergyScope TD* presents the additional benefits of both a reasonable computation time and the transparency of its open source models.

2 Current state

The models mentioned above are currently mainly designed to optimise the cost of the energy system, accounting for instance for internalisation of external costs [70] or under some constraints to achieve specific objectives, such as limiting the GHG emissions or targeting a 100% renewable energy system [53]. Regrettably, the available tools allow only a partial approach and do not permit to look at the whole picture.

Though, finding an optimal energy system is a multi-objective problem as it encompasses economical, technical, environmental and social aspects. The importance of accounting for several criteria when assessing an energy system is well illustrated by Afgan and Carvalho, in their paper on multi-criteria assessment of new and renewable energy power plants [5]. The authors have evaluated different types of energy power plants against several indicators (installation cost/kW, area/kW, efficiency, electricity cost/kWh, CO₂ emissions). Their study shows that the rating of these power plant options is highly dependent on the indicator selected (a single indicator or a weighted combination of indicators). For instance, if the installation cost indicator has priority, the gas power plant is the first on the rating list of the options under consideration. On the contrary, if a high weight is put on the CO₂ production and area indicators, the hydro and nuclear power plants are rated first. Taking several criteria into account, often conflicting, leads to a more resilient solution made of a mix of technologies. Braune et al. in [14] also emphasise that, for sustainable development, "energy systems have to be looked at from different disciplines as to incorporate all the consequences brought along with their implementation", however recognising that this approach makes the appraisal more complex.

The evaluation of an energy system should therefore not be limited to cost and global warming potential indicators as usually done. Researches in the literature have shown that a multi-criteria approach has been extensively applied to the electricity sector with Generation Expansion Planning studies [60]. However, it is very lacking in current multi-sector energy planning optimisation models. The closest model found was the *EPLANopt* model [62] that couples the *EnergyPLAN* simulation software with an external Multi-Objective Evolutionary Algorithm. Still, as indicated in [52], this method does not optimise all the design and the hourly operation over a year and it is not fully open source.

In terms of metrics, currently the global warming potential (GWP) of direct GHG emissions is taken as the environmental gauge. However, this indicator is too narrow since it does not include indirect emissions due to the extraction, conversion and transportation of resources as well as emissions linked to the construction of the energy system. As identified by [54] and [22], taking indirect emissions into consideration (accomplished in the referenced studies by linking an environmentally-extended input-output model to the *TIMES* energy system model) affects the relative attractiveness of specific renewable technologies in low carbon scenarios (even if fossil fuels are still predominantly responsible for emissions). The concept of direct and indirect emissions is illustrated on figure 1.1 for an industry.

As seen above, in order to implement an energy transition policy that meets the objectives of the European climate law, there is currently a lack of energy system models allowing multi-criteria optimisation. Furthermore, the indicators chosen do not always give a complete picture of the energy situation and its multi-facet impacts.

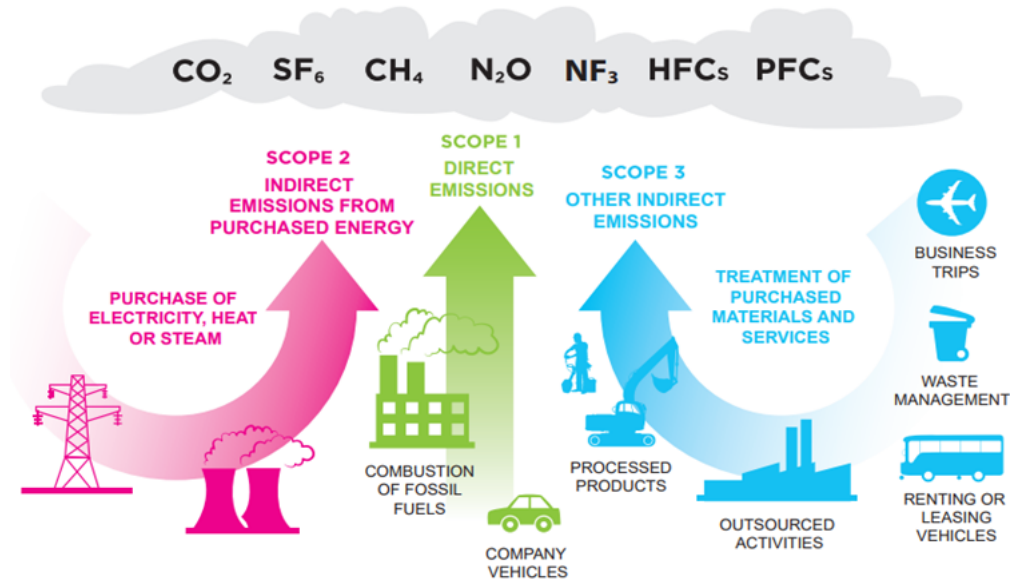


Figure 1.1: Illustration of direct and indirect emissions for an industry. The figure was taken from [33]

3 Contribution of this thesis

In view of the gaps in the current energy system models capabilities, we propose a multi-objective extension to the *EnergyScope TD* model based on goal programming. *EnergyScope TD* has been chosen since, as explained in section 1, it best fits the requirements for an energy system model to cope with the energy transition while being open source.

In this effort, thanks to the multi-criteria approach, we will aim at providing a more complete and global view of future possible energy systems and, to reach this goal, a couple of research questions will have to be answered:

- What are the key criteria to design an optimal energy system?
- How to implement multi-criteria optimisation within a traditional single objective linear programming model?
- What additional perspectives can multi-criteria optimisation provide for energy system analysis and low carbon scenarios in particular?

These research questions underlie the structure of our thesis:

- In order to address the first research question, we will start with the characterisation of the energy system, encompassing the selection of key performance indicators and the methodology to assess the retained criteria.
- The implementation of multi-criteria optimisation in an energy system model will be our next focus, tackling the second research question.
- In the process of addressing the third research question, the Belgian energy system will serve as an application case. Belgium, with its scarce natural resources and high energy demand, is an interesting country to examine how to move towards a decarbonised solution, accounting for multiple criteria. Also, it is expected that the insights from that case study will be transferable to other countries.

Energy system characterisation

In view of the ambitious environmental objectives pursued by the European Union for its energy policy and the various challenges associated with the choices that will be made, it is crucial that the intended energy system analysis takes into account the entire life cycle of the processes involved so as to give as complete a picture of the system as possible. A so-called life cycle assessment (LCA) method will therefore be adopted.

In its broadest version, it evaluates the environmental impacts of a product or process from raw material extraction and processing (cradle) to the product or process end of life, including final waste disposal (grave) and, when possible, recycling ("cradle-to-cradle" closed cycle). For that assessment of the cumulative environmental impact of an energy system, the LCA study involves a thorough inventory of the energy and materials that are required across the whole cycle and its multiple sub-processes.

It is important not only to have a comprehensive view of the energy system, but also that the selected metrics to analyse it provide insights into different aspects of the problem: economic, environmental, societal, etc. Therefore, as we will see, the cost and the GWP of the system, as well as the societal energy return on investment (EROI), will be our key performance indicators (KPIs), used for energy system optimisation. Once, based on the chosen criteria and their relative weights, optimised solutions are reached, we have elected, even if this was beyond the initial scope of our thesis, to look at some additional metrics characterising the system, in order to cover even more perspectives. For example, criteria such as damage to ecosystems or to human health will be examined to ensure that undesirable impacts other than GWP are not aggravated when attempts are made to minimise GHG emissions (one wants to avoid the so-called "burden shifting" from one type of pollution to another).

Following the LCA cradle-to-cradle approach, data for all selected metrics need to be gathered for all stages of the energy system life cycle. Collecting this large amount of data represents a considerable effort and requires the use of appropriate databases and tools. It must be noted that, in the context of our thesis, we will focus on the energy sectors, i.e. electricity, heat and mobility.

These topics are the object of **chapter 2**:

- First, in section 1, the principles of a life cycle assessment approach are explained.
- Then, section 2 discusses the databases and associated tools available to us and the choice made for this thesis: *ecoinvent* database coupled with *SimaPro* software.
- The selection of the criteria for the energy system study is the object of section 3 which describes the key performance indicators retained for the energy system optimisation and the complementary criteria that we have decided to examine.
- Finally, data computation is the object of section 4 that explains how the energy system model parameters are derived from the available LCA data.

Implementation of multi-criteria optimisation in energy system model

After the better energy system characterisation through the introduction of key metrics and the establishment of a methodology for the related data collection and computation, the energy system model itself has to be addressed. As explained in sections 1 and 2 above, various models exist, but they lack a multi-criteria optimisation capability to establish an energy system tackling the challenging EU climate goals while considering socio-economic aspects. A major contribution of this thesis is to introduce this capability in the existing *EnergyScope TD* model, selected, as said before, for its multi-sector coverage (electricity, heat and mobility), its hourly resolution, its open source nature, its reasonable computation time and, naturally, its existing cost optimisation ability.

Chapter 3 deals with the energy system model:

- Section 1 explains the current *EnergyScope TD* model: its architecture, the use of typical days (TD) to speed up the resolution time, the computation of the criteria of interest (that are constrained or, for the total cost, to be optimised) and its single-objective function.
- In section 2, existing multi-objective approaches are discussed and the interest of the goal programming method is emphasised in light of the current *EnergyScope TD* optimisation model. The goal programming method indeed allows to transform a multi-objective problem into a single-objective one.
- The changes made to *EnergyScope TD* model are the object of section 3. The equations to compute the different criteria considered in addition to the cost are reported and the new objective function used to optimise the selected key performance indicators is provided. The new *EnergyScope TD Multi-Criteria* version can be found in repository [56].

Application case

The extension of *EnergyScope TD* energy system model capabilities by implementation of a multi-criteria optimisation and the introduction of additional metrics, with their underlying data, are essential contributions towards the exploration of possible energy system transformations in view of a greener future. In order to understand the additional perspectives that multi-criteria optimisation can offer for the analysis of energy systems, a study is conducted with *EnergyScope TD Multi-Criteria* on a selected application case: the Belgian energy system in 2035. However the conclusions reached may be extended to other countries. The exploitation of the model includes several parts:

- In a first stage, the object of the case study is motivated and described: the Belgian energy system. The available resources, the end-use demand (EUD), the political context and the technologies allowing to transform the resources to meet the EUD are discussed for the 2035 time horizon. The Belgian energy system in 2015 is analysed to serve as comparison basis when strategies for 2035 will be investigated. This is the object of **chapter 4**.
- In **chapter 5**, single criterion optimisations of that Belgian energy system for 2035 are then pursued, for each key performance indicator separately.
- Then, in **chapter 6**, multi-criteria optimisations are performed. They allow to obtain a general map of the implemented technologies as well as to evaluate the impacts of the system depending on the weights attributed to the criteria. Finally, a scenario is selected to illustrate the transition towards a clean Belgian energy system.

The outcome of our work and some improvement paths are discussed in **chapter 7**.

Chapter 2

Energy system characterisation

As explained in the introduction (chapter 1), the first part of our thesis addresses our first research question and therefore deals with the characterisation of the energy system, including the selection of key performance indicators and the methodology to assess the retained criteria. The present chapter describes the steps that have been followed and outlines the encountered choices and challenges.

In order to have a comprehensive view of the energy system, as previously mentioned, a life cycle assessment approach is selected, allowing to capture the system impact (measured through selected indicators) at all stages of its life cycle. Therefore, we will start by briefly explaining what a life cycle assessment (LCA) is and the corresponding methodological steps.

Then, the source of data for the criteria assessment is discussed: the choice of the database and associated tool is delineated and further explanations about the selected database are also given.

Next, the criteria (or indicators) that were retained for the energy system analysis are described. The distinction is made between:

- the key performance indicators, based on consolidated data and aiming at providing a view on the multiple facets of the system, that will be the object of the optimisation effort,
- the additional criteria, non consolidated, that are selected to provide further insight into the energy system.

Finally, the processing and computation of the LCA data to derive the energy system model parameters are explained.

1 Principles of life cycle assessment

The purpose of a LCA is to compile and evaluate the environmental impacts associated with all the stages of the life cycle of a product or service. This approach avoids opting for a solution that simply shifts the burden from one phase of the life cycle to another.

The importance of considering the whole life cycle of a product, when looking for instance at its environmental impacts, is best illustrated by the case of photovoltaic panels. If we only look at the "product utilisation" stage, there is no production of greenhouse gases, but if we consider the energy needed to produce, install and recycle the photovoltaic panels and the fact that, at least currently, most of this energy is not green, the carbon footprint of photovoltaic panels is far from zero.

The merits of this LCA approach are well established and LCA is governed by widely recognised standards provided by the International Organisation for Standardisation (ISO) in the 14000 series of environmental management standards, in particular the ISO 14040 [3] and ISO 14044 [4] norms. ISO 14040 provides the principles and framework of the standard, while ISO 14044 is about the requirements and guidelines. Those standards describe, among other things, the four main stages of a LCA: goal and scope definition, inventory analysis, impact assessment and interpretation. They are illustrated on figure 2.1 and detailed in

the following sections.

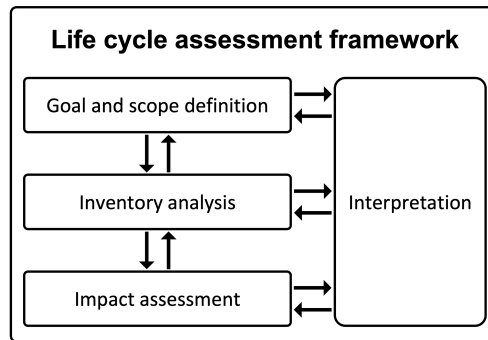


Figure 2.1: LCA stages as defined by ISO 14040

1.1 Goal and scope definition

Goal and scope definition is the first LCA stage where the aim of study, and pertaining to that, the breadth and depth of the study are established. As an example, there are two modes of LCA, whose choice will depend on the purpose of the study being carried out [77]:

- Descriptive LCA only looks at the attribution of impacts: which environmental problems can be attributed to a certain product and what its share is for each of them.
- Change-oriented LCA tries to assess the changes in environmental impacts if a certain option is chosen over another to fulfill a designated function.

Another example of choice that has to be made, with regard to the breadth of the study, is which extent of the life cycle of the product is considered. The three main approaches possible, illustrated in figure 2.2, are the following:

- The **cradle-to-gate** approach considers all impacts from the extraction of resources to the point where the product is ready to be used. The end of life is thus not considered.
- **Cradle-to-grave** adds more stages to that since it also encompasses the end of life up to the disposal of waste.
- The **cradle-to-cradle** approach goes even further and considers the recycling of waste and the potential reuse of the recycled goods. In that regard, it closes the cycle.

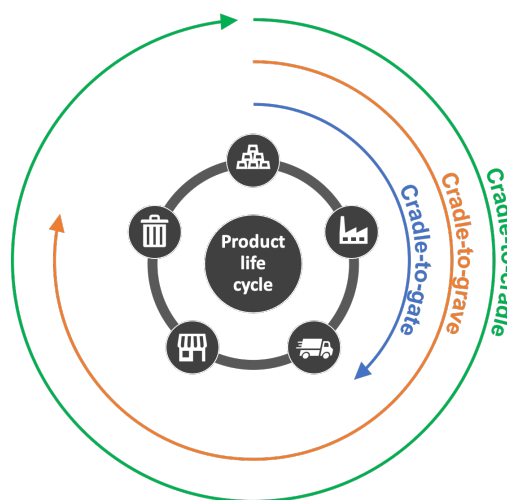


Figure 2.2: Illustration of the stages of a product life cycle: raw material extraction, fabrication, transport-distribution, usage, end of life

In this thesis, with the selected database, whose choice will be discussed in section 2, the data collected are founded on a descriptive type of LCA and, since recycling is part of the envisioned product life cycle, we are in the case of a cradle-to-cradle approach.

1.2 Inventory analysis

Inventory analysis, or life cycle inventory (LCI), involves creating an inventory of all the elementary flows, to and from the environment, of a product system. Elementary flows account for raw materials, energy requirements, emissions to the environment, water consumption, etc.

A first step is to start with a technical model of the system that accounts for all the processes and activities that are involved in the life cycle of a product. All these processes and activities are called unit processes and are the building blocks to model bigger processes and, in the end, the whole product system.

The unit processes are subsequently assessed to determine their elementary flows. LCI is then the process of aggregating all the elementary flows of the different unit processes involved in the product system.

1.3 Impact assessment

Life cycle impact assessment (LCIA) is the next stage in a LCA where the inventory is evaluated for its environmental impacts such as global warming potential (GWP), terrestrial acidification or fine particulate matter formation. They are called the midpoint impacts as they are considered to be links in the cause-effect chain of an impact category, before the endpoint is reached. Although they are not at the end of the cause-effect chain representing the environmental mechanisms and they only focus on a single environmental aspect at a time, they can already bear a lot of meaning when assessing the product system considered.

Endpoint indicators intervene at the end of the chain and are defined at the level of areas of protection (human health, ecosystems, resources, etc.). The midpoints are linked to them through damage pathways used to assess and quantify the effects on the endpoints. To implement those pathways, the emissions are connected to the endpoint impacts using atmospheric transport and dose effect relationships as is explained in [24]. Those relationships are based on dispersion models that translate emissions into concentration using meteorological and atmospheric-chemistry models, and on concentration response functions that convert the concentrations into the endpoint impacts.

An example of damage pathways is illustrated in figure 2.3 for emissions of greenhouse gases. The GWP accounts for the total of those emissions and constitutes a midpoint indicator. Through a cause-effect chain, the GHGs will impact human health and ecosystems, which represent endpoint categories.

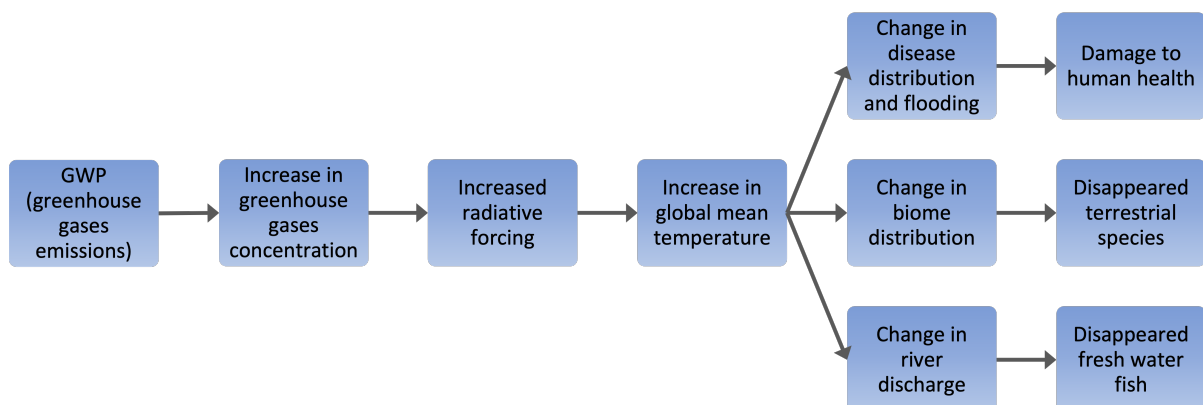


Figure 2.3: Illustration of damage pathways that link midpoints to endpoints in life cycle impact assessment: an example for greenhouse gases emissions (midpoint) that affect human health and ecosystems (endpoints)

Compared to midpoints, endpoints allow, with the knowledge currently available, to have a better understanding of the final impacts that the product system has on our society and, thereby, offer a more global perspective. The results obtained, however, are not free from uncertainty and, the further we go down the

cause-effect chain, the bigger the model and data uncertainty. Also, damage pathways from mid to endpoint often suffer from knowledge gaps that further increase the uncertainty [11].

ReCiPe

Several methods for LCIA exist and ReCiPe is one of them. It possesses one of the broadest set of midpoint impact categories and has been used to collect most of the data for this work.

ReCiPe was first developed in 2008 through collaboration between the Dutch National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, Leiden University and PRé Sustainability [72]. It has subsequently been improved in 2016 by RIVM, Radboud University Nijmegen, Norwegian University of Science and Technology and PRé Sustainability.

As indicated in [9], the ReCiPe method is one of the most complete, considering both human health and biodiversity impacts; it is scientifically robust and therefore widely accepted. It has been retained for our work because of all these reasons.

ReCiPe 2016 computes 18 midpoint and 3 endpoint indicators, which are illustrated, along with the damage pathways considered, in figure 2.4.

This method includes three different scopes that reflect three cultural perspectives. Each is representative of a set of choices on issues such as time horizon or expectations for technology development to avoid some of the future damages. These perspectives are the following:

- **Individualist:** it is short term based and considers undeniable impact types, with an underlying optimism that technology will be able to avoid many future problems;
- **Hierarchist:** it uses a medium time frame and is a consensus model based on commonly accepted scientific knowledge; it is often encountered in scientific literature and it can be considered as the default model;
- **Egalitarian:** it has a long term horizon and is based on precautionary principle thinking, accounting for impact types not yet fully established but for which some indication is available.

In this work, when the indicators sought (see section 3) were available through the ReCiPe 2016 method, the hierarchist perspective was selected.

1.4 Interpretation

The last stage in a LCA is the interpretation phase where the findings from the LCI and LCIA stages are reported to reach conclusions, the limitations of the study are explained and recommendations can be provided in relation to the initial objectives of the study [45]. The aim is to provide a comprehensive and intelligible picture of the results so that they can be exploitable in other studies or by decision-makers.

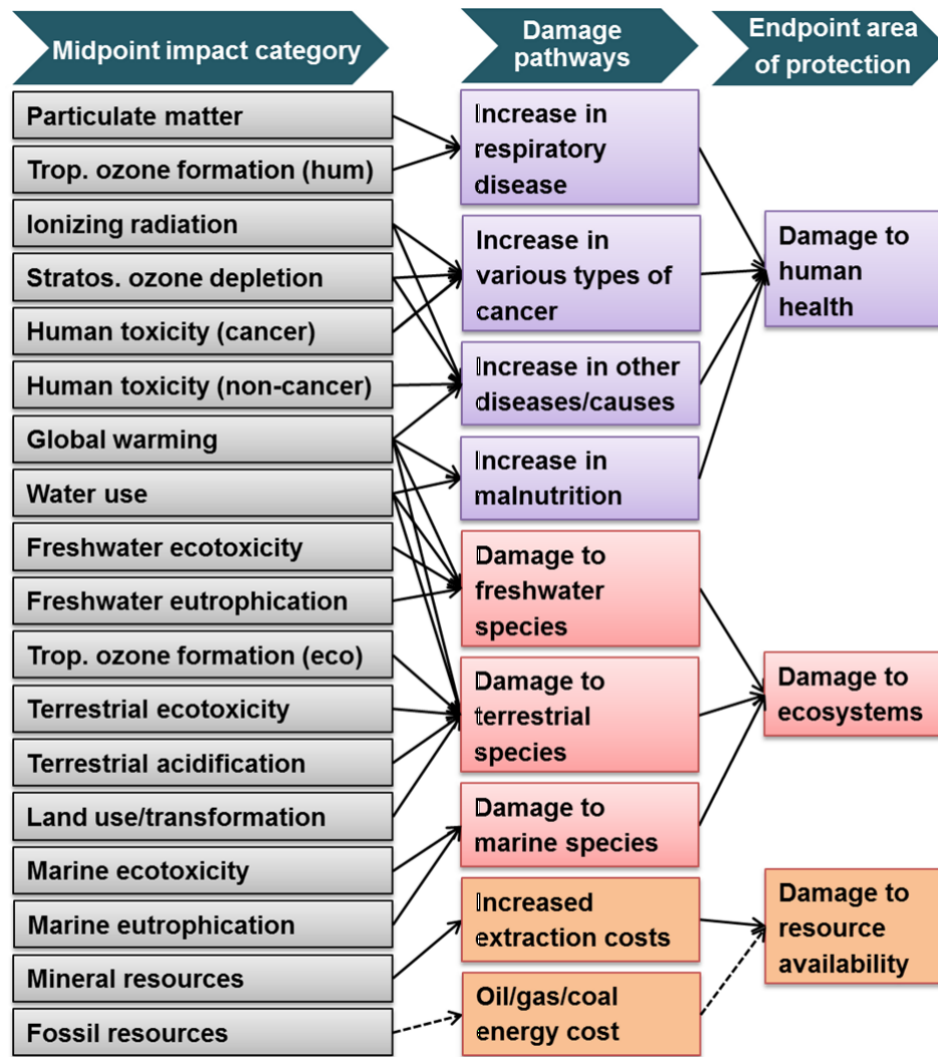


Figure 2.4: Overview of the structure of ReCiPe 2016 (figure taken from the RIVM report on ReCiPe [38])

2 Databases and software tools

2.1 Databases

In practice, LCA databases are used for the data gathering step. These databases are produced, among others, by governments, industries, research institutes and mostly contain industry region average information but sometimes refer to specific sites [44]. The content of the databases ranges from unit process raw data to aggregated cradle to cradle data.

In the context of our thesis, we are interested in databases related to the electricity, heat and transport sectors in Europe. With the softwares accessible to us (cfr. section 2.2), the free databases available that could be of interest to our work are the European reference Life Cycle Database (*ELCD*) and the New Energy Externalities Development for Sustainability (*NEEDS*) database.

- The *ELCD* database [57] contains LCI data for key materials, energy carriers, transport and waste management. However data on electricity and heat production technologies are not available and the database lacks metadata on process information, modeling etc.
- The *NEEDS* database [8], for its part, contains industrial LCI data on future transport services, electricity and material supply. It does not provide data for the heat sector though and it has not been updated since 2009.

Other databases, available for purchase, are the *LCA Commons* database and the *ecoinvent* database. These are much bigger databases than the free ones and cover all three sectors of interest (that are, to recall, electricity, heat and transport).

- *LCA Commons* [21] is specific to the US; it contains 9200 data sets with varying modeling viewpoints and nomenclature frames because it is an inter-agency database.
- Finally, we have *ecoinvent*, a database that contains transparent and consistent international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management and transport services.

Amongst all databases mentioned above, *ecoinvent* is the reference database that we have chosen as it completely tends to our needs for all sectors and technologies. It is further detailed in section 2.3.

2.2 Software tools

These databases are used in combination with LCA software tools to link the processes and produce the LCI, as well as to calculate the impacts. These calculations are complex due to the amount of data to process and assumptions to be made in the impact attributions.

Each LCA software is characterised by the dataset file formats it can use. As a result, the choice of the software is linked to the choice of the database. The LCA software tools that we have access to are *SimaPro* and the free open source *openLCA*. *OpenLCA* can read a large number of file formats while *SimaPro* is much more restricted. Nevertheless, both tools work with the selected *ecoinvent* database. Since *ecoinvent* is integrated by default in *SimaPro*, this software will be our tool of choice. Indeed, *openLCA* still requires users to buy access to the databases they need access to, while *SimaPro* offers the access to *ecoinvent*. Moreover, *SimaPro* software is already in use in our university, UCLouvain.

For other aspects, both softwares are comparable. They both allow for uncertainty analysis of LCIA results. In terms of user interface and result presentation, they are similar and can show results as Sankey diagrams. *SimaPro* does have additional specific features for professional LCA users, but they will not be used in the frame of this thesis.

2.3 System models in *ecoinvent*

Now that the database and the LCA software tool are chosen, let us go into the *ecoinvent* database in more detail. The database is further split into three different parts that are called system models [27]. A system model is a set of modeling choices that define where the impacts (also called "burdens") are allocated and how to handle the waste and recycling streams. To better understand where those system models come from, let us first go back to the grounds and see how everything is computed.

The raw database is made of unlinked data sets that describe unit processes by their inputs and outputs that can be multiple. Those inputs and outputs are either to/from the technosphere (electricity, steel, fuels, ect.) or the environment (ores, water, CO₂ or NO_x emissions). The outputs to the technosphere can be classified in different categories: reference product, by-products, recyclable materials and waste as illustrated on figure 2.5.

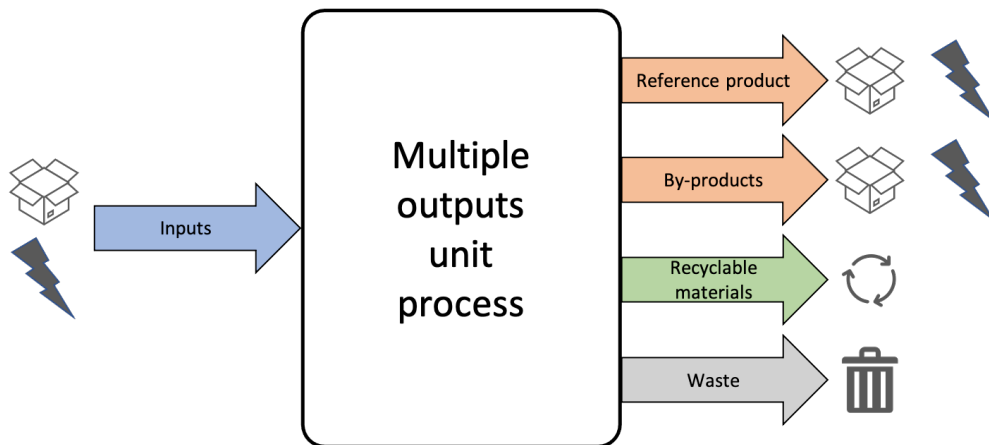


Figure 2.5: Illustration of a multiple output unit process

The problem with multiple outputs unit processes lies in the way the life cycle inventories are computed. They are computed using matrices that need to be square and this implies that the unit processes need to have a single output [47]. The multiple outputs unit processes therefore need to be turned into Single Output Unit Processes (SOUPs). An illustration of such a conversion is provided on figure 2.7.

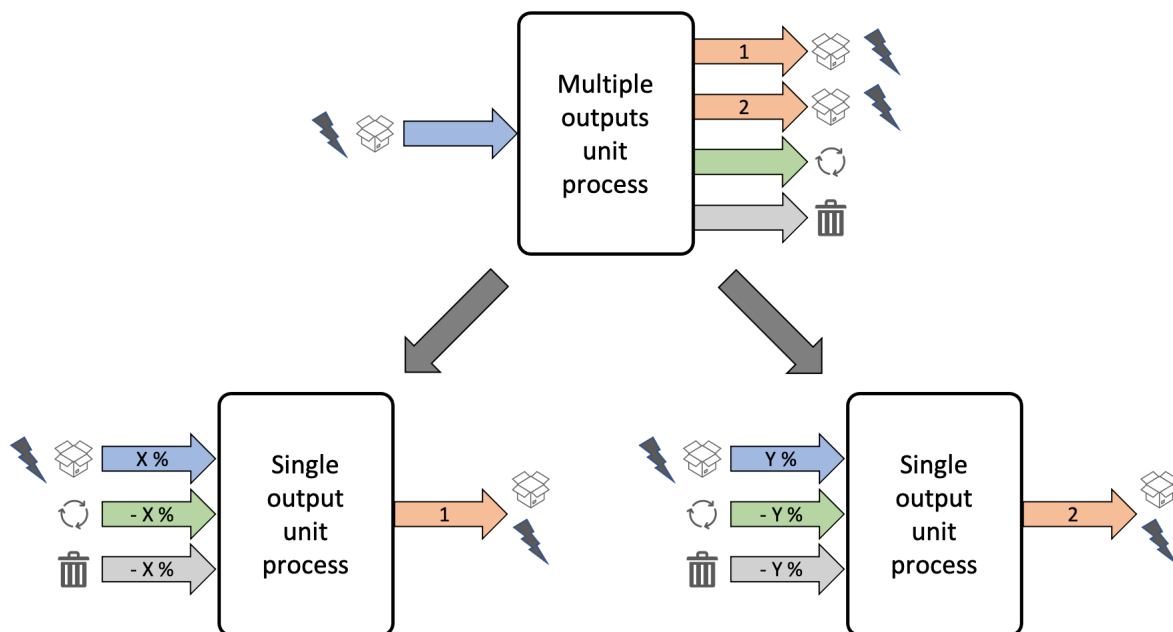


Figure 2.6: Illustration of a conversion of a multiple outputs unit process into several single output unit processes

Then those SOUPs can be linked together to form a whole process. They can be linked either directly or via a market (cfr. figure 2.7). A market regroups the suppliers of a certain product at one end and the consumers of that same product at the other end. For a given product, several markets can exist, each associated with a geographical region [66]. These local markets can be defined per continent, country, etc. A global market gathers all suppliers and all consumers of the product at hand.

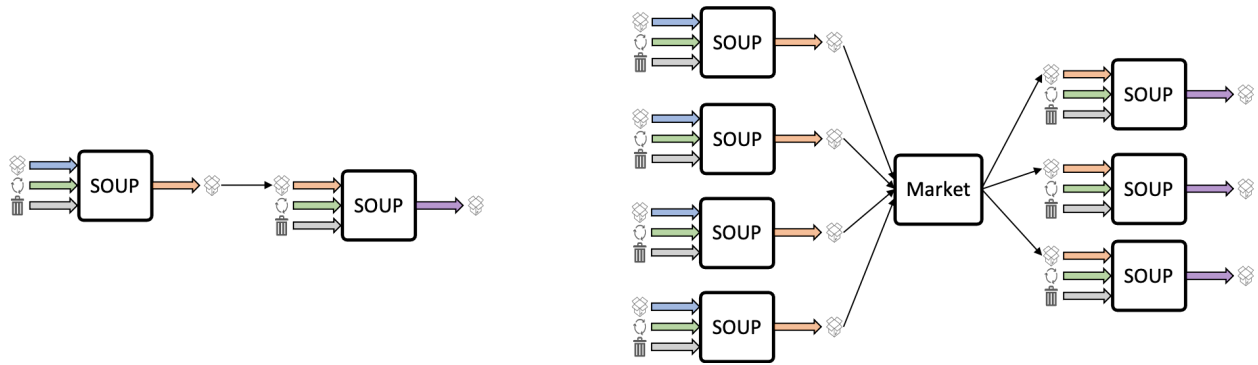


Figure 2.7: Illustration of the two types of links between unit processes: a direct link on the left, and a link via a market on the right

There are lots of different ways to make the SOUPs and to link them together. The choices that will be made in those regards will define the three system models of *ecoinvent*:

- Substitution, consequential, long term approach (**consequential**)
- Allocation at the point of substitution (**APOS**)
- Cut-off / recycled content approach (**cut-off**)

These three models are detailed in the following subsections.

2.3.1 Consequential system model

In the consequential approach, the reference product will be burdened with all the impacts of the activity and it will be credited with the benefits of the by-products and recyclable materials. The benefits are the burdens that are avoided by not having to produce the by-products or recyclable materials using an alternative route dedicated to them.

The burdens of the waste treatment or disposal are fully allocated to the waste producer.

When the link between two unit processes is made via a market, only the producers that can adapt to the changes in the demand can supply the market [1]. These are called the unconstrained or marginal suppliers and only account for a fraction of all the suppliers for a certain market.

To clarify our point, let us take an example with a simplified case: we will consider the production of bio-ethanol for household use (i.e. sold in small plastic bottles) obtained from wheat. The process (cfr. figure 2.8) has been strongly abridged and one single market has been added to keep it as clear as possible. In this case, straw is a by-product of cultivation and the stillage (a mix of wet spent grains and a bit of yeast) is a by-product of fermentation. The disposed bottles are deemed recyclable materials.

Straw and spent grains can be used as animal feed and their obtaining during the bio-ethanol process will avoid the need of producing them via other sources. The impacts of this alternative production are therefore avoided. The same goes for the discarded bottles after the bio-ethanol has been used: the recycled plastic avoids part of the production of virgin one.

The market for plastic will only be fed by the suppliers that can adapt their production to a change in the demand of plastic. Therefore only activities that have plastic as their reference product can enter the market which means that only virgin plastic will be fed into it. Indeed, the quantity of recycled plastic depends on the use of bio-ethanol and cannot be adapted. The recycling process will have the recycled plastic as a by-product while its reference product will actually be a negative quantity of disposed bottles: the recycling process offers the service of removing the disposed bottles.

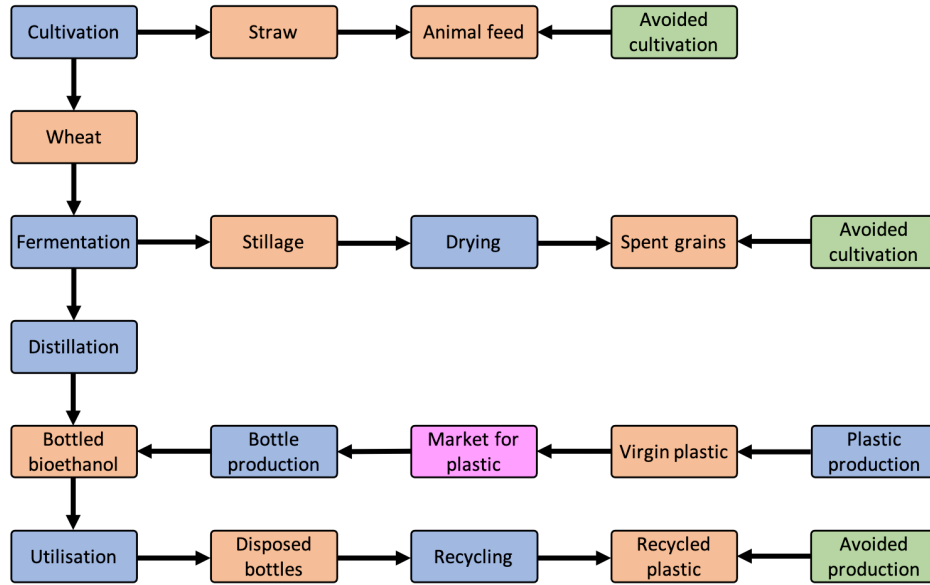


Figure 2.8: Consequential system model in *ecoinvent*: illustration of the production of bio-ethanol for household use. The blue boxes are the different activities or processes; the orange boxes are the materials and products; the pink box is a market; the green boxes represent the benefits of avoided production.

Theoretically speaking, out of the three system models, the consequential approach is probably the most representative of the reality [61]. However, its implementation in the *ecoinvent* database is still at an early stage and is rather basic due to poor underlying data for this approach [76]. Indeed, in practice, a lot of assumptions have to be made to account for the avoided burdens. An example would be the guesses about the quality of the recycled materials: do they have the same quality as their virgin counterparts and can they be used for the same applications? All assumptions taken must be thoroughly evaluated and substantiated, which constitutes the major problem for this approach.

The consequential approach is suited for long-term planning and for assessing the consequences of a change in an existing system. But it is limited to small-scale applications. Furthermore, it still needs improvement on critical markets such as electricity. Therefore, it does not seem appropriate for our application.

2.3.2 APOS system model

With APOS model, the system will allocate the burdens of the unit process to the different products (reference and by-products). This allocation is done following the ISO 14040/44 hierarchy [66]:

- Disaggregation: when it is possible, the system is sub-divided in smaller systems;
- Physical relationships: when they are available and meaningful, the system will use physical characteristics, such as mass, volume, energy content, etc, to split the burdens (for example, use of exergy to allocate the burdens between heat and electricity in a co-generation unit);
- Economic allocation: when none of the above is possible, which is the case most of the time, the allocation will be based on prices.

The burdens of the waste treatment and the recycling processes will be shared between the waste / recyclable materials producer and other activities that are making use of the valuable materials obtained.

With the APOS approach, when two unit processes are linked by a market, there are no conditions imposed on the suppliers as there were in the consequential system model. Here all producers can supply the market.

Let us take the example of the production of bio-ethanol for household use once again (cfr. fig. 2.9). With the APOS approach, the system will allocate the burdens of cultivation to the wheat and straw. But it goes further than that: the allocation of the burdens will result in bio-ethanol bearing parts of the burdens of cultivation, fermentation and distillation, but also of the drying of stillage. Conversely, spent grains will also bear parts of the burdens of fermentation and distillation.

As the disposed bottles are considered as recyclable materials, the burdens from the recycling process are partly allocated to the recycled plastic and partly to the bio-ethanol. The burdens from cultivation, fermentation, distillation and drying the stillage will also be partly allocated to the recycled plastic. As there are no constraints on suppliers to enter a market, producers of recycled plastic are allowed to supply the market for plastic.

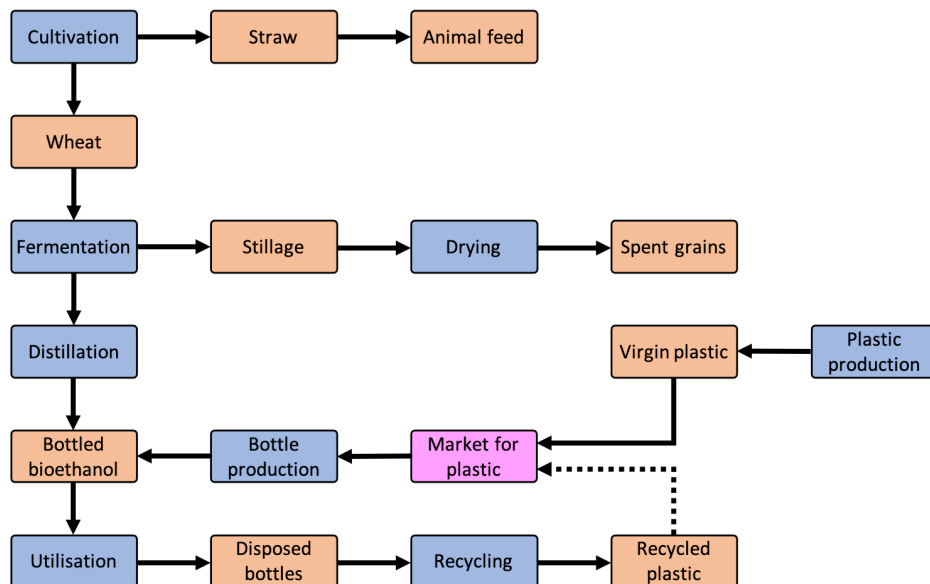


Figure 2.9: APOS system model in *ecoinvent*: illustration of the production of bio-ethanol for household use. The blue boxes represent the different activities or processes; the orange boxes are the materials and products; the pink box is a market.

APOS is a system model that is really complex and difficult to understand. Consequently, the results obtained can be hard to analyse and interpret. The system may sometimes lead to strange outcomes, not straightforward to explain: for example, some recycled materials might have bigger impacts than their virgin equivalents [61]. Results with APOS model would need to be systematically checked and compared to ones from simpler methods to see if they make sense.

2.3.3 Cut-off system model

In this model, the system will allocate the burdens where a product is sold and apply a cut-off where the recyclable materials leave the product system. The allocation method used is the same as for APOS and the markets will also be handled in the same way.

The main differences lie in the way waste and recyclable materials are treated.

- For waste, as in the consequential system model, the burdens of the treatment and/or disposal are fully allocated to the producer. Furthermore, the system will apply a cut-off after the treatment and all useful materials extracted from the waste will become burden-free for their users downstream as all the impacts lie in the producer. But the producer will not get any benefit from the production of these by-products.
- For the recyclable materials, the cut-off is applied directly where they are produced and they can be fed burden-free to a recycling process. The burden of the recycling process will be fully allocated to the recycled goods (which will only bear that burden) and nothing will be allocated to the producer of those recyclable materials. As for the waste, he will not get any benefit from the production of the recycled goods.

Let us look at the changes it entails for our example (cfr. fig. 2.10). The wet spent grains (i.e. the stillage) are sold for a negligible price and therefore no burdens will be allocated to them. Spent grains will only bear the burden of the drying process.

Likewise, the disposed bottles carry no burdens from before the point where they are gathered for recycling.

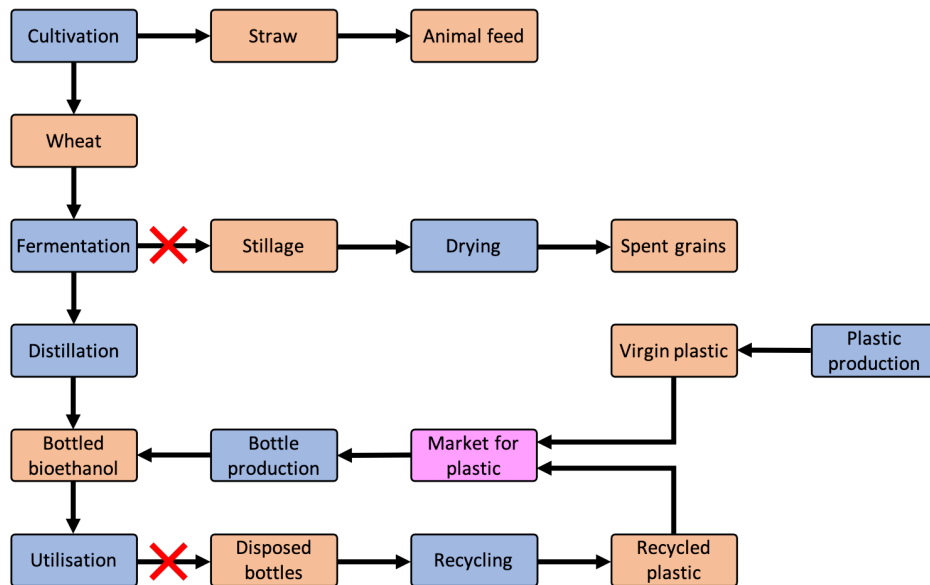


Figure 2.10: Cut-off system model in *ecoinvent*: illustration of the production of bio-ethanol for household use. The blue boxes represent the different activities or processes; the orange boxes are the materials and products; the pink box is a market.

The problem with that approach is that there is no incentive to recycle at the end of life, but on the other hand, the system will favor the use of recycled materials.

Nonetheless, the cut-off approach offers many advantages. It is easy to understand and is widely used throughout other databases. It was also used in previous versions of *ecoinvent* and is therefore more in line with previous works and studies.

For those reasons and because of the issues with the other two system models, it is the cut-off approach that has been selected to collect the data used in this thesis.

3 Selected criteria for energy system assessment

With a good grasp on LCA and now that the source of the future data has been chosen, it is time to select the criteria (or indicators) we want to extract from *ecoinvent*. As was explained before in chapter 1, assessing an energy system is not a trivial task due to the many aspects that can be taken into consideration and the relative importance one can attribute to them.

In this thesis, we have chosen to split the criteria we selected into two categories:

- The **key performance indicators** (KPIs) are the parameters that have been taken into account during the optimisations. They are the criteria deemed the most important and critical for our study and the corresponding data have been extensively checked and compared with the literature. The KPIs are therefore qualified as "consolidated" metrics.
- The **additional criteria** are all the other indicators that are used in the post-treatment steps to further assess the different solutions that have been found. Due to time constraints and a lack of independent studies, we have not been able to verify and validate the associated data as thoroughly as for the KPIs. These "non consolidated" metrics can nevertheless show the depth that can be brought to the analysis by adopting a multi-criteria perspective.

A KPI is a quantifiable measurement that demonstrates how effectively an energy system (in our case) is achieving its objectives. As such, the term KPI could be used for both of our categories and it is only by choice that it will be used only to refer to the first one in order to differentiate the most critical parameters from the others.

In the following sections, all criteria will be discussed so as to understand what they are about, what they entail and why they were selected. It must be noted that most of them were available through the ReCiPe 2016 method (cfr. section 1.3) and in those cases, the hierarchist cultural perspective was chosen.

3.1 Key performance indicators (consolidated)

Today, there is a growing awareness that the challenges of an energy system are multiple in nature: economic (micro and macro), technical, but also and especially environmental. Therefore, to capture those aspects, several metrics are necessary to assess the performance of the energy system.

According to [79], the 16 most popular metrics to characterise an energy system can be classified into four major categories: technical, economic, environmental, and social/policy.

In our work, we have decided to select indicators covering those four categories. The cost of the whole energy system and the global warming potential (GWP) have been chosen as they are the most commonly encountered metrics in the literature respectively for the economic and environmental points of view. For the technical and social aspects, we have elected to retain an hybrid metric: the energy return on investment (EROI), or actually the energy invested (E_{inv}) as explained in section 3.1.3. As also noted in that section, the EROI is at the same time an indicator of system efficiency (technical viewpoint) and can be related to social well-being (social viewpoint).

3.1.1 Cost [b€₂₀₁₅]

The cost of the system is rather self-explanatory: it encompasses the costs to build and maintain the whole energy system as well as the costs of the primary resources used to power it (i.e. respectively the investment, maintenance and operational costs). It will be expressed in euros of 2015, as will be all the criteria involving economical considerations. More precisely, the unit will be b€, i.e. billion (10^9) euros.

3.1.2 GWP [Mt_{CO₂eq}]

The global warming potential expresses the potential of greenhouse gases (GHGs) to trap heat in the atmosphere based on their radiative properties and the time they stay in the atmosphere. It is a measure of how much energy the emission of 1 unit of a certain gas will absorb over a given period of time, compared to the emission of 1 unit of carbon dioxide. It is therefore expressed in terms of an equivalent quantity of CO₂: in our case, in terms of megatons of CO₂ equivalent (Mt_{CO₂eq}).

The time a gas stays in the atmosphere has its importance as, the longer it stays, the more energy it will absorb. Accordingly, the time horizon considered for the GWP is a determining factor. The Intergovernmental Panel on Climate Change (IPCC) proposes three different horizons to choose from, based on policy goals:

- The 20-year horizon places more emphasis on minimising short lived GHGs, leading to short term reduction in global warming. However the benefits of this approach would disappear with time and the neglected long lived GHGs would eventually lead to more global warming.
- In a similar way, the 500-year horizon places more emphasis on long lived GHGs. This horizon could cause a short term increase in global warming since less attention will be given to the short lived gases due to their smaller impact on the long run, whereas these gases can cause high greenhouse effect on a shorter term. Hence, the choice of that time horizon might not be appropriate given the current context and the need to reduce quickly our impact on the climate.
- The 100-year horizon places itself in-between the two previous cases and seems to be a good compromise in order to take both long and short term impacts into account. In that regard, it is the most frequently used and most recommended time horizon and seemed the most suited for us.

To illustrate the influence of the time horizon selection, let us take the carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (NO₂) as examples. The values of the GWP for those elements are listed in table 2.1 for the three time horizons.

As was explained, the reference is CO₂ and its impacts will therefore always be equal to 1. Both CH₄ and NO₂ have higher radiative properties and thus cause more greenhouse effect, but when the gases leave the atmosphere (reflected by their lifetime), the GWP will decrease over time as they cannot trap heat anymore.

	Lifetime ^a [year]	GWP ₂₀ ^a	GWP ₁₀₀ ^a	GWP ₅₀₀ ^b
CO ₂	- ^c	1	1	1
CH ₄	12.4	84	28	7.6
N ₂ O	121	264	265	153

Table 2.1: GWP of some elements for the three IPCC time horizons

^a Values from the IPCC AR5 report [40] of 2013.

^b Values from the IPCC AR4 report [39] of 2007.

^c No single lifetime can be given.

3.1.3 Energy invested [TWh]

The societal energy return on investment is the ratio between the energy returned to society and the energy spent to extract, transport and refine the resources as well as to construct the energy system (the energy invested E_{inv}). A higher EROI leads to an increase in the net energy available for sectors other than the energy sector to prosper, thereby increasing economic and social well-being [46]. The EROI is a comprehensive indicator that encompasses technical aspects, as it captures the efficiency of energy conversion technologies, but that also provides some macro-economic perspective because of its link to the well-being of a society. Therefore, it seemed to us of significant importance to include the optimisation of the societal EROI in our model as it will provide additional insights. Multiple definitions of the EROI exist in the literature and the following one is considered in our thesis:

$$\text{EROI} = \frac{\text{energy returned to society}}{E_{\text{inv}}}$$

In our work, as will be explained later (cfr. chapter 3 section 1), energy services are expressed in terms of end-use demands, which translates the energy returned to society. Since the same end-use demands will be considered for each optimisation, maximising the EROI is equivalent to minimising the energy invested. This is the reason behind our choice to collect data directly on the E_{inv} instead of the EROI. The energy invested is expressed in terawatt-hour (TWh).

To fix the energy invested concept, let us look at a small example: the use of 1 kg of petroleum. To effectively use the energy content of this unit of petroleum, we decide to reinvest part of the energy in the extraction of 1 more kg of petrol (1 MJ). Then, we would like to fuel our car to travel for vacation and so, we will use part of the energy left to refine the petrol to diesel (6 MJ). The total energy for those two operations is the energy invested to produce diesel (7 MJ). The energy left under the form of diesel is the energy returned to society or end use energy (36 MJ). In this case, it allows us to travel around 17 km with a diesel car. The corresponding EROI of the diesel is equal to 36 MJ / 7 MJ = 5.1.

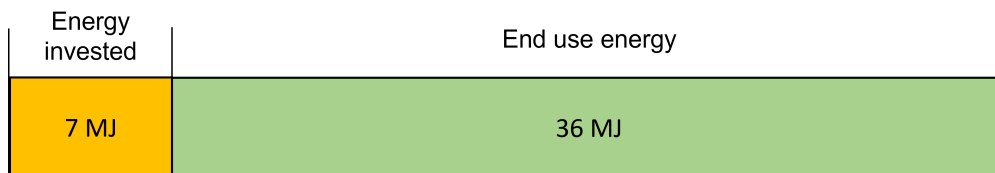


Figure 2.11: Energy content of 1 kg of petroleum

3.2 Additional criteria (non consolidated)

Now that we have defined the main criteria that will be the object of our optimisation effort, one question still stands: are those three KPIs enough to judge if an energy system is good or not? The short answer is probably no as there are many aspects to an energy system and only three KPIs could possibly not address all of them. This is why some additional criteria were chosen because they offer other important perspectives on which impacts an energy system can have.

First, as can be seen in [5], land use can bring some interesting insight into the technologies considered.

Also, we wanted to add environmental criteria to the simple GWP aspect. As explained in the Eco-Indicator 99 method [32], environmental impact can be defined by three types of damage: to human health, to ecosystems and to resources. These three metrics have thus been naturally adopted.

Next, in order to bring some social perspective to the environmental issue, the environmental prices, or "the social cost of pollution" [24], is considered.

Finally, since the raw materials are the first elements of the life cycle and the associated supply constraints must not be forgotten, the critical raw materials are added to the list of metrics.

All these criteria are further detailed in the following sections.

3.2.1 Land use [$\text{km}^2 \cdot \text{y}$]

This criterion represents the surface area that has been occupied or transformed by, or for, the energy system [42]. It is expressed as an area occupied over a certain period of time [$\text{km}^2 \cdot \text{year}$]. The temporal dimension has indeed to be taken into account as an area might not be used throughout the year only for the energy system. Let us take the example of crop fields: they are often harvested several times a year but the crops might sometimes be used to produce simply animal feed instead of bio-fuel. In that case, if the field is only used half a year for the energy system, the land use considered is: area of the field [km^2] $\times$ 1/2 [year].

This criterion is actually divided into two distinct ones depending on the type of surface area that is occupied:

- The urban land use accounts for all urban and industrial areas, roads, rail networks, etc. Factories or dump sites therefore fall into that category.
- The agricultural land use accounts for all other types of lands such as crop fields and forestry.

3.2.2 Damage to ecosystems [species.y]

This criterion reflects the damage made by the system to the ecosystem quality, i.e. its local species. It accounts for many midpoint impact categories through damage pathways using the ReCiPe 2016 methodology [38] as was explained before in section 1.

This indicator assesses the loss of local species integrated over time, which represents the species that have disappeared locally for a certain period of time because of climate changes, destroyed habitat or changes in the food web, to cite but a few causes. It is therefore an indicator on temporary loss of species in a designated area, hence the temporal integration, but it is not an indicator on completely extinct species.

The ecosystems are split into three categories: the terrestrial (*terr*), freshwater (*fw*) and marine water (*mw*) systems. The endpoint characterisation factor for the damage to ecosystems (CF_{DE}) can be derived as follows:

$$\text{CF}_{DE} = \text{PDF}_{terr} \times \text{SD}_{terr} + \text{PDF}_{fw} \times \text{SD}_{fw} + \text{PDF}_{mw} \times \text{SD}_{mw} \quad (2.1)$$

Where:

- SD_{terr} is the species density for terrestrial systems, in [species/ m^2];
- SD_{fw} and SD_{mw} are the species density for freshwater and marine water systems respectively, in [species/ m^3];
- PDF_{terr} is the potentially disappeared fraction of species [-] integrated over area [m^2] and time [year] for terrestrial systems, in [$\text{m}^2 \cdot \text{year}$];
- PDF_{fw} and PDF_{mw} are the potentially disappeared fractions of species [-] integrated over volume [m^3] and time [year] for freshwater and marine water systems respectively, in [$\text{m}^3 \cdot \text{year}$].

The resulting factor is therefore expressed in [species.year].

3.2.3 Damage to human health [DALY]

Human health, or more specifically the damage an energy system causes to human health, is of the utmost importance. What would be the point of a system that has a very limited GWP and is good with respect to the climate change but has a significant impact on our health. Both aspects are actually correlated as the damage to human health criterion is affected by the GWP, but it goes further and also accounts for other considerations such as NO_x emissions, ionising radiations, water use, etc. This criterion is also based on the ReCiPe 2016 methodology [38].

It is expressed in disability adjusted life years (DALYs), which represents the total amount of years of life lost and of years lived with a disability due to a disease or an accident.

3.2.4 Damage to resources availability [b€₂₀₁₅]

This criterion represents the potential surplus costs involved for future mineral and fossil resource extraction due to the degradation of excavated ore (less minerals of interest per unit of ore). It expresses the increase of cost for a resource with respect to the quantity that the system will use. It is once again based on the ReCiPe 2016 methodology [38].

As mentioned before, cost-related criteria are expressed in billions of euros from 2015.

3.2.5 Environmental prices [b€₂₀₁₅]

Environmental prices valuation is a method that expresses the external cost of one additional unit of pollution, i.e. "the social cost of pollution" (De Bruyn et al., 2018, [24]). The environmental prices indicate the loss of economic welfare that occurs when one additional unit of pollutant is released to the environment. The philosophy of that approach is to capture into a single monetary unit the loss in human health and ecosystem services and the loss in quality of buildings and resources that are caused by pollution. The retained criterion is expressed in billions of euros from 2015.

It accounts for some of the criteria aforementioned but brings them together with an economical point of view. Nonetheless, placing prices on human health or ecosystems is not an easy task as it is subject to many hypotheses and can always be questioned. The values obtained in our results for this criterion should therefore not be taken as face value, but more as an order of magnitude to compare different solutions.

3.2.6 Critical raw materials [kt]

This indicator corresponds to the cumulative weight of the critical materials (cfr. table 2.2) used for the energy system and will therefore be expressed in kilotons (kt). Critical materials are materials that are of economic importance to the European Union (EU) and are subject to supply risks. This criterion is important as many critical materials are necessary in the construction of clean technologies and will be of greater importance in a "greener" energy system.

Antimony	Cobalt	Heavy rare earths	Natural rubber	Silicon metal
Baryte	Coking coal	Indium	Niobium	Strontium
Bauxite	Fluorspar	Light rare earths	Phosphate rock	Tantalum
Beryllium	Gallium	Lithium	Phosphorus	Titanium
Bismuth	Germanium	Magnesium	Platinum group metals	Tungsten
Borates	Hafnium	Natural graphite	Scandium	Vanadium

Table 2.2: List of the critical raw materials as defined by the EU in 2020 [12]

It must be noted that not all materials yield the same criticality and one ton of a material could be more critical than one ton of another depending on their available potential and where the brunt of their potential is located. But as no criticality index was defined by the EU, all materials have the same weight and this criterion is thus not a criticality indicator. Accordingly it lacks a bit of meaning when taken all by itself but

can nonetheless give an rough idea of the dependence of a system on critical raw materials.

It must also be noted that all the materials in table 2.2 have been taken into account, with the exception of coking coal. Coking coal or metallurgical coal is used, notably, for steel production in blast furnaces. The reason it has been discarded is because, with the *ecoinvent* database, it is extremely difficult to isolate coking coal from regular coal used to produce energy in the life cycle of a certain technology or resource. It could have been done by hand but the time required would have been colossal because of the sheer number of technologies to get the data for and the extent of details in the processes the database can provide. However, discarding the coking coal is not as significant as one might think. Indeed, this material is actually a borderline case as it narrowly misses the economic importance threshold and was only kept by the EU on the list for the sake of caution [64].

4 Data computation methodology

Now that we have defined the chosen criteria to optimise our energy system, let us look at the methodology and assumptions made to gather the associated data.

The cost data were calculated previously by Gauthier Limpens [49]. For the other criteria, as already explained in section 2, the data have been obtained from the *ecoinvent* database using the *SimaPro* software (a quick user guide is provided in appendix E). For that purpose, the cut-off approach was used (cfr. section 2.3.3).

The geographical reference is Belgium (cfr. chapter 4 about the case study), but, in the cases where no data specific to Belgium were available, the next smallest region encompassing Belgium was selected: Europe without Switzerland, Europe, rest of the world^(a) or, finally, the whole world^(b).

In terms of time reference, *ecoinvent* data were collected from 2013 up to now. Though, we make use of them to study possible scenarios for 2035. This is justified for already mature technologies. However, for emerging technologies, it must be recognised that impacts might drastically change in the near future and corresponding data will have to be adjusted as science evolves and knowledge is progressing. As an example, in the case of photovoltaic (PV), the data were found to be outdated and have been adjusted following [13] for the GWP and E_{inv} criteria.

To explain the methodology for the data collection, it is important to first understand the different levels of information available using *SimaPro*.

- We have access to the results of life cycle impact assessment (LCIA) methods. From these, we can extract the total impact of a product for a given impact category (i.e. the different indicators).
- We have also access to the contributions of all the unit processes involved in the life cycle of the said product: their respective impacts that, when summed together, give the total impact aforementioned.
- Additionally, we can navigate in the network of processes and see how the impact propagates through them.

In this thesis, we make use of all three capabilities as more details than just the final value were sometimes needed. Furthermore, some contributions to the final score needed to be modified for some indicators, as will be explained in the next sections.

The following chapter will expand on the energy system model that has been used (*EnergyScope TD*, or *ESTD* for short) and the changes we brought to it. However, some elements composing the energy system model need already to be discussed since it will allow to better understand the explanations that follow. As will be detailed in chapter 3, an energy system model is made of three blocks, two of them being the resources (fuels or other energies that can be fed to the system, such as gas, electricity or uranium) and the technologies (plants or devices to convert the resources into other fuels, energies or energy services, such as

^(a) When selecting data, a few different origins were considered in the database, and the other ones were aggregated under the designation "rest of the world". When no data could be found about Belgium or Europe, it was therefore the next choice.

^(b) When no specific locations were available, the only location available was "global", which encompasses the whole world.

power plants, cars or electrolyzers). It is for these two parts that data needed to be gathered, and they are often treated differently from each other.

The links between the technologies and resources in *EnergyScope TD* and the processes in *ecoinvent* are provided in appendix D.

4.1 Accounting for direct and indirect impacts

The GWP for the technologies of the model were obtained with the IPCC 100-year method applied on the infrastructure processes including the construction and the end of life (EoL) of the technology.

In the case of resources, however, it is somewhat more complex due to direct and indirect emissions. A graphical representation of the ensuing explanations has been provided in figure 2.12.

The indirect emissions can be directly obtained from the GWP impact assessment of the resource up to the market activity, which corresponds to the point where the resource is sold to be subsequently used.

To obtain the direct emissions, the product of a combustion activity (electricity or heat produced for example) using said resource has to be studied. It can be found further down in the product chain and contains the combustion impact (the direct emissions that we are looking for), but also the indirect emissions of the resource, as well as the emissions linked to the construction and EoL of the facility, etc. The problem is that these emissions are expressed in proportion to the amount of product (1 kWh of electricity produced for example), not as a function of the resource used, and the quantity of resource used is not always easily found. Therefore the values of the emissions from the combustion (i.e. the direct emissions) are not relevant by themselves, but the ratio between these direct emissions of the resource (for one unit of product) and the indirect emissions (for one unit of product) can be extracted. The total emissions can then be computed as follows:

$$GWP_{tot} = GWP_{ind. \text{ from market}} \cdot \left(1 + \frac{GWP_{dir. \text{ from comb. activity}}}{GWP_{ind. \text{ from comb. activity}}}\right) \quad (2.2)$$

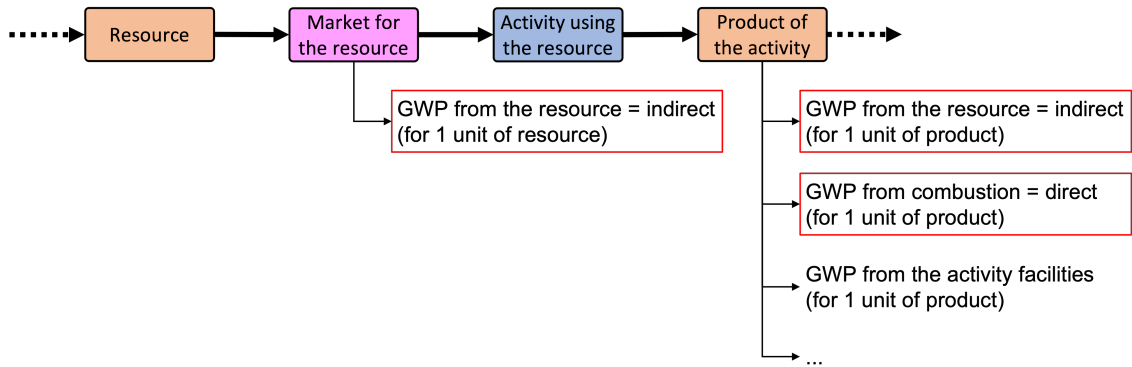


Figure 2.12: Illustration of the contributions to the GWP found at different stages in the product chain

Using natural gas (NG) as an example, the indirect emissions were obtained by looking at the cumulative GWP of natural gas from its extraction up to the high pressure NG market in Belgium. To obtain the direct emissions, the GWP of high voltage electricity production from a gas turbine was studied.

An exception was made for bio-fuels for which we neglect the direct emissions as it is difficult to find a relevant combustion activity.

The same methodology was applied for other criteria that are also dependent on the combustion activity (i.e. the combustion of the resource adds to the total impact): environmental prices, damage to human health, and damage to ecosystems. For other indicators where the combustion process has no impact, only the data at the market activity level was needed: agricultural and urban land occupation, damage to resource availability, and critical raw materials.

4.2 Obtaining the energy invested

As opposed to the other criteria that each have a corresponding LCIA method already implemented in *SimaPro*, or that we have created in the case of critical raw materials, there is no LCIA method for the energy invested (E_{inv}). There is however a method to compute the cumulative energy demand (CED), which corresponds to the energy content that has been extracted from the biosphere in the life cycle of the product. This is different from the energy invested by society as it includes additional contributions such as the energy content of resources lost along the life cycle (methane leaks for example).

For the technologies, the difference between the E_{inv} and the CED of construction (including the end of life) is negligible, and both have been considered to be equal. Indeed, the energy content of the resources lost throughout the life cycle is inconsequential compared to the energy content of the resources actually used. The data for the E_{inv} of the technologies were therefore considered to be the data for the CED of those technologies.

For the resources, computing the data was not as easy as the CED accounted for too much elements. A graphical representation of what the CED and E_{inv} account for is presented in figure 2.13 for the case of diesel. When looking at the CED at the market level for a certain resource, it corresponds to the sum of four main parts:

- the energy content of the primary resources extracted from the biosphere (petroleum for example), before conversion to the (targeted) secondary resource (diesel for our example);
- the energy required to extract, convert and transport these primary resources;
- the energy content of the losses at the extraction site (for losses further down the chain, their energy content was already accounted for in the energy of the primary resources);
- part of the CED of the facilities (for their construction and end of life).

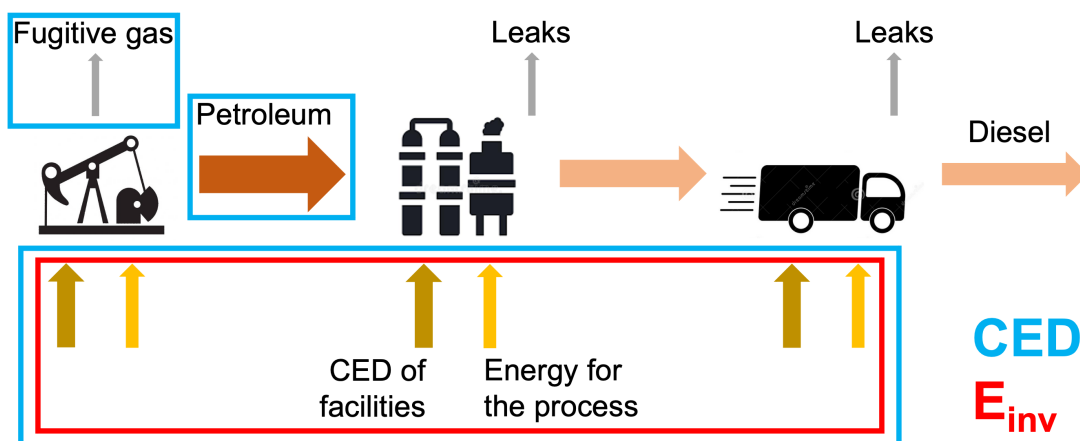


Figure 2.13: Difference between CED and E_{inv} illustrated for diesel

For the E_{inv} , only the energy invested in the facilities and in the processes should be considered. Regrettably, the difference is not made between the primary resources from which the secondary resource is derived and the primary resources required in the conversion process (for energy and infrastructures). A solution would be to entirely skip using CED and to gather data from the literature. However, most of the data available there correspond to the energy invested at the extraction site of primary resources and not the energy invested up to the point of use of secondary resources. Furthermore it is difficult to find values for all the resources considered in *EnergyScope TD*, especially emerging bio-fuels.

For these reasons, we have chosen to stay with *ecoinvent* and to manually navigate the network of processes in order to remove the unwanted energy contributions as explained in [10].

4.3 Converting the gathered data to the format of *EnergyScope TD*

Attention must be paid when feeding the data to the energy model, as it requires particular units to comply with how the system computes the final scores of the energy system. Conversions had to be applied and some hypotheses were also needed. These aspects are further detailed in the following (with some more details to be found in appendix A).

4.3.1 Resources

For the resources, *ESTD* requires the data to be expressed per GWh of the concerned resource. For example, the GWP for natural gas must be given in kilotons of equivalent CO₂ per GWh of natural gas [kt_{CO₂eq}/GWh].

However, in *ecoinvent*, data were often given per functional unit of the resource: 1 kg for liquid and solid fuels, or 1 Nm³ for gases. The energy content of 1 functional unit of resource is thus required to convert the data, but there is no consistent use of heating values in *ecoinvent* [10].

For our example of natural gas, the report [10] gives a lower heating value (LHV) of 36.6 MJ/Nm³. However, in the gas power plant dataset, the natural gas that is considered has a higher heating value (HHV) of 39 MJ/Nm³, which corresponds to a LHV of 35.1 MJ/Nm³. Furthermore, when computing the average LHV for the Belgian market by considering the diverse natural gas origins (as the LHV is different for each extraction site), a value of about 34.6 MJ/Nm³ was obtained.

Faced with these inconsistencies, it was decided to use the LHV of the resources from the combustion activity where they are used. Although, in the case of bio-fuels, for which no satisfying combustion activity could be found, the LHVs were taken from the report [10].

4.3.2 Technologies

In the case of technologies, data have to be given as specific values with respect to the power output: [criteria]/kW_e for technologies producing electricity, [criteria]/kW_{th} for technologies producing heat, [criteria]/(pkm/h)^(c) for the passenger mobility and [criteria]/(tkm/h)^(d) for the freight mobility.

In *ecoinvent*, the data could only be gathered for a functional unit of plant or vehicle, which represents the whole facility or vehicle. The size of each functional unit (i.e. its power output) was thus needed.

For some technologies, the conversion was straightforward as the impacts only had to be divided by their size to obtain the desired units. On the other hand, some others required a bit more computation and hypotheses on our part.

An example would be the cogeneration technologies: their size is expressed in electrical power output whereas *ESTD* requires to specify the value of the criteria with respect to their thermal power output. The cogeneration thermal and electrical efficiencies from *ESTD* are therefore used to apply the conversion. More details are given in appendix A.

Another example would be the transport sector: the criteria are computed per car, but *ESTD* needs them to be expressed in terms of [criteria]/pkm/h as was said above. Assumptions thus have to be made about the average number of passengers by car, its lifetime, its average speed, the time it is used every day, etc. The same hypotheses as in *EnergyScope TD* were taken (cfr. appendix A).

4.3.3 Monetary units

To be consistent between all criteria that are expressed in monetary values, they all had to be expressed in the same monetary unit. As the cost was already expressed in €₂₀₁₅, it has been kept as the reference unit. The indicator "environmental prices" was already expressed in the same unit, but the indicator "damage to resource availability" is expressed in \$₂₀₁₃ in *ecoinvent*. The change rate from dollars to euros in 2013 was taken from [73] (1 €₂₀₁₃ = 1.33 \$₂₀₁₃). The change rate in euros from 2013 to 2015 was computed using the

^(c) pkm stands for passenger-kilometre.

^(d) tkm stands for tonne-kilometre.

2013 Belgian consumer price index (BECPI): $100 \text{ €}_{2013} = 100.46 \text{ €}_{2015}$. The resulting conversion factor is about $0.7553 \text{ €}_{2015}/\text{\$}_{2013}$.

4.4 Missing technologies in *ecoinvent*

Sometimes, no data about certain technologies were available in *ecoinvent* and other means had to be used to obtain their impacts. As an example, for the mobility sector, very few data could be found about trucks or coaches.

In that regard, independent studies were investigated and extrapolations from similar technologies were made. Some technologies were also recreated by assembling diverse scaled parts from other related technologies. These computations are detailed in appendix A.

Chapter 3

Energy system model: Implementation of multi-criteria optimisation

After the energy system characterisation step in chapter 2 that addressed our first research question (see chapter 1), the next phase of our thesis focuses on the second one: the implementation of multi-criteria optimisation in an energy system model.

The aim of this chapter is to explain the bases of the energy system model that was chosen for this work (as a reminder, *EnergyScope TD*) and what has been subsequently modified to implement the possibility for multi-criteria optimisation. The chapter will be articulated as follows: a summary of how the existing *EnergyScope TD* model works (this version can be found in repository [48]), followed by the explanation of the multi-criteria method selected, and, finally, the changes and additions made to the model to incorporate that multi-criteria optimisation method.

1 Selected model: *EnergyScope TD*

EnergyScope TD is an open source energy system model that optimises investments and the operating strategy related to the energy system of a defined area, which is usually a region or country, represented in a single cell. It has been developed by G. Limpens et al. in a collaboration between UCLouvain and EPFL universities. It is a multi-sectoral model expressed in a linear programming (LP) formulation. The model proposes an hourly resolution of the system over a year using Typical Days, which is what TD in *EnergyScope TD* stands for. The concept of typical days is explained later in this section.

In the following subsections, the basic principles behind the model are explained. For a complete mathematical description, the reader shall refer to *EnergyScope TD* Supplementary Material [50].

1.1 Architecture of the model

To build an energy system, *EnergyScope TD* relies on 3 types of blocks that it will use to make a coherent and functioning system: the resources, the conversion technologies and the demands. These three parts are illustrated in a conceptual system in figure 3.1. The task of the model is to identify the optimal energy conversion system to meet the demand with the resources available. It must be noted that, each time, the model will build an energy system from scratch, without taking into account the current state of the energy system.

- The **resources** account for the primary energies that can either be produced or extracted locally (wind, solar, biomass, waste, etc.), or that can be imported from abroad (natural gas, oil, hydrogen, electricity imports, etc.).

- The **demand** is expressed in terms of end-use demand (EUD), which differs from most models that use the final energy consumption (FEC). The EUD is the energy demand expressed in terms of energy services (passenger mobility, heating, etc.) whereas the FEC is "the energy which reaches the final consumer's door" [29]. The FEC can therefore be defined as the energy that a technology uses to satisfy the EUD. As an example, in the case of mobility, a user will need passenger mobility (expressed in passenger-kilometre), which is the EUD, but to obtain it, he will need to put diesel in his car and the quantity of diesel used is the FEC.

The EUDs are composed of four sectors: electricity, heating, mobility and non-energy demand. The EUDs are then further split into more specific demands, called end-use types (EUTs). For example, mobility is split into two EUTs: passenger mobility and freight.

Non-energy demand has been defined by the International Energy Agency [7] as "fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel".

- The **conversion technologies** are the links between the resources and the demands. To be more precise, they can be defined as links between layers.

Indeed, to obtain a coherent and functioning system, the model uses layers that can be characterised as elements that need to be balanced at all times. These layers include the resources and the EUTs. They can either convert energy from a resource layer to another, convert energy from a resource layer to an EUT layer (those technologies will be called technologies of EUT), or store energy.

For a storage technology, the inflow and outflow are localised in the same layer. Energy can be taken from the layer at a given time and delivered at another point in time when needed.

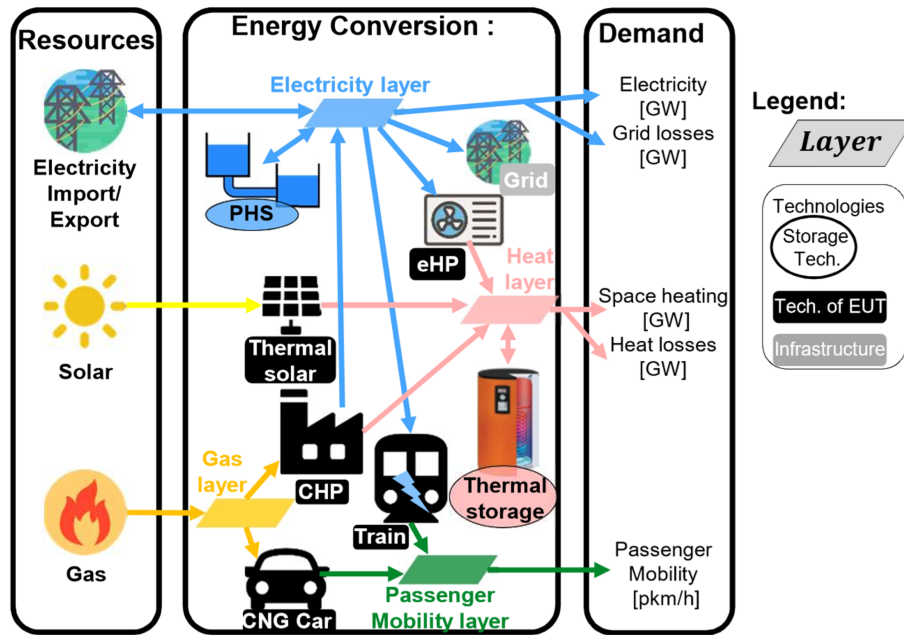


Figure 3.1: The three parts of *EnergyScope TD* illustrated in a conceptual energy system. Abbreviations: pumped hydro storage (PHS), electrical heat pump (eHP), combined heat and power (CHP), compressed natural gas (CNG), end-use type (EUT). Figure taken from G. Limpens et al. article on the Belgian energy transition [51]

1.2 Typical days

As mentioned before, the model works with an hourly resolution and needs to balance the layers at each time period over a whole year: the hourly demand will have to be met with the appropriate hourly production. The hourly resolution is required as intermittent energies such as solar or wind are taken into account. Furthermore, the energy demand is also time-dependent and varies throughout the year, but also throughout the day. Consequently, *EnergyScope* uses hourly time series (TS) to describe the time-dependent variables: the production profiles of intermittent energies, which actually depend on the TS of the weather conditions, and the EUDs profiles.

As the energy system is optimised over a year, to reduce the computational cost, *EnergyScope TD* uses those TS to compute 12 days, called typical days (TDs), that will best represent the profiles of the different days of the year. The selection of the TDs is done by using a clustering method: the 365 days of the year are regrouped into 12 clusters and each cluster will be defined by a representative day (i.e. a TD). In the end, *EnergyScope TD* will only have to solve an optimisation problem for a year made of 12 TDs instead of 365 different days.

The number of TDs selected has its importance as it will have an impact on the computational cost but also on the precision of the model. As explained by G. Limpens et al. [52], selecting 12 TDs reduces heavily the computational time without affecting the validity of the results.

1.3 Criteria computation and objective function

The optimisation part of the model is handled using a linear programming formulation that consists of linear constraints (i.e. equalities or inequalities) and a linear objective function. The objective function represents what *EnergyScope TD* needs to optimise.

The inputs to the model are the parameters defining the resources and their availability, the technologies, and the EUDs.

In order to find the best system possible, the model can choose what and how much of a resource to use, the installed capacity for each technology and their operation at each point in time (i.e. for the 8760 hours of the year). In that regard, the optimal solution is expressed in terms of those parameters.

The goal of *EnergyScope TD* is to find the energy system that minimises its total cost while meeting the EUDs and not exceeding an upper limit on its total GWP. As such the total cost and total GWP are the two criteria (or indicators) considered, where one is optimised and the other is only subject to a constraint. The system must also comply with other constraints that will not be detailed in this work (as already mentioned, the reader can refer to the Supplementary Material [50] for more details).

The objective function can therefore be expressed as the minimum total cost of the system, which is the sum of the capital expenditure (CAPEX) and the operational expenditure (OPEX). In the model, those costs are split into three parts: the technologies total investment costs ($\mathbf{C}_{\text{inv}}(j)$), the technologies yearly maintenance costs ($\mathbf{C}_{\text{maint}}(j)$), and the total cost of the resources ($\mathbf{C}_{\text{op}}(i)$). To be more precise, the objective function is about the total annualised cost of the system ($\mathbf{C}_{\text{tot}}$), as defined in equation 3.1, since the investment costs are considered to be paid throughout the whole lifetime of the technologies.

$$\mathbf{C}_{\text{tot}} = \sum_{j \in \text{tech}} \left(\tau(j) \cdot \mathbf{C}_{\text{inv}}(j) + \mathbf{C}_{\text{maint}}(j) \right) + \sum_{i \in \text{res}} \left(\mathbf{C}_{\text{op}}(i) \right) \quad (3.1)$$

$$\tau(j) = \frac{i_{\text{rate}} \cdot (i_{\text{rate}} + 1)^{\text{lifetime}(j)}}{(i_{\text{rate}} + 1)^{\text{lifetime}(j)} - 1} \quad \forall j \in \text{tech} \quad (3.2)$$

$$\mathbf{C}_{\text{inv}}(j) = c_{\text{inv}}(j) \cdot \mathbf{F}(j) \quad \forall j \in \text{tech} \quad (3.3)$$

$$\mathbf{C}_{\text{maint}}(j) = c_{\text{maint}}(j) \cdot \mathbf{F}(j) \quad \forall j \in \text{tech} \quad (3.4)$$

$$\mathbf{C}_{\text{op}}(i) = \sum_{t \in T \mid (h, td) \in T_H_TD(t)} \left(c_{\text{op}}(i) \cdot \mathbf{F}_t(i, h, td) \cdot t_{\text{op}}(h, td) \right) \quad \forall i \in \text{res} \quad (3.5)$$

Where:

- $\tau(j)$ is the investment cost annualisation factor of the technology j ;
- i_{rate} is the interest rate;
- $\text{lifetime}(j)$ is the lifetime of the technology j ;
- $\mathbf{F}(j)$ is the installed capacity (with respect to the main output) of the technology j ;
- $c_{\text{inv}}(j)$ is the specific investment cost of technology j [M€/GW] (i.e. the investment cost per GW installed of the technology j);
- $c_{\text{maint}}(j)$ is the specific maintenance cost of the technology j [M€/GW/y] (i.e. the maintenance cost per year per GW installed of the technology j);

- $c_{op}(i)$ is the specific cost of the resource i [M€/GWh];
- $\mathbf{F}_t(i, h, td)$ is the quantity of the resource i that is used at the hour h of the typical day td [GWh];
- $t_{op}(h, td)$ is the time period duration (1h by default);
- $tech$ is the set of all the technologies in the model;
- res is the set of all the resources in the model;
- T is the set of all the periods of the year (i.e. the 8760 hours);
- $T_H_TD(t)$ is the hour h and the typical day td associated to the period t .

As mentioned, there is an upper limit on the total GWP of the system. Similarly to the cost, it is split into several parts: the technologies total emissions ($\mathbf{GWP}_{constr}(j)$) and the total emissions of the resources ($\mathbf{GWP}_{op}(i)$). No maintenance part is considered and the technologies total emissions account for the construction and the decommissioning of said technologies. Once again, it is the total annualised GWP ($\mathbf{GWP}_{tot}$) that is of interest (cfr. eq. 3.6) as the emissions related to the technologies will be considered to be spread over their lifetime.

$$\mathbf{GWP}_{tot} = \sum_{j \in tech} \left(\frac{\mathbf{GWP}_{constr}(j)}{lifetime(j)} \right) + \sum_{i \in res} \left(\mathbf{GWP}_{op}(i) \right) \quad (3.6)$$

$$\mathbf{GWP}_{constr}(j) = gwp_{constr}(j) \cdot \mathbf{F}(j) \quad \forall j \in tech \quad (3.7)$$

$$\mathbf{GWP}_{op}(i) = \sum_{t \in T \mid (h, td) \in T_H_TD(t)} \left(gwp_{op}(i) \cdot \mathbf{F}_t(i, h, td) \cdot t_{op}(h, td) \right) \quad \forall i \in res \quad (3.8)$$

Where:

- $gwp_{constr}(j)$ is the specific greenhouse gases emissions of the technology j [Mt_{CO₂eq}/GW];
- $gwp_{op}(i)$ is the specific green house gases emissions of the resource i .

2 Choice of a multi-criteria method

In the previous section, we have seen an energy system model with a unique objective function. The goal of this thesis is to go one step further and to propose a way to implement a multi-criteria optimisation of energy systems. The capability to take into account multiple criteria at the same time is crucial because these criteria can be conflicting and improving one alone often means deteriorating the others. For example, the system will want to go one way for the cost-optimum case but may go a completely other way for the GWP-optimum case. Depending on the constraints one has, a compromise solution can be found that might be better than the solutions based each on an single-criterion optimisation. In a multi-objective problem, the solution is not a single one anymore, but a set of cases that is called the Pareto front: it is the set of all the points where you cannot improve the value of one criterion without deteriorating the value of the other ones. An example of a 2D minimisation problem is illustrated in figure 3.2.

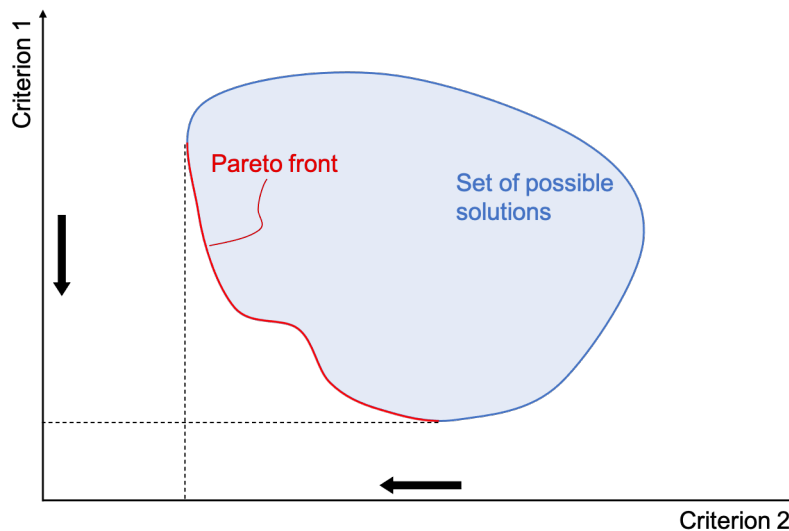


Figure 3.2: Example of a bi-criteria optimisation problem where both criteria have to be minimised. The blue shaded area represents the set of all solutions to said problem.

If only two criteria were to be taken into account for the optimisation, a simple exploration of the Pareto front of the data set would suffice. In that regard, a mono-criterion optimisation on the first parameter combined with a limit on the second parameter that one varies would be enough to draw the said Pareto front.

For example, optimising the cost with different limits on the GWP will give a set of Pareto-optimal solutions to choose from. Then it is up to the decision-maker to choose what point in the set suits him the most.

When three or more criteria are important for the decision-maker, it becomes more complicated as exploring the Pareto front becomes less clear and intuitive because of its representation. Indeed, while the representation on a 2D graph is still possible for 3 criteria, it becomes impossible when even more have to be taken into account. Thus the need for another method arises.

2.1 From *EnergyScope TD* single criterion optimisation to a multi-objective method

There are many possible multi-criteria methods to choose from, but not all would be easily compatible with the current version of *EnergyScope TD*. In the end, as explained in the following paragraphs, the goal programming method was chosen because of its compatibility with *EnergyScope TD (ESTD)*, its easy implementation and because its adaptation to a higher number of criteria is straightforward and should not cause any problem. Furthermore, it is the most used method for multi-objective optimisations [63].

The current version of *ESTD* can only handle single-criterion optimisations, or more specifically, can only optimise a single objective function (cfr. section 1.3). The objective function models the goal to be reached: what has to be minimised or maximised, such as the total cost of the system, the total energy invested or even only the operational part of the GWP (i.e. the part linked to the consumption of resources such as gasoline, coal or natural gas) of the system.

Our aim was to find a method that allows to handle multiple criteria while keeping a single objective function so as not to have to completely change the way the program handles the optimisations. This is why the goal programming method seemed to be a good candidate for our application. This method can be characterised as a generalisation of linear programming in order to handle multiple objectives that can be conflicting [41]. Incidentally, as *ESTD* is formulated as a linear programming problem (cfr. section 1), this method appeared as the next logical step.

Other methods were considered but none yielded the same appeal as goal programming. To name but a few, linear aggregation, epsilon-constrained or min-max approaches were contemplated as they also allow to keep

only one objective function, but were subsequently dismissed. They are briefly discussed hereafter.

- Linear aggregation, or the weighted sum method, is a very simple, but highly efficient method from an algorithmic point of view [59]. Its biggest drawback is the fact that no matter what set of weights you take, the method does not allow to find solutions that are trapped in non-convex parts of the Pareto front (cfr. fig. 3.3). It means that if there was a concave part to the Pareto front, some solutions would never even be considered. This problem is not encountered with goal programming.
- The epsilon-constrained method is also known as compromise programming. Its philosophy is to keep only one criterion to optimise in priority and to transform the other objectives into constraints: minimise $f_1(x)$ such as $f_2(x) \leq \epsilon_2, \dots, f_n(x) \leq \epsilon_n$. Whilst this approach does not suffer from the concavity restriction, the added constraints amplify the complexity of the problem and could lead to an unsolvable problem if not chosen carefully. It requires the decision-maker to have an in-depth knowledge of the original problem and is therefore not user-friendly [78].
- The min-max method consists in translating the multi-objective problem into a single-objective one where one tries to minimise the relative gap with respect to a reference point (RP). The method will minimise the biggest gap between a criterion ($f_i(x)$) and its objective (RP_i): $\max(|RP_i - f_i(x)|)$. The reference point plays a crucial role as it could really hinder the search of an optimal solution if badly selected. With a judicious choice, the problem of non-convex Pareto front can be dealt with [78]. Once again, extensive foreknowledge of the initial problem is required.

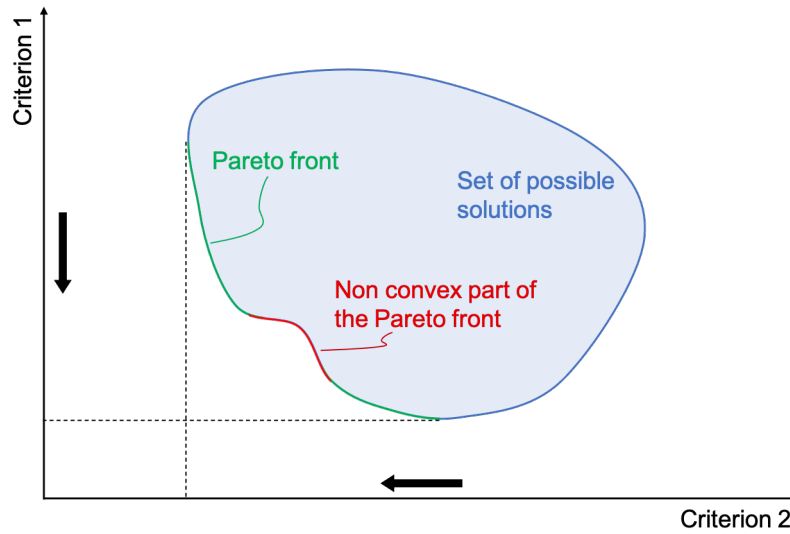


Figure 3.3: Example of a bi-criteria optimisation problem where both criteria have to be minimised. The red line is the concave part of the Pareto front which would never be reached by the linear aggregation method.

2.2 Selected method: The goal programming method

The principle of this method is to transform a multi-objective problem into a single-objective one. It allows to express all the desired criteria (or key performance indicators, as defined in section 3) into a single objective function that will actually be a simple weighted sum of the deviations of the criteria with respect to their target values. Then the objective function so obtained has to be minimised in order to find the solution that will be the closest to meet the said target values.

Let us denote the objective function as OF and the target values as goals. Let $goal = [goal_1, \dots, goal_n]$ be the vector containing the goals for each criterion and $f = [f_1, \dots, f_n]$ be the vector of the values of the criteria. Let $d^+ = [d_1^+, \dots, d_n^+]$ and $d^- = [d_1^-, \dots, d_n^-]$ be the vectors containing the deviations with respect to the goals (cfr. fig. 3.4).

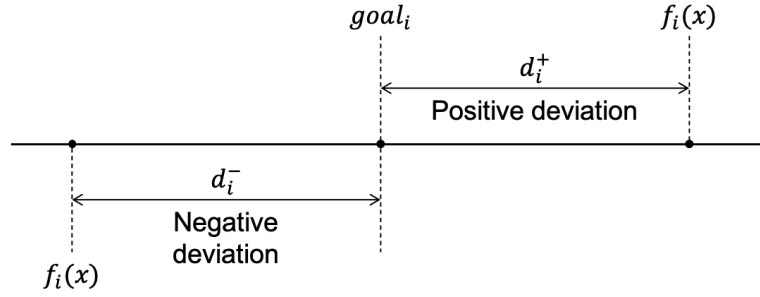


Figure 3.4: Illustration of the deviations for the goal programming method

When the value of the criterion f_i is above its *goal*, the positive deviation d_i^+ will be the (positive) difference between the two and the negative deviation d_i^- will be set to zero. In the same way, when the value of the criterion is below its goal, d_i^+ will be set to zero and d_i^- will be the (positive) difference between the two. The problem can then be expressed as follows (cfr. equations (3.9–3.15)):

$$\text{Objective} = \min(OF) \quad (3.9)$$

$$OF = \sum_{i \in \text{crit}} (w_i \cdot \{d_i^+ \text{ or } d_i^- \text{ or } d_i^+ + d_i^-\}) \quad (3.10)$$

$$\sum_{i \in \text{crit}} w_i = 1 \quad (3.11)$$

Subject to

$$f_i(x) + d_i^- - d_i^+ = \text{goal}_i, \quad \forall i \in \text{crit} \quad (3.12)$$

$$d_i^+, d_i^- \geq 0, \quad \forall i \in \text{crit} \quad (3.13)$$

$$\left. \begin{array}{l} h(x) = 0 \\ g(x) \leq 0 \end{array} \right\} \text{Additional constraints} \quad (3.14)$$

$$x \in \text{solutions that produce a functional energy system} \quad (3.15)$$

As shown in equation 3.10, different combinations of the deviations can be minimised. The choice, for each criterion, will depend on how the achievement of the goal is considered. The three possible cases are detailed in table 3.1.

Case	Combination of deviations to minimise	Theoretical objective
If the objective for the i-th criterion is to be below or equal to the i-th goal (but the i-th criterion tends to be above it), then the positive deviation shall be minimised.	d_i^+	$f_i(x) \leq \text{goal}_i$
If the objective for the i-th criterion is to be greater than or equal to the i-th goal (but the i-th criterion tends to be below it), then the negative deviation shall be minimised.	d_i^-	$f_i(x) \geq \text{goal}_i$
If the objective for the i-th criterion is to be equal to the i-th goal, then the sum of the deviations shall be minimised.	$d_i^+ + d_i^-$	$f_i(x) = \text{goal}_i$

Table 3.1: Goal programming: Alternatives for the deviations to minimise

It is important to highlight that, in the first two cases, the value of the i-th criterion is allowed to exceed the i-th goal: it can be lower than the goal if the criterion has to be minimised and higher if it has to be maximised. However, going beyond the goal does not bring more benefit than simply reaching it. Indeed, the undesirable variation, the one set to be minimised, would be equal to zero should the goal be reached or exceeded. The corresponding term in the sum (cfr. eq. 3.10) would then also be equal to zero but could never become negative and help to further reduce the objective function. It means that the minimal value for the objective function is zero whether all the goals are perfectly met or some of them are exceeded.

As the criteria might have different units, it is crucial to normalise both their values and their goals:

$$f_i^{norm}(x) = \frac{f_i(x) - f_i^{min}}{f_i^{max} - f_i^{min}} \quad \forall i \in crit \quad (3.16)$$

$$goal_i^{norm} = \frac{goal_i - f_i^{min}}{f_i^{max} - f_i^{min}} \quad \forall i \in crit \quad (3.17)$$

Where f_i^{min} and f_i^{max} are the minimum and maximum values of the i -th criterion respectively. They are obtained by performing single-criterion optimisations on one criterion at a time and by extracting the minimum and maximum values attained in the whole set of results.

In this thesis, each goal has been chosen to be the minimum value for its corresponding criterion. In addition, as all the criteria considered are to be minimised, only the positive deviations have to be taken into account such as in the first case described in table 3.1. With the normalisation expressed at equations (3.16–3.17)), the objective function 3.10 can therefore be expressed as follows:

$$\begin{aligned} OF &= \sum_{i \in crit} (w_i \cdot d_i^+) \\ &= \sum_{i \in crit} (w_i \cdot (f_i^{norm}(x) - goal_i^{norm})) \\ &= \sum_{i \in crit} \left(w_i \cdot \frac{f_i(x) - f_i^{min}}{f_i^{max} - f_i^{min}} \right) \end{aligned} \quad (3.18)$$

It must be noted that the non pre-emptive goal programming formulation has been used in this work: all the objectives have the same level of priority but can still be given different relative importance via the weights. The pre-emptive formulation would allow to prioritise some objectives over others by giving them a greater priority level [18]. There would then be several objective functions similar to the one for the non pre-emptive formulation: one for each priority level. The system would then proceed to minimise the first objective function (OF_1) reaching a value V_1 , and then the second one (OF_2) while imposing that OF_1 has to keep the same value V_1 . It would then go on until it has gone through all the priority levels. The non pre-emptive formulation can thus be assimilated to the second formulation with only one priority level.

While the pre-emptive formulation allows the decision-maker more control over his choices, it also requires more computational time as the optimisation has to be run several times. Therefore, it would not be directly compatible with the current version of *EnergyScope TD* and would require a more in-depth adaptation of the program. Moreover, as the number of criteria considered in the objective function up to now is quite small (only three), the non pre-emptive formulation was deemed sufficient.

When using this method, one should choose the set of goals carefully as one problem that could arise is to find a non Pareto-optimal solution, meaning that one or several criteria could still be further improved. It is due to the fact that when a goal is reached for a criterion, going beyond that goal is not rewarded as was explained before. Choosing goals that are too easy to meet could then result in a non-optimal solution as shown in figure 3.5 where the green area represents the set of solutions the system could return.

In this work however, as the goals have been chosen to be the minimum for each criterion, such a situation cannot appear.

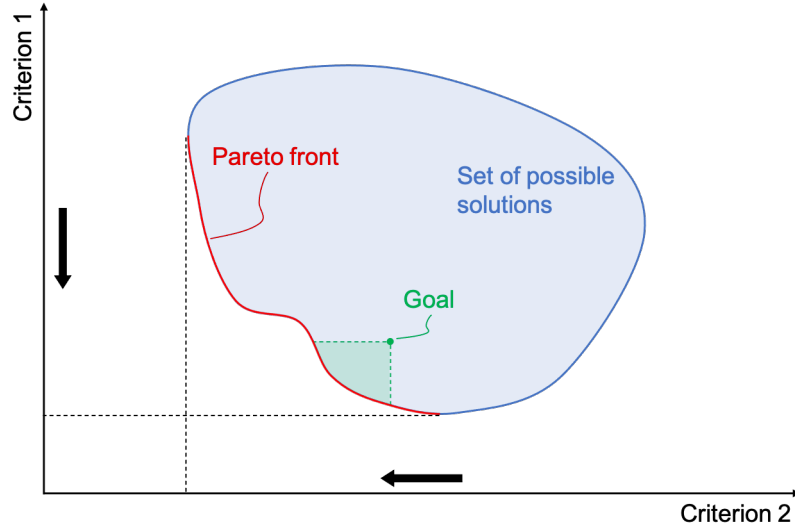


Figure 3.5: Example of a bi-criteria optimisation problem where both criteria have to be minimised. The blue shaded area represents the set of all solutions to said problem and the green shaded area represents the set of solutions that could be obtained by the goal programming method with the indicated goal.

3 Changes to *EnergyScope TD* model

Once the multi-criteria method has been selected, it is now necessary to consider the changes that had to be made to the model to enable its implementation: what has been added to the model and what are its limitations. As explained in the previous section (cfr. section 2), the goal was for the multi-criteria method to be easily compatible with the previous version of *ESTD*. The consequence is that nothing had to be modified from the previous version in terms of equations, and only additional parameters, variables and constraints were needed.

3.1 Addition of new criteria

The first step towards multi-criteria optimisation was to add other criteria that could be evaluated and added up. All those new criteria have been implemented and are treated in the same way as the GWP is in the previous version of *ESTD* (cfr. section 1.3).

As a reminder, for each criterion, the following set of equations (3.19–3.21) has been appended:

$$\mathbf{CRIT}_{\text{tot}} = \sum_{j \in \text{tech}} \left(\frac{\mathbf{CRIT}_{\text{constr}}(j)}{\text{lifetime}(j)} \right) + \sum_{i \in \text{res}} \left(\mathbf{CRIT}_{\text{op}}(i) \right) \quad (3.19)$$

$$\mathbf{CRIT}_{\text{constr}}(j) = \text{crit}_{\text{constr}}(j) \cdot \mathbf{F}(j) \quad \forall j \in \text{tech} \quad (3.20)$$

$$\mathbf{CRIT}_{\text{op}}(i) = \sum_{t \in T \mid (h, td) \in \text{T_H_TD}(t)} \left(\text{crit}_{\text{op}}(i) \cdot \mathbf{F}_t(i, h, td) \cdot t_{\text{op}}(h, td) \right) \quad \forall i \in \text{res} \quad (3.21)$$

Where:

- $\mathbf{CRIT}_{\text{tot}}$ is the total annualised value of the criterion [$\text{Units}_{\text{crit}}/\text{y}$];
- $\mathbf{CRIT}_{\text{constr}}(j)$ is the total value of the criterion for the technology j [$\text{Units}_{\text{crit}}$];
- $\mathbf{CRIT}_{\text{op}}(i)$ is the total value of the criterion for the resource i [$\text{Units}_{\text{crit}}/\text{y}$];
- $\text{crit}_{\text{constr}}(j)$ is the specific value of the criterion of technology j [$\text{Units}_{\text{crit}}/\text{GW}$];
- $\text{crit}_{\text{op}}(i)$ is the specific value of the criterion of the resource i [$\text{Units}_{\text{crit}}/\text{GWh}$];

- $lifetime(j)$ is the lifetime of the technology j ;
- $F(j)$ is the installed capacity (with respect to the main output) of the technology j ;
- $F_t(i, h, td)$ is the quantity of the resource i that is used at the hour h of the typical day td [GWh];
- $t_{op}(h, td)$ is the time period duration (1h by default);
- $tech$ is the set of all the technologies in the model;
- res is the set of all the resources in the model;
- T is the set of all the periods of the year (i.e. the 8760 hours);
- $T_H_TD(t)$ is the hour h and the typical day td associated to the period t .

As explained in chapter 2, the data were gathered for all the new criteria and were also updated for the GWP. As for the costs, they have not been amended and have been kept the same.

In order for the model to provide the results for the new indicators, the print section of the code had also to be complemented.

3.2 Modified objective function

The second step was to implement the new objective function, which also required new sets of parameters and variables:

- For each KPI, two new parameters have to be imparted to the model for the normalisation part (cfr. section 2.2). These are the maximum and minimum values observed during the single-criterion optimisations (respectively $crit_{max}$ and $crit_{min}$).
- To define the relative importance of each KPI, weights have also to be provided to the model. With the three KPIs selected in chapter 2, this represents three new parameters ($weight_{crit}$).
- The goals can be given directly in their normalised form. This adds three parameters as well.
- The computation of the deviations is achieved in two steps: first, the values for the KPIs are normalised, then, the deviations can be computed with the normalised values for the KPIs and the goals. As such, it requires six new variables (two per KPI): the total normalised value for the criterion ($TotalCrit_{norm}$) and its positive deviation ($Positive_Deviation_{crit}$).
- Finally, a last variable that contains the value of the objective function has to be added ($Multi_crit_obj$). Its computation is reminded in equation 3.22.

$$\begin{aligned}
 Multi_crit_obj = & \quad weight_{cost} \times Positive_Deviation_{cost} \\
 & + weight_{gwp} \times Positive_Deviation_{gwp} \\
 & + weight_{env} \times Positive_Deviation_{env}
 \end{aligned} \tag{3.22}$$

In the updated version of *EnergyScope TD*, four choices for the objective function to optimise are offered to the user: the total cost, the total GWP, the total E_{inv} or the multi-criteria objective. It must be noted that, although the three single-objective options are available, it is also possible to obtain them with the multi-criteria optimisation by allocating a weight of 1 to the criterion of interest and 0 for the other two.

In terms of model limitations, it can be noted that no additional ones are added with respect to the original version of *EnergyScope TD* described in [49]. The only remark is on the goal selection, which must be done carefully as was explained in section 2.2.

The new *EnergyScope TD Multi-Criteria* version can be found in repository [56].

Chapter 4

Case study: The Belgian energy system

The main methodological contributions of this thesis, addressing the two first research questions presented in the introduction (chapter 1), have been presented in the previous chapters:

- In chapter 2, the energy system has been better characterised: key performance indicators have been selected, some complementary metrics have been introduced and the methodology to assess all these criteria has been defined.
- In chapter 3, the possibilities of optimisation of the *EnergyScope TD* model have been broadened: a multi-criteria approach has been implemented.

In order to demonstrate the relevance of these contributions, the new model must now be applied to a meaningful case study. The selection of that case study and the description of its model are the object of the present chapter.

1 Choice of the case study

To bring valuable results, a coherent and challenging application case must be selected. It will be coherent if the energy system considered can be condensed into a single coherent cell: the geographical area considered must have homogeneous weather conditions and all sub-areas of the system must be well connected (i.e. there are well developed networks) so as to allow smooth flows and avoid energy congestion. A challenging case study will cope with an energy system where there is a substantial demand in all the sectors, where resources are limited in their available amount and where defossilisation cannot be easily reached.

As the work done in the present thesis builds upon Gauthier Limpens' PhD thesis [49] about the optimisation of energy transition pathways, and more specifically on the so-called "snapshot" version of *ESTD* for Belgium, the selected application case will essentially be the same as it meets all the criteria: the Belgian energy system. To be more precise, the purpose of the case study will be to optimise the Belgian energy system for the year 2035.

The country is quite small and made up of a 65 km coastline, plains in the north and hills in the south. The weather is homogeneous with a temperate maritime climate: moderate seasons with rainfall distributed throughout the year and quite uniform wind. The energy networks are well developed and connected throughout the country.

The challenging part comes from the limited access to local renewable resources which makes decarbonation an arduous task. Indeed, a small geographical area combined with a high population density and a strong industry creates a high energy demand while the production potential is reduced. The renewable resources are wind, solar, biomass (wet and woody), hydro and geothermal, but are very limited.

The year 2035, as explained by G. Limpens et al. [51], appears to be a good trade-off between a long-term horizon where policies can still be implemented and a horizon short enough to be representative of tomorrow

society with a toolbox of technologies already known.

2 Belgian energy system modeling

As explained in chapter 3 section 1, *EnergyScope TD* splits the energy system into three parts:

- the resources that can be fed to the system (i.e. the primary energy);
- the end-use demands (EUD) which translate the needs of the system and therefore the final energy consumption;
- all the in-between networks and technologies that will transform the resources into the EUD.

The Belgian energy system implemented in the model is shown in figure 4.1. It consists of 10 end-use types, 101 technologies and 28 layers. It must be noted that each technology actually refers to a set of different products that fall into the same category (e.g. wind turbines can be of different sizes with different powers, diesel cars can be found in hundreds of distinctive models, etc.). Choosing the appropriate technologies to find relevant data to characterise the whole category is thus a real challenge and must be done with care.

As the case study is strongly based on the one in G. Limpens' PhD thesis [49], readers are advised to refer to that work should they want more details about the underlying studies and assumptions, but the relevant information has been restated in this chapter. There will therefore be redundancies. Nonetheless, some other assumptions were made and will be detailed. As already mentioned, the data collected for the criteria will differ from G. Limpens' work, except for the cost that was not modified. All the data will be available in appendix A.

The following subsections will outline the figures and important aspects of the Belgian energy system and its projection for 2035:

- The available resources to the system will be detailed with a focus on their estimated potential (section 2.1).
- The projection for the energy demand and the current political stance for the future will then be presented (section 2.2).
- Afterwards, technologies will be briefly discussed (section 2.3).

It can be noted that, in the next section (section 3), the application of the model to the 2015 Belgian energy system will be presented. Since the model has already proven itself, the objective is not really to validate the model, but rather to obtain a reference case to which future results can be compared.

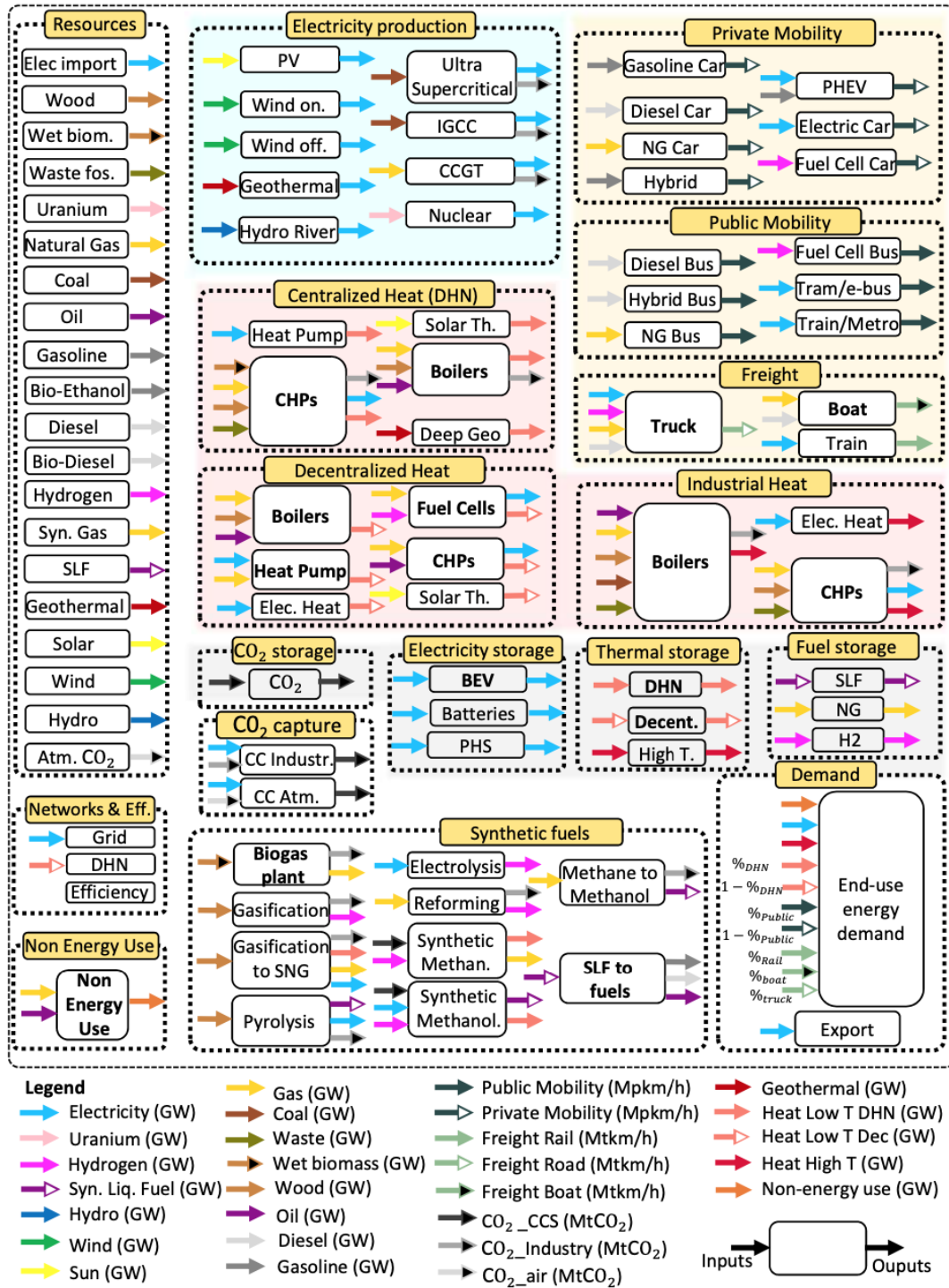


Figure 4.1: Application of *EnergyScope TD* to the Belgian energy system: overview of the resources, technologies and demands implemented in the *EnergyScope TD* model. Technologies (in **bold**) represent groups of technologies with different energy inputs (e.g. Boilers include gas boilers, oil boilers ...). ‘Decent.’ represents the group of thermal storage for each decentralised heat production technology. Abbreviations: synthetic liquid fuel (SLF), Atm. (atmospheric), hydrogen (H₂), photovoltaic (PV), integrated gasification combined cycle (IGCC), combined cycle gas turbine (CCGT), carbon capture and storage (CCS) cogeneration of heat and power (CHP), heat pump (HP), natural gas (NG), plug-in hybrid electric vehicle (PHEV), district heating network (DHN), battery electric vehicle (BEV), pumped hydro storage (PHS), power to gas (PtG), CC (carbon capture), methan. (methanation), onshore (on.), offshore (off.), decentralised (decent.). The figure has been taken from G. Limpens’s PhD thesis [49].

2.1 Resources

Resources can be split into two categories: endogenous and exogenous. Endogenous resources are produced locally and their potential is therefore limited. Almost all of them are renewables with the exception of waste. They encompass solar, wind, hydro, biomass and geothermal. Exogenous resources are the ones imported from abroad such as electricity, hydrocarbons, hydrogen, uranium and coal.

2.1.1 Local resources

The maximum estimated capacity for the renewable energy (RE) based technologies and the available potential for the local resources are summarised respectively in table 4.1 and table 4.2 where they are put into perspective with the data from 2015.

	Technology	2015	Max. capacity	Units
Electricity production	Photovoltaic	3.85	59.2	[GW _p]
	Onshore wind	1.18	10	[GW _p]
	Offshore wind	0.69	3.5	[GW _p]
	Hydro river	0.11	0.12	[GW]
	Geothermal	0	≈ 0	[GW]
Heat production	Geothermal	≈ 0	≈ 0	[GW]
	Centralised solar thermal	0	71.4	[GW _p]
	Decentralised solar thermal	≈ 0	71.4	[GW _p]

Table 4.1: Comparison of the installed capacity in 2015 of renewable energy based technologies and their maximum capacities in the model for 2035.

	Resource	2015	Max. potential	Units
Renewables	Woody biomass	13.9	23.4	[TWh/y]
	Wet biomass	11.6	38.9	[TWh/y]
Non renewables	Waste	7.87	17.8	[TWh/y]

Table 4.2: Comparison of the amount of local resources used in 2015 and their maximum yearly potential in the model for 2035.

Solar

The maximum capacity for photovoltaic (PV) or solar thermal is dependent of the land availability to install those panels, which is highly speculative. Nonetheless one can use the following approach to obtain an order of magnitude for this limit. Assuming that 250 km² of well oriented roof is available [26] (which would correspond to a bit less than 1% of Belgium's land area) and that the PV efficiency will be 23% [6] in the future, given a power density of 0.2367 GW_p/km² in Belgium, the limit of the installed capacity becomes 59.2 GW_p^(a). For solar thermal, with a future efficiency of 28 %, given a power density of 0.2857 GW_p/km², the limit would be 71.4 GW_p.

Wind

The onshore wind potential is estimated at 10 GW_p and the offshore potential at 3.5 GW_p. Those potentials are subject to change in the future as wind energy is at the center of attention and massive investments are poured into it. Europe is at the forefront in the wind power industry and benefits from one of the best potential in the world. Taller and wider wind turbines are being developed, allowing access to a more constant and rapid wind (the higher the wind turbine, the better the access to constant wind). In that regard, the offshore potential might be underestimated. On the other hand, even with those improvements, the onshore potential might be overestimated as developers often see their projects blocked by citizens. All things considered, the total estimated potential is still deemed relevant whilst maybe somewhat undervalued.

^(a) GW_p stands for gigawatt peak; it refers to the maximal power output of a device or facility (also called its nominal power). As an example, for a solar panel, its nominal power is the maximum power output under standard conditions (in terms of solar irradiance, temperature, etc).

Hydro

Due to Belgium's topography, the hydro potential is very restricted and almost fully exploited. In 2015, the installed capacity was 0.11 GW and no important investments are foreseen.

Geothermal

Researches about the potential of geothermal energy in Belgium are still at an early stage and it has not yet been accurately estimated. There is no large facility, but only a few projects where the installed capacity does not exceed a few megawatts. Therefore the associated potential will be considered as null.

Biomass and waste

Waste and biomass are often merged in the literature whereas a clear distinction is made in the model. Waste account for all the fossil waste such as plastics, while biomass accounts for organic matter and is therefore assumed renewable. The biomass is further split into two categories:

- The wet biomass is made up of everything that can be digested such as grass cuttings, food residues, etc.
- The woody biomass accounts for the rest that cannot be digested such as wood, industrial wood residues, sawdust, etc.

Municipal waste is therefore split between the three aforementioned categories: their organic waste is categorised as either wet or woody biomass, but not fossil waste, and the rest is considered as waste. The yearly biomass potential considered in the model is 23.4 TWh for woody biomass and 38.9 TWh for wet biomass. The waste potential amounts to 17.8 TWh.

2.1.2 Imported resources

Many different resources can be imported from abroad as shown in figure 4.1: some are fossil (oil, natural gas, diesel, etc.), some are renewable (bio-ethanol, hydrogen, etc.), and there is also uranium, which is a fissile fuel. Imports will be characterised by an infinite amount of the resource available, except for electricity imports and coal, which will be discussed in the next section (cfr. section 2.2).

The future prices for the resources are a complex subject and highly difficult to predict. In fact, as G. Limpens said in his PhD thesis [49], "the only certainty for those who forecast future fuel prices is that they will be wrong". Nonetheless, projection were made and are specified in table 4.3 (prices for endogenous resources are also specified in the table).

Non-renewable			Renewable			Units
Year	2015	2035		2015	2035	
Light fuel oil	43	60	Synthetic liquid fuel	240	211	[€ ₂₀₁₅ /MWh]
Gasoline	59	82	Bio-ethanol	260	226	[€ ₂₀₁₅ /MWh]
Diesel	57	80	Bio-diesel	280	240	[€ ₂₀₁₅ /MWh]
Natural gas	30	44	Synthetic natural gas	220	197	[€ ₂₀₁₅ /MWh]
Coal	15	18	Woody biomass	29	33	[€ ₂₀₁₅ /MWh]
Waste	20	23	Wet biomass	5	6	[€ ₂₀₁₅ /MWh]
Uranium	4	4	Hydrogen (H ₂)	200	177	[€ ₂₀₁₅ /MWh]
			Electricity imports	57	84	[€ ₂₀₁₅ /MWh]

Table 4.3: Comparison of the resources prices in 2015 and their projection for 2035. Electricity imports are placed in the renewable category because the majority of the electricity mix comes from renewables, though there is also a part of uranium and fossil fuels (it will be detailed later in this section).

For several renewable resources, to collect the data about the complementary criteria introduced in this thesis, hypotheses had to be made about their origin, their mode of production, or the energy mix used to produce them. In the following, these assumptions are detailed for the electricity imports, the hydrogen, and the other bio-fuels (synthetic liquid fuel (SLF), synthetic natural gas (SNG), bio-ethanol and bio-diesel).

Electricity imports

Belgium already has electric interconnections with its main neighboring countries and new projects are also in the making: for example, an underwater interconnection with Denmark is planned and should become operational between 2030 and 2033 [35]. Electricity can therefore be imported from many countries with quite different foreseen energy mixes. In that regard, a global European mix was considered, more specifically the projected European electricity mix for 2035 as estimated by the European Union (EU) [16]. The EU estimation corresponds to the projection of the current trends up to 2050 based on the policy context of 2020, framework conditions and historical trends. This projection serves as a guide for further policies and does not however mean that the EU goals for 2050, in terms of climate change, will be reached. The resulting electricity mix is illustrated in figure 4.2 and is made up of about 66% of renewables, 20% of fossil fuels and 14% of nuclear.

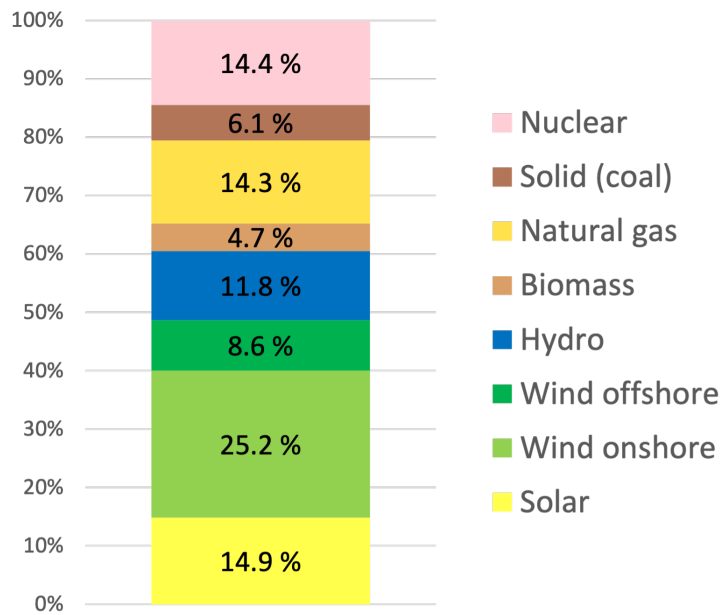


Figure 4.2: European electricity mix of 2035 as projected by the EU [16]

As a side note, a completely clean electricity mix for 2050 has also been computed and can be found in appendix B for scenarios pertaining to more long-term horizons.

Hydrogen

Hydrogen is predicted to be one of the future energy vectors for the energy transition. To be considered as a "green" alternative to natural gas or other fossil fuels imports, it must be produced through renewable energies and not through methane reforming. In this work, all hydrogen imports are therefore considered to be "green".

It is complicated to predict the future import mix of "green" hydrogen due to the lack of clear political framework and choices. Belgium however has a massive plan for importing green hydrogen from outside Europe. The report of the Hydrogen Import Coalition [20] identifies the following origins of imported hydrogen:

- from Iberia and North Sea, using offshore wind for production, with transport by pipeline or by ship;
- from Australia, Chile, Oman and Morocco, using PV, with transport by pipeline or by ship.

A future market with imports from these countries is not specified. However, we expect most wind power in Europe to be used in the electricity grid. It has then been considered that only 10% of hydrogen imports will come from wind in the North sea and 10% from wind in the Iberian peninsula, both by pipeline. A further 10% comes from solar in Morocco by pipeline and 20% from Oman by ship. The 50% left will be

divided equally between Chile and Australia where solar will be used and the transport will be by ship. This distribution is illustrated in figure 4.3 where it is put into perspective on a map with photovoltaic power potential.

As a side note, the possibility of transport by pipeline from Oman was investigated but put aside as other pipeline projects (for oil or natural gas) have been rejected or aborted due to political contention between countries in that region [67].

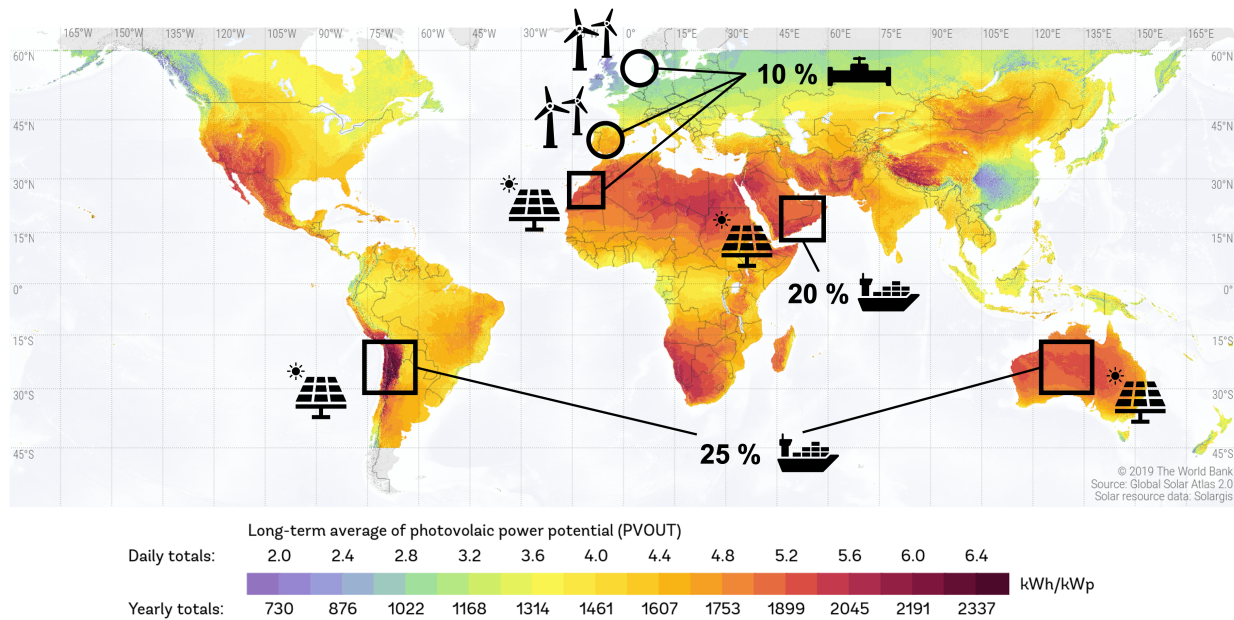


Figure 4.3: Hydrogen import mix for 2035 put into perspective on a map with photovoltaic power potential around the globe. The map was taken from [71]

The impacts of H_2 imports account for the electricity production in each country, the electrolyzers construction, the transport to Belgium and all the losses in the conversion process.

Firstly, the losses when converting electricity into H_2 by electrolysis were considered using the efficiency of the electrolyzers implemented in *ESTD*. The electricity production was also scaled to match the power potentials of the selected origins [28].

Secondly, the transport route was taken into account. In the case of transport by pipeline, H_2 losses are estimated at 0.001% [34]. When transport by ship is considered, the hydrogen is assumed to be transported under the form of ammonia (NH_3) as it is the cheapest transport pathway identified by the Hydrogen Import Coalition and the corresponding conversion efficiencies were taken from J. Tjdgat's PhD thesis on renewable hydrogen shipping [74].

Finally, the constructions impacts of the electrolysis plants were added and account for about 10% of the total impacts.

Other bio-fuels

For a decarbonated energy system, bio-fuels are alternatives to replace their equivalent fossil fuels. They can be obtained from two different feedstocks: electricity and biomass.

- Woody biomass, or lignocellulosic biomass, can be converted through processes such as gasification or pyrolysis into hydrogen, methane or synthetic liquid fuel (SLF). Digestible biomass, also called wet biomass, can be digested to produce synthetic natural gas (SNG).
- When produced from electricity, bio-fuels are categorised as electro-fuels. In that case, hydrogen is produced with electricity via electrolysis and is subsequently combined with carbon dioxide (CO_2) to produce SNG or SLF. For that purpose, CO_2 must have been captured from industrial processes or through atmospheric carbon capture.

To account for the impacts of the imported bio-fuels, a choice for their method of production has been made and only conversions from biomass were retained. This decision is driven by the fact that, nowadays, most of the bio-fuels are obtained from converting biomass. This does not mean that electro-fuels cannot be part of the energy mix anymore. Indeed, they can still be obtained from conversion of imported H_2 .

2.2 Energy demand and political framework

2.2.1 Energy demand

The future yearly end-use demands (EUDs) were calculated by G. Limpens from the forecast carried out by the European Commission for Belgium (cfr. report [17]) and the calculations are detailed in his thesis [49]. Table 4.4 shows the comparison between the EUDs from 2015 and the projections for 2035.

EUD	2015	2035	Units
Electricity	81.8	91.9	[TWh/y]
Heat low temperature	150.7	147.3	[TWh/y]
Heat high temperature	70.0	50.4	[TWh/y]
Mobility passenger	157.6	194.1	[Gpkm/y]
Mobility freight	66.3	98.0	[Gtkm/y]

Table 4.4: Comparative table of the end-use demand (EUD) for each sector between the years 2015 and 2035. Units for passenger and freight mobility are respectively passenger-kilometre (pkm) and tonne-kilometre (tkm)

The increase in demand for both passenger and freight mobility is linked to the increase in population. Increase in population also increases the needs for electricity and low temperature heat, but it is countered by efficiency measures that reduce the EUD for the same energy service. In the end, the electricity demand should increase while the demand for low temperature heat should slightly decrease. Those efficiency measures also cause a decrease in the high temperature heat demand.

An example of efficiency measure is the insulation of a building: a better insulated building requires less heating (the EUD) to provide the same pleasant temperature (the energy service).

It has been previously stated that *EnergyScope TD* handles 4 types of EUDs: electricity, heat, mobility and non-energy demand (cfr. chapter 3 section 1.1). The non-energy demand is non-negligible as it represented about 98 TWh/y for Belgium in 2015. It accounts for fuels used to produce goods such as plastics that are made from hydrocarbons. As mentioned before, the renewable potential is limited in Belgium and alternative resources required for the petrochemical industries will therefore have to be imported, or the industries relocalised. In that regard, this demand has not been considered in this work as it could be treated separately. Consequently, it constitutes a limitation of the present study.

2.2.2 Political framework

Today, nuclear represents about 50% of the electricity production in Belgium. However, it has been chosen to shut down all reactors by 2025. Though discussions are in progress to prolong the use of several reactors, for 2035, no nuclear facilities are allowed to be installed in the model.

Phasing out nuclear implies that other means of production have to take its place. The current goal is towards a scenario where 50% of electricity would come from renewables. This objective might seem unrealistic given the small area of Belgium and important energy imports will in fact be required. To ensure supply security, electric interconnections are set to be reinforced and new ones are in the making [58]. From 6880 MW of estimated interconnections in 2020, Belgium could reach up to 14 780 MW in 2035. Though it is estimated that the full capacity cannot be used at the same time. A ratio of about 2/3 is considered, giving an effective maximum capacity of about 9720 MW in 2035.

In order to restrain the electrical dependence from neighbouring countries, the yearly electricity imports are maxed out to 30% of the yearly electricity EUD, which gives maximum imports of about 27.6 TWh/y. To

put it into perspective, historically, Belgium has imported around 10% of its electricity.

With the European green deal, which states that European societies shall not be net emitters of greenhouse gases (GHG) in 2050, Belgium should continuously decrease its GHG emissions. It means using less and less fossil fuels, except waste which is allowed. Nevertheless, coal is still used in Belgium for industrial purposes such as high temperature heat production in blast furnaces. With that in mind, coal is considered still available in 2035, but in a limited quantity that corresponds to what was used in 2015 (approximately 33.3 TWh).

2.3 Technologies

Over the years, technologies are expected to evolve and research on promising ones should lead to cost reductions and efficiency increase. Although, some could become more expensive due to an increase in their complexity to comply with more and more strict regulations. The efficiencies and prices of the implemented technologies have been projected for 2035 by G. Limpens in his thesis [49].

Two small modifications have been made: one concerning the maintenance cost of fuel cell cars, and one concerning the conversion rates for synthetic methanation facilities.

- Both fuel cell and electric cars possess a similar power train (i.e. they both rely on electric motors) which is often the main source for maintenance needs. In that regard, both should have similar maintenance costs, which has then been changed in the model: fuel cell cars had maintenance costs that seemed too low and these were consequently increased to match those of electric vehicles.
- An inconsistency was noticed for synthetic methanation facilities which had impossible conversion rates. These facilities use H_2 and combine it with CO_2 to produce SNG. A by-product of this transformation is the production of some low temperature heat. The problem was that, in the model, the energy content of the outputs was higher than the one from the inputs. Therefore, the heat release was adapted to address this issue.

As criteria were added in this work in comparison with [49], corresponding data had to be gathered for all the technologies. The database used for this step (*ecoinvent*, cfr. chapter 2) contains data about current technologies and the considered energy mixes are also the current ones. Readers should therefore be aware of that fact since those data were not extrapolated for 2035 as it overstepped our competences and the scope of this work. Indirect (or grey) emissions might therefore be overestimated as future means of production or transport could be more decarbonated. This must thus be kept in mind when looking at the results presented in further chapters.

3 Reference case: Belgium in 2015

With a good grasp on the different elements composing the Belgian energy system (resources, technologies and demands) and its political framework, let us now analyse the Belgian energy system of 2015. This will help us to understand the impacts of a "classic" fossil fuel-based energy system in terms of our chosen criteria and will give us a comparison basis when optimised strategies for 2035 will be investigated in chapters 5 and 6.

3.1 System overview

The objective is to model the Belgian energy system as it was existing in 2015 and, since it is not optimal with respect to our selected key performance indicators, it cannot be obtained as a Pareto optimum solution, by optimisation. Instead, resources and technologies fulfilling the demands need to be imposed in the model. The energy mix of 2015 has been obtained from [49], as well as all related cost data.

The resulting energy system is illustrated on figure 4.4 under the form of a Sankey diagram. This type of chart describes the yearly energy flows from the resources to the EUDs with the different conversion routes and types of technology used. It is a great source of insight into the performance of an energy system and will be extensively used in the analysis of Pareto optimal solutions later in this report.

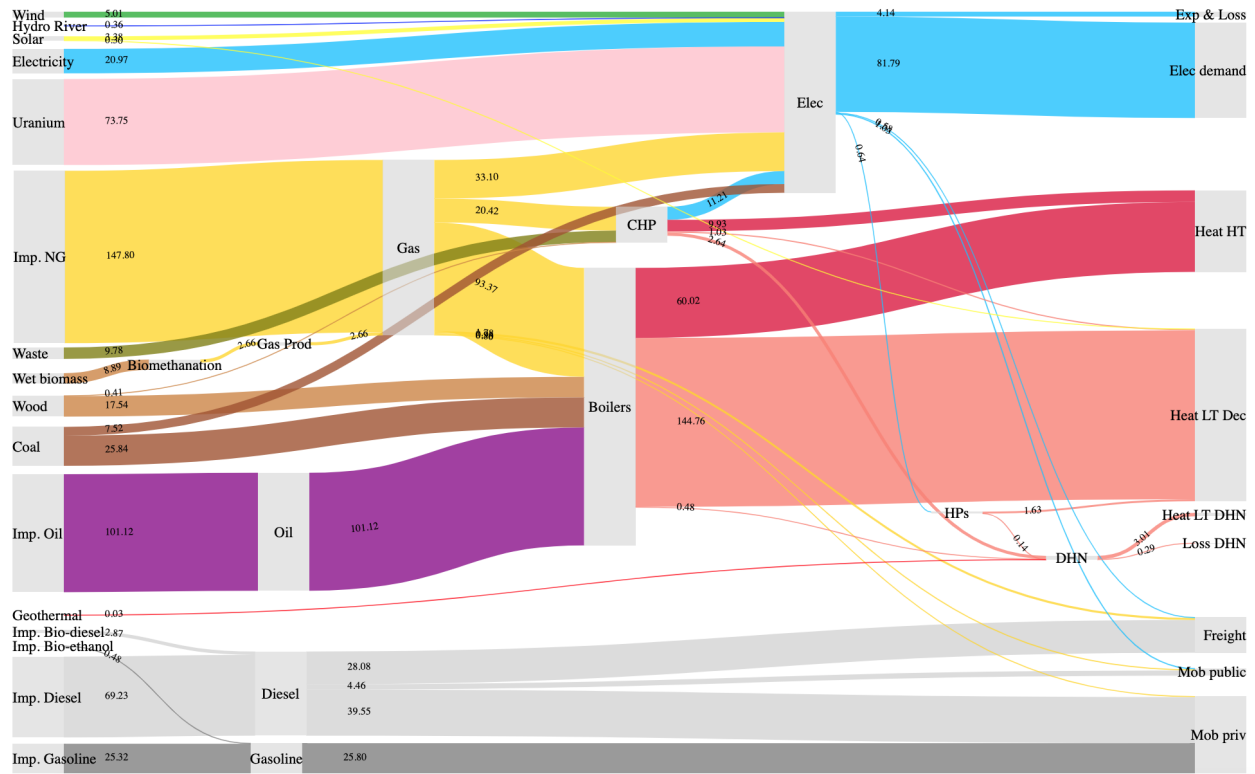


Figure 4.4: Sankey diagram of the 2015 Belgian energy system. Resources are gathered on the left side and the right side gathers the final energy consumption. The conversion technologies in the middle are aggregated by families. Abbreviations: natural gas (NG), import (Imp), production (Prod), heat and power cogeneration (CHP), electricity (Elec), Export (Exp), district heating network (DHN), decentralised (Dec), heat pumps (HPs), low temperature (LT), high temperature (HT), mobility (Mob), private (priv).

Since Belgium is lacking local resources, it must rely on imported resources to meet its demands. From the Sankey diagram, it can be observed that the 2015 Belgian energy system is very heavily reliant on imported resources as they amount to 91% of all primary resources. Moreover, with its use of 78% of fossil fuels, the system is very polluting.

Also, the different sectors of the energy system are very decoupled, with the exception of a little industrial combined heat and power (CHP) production. Let us analyse these sectors in more detail:

- The transport sector runs on classic internal combustion engine (ICE) technologies with diesel and gasoline fuels. Hybrid technologies are not yet present. The share of public mobility is small (20% of all the mobility demand).
- The heat sector runs mainly on boilers, with a large variety of fuels. A little bit of CHP is used for industrial purposes as well, but district heating is barely implemented. Gas and oil boilers provide the low temperature (LT) and high temperature (HT) heating. Wood exclusively serves for LT heat while coal is used for HT heating in boilers. Finally waste and a portion of gas are used in industrial CHP plants.
- 98% of the electrical sector caters for the electricity demand. The system has a negligible electrification of other sectors. The electricity is provided by nuclear plants, combined cycle gas power plants and electricity imports with a share of 28%, 23% and 24% of the primary electricity mix respectively. Renewables contribute to only 10% of this mix while the rest is provided by the cogeneration plants and by a small part of the coal power plants.

3.2 Indicators analysis

Let us now analyse this energy system from the point of view of our chosen criteria. For memory, three key performance indicators have been retained (and will serve to optimise the strategies for the future): cost,

GWP and energy invested. As detailed in chapter 2 section 3, additional criteria have also been considered, in complement to these KPIs, in order to provide more insight into the energy system.

For each criterion, we will look at the global impact of the system as well as the driving factors and individual contribution of technologies and resources to the impact. It must be noted that, in the following analysis, the imported electricity of 2015 is classified as a non-renewable resource due to its high GWP.

Cost

The cost of the system amounts to 43.6 b€₂₀₁₅/y and its breakdown is shown on figure 4.5. Cars and resources are costly and contribute to 37% and 41% of the total cost respectively. These contributions are examined more thoroughly hereafter.

As a matter of fact, Belgium has a high number of passenger cars per inhabitant, with a ratio of 0.497, above the European mean of 0.471 in 2015 (Eurostat). Furthermore, cars are not cheap. To illustrate this, it is interesting to look at the household budget allocated to the purchase and maintenance of cars in Belgium. The Bureau Fédéral du Plan found that, in 2017, the budget allocated for the aforementioned use was 6.6% of a household's budget [23]. This contribution of car maintenance and investment costs does not vary much with the choice of car technology and will remain important in future optimisations as we shall see.

On the other hand, the investment costs of other technologies are much smaller, in the order of magnitude of 5% per sector (freight, heating, electricity, and grids and efficiency measures) as can be seen in figure 4.5.

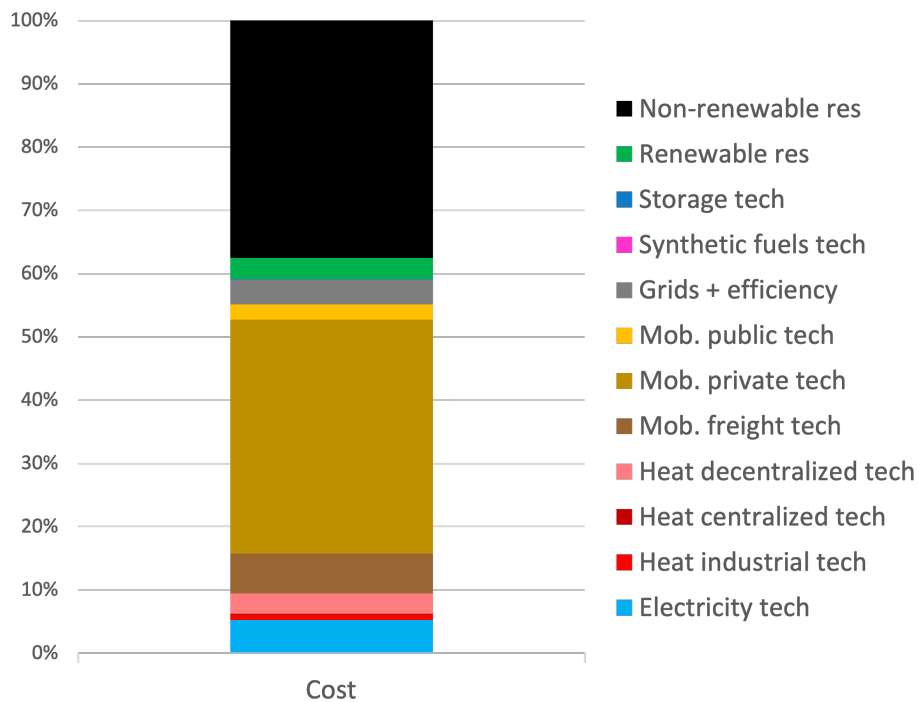


Figure 4.5: Breakdown of the total cost for the 2015 Belgian energy system between primary resources (res) and technologies (tech). The resources are split between renewables and non-renewables, and electricity imports are included in the renewables. The technologies are split between several categories. The category "Grids + efficiency" includes costs related to the power grid, district heating networks and efficiency measures (such as insulation).

Concerning the resources expenses, more than 90% of the cost comes from the non-renewable resources. The cost distribution between the non-renewable resources is not uniform however: the imported electricity as well as the refined petroleum products (diesel, gasoline and light fuel oil) are the costly non-renewable resources. On the other hand, the 33 TWh of coal and 74 TWh of uranium are cheap and their combined

cost is inferior to the expensive 2.8 TWh of imported bio-diesel. In the overall cost of renewable resources, the cheap price of woody and wet biomass counterbalances the expensive bio-diesel.

GWP

In terms of GWP, the system emits 131.6 MtCO₂eq/y, with a breakdown as illustrated on figure 4.6. If one would only consider the direct emissions of fuel combustion, as traditionally done, the system would seem to emit only 96.3 MtCO₂eq/y, thereby ignoring 35.3 MtCO₂eq/y of indirect emissions.

Of these indirect emissions, 29 MtCO₂eq/y are from the production, refining and transport of resources and 5 MtCO₂eq/y are from the private transport sector (cars). The use of fossil fuels is the overwhelming factor in the GWP of the system and the production of cars, due to their considerable number, is also a noticeable contributor that is not expected to decrease much in future systems.

While one could expect power plants and boilers to have a visible contribution to the emissions, figure 4.6 shows that it is actually not the case. For the power plants, the construction emissions are indeed not small. But, as the impacts of the energy system are annualised, these emissions are spread through the lifetime of the plants, which ranges from 25 to 60 years. As for the boilers, their lifetime is smaller (17 years in the model), but their construction emissions are actually quite low as they are relatively basic technologies.

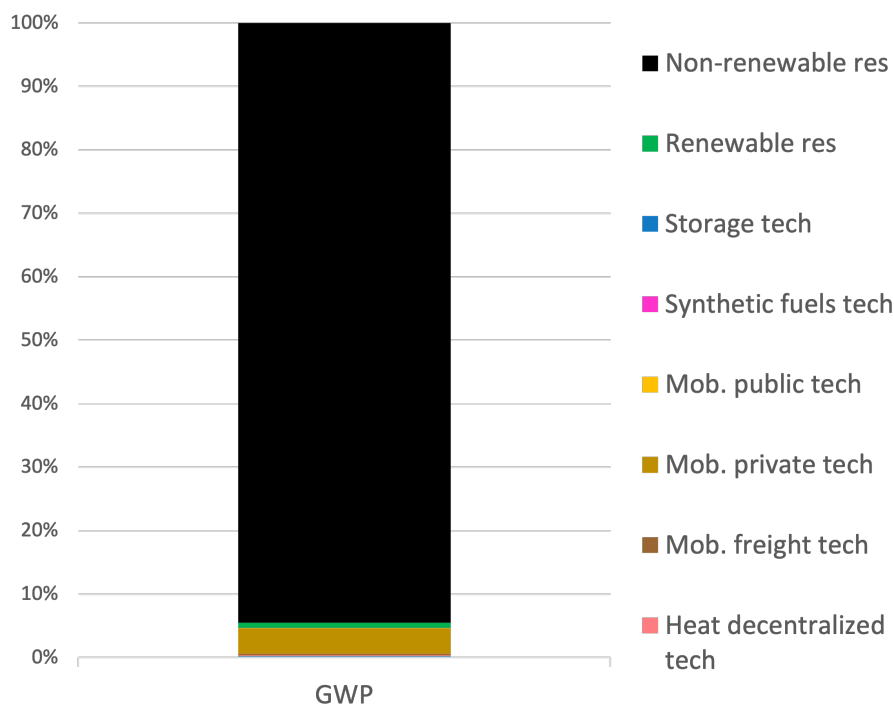


Figure 4.6: Breakdown of the total GWP for the 2015 Belgian energy system between primary resources (res) and technologies (tech). The resources are split between renewables and non-renewables, and electricity imports are included in the renewables. The technologies are split between several categories.

Energy invested

In terms of energy invested (E_{inv}), the system requires 87.7 TWh. The breakdown is provided on figure 4.7 showing that resources amount to 73% of the total. The most contributing ones are imported electricity and refined petroleum products, as for the contribution to the cost of the system. The impact of coal that was very small on the cost is more significant in terms of E_{inv} and is even larger than the one of nuclear fuel. We also see the large contribution of cars again, with 23% of the required energy investment.

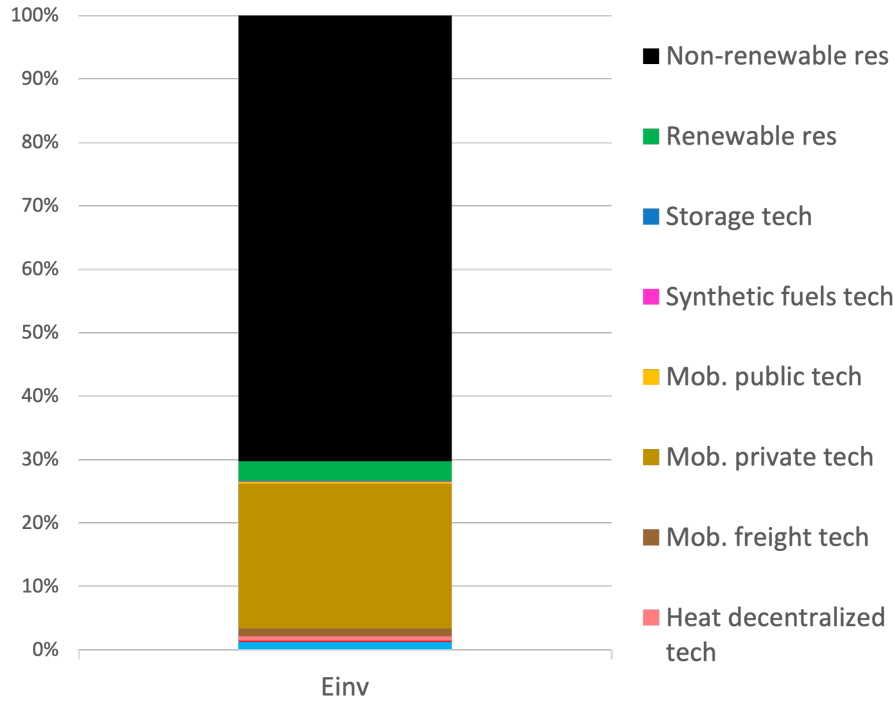


Figure 4.7: Breakdown of the total energy invested for the 2015 Belgian energy system between primary resources (res) and technologies (tech). The resources are split between renewables and non-renewables, and electricity imports are included in the renewables. The technologies are split between several categories.

Conclusion for the KPIs

To conclude, we have seen that resources are the most contributing factors for all KPIs, with the private mobility in second place. Although the Belgian energy system of 2015 uses a small amount of renewable resources, these have already a noticeable impact in terms of E_{inv} and cost. However, the distribution of impacts between the resources is not uniform and it is with the optimisation of the system that the best alternatives are expected to come to light.

Other criteria

Let us now take a quick look at the additional metrics introduced in chapter 2. For memory, six complementary criteria are considered: land use, damage to ecosystems, damage to human health, damage to resource availability, environmental prices and critical raw materials.

The agricultural land use of the system is 19 888 km². This is a very large amount that corresponds to around 2/3 of the surface area of Belgium. This land is used for the production of woody biomass, bio-diesel and wet biomass, with respective shares of 78%, 8% and 6%. Woody biomass consists of available wood as well as waste wood such as industrial residues, sawdust etc. The impacts of biomass however have been assimilated to those of the production of wood chips. Therefore, the results are overestimated as the impacts of waste wood should be attributed to the waste wood producers and not to the energy system. Whatever the attribution however, wood has to be produced and it holds true that wood production requires a lot of land. The productivity of wood production in *ecoinvent* database is 7.8 m³/ha/y, which is somewhat smaller than the values that can be found for Belgium in [65]. The land use value obtained is thus a good indicator of the impacts of the production of woody biomass, even though it is a little overestimated. Anyway, woody biomass production requires a very large amount of land and this conclusion can be generalised to bio-fuels made with dedicated extensive crops cultivation.

In terms of urban land occupied by the system (667 km²), 65% of this occupation can be attributed to the resources, with coal and woody biomass as the biggest contributors (20% and 15% respectively). The urban

land occupation of coal is linked to the mines, dump sites and railway infrastructure, whereas the urban land occupation from woody biomass is linked to the land occupation of forest roads. Besides resources, the photovoltaic (PV) installations (considered as open ground) are the main contributor in the occupation of urban land, with 140 km².

In *ecoinvent*, 1 kW_p requires 7.5 m² of PV panels and every m² of installed PV panel requires 4.7 m² of land. These figures are quite large and again show that the results associated with the additional criteria should be treated with caution. When computing the GWP and E_{inv} key performance indicators, it was noted that the values associated with PV technology were outdated and these values were corrected, but for the KPIs only, not for the additional criteria. It can be considered that the efficiency of PV panels, already in 2015, but even more in 2035, is much better than what can be found in *ecoinvent*, thereby requiring much less surface area per kW_p. Considering a power density of 1 kW_p for 4.22 m² of panels as was done in [49] and keeping the value of 4.7 m² of land per m² of panel, the land occupation is reduced to 19.834 m² per kW_p. This is much closer to the 25 m²/kW_p value found for the Bhadla Solar Park in India commissioned in 2020. In addition, all PV panels will not be open ground modules but will also be installed on roofs, reducing the Belgian land use even more. Thus, our model tends to overestimate the PV land use. However, even if corrections were done to the data, the contribution of solar panels to the urban land use would still be of great significance.

Concerning the ecosystems, 608 species temporary equivalent are lost while the system is running. 80% of the damage is attributable to the impact of climate change from the use of fossil fuels. 10% is due to the use of biomass owing to the high amount of land used and transformed.

In terms of damage to human health, the distribution between resources, technologies and infrastructures is very similar to that of the GWP, with a slightly larger impact of private mobility. Most of the impacts are due to fine particulate matter emissions, especially SO₂, and the climate changes associated with the GWP. Coal, that contributes to 10% of GWP impact, is however responsible for 21% of all human health impacts. This is due to its higher sulfur content as opposed to other fossil fuels (that have mostly been desulfurised). The total impact of the system on human health amounts to 235 kDALY/y, which means that, every 4.2 years, a million years of life are lost globally due to disability or early death.

The damage to resources is estimated at 12 b€₂₀₁₅/y and, as could be expected, non-renewable resources cause 96.7% of this damage. Further extraction of resources will therefore be more costly.

The impact on environmental prices is 26.5 b€₂₀₁₅/y, with most of the cost coming from impacts on human health and ecosystems.

Finally, 103.3 kt raw critical materials are used by the system, which is a very large amount. In addition, very few renewable technologies are used. It turns out that non-renewable resources contribute to 95.5% of the critical raw materials. Fossil fuels, for example, require a lot of critical raw materials as a lot of baryte is used to drill the wells. Baryte is used in the drilling mud for its chemical inertness, softness and, most importantly, its density. This density increases the hydrostatic pressure of the mud preventing the high underground pressures to blow natural gas and petrol out of the well. Geothermal technologies use a lot of critical raw materials for the same reason.

The Belgian situation in 2015 as described above will serve as a comparison basis when optimised solutions will be explored in chapter 5 with a single criterion at a time, and in chapter 6 in a multi-criteria approach.

Chapter 5

Single-criterion optimisations: Belgium 2035

As explained in chapter 3 section 2.2, in order to implement a multi-criteria optimisation with the goal programming method, an initial step of single-criterion optimisations is needed beforehand, as recalled hereafter.

The KPIs have different units and, for them to be considered in a single objective function, they need to be normalised. The normalisation requires a maximum and a minimum value for all KPIs and, to that end, optimisations have to be run on each KPI separately. They are our so-called single-criterion optimisations as they only look at one aspect of the energy system at a time.

Nonetheless, these optimisations already present interesting results and reveal several trends in terms of energy system strategies. Digging deeper into the solutions provides valuable insight on key sectors, technologies and resources in the model. It also allows a good comprehension of why certain choices are made by *EnergyScope TD* and will help in understanding the future multi-criteria optimisations, which will require trade-offs between the KPIs.

This chapter outlines the three optimisations realised on the cost, the GWP and the energy invested for the Belgian energy system in 2035. An overview of the resulting solutions is given and critical choices made by the program are investigated. The impacts of the three energy systems obtained, in terms of our chosen criteria, are briefly discussed and compared to our reference case, Belgium in 2015.

The main outcomes of those single-criterion optimisations are then subsequently summarised.

As a side note, it must be kept in mind that, as these optimisations only focus on one indicator at a time and as the model computes mathematical solutions, the resulting energy system might not always be viewed as a viable solution when applying common sense. For example, if the solution involves fueling the whole energy system with only hydrogen, it might be technically feasible, but no one would go for a system relying on a sole energy source.

As was said, at this stage, the solutions are therefore presented for the insight they give and not as future possibilities for the Belgian energy system.

1 Belgium in 2035: Cost optimisation

The first optimisation that was carried out is the one on the total cost of the energy system. It accounts for the costs of resources and all the installed technologies. As a reminder, the cost for technologies is split between the investment and maintenance costs: the maintenance part has to be paid every year and the investment part is paid over the lifetime of the technologies (taking into account a yearly interest rate).

1.1 System overview

Let us first look at the broad picture of the system resulting from the optimisation, in terms of resources used and technologies implemented. An overview of the solution under the form of a Sankey diagram is

shown in figure 5.1.

Natural gas is heavily used, accounting for 55% of the primary energy consumed. Renewables also represent a substantial part of this primary energy, reaching 28% with biomass, wind and solar. The rest is composed of coal, waste and electricity imports.

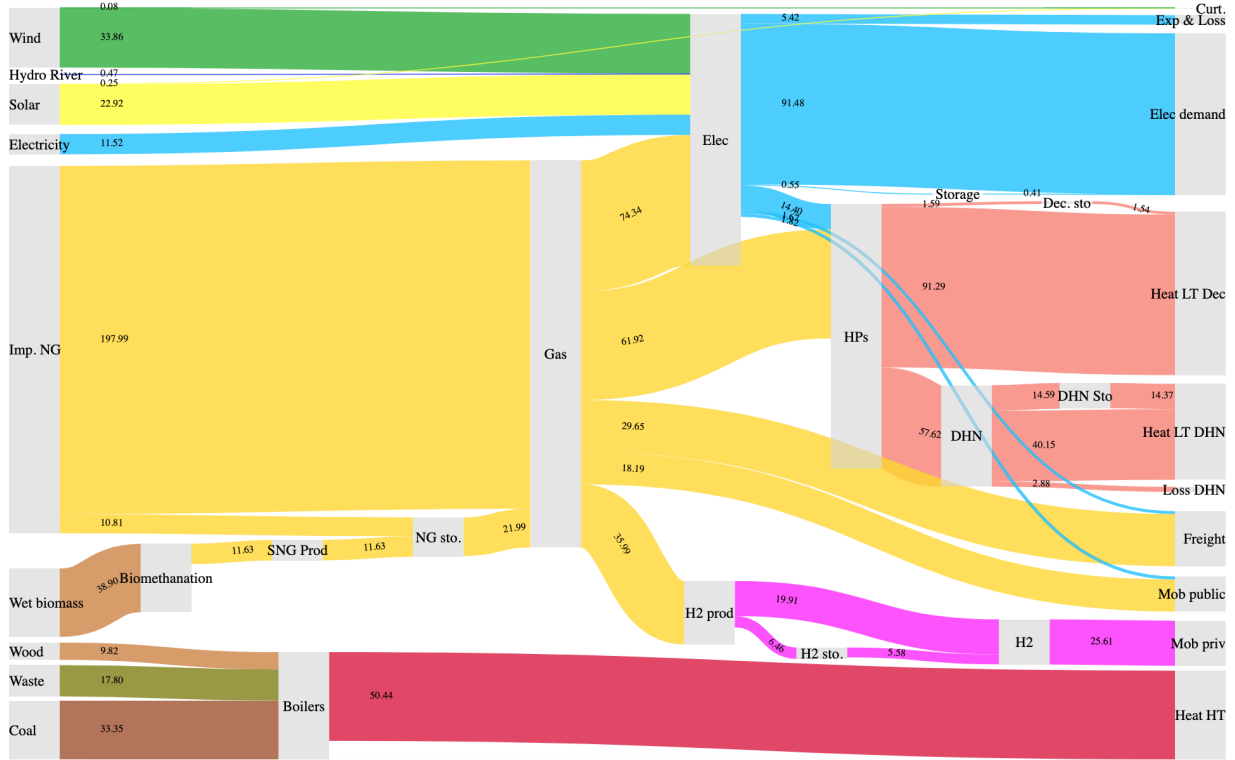


Figure 5.1: Sankey diagram of the cost-optimum Belgian energy system for 2035. Resources are gathered on the left side and the right side gathers the final energy consumption. The conversion technologies in the middle are aggregated by families. Abbreviations: natural gas (NG), import (Imp), storage (sto), production (prod), synthetic natural gas (SNG), hydrogen (H2), heat and power cogeneration (CHP), electricity (Elec), Export (Exp), heat pumps (HPs), district heating network (DHN), decentralised (Dec), low temperature (LT), high temperature (HT), mobility (Mob), private (priv).

Electricity is produced by wind, hydro and solar for the renewable part, and by combined cycle power plants (CCGT) using natural gas for the non-renewable part. It is completed by the electricity imports that account for 10% of the electricity produced, which is of the same order as historical values.

The low temperature heat demand is provided through two types of heat pumps (HPs): thermal HPs, fueled by natural gas and used for the decentralised production, and electrical HPs, used for the centralised production through district heating networks (DHNs). DHNs supply 37% of this demand, which is the maximum share allowed in the model (in line with [49]).

The high temperature, for its parts, is produced through boilers using coal, waste and woody biomass.

The freight and public mobility sectors, are mostly fueled by natural gas that is used in buses, trucks and boats, but also by electricity for trains, tramways and trolleys.

In the case of private mobility, fuel cell cars are used, though the hydrogen used to power them is produced via methane reforming. The reason why hydrogen is produced in that way and not directly imported will be explained in the next section.

1.2 Cost-optimal strategy: Understanding the program's choices

With the picture of what this energy system entails in mind, the rationale behind the choices of the model can now be examined. First, the mix of primary resources will be discussed. Then the case of private mobility will be addressed to understand the use of hydrogen, instead of natural gas directly.

Primary resources

Endogenous resources, as they are produced locally, are much cheaper than most imported ones and especially bio-fuels and those requiring a lot of refinement. Therefore, it comes without surprise that the system uses a lot of biomass, waste, as well as wind and solar potential. Though woody biomass and solar are not exploited to their fullest potential.

The woody biomass is used in boilers to provide industrial high temperature heat, but only as a complement since waste and coal actually cost less and are therefore used to their maximum availability.

Still, the cost per GWh of resource is lower for wood than for natural gas (NG). So, why not producing synthetic natural gas (SNG) by gasifying the remaining available wood? The answer lies in two factors: the conversion rates and the investments to build the required technologies. When taking into account the conversion rates of the gasification, to produce a same quantity of gas, the costs for wood and NG become almost similar. However, when taking into account the cost related to the gasification facilities, the produced SNG would have a total cost that is about 80% higher than imported NG.

While the wind potential is completely exploited, only 37% of the photovoltaic (PV) capacity is installed. It is due to the intermittent character of these technologies that would require electrical storage for them to be more integrated in the system, but this kind of storage comes with high prices and has to be avoided when optimising the cost. Nevertheless, pumped hydro storage is quite efficient in that regard and fully used in the cost-optimal solution. Unfortunately, its capacity is really limited for Belgium as can be seen on the Sankey diagram (cfr. figure 5.1) where electrical storage is almost negligible.

As it is, the system has reached the maximum integration of intermittent renewable energy sources. Indeed a bit of curtailment, i.e. deliberately reducing the power output (of intermittent sources) to balance the electricity supply and demand, is already needed and even more would be necessary if no storage was installed.

To meet the demand, endogenous resources are far from being enough and natural gas is imported in large quantities as it is the second cheapest exogenous resource behind coal. The 209 TWh of NG imported represent an increase of about 40% compared to the 2015 case.

Some electricity is also imported from abroad, to compensate for the lack of production when solar and wind do not produce enough and the demand is too high for the CCGTs to cope with it: mostly in the mornings and evenings, and especially during winter. Electricity imports have high prices, but using them to fill the production gaps costs less than installing additional CCGTs. Indeed, to meet the demand peaks, the installed capacity should almost be doubled and much of these new plants would be left unused for a big part of the year when solar and wind can generate electricity.

Private mobility

The first step to understand the choices made for the private mobility sector is to look at the cost for the cars themselves. As can be seen on figure 5.2, the annualised investment cost is very similar for all types of cars, but the maintenance cost is what makes the difference in the end. So, electric and fuel cell cars are globally the cheapest technologies (thanks to their small maintenance costs, even if they have somewhat higher investments costs with respect to cars with traditional combustion engines).

The cost of the resources needed to fuel the cars also has to be taken into account if one is looking at the total cost of the system. When it is added to the equation, using fuel cell cars with hydrogen produced via methane reforming is the cheapest solution, although only by a slim margin if compared to electric cars. But, in a linear programming model, even a very small difference with respect to the final objective can make the system completely switch from one solution to another.

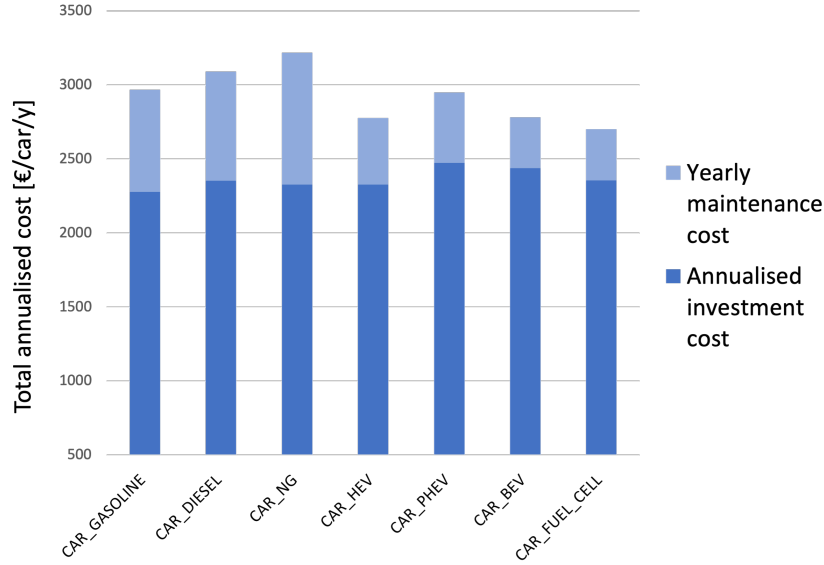


Figure 5.2: Annualised costs of cars for Belgium in 2035 as implemented in *EnergyScope TD*. The lifetime of a car is considered to be 10 years. Abbreviations: natural gas (NG), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV).

The only question that remains to be addressed is about the choice of using methane reforming rather than directly importing hydrogen: does it really cost less?

Directly importing renewable hydrogen (H_2) from abroad is estimated to cost about 177 €/MWh. When choosing the methane reforming route, natural gas is imported, costing only 44 €/MWh. Adding the cost of the conversion between natural gas and H_2 , the cost related to the facilities needed, etc, H_2 produced via methane reforming costs, all in all, about 73 €/MWh, which remains a lot less costly than imported H_2 .

1.3 Assessing the system: Review of the indicators

Now that we better understand the solution resulting from an optimisation on the total cost of the system, let us look at what it entails in terms of the other selected indicators.

The global impacts of the system can be found in table 5.1 and will be discussed in the following.

Criterion	Units	Cost-optimum 2035
Cost	[b€ ₂₀₁₅ /y]	38.5
GWP	[Mt _{CO₂eq} /y]	81.4
E _{inv}	[TWh/y]	54.7
Land use agricultural	[km ² .y/y]	15 748
Land use urban	[km ² .y/y]	1348
Damage to human health	[DALY/y]	165 519
Damage to ecosystems	[species.y/y]	421
Damage to resources availability	[b€ ₂₀₁₅ /y]	6.7
Environmental prices	[b€ ₂₀₁₅ /y]	19.1
Critical raw materials	[kt/y]	39.2

Table 5.1: Impacts of the cost-optimal solution for the 2035 Belgian energy system. These impacts have been annualised and each indicator is therefore expressed per year.

The breakdown of each KPI is shown on figure 5.3. It must be mentioned that, as the imported electricity is mainly made from renewables and is very decarbonated (see European electricity mix for 2035 in chapter 4 section 2.1.2), it is classified as a renewable resource in this analysis for 2035 and in the subsequent ones.

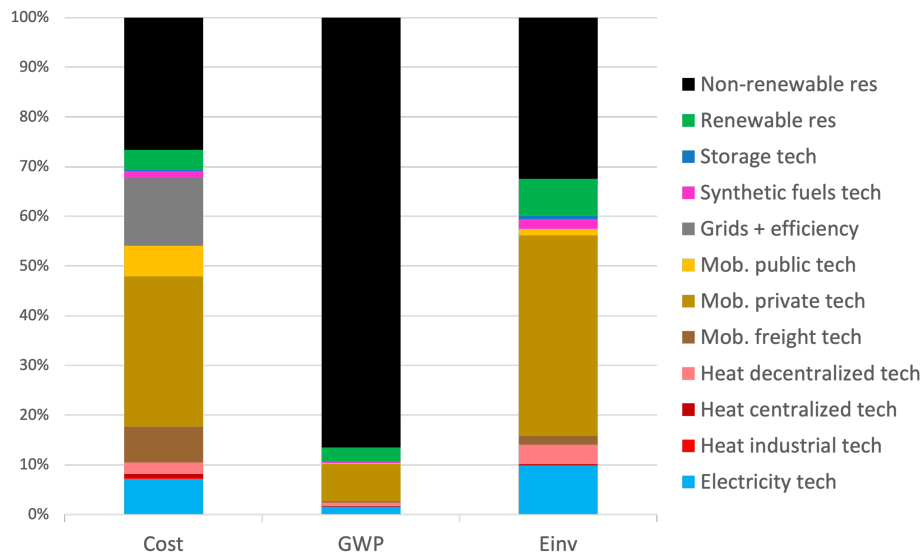


Figure 5.3: Breakdown of the KPIs for the 2035 cost-optimal Belgian energy system between primary resources (res) and technologies (tech). The resources are split between renewables and non-renewables, and electricity imports are included in the renewables. The technologies are split between several categories. The category "Grids + efficiency" includes costs related to the power grid, district heating networks and efficiency measures (such as insulation).

Cost

Resources and private cars are the biggest contributors to the total cost of the system, amounting to about 30% each.

The implementation of DHNs, efficiency measures and power grid reinforcement (needed because of the increased part of intermittent energies) do not come cheap and constitute almost 14% of the total cost.

The other sectors are less prominent and each represents a contribution to the total score between 5% and 7%.

A comparison to the 2015 system (presented in chapter 4 section 3) shows that, thanks to the optimisation effort, the total cost of the system in 2035 has slightly decreased, despite an overall increase in the demands with respect to 2015.

GWP

In terms of GWP, as fossil fuels are massively imported, their overwhelming contribution to the final score comes without surprise. However, thanks to the growing share of renewables and the discontinuation of the use of liquid fossil fuels (gasoline, diesel, etc) in favor of natural gas, the overall GWP has decreased by more than a third when compared to the 2015 case, even with an overall increase in the demands.

E_{inv}

This discontinuation of the use of liquid fuels, that require a substantial amount of energy for their refinement step, has also a big positive incidence on the energy invested.

On the other hand, the construction of fuel cell cars involves more energy expenditures. It explains the huge contribution (40%) of the private mobility sector.

The large increase, with respect to 2015, in the contribution from the electricity technologies comes from the implementation of wind turbines and PV.

Additional criteria

The additional environmental criteria (damage to ecosystems and to human health, as well as environmental prices) have all decreased by about a third, which is in line with a decreased utilisation of fossil fuels.

The reduction in the quantity of critical raw materials used can be explained, once again, by the fact that liquid fossil fuels are not used anymore. As mentioned in chapter 4 section 3, the drilling process for those resources requires very large amounts of baryte. The decrease in critical raw materials is therefore substantial, and represents a cutback of almost two thirds compared to 2015.

2 Belgium in 2035: E_{inv} optimisation

The second optimisation of the energy system that we will look at is the one on the total energy invested. As a reminder, the energy invested accounts for the energy expanded in the construction (and later the decommissioning) of the technologies, and for the energy used in the extraction, refinement and transport of the resources, but it does not account for the energy content of the resources themselves.

The solution will be presented in the same manner as the cost-optimal case: a quick depiction of the energy system obtained, followed by an investigation of the choices made by the program with respect to the optimised KPI, and finally a brief discussion about the impacts of the system on the other criteria.

2.1 System overview

The E_{inv} -optimal energy system is depicted in a Sankey diagram on figure 5.4. It is heavily reliant on fossile fuels imports under the form of natural gas. Those imports add up to 305 TWh of natural gas per year, which represents more than double the amount of 2015.

The production of electricity is structured as follows: 23% from wind turbines, 37% from cogeneration plants and 39% from CCGTs. The last percent is provided with electricity imports and all the hydro potential available.

The cogeneration plants provide all the high temperature heat demand. For the low temperature heat, it is mainly generated by electrical heat pumps that account for 96% of the production.

All the mobility sectors are fueled by electricity and/or natural gas. Electricity powers tramways and trolleys for the public mobility, and trains for both the freight and public mobility. Everything else operates with natural gas: boats, trucks, buses and cars.

2.2 E_{inv} -optimal strategy: Understanding the program's choices

For the energy invested optimal case, the choices made by the program in regard to the technologies that would need to be installed stem primarily from the choice of primary resources. Then, it is only a matter of finding the right conversion pathways to meet all the EUDs while consuming as little of primary resources as possible.

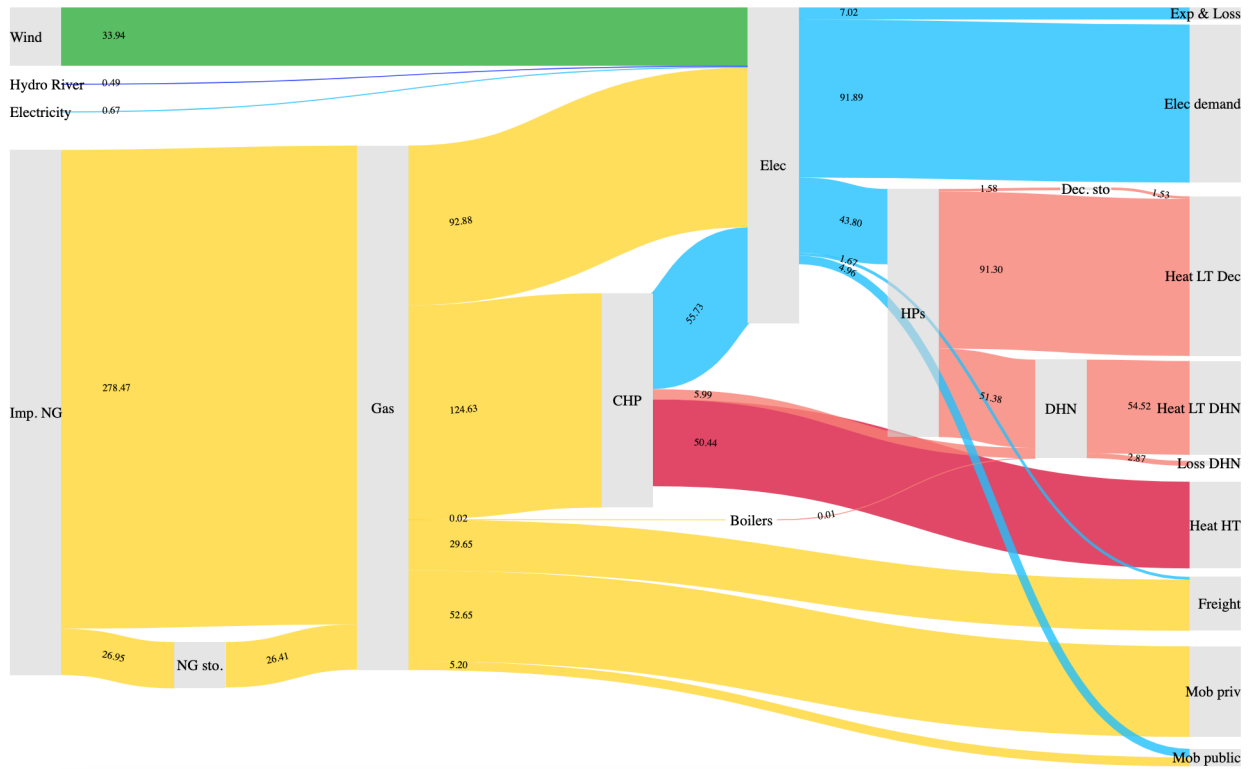


Figure 5.4: Sankey diagram of the E_{inv} -optimum Belgian energy system for 2035. Resources are gathered on the left side and the right side gathers the final energy consumption. The conversion technologies in the middle are aggregated by families. Abbreviations: natural gas (NG), import (Imp), storage (sto), heat and power cogeneration (CHP), electricity (Elec), heat pumps (HPs), district heating network (DHN), decentralised (Dec), Export (Exp), low temperature (LT), high temperature (HT), mobility (Mob), private (priv).

Primary resources

In terms of resources to import, natural gas emerges as the best one. While biomass and waste both require a bit less energy invested for a same energy content, the subsequent technologies efficiencies are better for the natural gas. Therefore, as less natural gas is needed, it becomes a better solution.

One could still wonder if natural gas is really better than refined petroleum products (gasoline, diesel and light fuel oil) or coal. For the former, while oil still has a good EROI after it has been extracted from the ground, the refinement process it needs to undertake is highly energy-intensive, causing the EROI to drop drastically. Natural gas also needs to go through a refinement step, but due to its nature, this process is easier and requires less energy.

For its part, coal does not require refining, and it is the transportation step that is the cause of most of the energy needed to be invested. In that regard, the origin of the coal used is a decisive factor. If only coal extracted in Europe is considered, then it requires less E_{inv} than NG. But coal is actually also imported from other more foreign countries, such as Russia or Australia, and is therefore less attractive than NG.

Electricity production

Though natural gas is the main resource, for the electricity production, wind turbines are a better alternative and are therefore implemented to their maximum capacity. Indeed, the EROI of electricity produced from wind turbines (onshore and offshore put together) is 26.5^(a), whereas electricity produced from natural gas

^(a) This value is obtained by dividing the yearly electricity production of the turbines by the annualised energy invested to build them. It is in line with the literature [19] for wind turbines with a nominal power above 1 MW.

through CCGTs has an EROI of about $10^{(b)}$.

Low heat temperature sector

Two aspects can be discussed concerning the low temperature heat sector: the use of electrical heat pumps (eHPs) and the implementation of district heating networks.

Concerning the use of eHPs, the choice is easily understandable as this technology allows to drastically reduce the primary energy consumption: it is cut in half when compared to heat production via NG boilers. A quick calculation can readily be made to support our claim. To produce 1 GWh of heat with boilers, about 1.11 GWh of natural gas is needed. With eHPs, as their $\text{COP}^{(c)}$ in the model is 3, to produce the same amount of heat, only 0.33 GWh of electricity is needed. If we consider that this electricity is produced with CCGTs, with an efficiency of 63%, the final quantity of natural gas consumed to produce 1 GWh of heat with eHPs is 0.53 GWh.

As can be seen on the Sankey diagram (cfr. figure 5.4), district heating networks provide 37% of the low temperature heat, which, as has already been said, represents the maximum share of this technology foreseen for 2035. Once again, it is implemented because it allows to reduce the primary energy consumption. Indeed, as the production of heat is centralised, it implies the use of more efficient technologies. For example, when looking at the electrical heat pumps, while the decentralised ones have of COP of 3, the centralised eHPs present a COP of 4 and allow to save a further 25% of primary energy. Though, some losses in the heat networks have yet to be accounted for. Nevertheless, the gain in primary energy consumption is still there.

2.3 Assessing the system: Review of the indicators

The impacts of the system in terms of our selected criteria are summarised in table 5.2. They will be briefly discussed in the following and comparisons will be made with the energy system of 2015, and with the cost-optimal system for 2035.

Criterion	Units	E_{inv} -optimum 2035
Cost	[b€ ₂₀₁₅ /y]	43.8
GWP	[Mt _{CO₂eq} /y]	84.7
E_{inv}	[TWh/y]	37.3
Land use agricultural	[km ² .y/y]	268
Land use urban	[km ² .y/y]	110
Damage to human health	[DALY/y]	106 957
Damage to ecosystems	[species.y/y]	273
Damage to resources availability	[b€ ₂₀₁₅ /y]	8.7
Environmental prices	[b€ ₂₀₁₅ /y]	9.6
Critical raw materials	[kt/y]	30.1

Table 5.2: Impacts of the E_{inv} -optimal solution for the 2035 Belgian energy system. These impacts have been annualised and each indicator is therefore expressed per year.

^(b) The value is computed by dividing the yearly electricity produced with CCGTs by the sum of the annualised E_{inv} to build them and the total E_{inv} of NG burned yearly in the CCGTs. The CCGTs have a capacity factor of 75% in our case.

^(c) COP stands for "coefficient of performance" and is the ratio between the heat power drawn out of a heat pump, and the power that is supplied to it.

On figure 5.5, the KPIs are broken down to show the contribution of the different parts of the energy system to the total.

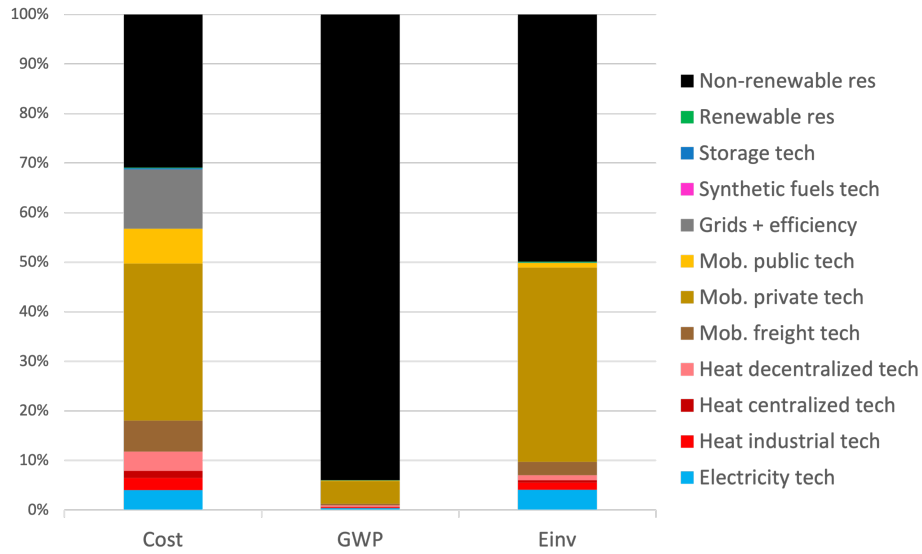


Figure 5.5: Breakdown of the KPIs for the 2035 E_{inv} -optimal Belgian energy system between primary resources (res) and technologies (tech). The resources are split between renewables and non-renewables, and electricity imports are included in the renewables. The technologies are split between several categories. The category "Grids + efficiency" includes costs related to the power grid, district heating networks and efficiency measures (such as insulation).

Cost

The yearly total cost is 43.8 b€₂₀₁₅, which is almost exactly the same value as for the 2015 energy system, and only 10% higher than the cost-optimal solution for 2035. Indeed, as natural gas is one of the cheapest fuel, it is not surprising to obtain a cost-effective solution when NG accounts for the large majority of the resources.

It could have been expected since the prices of the resources are somewhat correlated to their energy invested: if one has to spend a lot of energy to produce a marketable fuel, it will cost him more and this will therefore be reflected in the price of that fuel.

As can be seen on figure 5.5, the breakdown of the cost of the system is very similar to the cost-optimal case.

GWP

Concerning the GWP, surprisingly, the total score is not far from the cost-optimal system where the share of renewables was however much higher: the total GWP only increases by 4% while the renewable share drops from 28% to 10% between the two solutions.

The main reason is that coal is used in the cost-optimal solution, but not in the E_{inv} -optimal one. Indeed, coal is the resource with the highest specific GWP (i.e. the GWP per GWh of the resource) and using natural gas instead allows for a cutback of 35% in greenhouse gases emissions.

With a system based as heavily on fossil fuels as this one, the GWP comes, without surprise, overwhelmingly from the use of such fuels.

E_{inv}

As explained before, the energy invested is mainly driven by the primary resources that, without surprise, represent 50% of the total. The second contributor is the private mobility sector (40%) due to the high

number of cars.

Additional criteria

One thing that jumps out when looking at the impacts of the system is its land occupation that is really small when compared to the 2015 and cost-optimal cases. For those cases, the main causes behind their high land occupation are the use of biomass, which requires large areas to be grown, and the installation of PV panels.

Another very interesting thing to notice is that, while the GWP increases a bit with respect to the cost-optimal system, damages on ecosystems and human health are actually much lower. This illustrates why multiple metrics are essential to really grasp the diverse impacts of energy systems and how GWP cannot, by itself, be representative of all environmental aspects.

The damage to human health indicator is strongly linked to emission of fine particulate matter and nitrogen oxides (NO_x). Therefore, stopping the use of coal is one of the main reason for its decrease.

3 Belgium in 2035: GWP optimisation

The last single-criterion optimisation is the one on the total GWP accounting for the direct and indirect greenhouse gases emissions.

The solution will be presented in the same way as for the two other optimisations: a description of the resulting system with the implemented technologies, then an analysis of the choices made by the program to minimise the GWP, and at last, a review of the other impacts of the system.

3.1 System overview

The Sankey diagram depicting the GWP-optimal energy system can be found on figure 5.6. In this solution, the primary energies are entirely made up of renewables. While a small part of the electricity imports comes from fossil fuels, it will still be considered as a renewable in the subsequent discussions, as was said previously in section 1.3.

Wind and PV are installed to their maximum capacity and all the available woody biomass is used. To meet the energy demands, massive imports of hydrogen are needed, reaching a share of 56% of all the primary energies. Some electricity is also imported to compensate when PV is not producing.

The private mobility sector is entirely composed of battery electric vehicles (BEVs), i.e. fully electric cars. The freight and public mobility sectors are also partly fueled by electricity for the trains, tramways and trolleys. The rest is supplied with hydrogen, either directly for trucks and buses, or indirectly for boats as there are no fuel cell technologies for them: in that case, synthetic natural gas (SNG) is produced by combining hydrogen with CO_2 .

The high temperature heat is produced through several means: with woody biomass in boilers, with SNG in cogeneration units, or with electricity.

The low temperature heat demand, for its part, is mainly provided by electrical heat pumps. Some heat comes also from the hydrogen cogeneration units and from the SNG production process: in both cases, the heat produced is not the desired main output but is a valuable by-product.

explained in section 2.2.

The high temperature heat, as already mentioned, is produced through several means. Some of them are linked to the electricity layer and the heat they supply is therefore highly dependent on when those technologies are allowed to produce or consume electricity.

First, the heat produced with electricity is only available when the PV production is at its peak, only on particularly sunny days.

Then the gas cogeneration units can supply heat when they are required to produce electricity. When wind and solar are sufficient, no electricity, and therefore also no heat, is allowed to be produced by the cogeneration units.

Finally, wood boilers are used to make up the unavailability of the two other means.

Though it must be noted that the dynamic between the gas cogeneration units and the wood boilers is actually not that simple because they also interact with each other through the synthesis of the gas required for the former. Indeed, to synthesise SNG from hydrogen, a source of carbon is needed and this carbon comes mainly from the wood boilers in this energy system. The CO₂ produced through the woody biomass combustion is captured and stored to later serve in the SNG production process. Accordingly, the cogeneration units would not be able to function if the boilers are not also used.

To reduce the dependence from the use of woody biomass, some atmospheric carbon capture facilities are installed. Though, as they are much less efficient, they only serve as supplement when absolutely needed.

Balancing electricity production and demand

As 54% of the production of electricity is done via intermittent energies, the system needs to be able to store energy in order to meet the demand at all times. This storage is achieved through several means that are located at different stages in the conversion processes and in different sectors.

The first method is to store molecules, that are, in our case, hydrogen and SNG. It serves as a long-term storage to deliver energy in winter when the PV production is low.

Pumped hydro storage also stores energy with molecules: not in chemical bonds in the molecules themselves, but under the form of potential energy as water is pumped and stored at a higher altitude.

The second method is to store heat. As most of the low temperature heat production is done with eHPs, it depends on the electricity availability. Storing heat when electricity is produced in high quantity to use it at a later time is better in terms of GWP than storing directly electricity and using it when heat is needed. In the low temperature heat sector, about a fourth of the heat produced is stored.

Finally, the third method is to store directly electricity using batteries. It is designed for a small timescale and is used as a buffer for intraday variations. Batteries have a high GWP linked to their construction and the model tries to install as few of them as possible. In that regard, the two other aforementioned methods are used first and foremost.

Thanks to the fact that the private mobility is made up of BEVs, the system has already access to a certain number of batteries through the vehicle-to-grid (V2G) dynamic. V2G allows the car's batteries to deliver electricity to the grid when it is required, and it manages their charge level so as for them to be ready to go when needed^(d). However, the whole capacity of electric vehicles cannot be used to feed the grid as all cars will not be connected to it at the same time. Therefore additional lithium-ion batteries still have to be installed: for the GWP-optimal system, it amounts to 34 GWh of additional batteries.

To grasp the full potential of the intermittent energies, a small quantity of electrolyzers is installed. Indeed, when solar and wind are both producing at the same time, rather than throwing away, as curtailment, the surplus in electricity that could not yet be handled, this electricity is used in electrolyzers to produce hydrogen. This hydrogen is subsequently stored to be used when needed.

^(d) A more in-depth explanation of how V2G is implemented in *EnergyScope TD* can be found in [49].

3.3 Assessing the system: Review of the indicators

Let us now look at the impacts of the GWP-optimal energy system for 2035 with respect to our selected indicators. The global impacts are summarised in table 5.3 and will be discussed in the following. Comparison with the 2015 system and with the cost-optimal and E_{inv} -optimal solutions will also be provided.

Criterion	Units	GWP-optimum 2035
Cost	[b€ ₂₀₁₅ /y]	79.4
GWP	[Mt _{CO₂eq} /y]	17.7
E_{inv}	[TWh/y]	136.2
Land use agricultural	[km ² .y/y]	22 004
Land use urban	[km ² .y/y]	8965
Damage to human health	[DALY/y]	98 985
Damage to ecosystems	[species.y/y]	261
Damage to resources availability	[b€ ₂₀₁₅ /y]	1.4
Environmental prices	[b€ ₂₀₁₅ /y]	13.4
Critical raw materials	[kt/y]	72.4

Table 5.3: Impacts of the GWP-optimal solution for the 2035 Belgian energy system. These impacts have been annualised and each indicator is therefore expressed per year.

Figure 5.7 presents the breakdown of the three KPIs into their contributing elements.

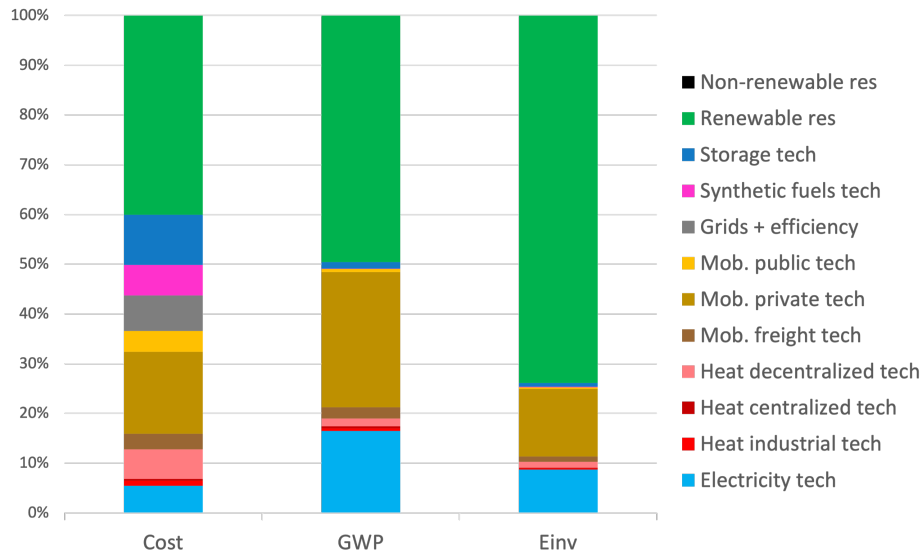


Figure 5.7: Breakdown of the KPIs for the 2035 GWP-optimal Belgian energy system between primary resources (res) and technologies (tech). The resources are split between renewables and non-renewables, and electricity imports are included in the renewables. The technologies are split between several categories. The category "Grids + efficiency" includes costs related to the power grid, district heating networks and efficiency measures (such as insulation).

Cost

Obtaining a highly decarbonated solution is not easy and it reflects on the total cost of the energy system: it has almost been doubled with respect to the 2015 system.

This high cost can be explained by two main reasons: the technologies that need to be installed require very high investment expenditure, and hydrogen is a very expensive resource to import. It is reflected in the breakdown of the cost (cfr. figure 5.7) where the share from storage technologies is 10% whereas it was almost non-existent for the other cases.

The facilities needed to produce the synthetic fuels are also costly, and especially the carbon capture and storage infrastructures. As for the storage technologies, their contribution is not negligible anymore.

As extensive amounts of hydrogen are imported, the share of the cost related to the resources increases from around 30% for the cost-optimal and E_{inv} -optimal systems to 40%.

GWP

In table 5.3, one can observe that the total GWP of the system has been considerably improved by the optimisation. However it is not zero yet. This is mainly due to the indirect emissions that still contribute to it. In terms of breakdown (figure 5.7), the contribution of the resources decreases with the increasing use of renewable resources, whereas the contribution of the electricity technologies increases, mainly driven by the PV.

E_{inv}

In terms of E_{inv} , there is a huge increase with respect to the other solutions. The reason is the important use of imported H_2 and solar power in the GWP-optimum solution. On one hand, the imported H_2 , since synthesised using mostly solar electricity, explains the large contribution of renewable resources to the total E_{inv} . On the other hand, the PV usage participates to the E_{inv} under the electricity technologies category. Finally, one observes a decrease in the share of private mobility, even if it remains a noteworthy contributor.

Additional criteria

Looking at table 5.3, one can notice a considerable increase of the land use:

- The agricultural land use is mainly attributable to the wood production (at 90%). The biomass part of the imported electricity mix, as well PV and H_2 , explain the remainder. The PV's land use is associated to some of the materials required for its construction. The H_2 contribution is actually linked to PV as most of the electricity used to produce it comes from solar energy.
- The urban land use is much higher than for all the other solutions due to, again, PV technology and imported H_2 . However, it may have been somewhat overestimated as explained previously in chapter 4 section 3.2.

Besides the land use, the critical raw materials also increase a lot. Again this is linked to the use of PV and imported H_2 produced from solar energy. In addition, the batteries in electrical cars contribute much to that metric.

Thanks to the extensive use of renewables in that solution, the damage to resources is low compared to the cases discussed before. However, the damage to human health or to ecosystems does not improve a lot, especially with respect to the E_{inv} -optimum solution. Indeed, PV technology production and re-treatment are not genuinely environmental friendly. This highlights the need to look at more indicators than just the few KPIs when evaluating an energy system.

4 Outcomes

The three single-criterion optimisations presented in previous sections have provided great insight into the strategies used to optimise the energy system with respect to one or the other of the KPIs.

Several common trends can be identified and are expected to stay true for the future multi-criteria optimisations:

- Heat pumps and district heating networks are heavily used in the low temperature heat sector. The reduction in the need of primary energies provided by those technologies is substantial and, since the low temperature heat sector represents the biggest energy demand, the benefit of their usage is even more pronounced.
- Onshore and offshore wind turbines are good technologies from all perspectives: they are very good for the environment and especially for the GWP, their EROI is one of the largest between all possible energies, and their initial high investment costs are really worth it in the end.
- Electrical storage is avoided as much as possible as it is costly and batteries have a high GWP linked to their construction.
- In Belgium, endogenous resources do not present enough potential to fuel the whole energy system and there will always be a need to import energy from abroad.
- The private mobility sector, due to the very large number of cars, is a major point of focus in the energy system as it represents a big contributor to its indicators.

Other observations can also be made:

- Endogenous resources are the cheapest ones and most of them are renewables. Therefore using them is beneficial for the cost, but also for the GWP. However, when intermittent energies represent a large share of the mix, there is a high need for storage and, due to the cost of that storage, the model tends to cap the use of PV.
- Natural gas is a very good resource in terms of cost and energy invested. Furthermore, amongst the fossil fuels, it is the one that presents the smallest environmental impacts.

Despite the interesting information that can be provided by the single-criterion optimisations, the solutions they bring do not comprehend all the aspects of the problem.

Criterion	Units	2015	Cost-optimum 2035	E _{inv} -optimum 2035	GWP-optimum 2035
Cost	[b€ ₂₀₁₅ /y]	43.6	38.5	43.8	79.4
GWP	[MtCO _{2eq} /y]	131.6	81.4	84.7	17.7
E _{inv}	[TWh/y]	87.7	54.7	37.3	136.2
Land use agricultural	[km ² .y/y]	19 888	15 748	268	22 004
Land use urban	[km ² .y/y]	667	1348	110	8965
Damage to human health	[DALY/y]	235 304	165 519	106 957	98 985
Damage to ecosystems	[species.y/y]	608	421	273	261
Damage to resources availability	[b€ ₂₀₁₅ /y]	11.9	6.7	8.7	1.4
Environmental prices	[b€ ₂₀₁₅ /y]	26.5	19.1	9.6	13.4
Critical raw materials	[kt/y]	103.3	39.2	30.1	72.4

Table 5.4: Impact summary of the single-criterion optimised solutions for the 2035 Belgian energy system compared to 2015 situation. These impacts have been annualised and each indicator is therefore expressed per year.

First, as was said when introducing the single-criterion optimisations, if the optimisation focuses on one KPI only, it may lead to a system configuration that is totally unacceptable for one or the other criteria, even if the solution is "mathematically" correct. For example, amongst the solutions presented in table 5.4, the E_{inv}-optimum solution is, to us, problematic since it relies only on wind and imported natural gas, which may lead to supply issues. The multi-criteria approach should lead to a more balanced and resilient solution.

Also, looking at the results obtained in table 5.4, one can see that none of the single-criterion optimised solution can improve all the criteria additional to the KPIs at once. When one gains on the environmental side (such as damage to human health or damage to ecosystems), one lose on the other side (such as land use or critical raw materials). So, it will be important to keep an eye on these additional indicators when multi-criteria optimisations will be pursued.

Finally, concerning the KPIs themselves, it is evident that optimising the GWP alone is very detrimental to the other two KPIs. There is possibly some intermediate solution, still well decarbonised, but with a better cost and energy invested. This is where the multi-criteria optimisation comes into play, in order for a compromise solution to be found. This optimisation will be the object of our next chapter (see chapter 6).

Chapter 6

Multi-criteria optimisations: Belgium 2035

This chapter deals with the exploitation of the core of the enhanced *EnergyScope TD* model: the multi-criteria optimisation (note: the new *EnergyScope TD Multi-Criteria* version can be found in repository [56]). It will aim at answering our last research question (see chapter 1): What additional perspectives can multi-criteria optimisation provide for energy system analysis and low carbon scenarios in particular?

Naturally, one could wonder if the results obtained with multi-criteria optimisations would not simply be an aggregation of the three single-criterion cases (depicted in chapter 5) depending on the relative importance given to each KPI. In the subsequent analyses, it will become clear that it is in fact not the case.

While the mix of resources actually stays similar, for the most part, to the single-criterion solutions and can, in fact, be seen as a combination that varies with the weights applied to the KPIs, some exceptions already appeared (as will be seen in section 1.1).

But it is mainly for another aspect of the energy system that the multi-criteria optimisation shows all its interest: the conversion technologies. Indeed, the way the resources will be used, i.e. with which technologies and in which sectors, differs from the single-criterion optimisations, quite drastically sometimes (as will be observed in section 1.2).

In that regard, a mapping of the solutions for Belgium in 2035 will be presented in section 1, exploring the changes induced by selecting different sets of weights, and illustrating the relevance of a multi-criteria optimisation approach.

Then in section 2, one case will be further developed to show the trade-offs that must be made to keep a good balance between the KPIs for a system well on its way towards defossilisation.

Finally, section 3 will present the outcomes of the multi-criteria optimisations and highlight their value to problem solving. So, this section will provide the answer to our last research question.

1 Exploration of the strategies: Mapping the trends

This section presents an exploration of the strategies determined by the program for the energy system when multi-criteria optimisations are performed. For that purpose, dozens of cases with different sets of weights for the KPIs were run and examined. The findings are summarised in the following sections and several maps in the form of ternary graphs will illustrate our explanations.

An example of empty ternary graph is shown in figure 6.1. Each side of the triangle is an axis along which the weight for one KPI varies from 0 to 1. The lines that shoot out of one axis represent all the cases that have the corresponding weight for the KPI. All intersections between 3 lines are the sets of weights for which an optimisation has been run: every combination of weights with 10% increments.

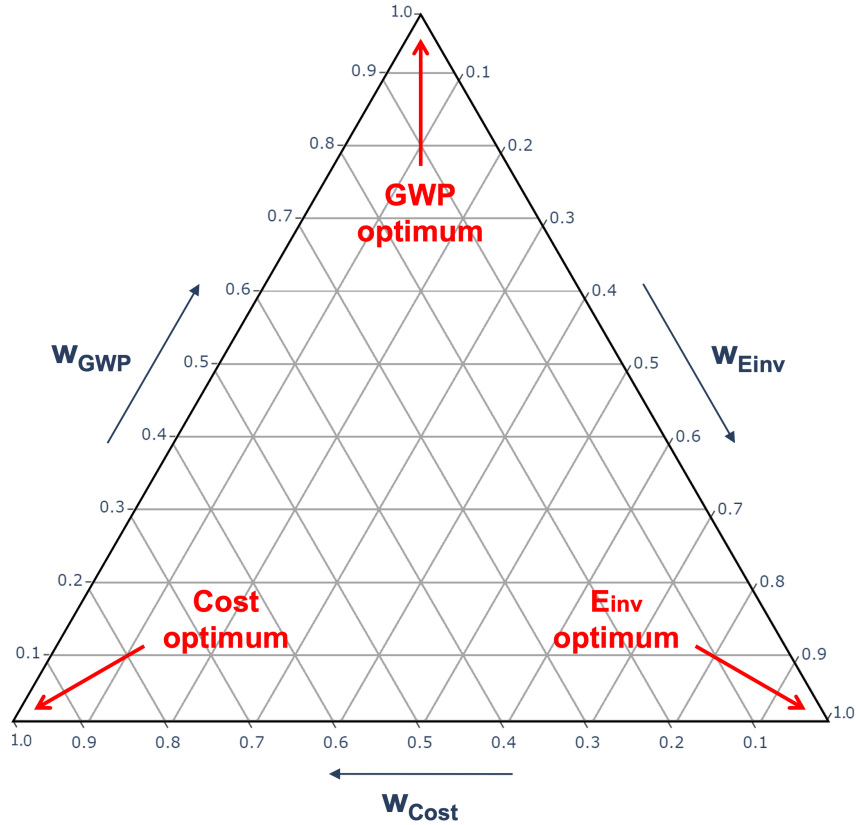


Figure 6.1: Illustration of an empty ternary graph

In the outcomes of the single-criterion optimisations (cfr. chapter 5 section 4), common trends had been identified and were expected to stay true no matter the set of weights considered. This assumption has indeed been confirmed and those aspects will therefore not be discussed again in this chapter.

The discussion of the other interesting facts on the cloud of solutions obtained will be articulated in three parts:

- First, the primary resources used by the system in the different solutions will be examined.
- Then, the technologies adopted will be discussed. Since a wide range of combinations is possible, the transition between these different sets of implemented technologies, depending on the weights chosen, will be illustrated only for some selected cases.
- Finally, the values obtained for our key performance indicators, depending on the associated weights, will be pictured. Some of the complementary criteria will also be briefly commented.

Concerning the ternary graphs that will illustrate our words, it must be noted that, as a sanity check, we verified that the solutions obtained at the vertices of the triangle were well corresponding to the single-criterion solutions found before. Since they were already discussed in chapter 5, they will not be further commented in the present chapter.

1.1 Choice of primary resources

Endogenous resources are used in almost all solutions because they make for a good compromise between the different key performance indicators.

As they are grown locally, transport is therefore not needed, which results in a smaller energy invested. Indeed, transport was often one of the main contributors to the E_{inv} of imported resources. Furthermore, these endogenous resources, with the exception of waste, are actually renewable. Consequently, their impact on the GWP is limited. Finally, their price is also competitive due to their local nature, as has been seen in

the cost-optimal energy system in chapter 5.

With a combination of those criteria, the use of endogenous resources is thus strongly advocated.

As was seen in the single-criterion optimisations, the resources are the biggest contribution to the total GWP of the energy system. The choice of the primary energy mix is thus highly correlated to the relative importance of the GWP.

Therefore, using more endogenous resources is further driven by an increase in the weight for the GWP. At a weight of 20%, woody and wet biomass are already used to their maximum potential and PV reaches 3/4 of its maximum capacity. When the GWP weight hits 40%, the use of PV is maximised and further improvements in GWP will require to work on the imported fuels.

The resources that the system chooses to import are mapped on a ternary graph in figure 6.2.

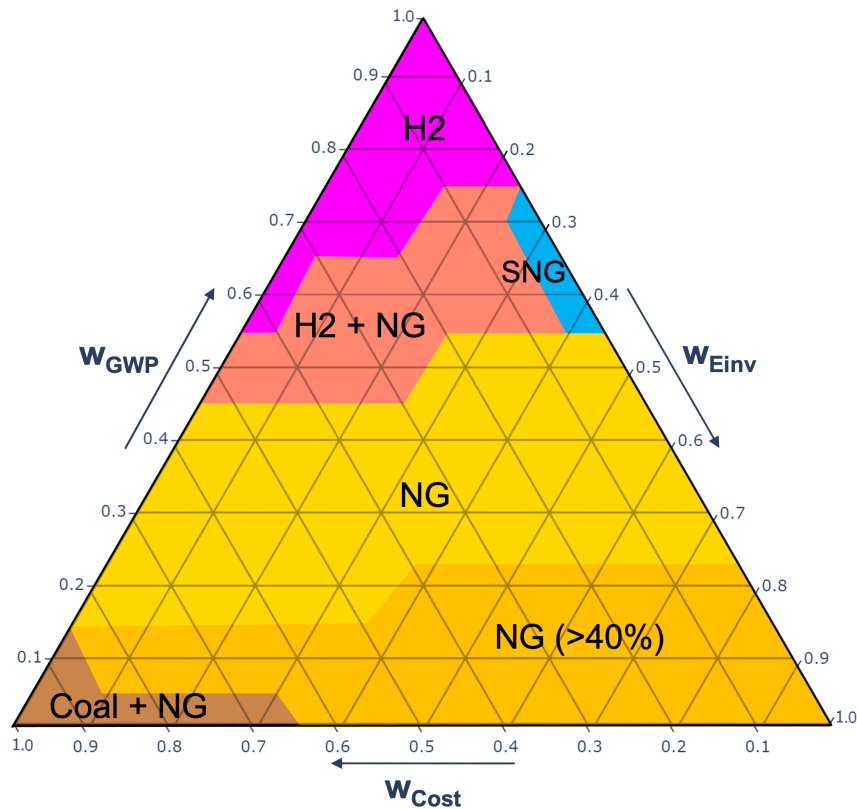


Figure 6.2: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the resources imported from abroad based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv}). The area "NG (>40%)" represent the cases where natural gas imports accounted for more than 40% of the primary energies. Abbreviations: hydrogen (H2), natural gas (NG), synthetic natural gas (SNG).

Under a weight of 40% for the GWP, natural gas is almost the only imported resource and, as explained above, it is the quantity of endogenous resources that varies (more specifically the installed PV capacity). When the GWP weight exceeds 40%, a transition from natural gas to hydrogen is performed. This transition is slowed down when the E_{inv} weight is high as hydrogen requires a very large energy invested and is detrimental to that KPI. On the other hand, when more emphasis is put on the cost of the system, this transition is facilitated by the fact that fuel cell cars are cheaper than other alternatives (as was explained in chapter 5 section 1.2).

When cost has no impact on the solution (i.e. when the weight of cost is zero), the transition is first made to SNG. Consequently, this solution differs from a simple linear combination of the single-criterion cases and could not have been foreseen without a multi-criteria approach.

We can also identify the use of coal in the bottom left corner, close to the cost-optimal solution. On the bottom right corner, systems close to the E_{inv} -optimum all rely very heavily on natural gas and do not

vary much in their strategies. These regions are not of great interest since they are close to single-criterion optimisations and the conclusions reached for the latter can be extended to them. The same thing goes for the systems with high GWP weights (80% and above).

1.2 Shifts in implemented technologies

Although the variety of resources is limited, the changes in the way they are used lead to a large diversity in the solutions. These changes are often prompted by a need to adapt the strategy or the technologies used in major sectors, in order to comply with the varying weights. In that regard, the mobility and high temperature heat sectors are the two most influential ones as will be seen in the next sections.

1.2.1 Biomass related technologies

Let us take biomass as an example: depending on which sector needs it the most, the woody biomass can be used in three completely different ways. It can either be burned in boilers, gasified to produce synthetic natural gas, or used to produce synthetic liquid fuel (SLF) through pyrolysis. Figure 6.3 presents a map showing for which sets of weights these options are taken.

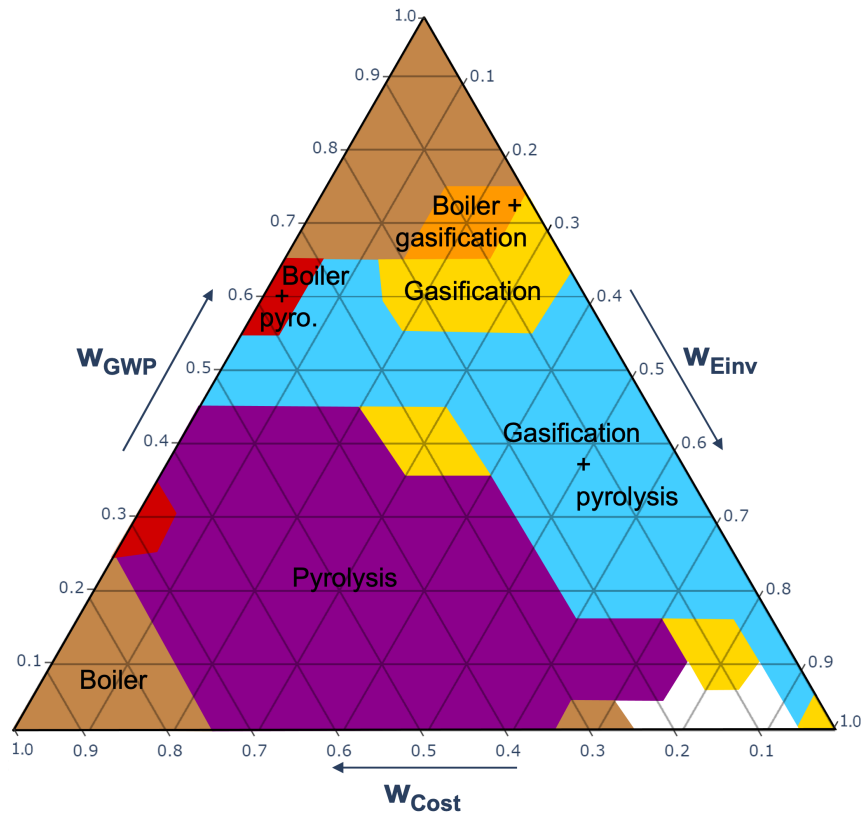


Figure 6.3: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the different uses of the woody biomass based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv}).

Woody biomass

When used for the high temperature heat sector, the woody biomass is burned in industrial boilers. It happens mostly for systems with a low weight on the energy invested, and that are either cost-effective (weight of cost $\geq 80\%$) or low in GWP (weight of GWP $\geq 70\%$).

For scenarios with lower weights on GWP, when the E_{inv} is gaining in importance, the use of woody biomass switches to pyrolysis in order to produce SLF that will then be refined into other synthetic fuels (bio-diesel or bio-gasoline). They will then be used to fuel parts of the mobility sectors. Of course, the quantity of

wood available could never supply all the transport sectors with synthetic fuels. The parts that are fueled in such a way vary with the weights applied.

When more emphasis is placed on the energy invested, the system uses more natural gas (NG) and therefore more NG-fueled technologies. In that cases, woody biomass is gasified to help supply these technologies. Though, a fraction is still converted to synthetic fuels for hybrid diesel buses. In lower GWP scenarios, less pyrolysis is needed as the mobility becomes more electrified.

Wet biomass

The wet biomass, on its hand, is gasified to produce synthetic natural gas. But it can also be used in cogeneration plants to produce both electricity and low temperature heat. The use of these cogeneration units coincides with the full electrification of the private mobility as more electricity is needed.

1.2.2 Mobility

As we just explained, the use of biomass is thus heavily reliant on the choices for the mobility sectors, and especially for the private mobility.

Private mobility

Figure 6.4 shows the different technologies that have been considered for the private vehicles and in which case they are used.

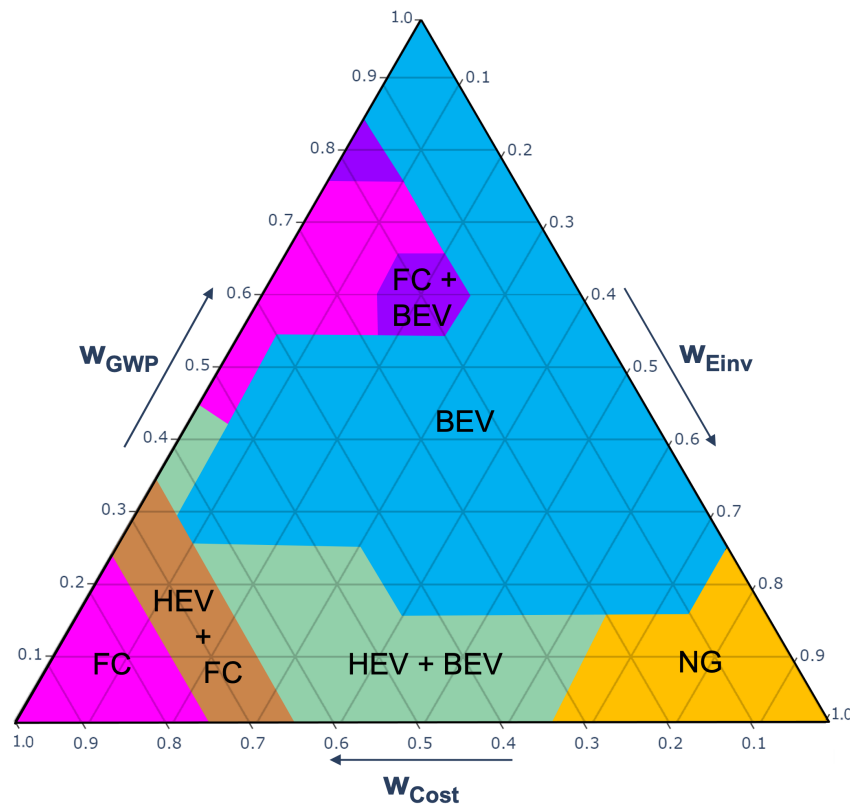


Figure 6.4: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the different vehicles for the private mobility sector based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv}). Abbreviations: natural gas (NG), battery electric vehicle (BEV), hybrid electric vehicle (HEV), fuel cell (FC).

When the GWP has a low relative importance (weight $\leq 40\%$), the choice of car technology is more dictated by the cost and the energy invested of the vehicles themselves, rather than the fuel used.

Starting from fuel cell (FC) cars for the more cost-driven scenarios, the mobility switches to hybrid electric vehicles (HEVs) when the importance of the E_{inv} becomes more pronounced. Then, going further in that direction, what remained of FC cars is replaced by battery electric vehicles (BEVs). Indeed, FC vehicles require a higher amount of energy invested than BEVs. Though it might seem counter-intuitive as batteries for the electric vehicles involve big expenses in energy. But, in the model, electric vehicles with a moderate autonomy, and therefore limited battery size, are considered.

However, current trends show that battery size for electric vehicles is increasing to boost their autonomy. What is considered in the model might therefore become outdated. Furthermore, as a lot of research is done on the subject, new technologies of batteries might appear and processes to produce them might evolve. These kinds of emerging technologies will thus have to be checked regularly to update accordingly data used in the model.

For cases with high weights on the GWP, the choice of cars is between FC vehicles and BEVs. For the same reasons as explained above, the former is used when more emphasis is put on the cost and the latter when the E_{inv} prevails.

Freight mobility

For the freight sector, the observed changes concern the technology of trucks used. These changes are mainly driven by the switches in private mobility as will be shown below.

Trucks fueled by natural gas are used first and foremost for low cost and energy invested systems. For the more decarbonated systems, FC trucks are chosen and are fueled thanks to the hydrogen that is imported, as could be seen on figure 6.2.

In-between, when the switch to BEVs occurs, the SLF produced with woody biomass that was used for the HEVs becomes available and diesel trucks are put to use. The introduction of that technology seems to go against the line that is followed (less weight on cost and more on E_{inv}) since the use of diesel trucks increases somewhat the E_{inv} (compared to NG trucks) and decreases the cost. In fact, as said above, the freight mobility must be looked together with the private one and the sum of the changes occurring in those two sectors lead overall to smooth and coherent changes in the KPIs.

1.2.3 Industrial heat sector

Another critical sector that was already mentioned is the high temperature heat production, especially for scenarios where GWP is of high importance (GWP weight $\geq 70\%$).

For lower GWP weights, waste was used in boilers to provide a part of the high temperature heat demand. But, in order to further decrease the total emissions, waste cannot be used in the energy system anymore. It is then replaced by the use of woody biomass, also in boilers.

We can see that waste is the last non-renewable resource to be removed for the very low carbon scenarios. Totally suppressing it from the solution for these scenarios is understandable from a pure mathematical optimisation point of view. However it would be a drawback not to valorise them, among others through heat production. Waste treatment and management is a topic on its own. If waste valorisation wants to be pursued, a solution would be to modify the energy system model to remove the waste contribution to the GWP.

When the waste is removed from the solution, the woody biomass available is not enough to produce all the heat, and gas cogeneration plants are used as a complement, as was seen in the single-criterion optimisation on the GWP. These gas cogeneration plants are used in almost all solutions, except for the ones close to cost-optimal system where coal is available. The cogeneration units are fueled with synthetic natural gas that is produced from wet biomass digestion or synthesised by combining hydrogen and captured CO_2 .

1.2.4 Electricity sector

The means of electricity production are more or less always the same: local renewable energies (wind, hydro and solar), imports of electricity from neighbouring countries, and some additional power from the gas cogeneration plants.

In solutions for which GWP has a big importance, PV is used at its maximum capacity and cogeneration plants fueled by hydrogen are part of the mix. On the other hand, when the weight for the GWP is low, the PV capacity is lowered and CCGTs are used instead.

For the systems with a high weight on the GWP, as the electricity sector is highly linked to other ones (heating and mobility), balancing the generation and the consumption of electricity can become quite complicated. The high share of intermittent energies in the electricity production does not help either. In consequence, lithium-ion batteries need to be deployed to handle the ensued variations in both the demand and the production.

1.3 Systems assessment: Indicators review

The following section looks first at the final values of the key performance indicators for the different weight possibilities. Values were obtained for each 10% increment of the criteria while values in between have been interpolated linearly for the graphical representation.

As seen on figure 6.5, generally, when the GWP weight increases from 0 to 20%, the GWP of the system decreases drastically (from 85 to 45 $\text{Mt}_{\text{CO}_2\text{eq}}/\text{y}$). The reduction of GWP then stalls with the increase of GWP weight up to 60%. The GWP then decreases rapidly until a GWP weight of 70% due to the switch to hydrogen, before hitting a plateau as has been explained before (in section 1.1). This switch to hydrogen and decrease of GWP happen sooner when the weight of E_{inv} is low and later when it is high. In the middle region, for a given GWP weight, a decrease in cost weight leads to a decrease in GWP.

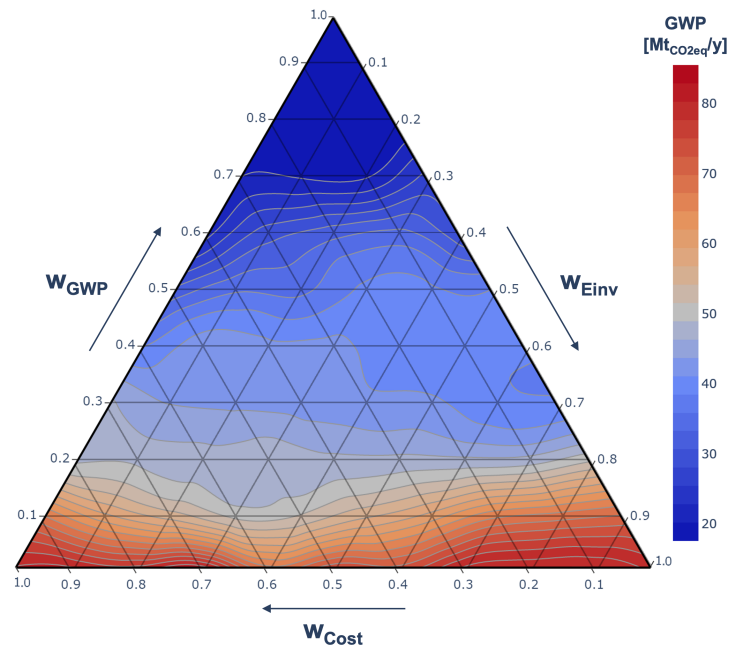


Figure 6.5: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the total GWP based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

The cost of the system (illustrated on figure 6.6) remains relatively low as long the GWP weight does not go above 50%. Then, a rapid cost increase is observed above a GWP weight of 60%, which means that every further reduction in GWP goes with high cost investments (mainly related to the switch from NG to H₂ imports).

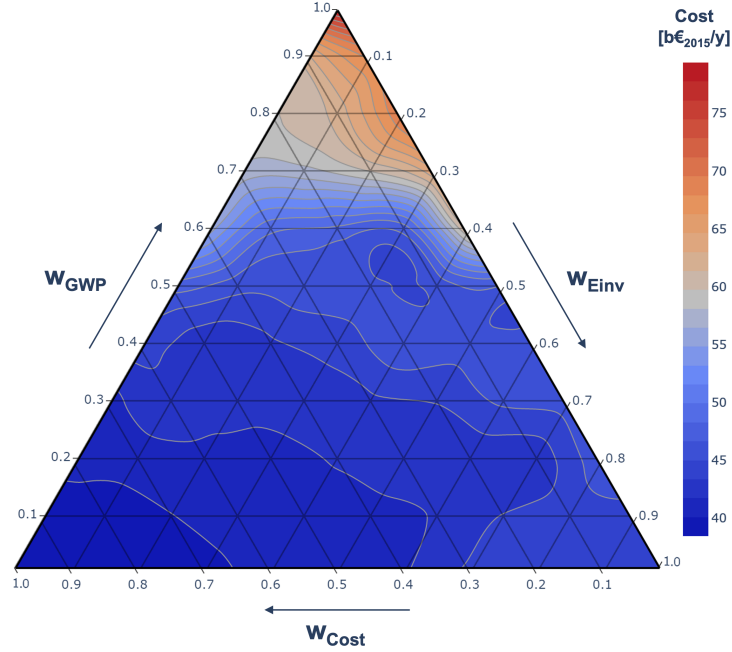


Figure 6.6: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the total cost based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

Similarly to the cost, the E_{inv} (see figure 6.7) remains low when GWP weights are moderate. But it tends to increase sooner than the cost when the GWP weight increases: this tendency can be observed for GWP weights above 40%.

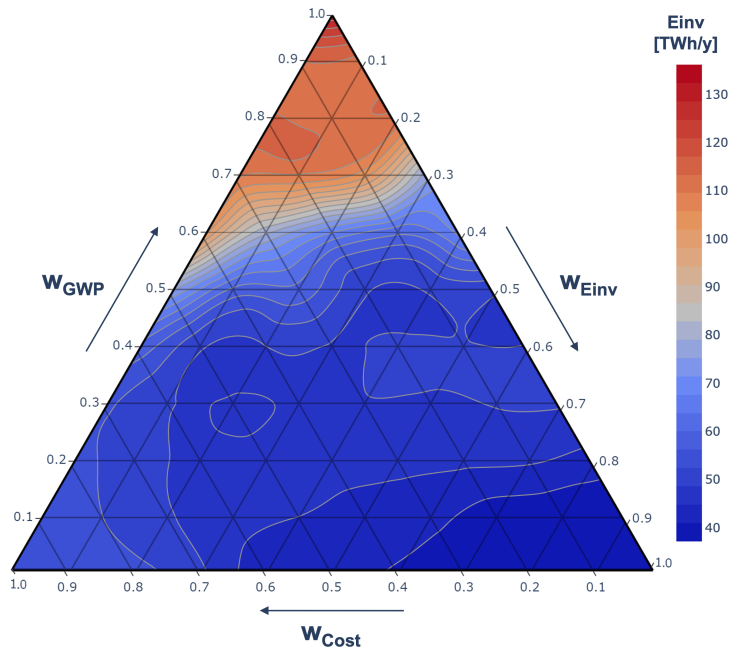


Figure 6.7: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the total E_{inv} based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

Finally, on both cost and E_{inv} maps, it can be observed that the transitions are not always smooth. In a zone with a given range of values (one color) for the indicator X, there can be a pocket with some higher or lower values (another color). This is linked to the switches in technologies at these places, made to improve the other KPIs. This leads to no reduction (or even an increase) in the indicator X value whereas its weight is increased.

After the examination of the KPIs, some of the maps for the additional criteria are also provided because they are illustrative of certain statements made previously. The other maps can be found in appendix C.

As a first example, the damage to human health is shown on figure 6.8. Two observations can be made on this map. There is a zone with high impact in the bottom left corner, when coal is part of the energy mix. On the other hand, the rest of the map remains in a limited range of values. This means that improving the GWP does not go especially hand in hand with a reduction of the damage to human health. Indeed, going to low GWP solutions implies the transition from NG to renewable resources, but, at the same time, the introduction of PV technology.

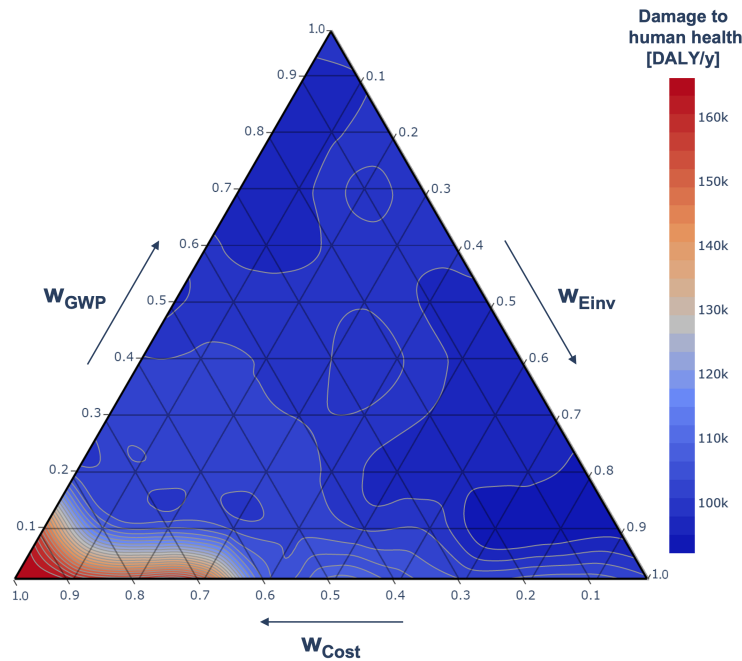


Figure 6.8: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the damage to human health indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

As another illustration, let us look at the critical raw materials on figure 6.9. For that metric, the transition to a decarbonated solution is clearly degrading this criterion. If one compares the shape of the color zones on that map with the technology map for private mobility (figure 6.4), one can clearly see the negative impact on our metric associated with the electric vehicles using batteries. The massive use of PV in low GWP solutions, together with additional batteries for electrical storage, has also an adverse effect on the critical raw materials metric.

These two examples illustrate once again the necessity to keep an eye on other metrics in complement to the KPIs.

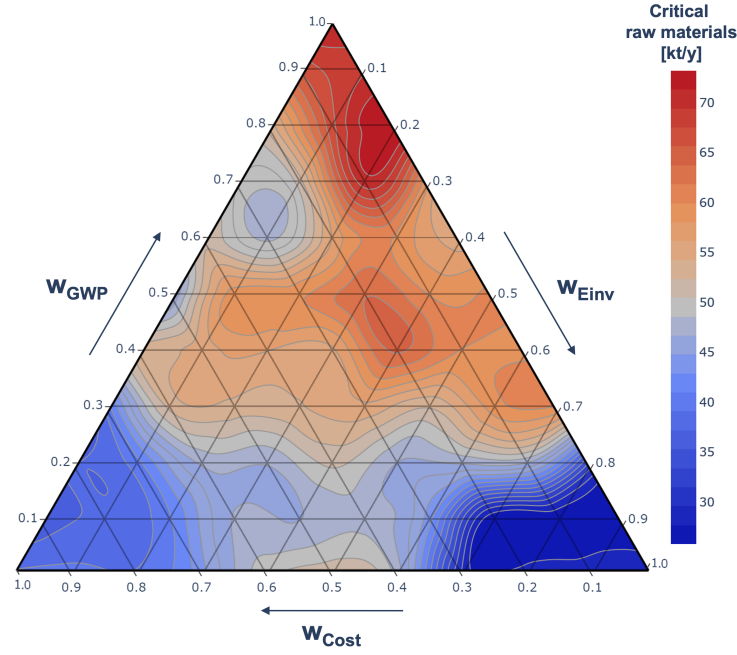


Figure 6.9: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the critical raw materials indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

2 Analysis of a trade-off solution towards a decarbonised system

For illustration purposes, amongst the cloud of solutions generated by the multi-criteria optimisations and mapped in section 1, we have selected one of the obtained energy systems that represents a good compromise solution when transitioning to a decarbonised system:

- The GWP weight is set at 60% so as to achieve a major improvement in greenhouse gases emissions in comparison to 2015, while still leaving some room for optimisation of cost and energy invested. We indeed saw in chapter 5 table 5.4 that these two KPIs are much higher than in 2015 if only an optimisation on GWP is performed, which may be unacceptable for decision-makers concerned by the different aspects of the energy issue.
- The weight for both the cost and the E_{inv} is set at 20% in order to avoid the solutions that are extremely negative for these KPIs (obtained for very low weights and corresponding to the red zones in the associated maps presented in section 1.3).

2.1 System overview

The strategy of the system consists in the maximum use of local resources as well as the import of natural gas and hydrogen. Renewables amount to 74% of the primary energy mix.

Let us start with the high temperature heat demand as it is a critical sector. It is provided by industrial waste boilers as well as gas cogeneration plants (CHPs). To decrease the emissions associated with it, part of the NG used in the CHPs is synthetic natural gas produced from wood.

Concerning the low temperature heat, it is mainly provided by electrical heat pumps. Some heat is also produced by CHPs that are fueled with wet biomass and the last small contribution comes from heat released in the gasification process of the woody biomass. It must also be noted that district heating networks are largely developed.

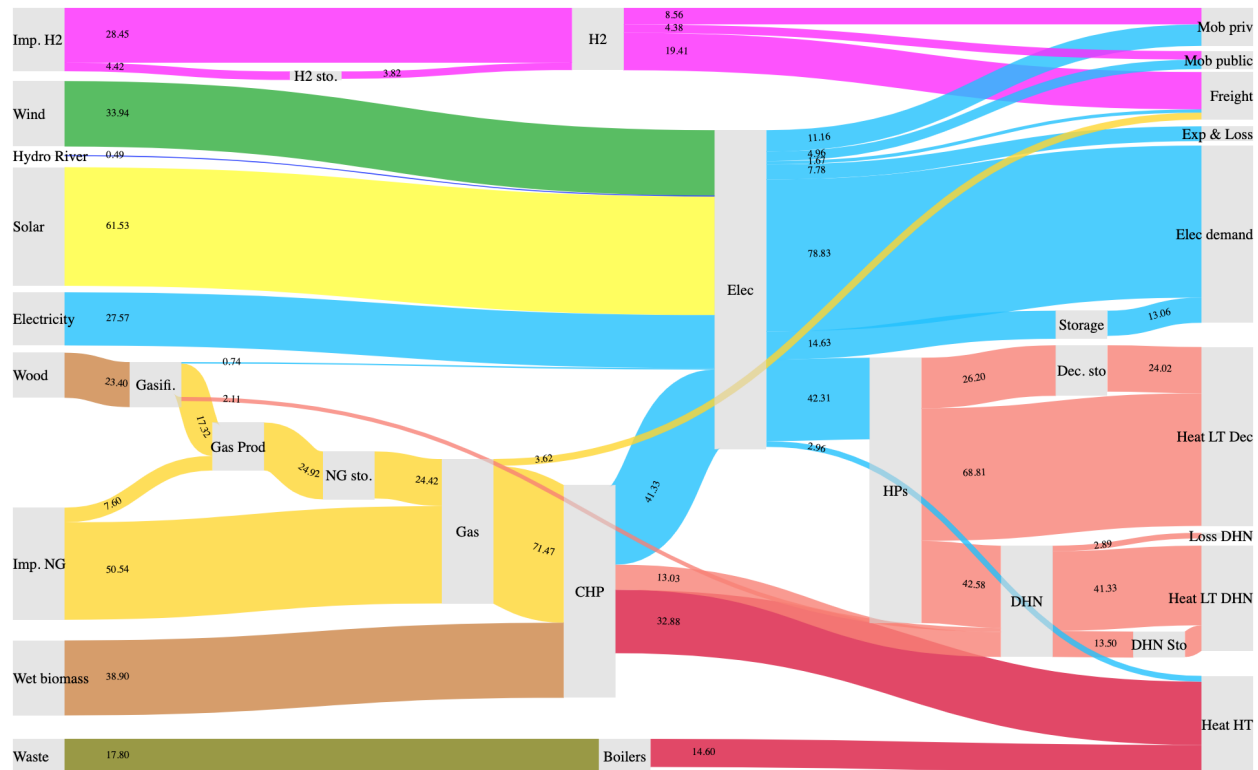


Figure 6.10: Multi-criteria optimisation of the 2035 Belgian energy system: Sankey diagram of a low GWP solution (weights: $w_{\text{GWP}} = 60\%$, $w_{\text{Cost}} = 20\%$, $w_{\text{Einv}} = 20\%$). Resources are gathered on the left side and the right side gathers the final energy consumption. The conversion technologies in the middle are aggregated by families. Abbreviations: hydrogen (H2), import (Imp), storage (sto), gasification (Gasifi.), production (prod), natural gas (NG), heat and power cogeneration (CHP), electricity (Elec), Export (Exp), heat pumps (HPs), decentralised (Dec), district heating network (DHN), low temperature (LT), high temperature (HT), mobility (Mob), private (priv).

The electricity is mostly provided by solar and wind. Massive imports of electricity from neighbouring countries (at their maximum capacity) and CHPs complete the electricity supply. A large quantity of electrical storage is needed and is provided through the installation of 78.6 GWh of lithium-ion batteries, and also through the use of the vehicle-to-grid dynamic.

Finally, as this solution is a trade off between cost and energy invested, the private mobility sector is composed of both battery electric vehicles and fuel cell cars. Solutions with a higher weight on the energy invested see a completely electrified private mobility, while solutions with more weight on the cost use more fuel cells.

2.2 Indicators analysis

The results for the different criteria of this low GWP system are presented in table 6.1, compared with the situation of 2015.

Key performance indicators

The cost of this low GWP solution is 8.7% higher than the one of the 2015 energy system, but it is still lower than the GWP-optimal solution presented in the single-criterion optimisations chapter (chapter 5 table 5.4). Major contributors are the private mobility (26% of the cost), the renewable resources (19%), mostly electricity imports and H₂, and the local renewable technologies (9%), mainly solar and wind turbines.

Criterion	Units	2015	GWP _{low} solution 2035
Cost	[b€ ₂₀₁₅ /y]	43.6	47.4
GWP	[Mt _{CO₂eq} /y]	131.6	32.5
E _{inv}	[TWh/y]	87.7	66.9
Land use agricultural	[km ² .y/y]	19 888	28 291
Land use urban	[km ² .y/y]	667	4222
Damage to human health	[DALY/y]	235 304	98 266
Damage to ecosystems	[species.y/y]	608	284
Damage to resources availability	[b€ ₂₀₁₅ /y]	11.9	2.7
Environmental prices	[b€ ₂₀₁₅ /y]	26.5	13.6
Critical raw materials	[kt/y]	103.3	56.8

Table 6.1: Impacts of a low GWP solution (weights: $w_{\text{GWP}} = 60\%$, $w_{\text{Cost}} = 20\%$, $w_{\text{Einv}} = 20\%$) for the 2035 Belgian energy system compared to 2015 situation. These impacts have been annualised and each indicator is therefore expressed per year.

In terms of GWP, the system fares much better than the 2015 case with a 75% reduction in emissions, but it is not yet at its optimum (chapter 5 table 5.4). The major contributor to GWP remains NG, contributing to 55% of the emissions. Indirect emissions from renewables, be they imported or local, is not negligible though, with 24% of the emissions. The indirect emissions of private mobility amount to 16% of the impact. At the end, the total indirect emissions of the system represent more than the half of the emissions.

The energy invested is also reduced with respect to 2015, but to a lesser extent than GWP. Compared to the GWP-optimal solution presented in chapter 5 table 5.4, the energy invested is much lower, since it is around half of the value of the GWP-optimal solution. The main contributors are the renewables (56%) and the private mobility sector (29%).

So, in terms of KPIs, the low GWP system, with its reasonable cost and energy invested, but an already well reduced GWP, represents an interesting balanced solution on the way to decarbonation.

Additional criteria

In terms of land use, the requirements of the energy system are high and the total amounts to 32 500 km². To give an order of magnitude, Belgium's area is about 31 700 km². The value obtained might thus seem extreme, but it must be kept in mind that not all land use is located in Belgium.

The urban land use comes mainly from the PV installations and the imported hydrogen (because it is essentially produced with solar energy). Although, as explained in chapter 4 section 3.2, this value is somewhat overestimated for the local PV installations.

The agricultural land use comes almost entirely from the wet and woody biomass (92%) which are used to their maximum potential. The value for woody biomass might also be a bit overestimated as not all of it is grown in Belgium. Indeed some of its potential comes from industrial and municipal waste, but this is not taken into account when computing the woody biomass land use.

All the other environmental indicators have been improved with respect to the 2015 Belgian energy system, mainly thanks to the elimination of harmful fuels (coal and petroleum derivatives) from the energy mix.

Finally, the critical raw materials metric also improves with respect to 2015 thanks to a shift in energy mix, but it remains nevertheless high due to the usage of batteries in cars and for electrical storage, which are major contributors to that metric as explained before.

3 Outcomes

In this chapter, we have applied the enhanced version of *EnergyScope TD* developed in chapter 3 (note: the new *EnergyScope TD Multi-Criteria* version can be found in repository [56]) to the "Belgium in 2035" case study described in chapter 4 in order to perform a multi-criteria optimisation of its energy system, with the key performance indicators selected in chapter 2.

For the purpose of exploring the possible strategies for Belgium in 2035, we have analysed multiple cases with varying weights between the KPIs.

In section 1, the cloud of solutions obtained has been studied to understand the resources used, the trends in terms of technologies, as well as the impact on our indicators, depending on the weights selected.

This analysis has shown that a multi-criteria approach offers trade-off solutions that could not be obtained with a single-criterion optimisation or a linear combination of them (see chapter 5 for the results of the single-criterion optimisations). For different mixes of weights, but the same resources, it was interesting to see the changes in the technologies selected and in the sectors where they were applied.

Also, we noted that examining the additional metrics associated with a solution and their main contributors may bring some additional perspectives. For example, a balanced (in terms of our KPIs) solution that still considers the use of coal will have a negative impact on damage to human health and to ecosystems. Removing the coal from that energy system may then lead to a more acceptable solution from a global point of view. As another example, it must be observed that GWP-optimised solutions containing a lot of PV or biomass lead to a high land use, and in addition for the PV, to increased environmental damages.

In section 2, an illustrative example of a trade-off solution for Belgian in 2035 has been further commented. Since, by then, we want to be on the way towards climate neutrality, a weight of 60% was assigned to the GWP, while the other two KPIs were weighted with 20%. An interesting compromise between technologies was observed.

The case study presented in this chapter has demonstrated the value of a multi-criteria optimisation to obtain a balanced solution for an energy system with conflicting KPIs at hand. This is a really powerful tool for the policy-makers. However, their decision-making process should not be limited to the selection of the weights to be attributed to each KPI, but they should keep an eye on the other indicators associated with the energy system, in order to ensure that the solution is not only balanced, but also resilient.

Furthermore, even if Belgium was selected as application case, it is believed that the findings in sections 1 and 2 can be generalised to other countries with similar constraints and objectives.

It must be recalled that, when the model was built up in chapter 4, certain assumptions have been taken and some constraints have been imposed to the model. These assumptions and constraints are however not cast in concrete and need to be revised if the political context evolves or if the technological progress opens up new avenues. For Belgium, as an example, a decision to extend the life of the nuclear power plants or the possibility of exploiting geothermal potential, as is currently being studied, could change the equation.

Chapter 7

Conclusions

In the context of global warming issue, the European Union is aiming at decreasing drastically its environmental footprint. To help the decision-makers to prepare the energy transition, energy models are key tools to study the effects on the environment and to search for an optimal energy system. Several perspectives - economical, technical, environmental and social - are necessary to obtain a meaningful solution. To cope with the current lack of models allowing a multi-criteria optimisation, this thesis had as **objectives** (see **chapter 1**):

- To determine key performance indicators for the design of an optimal energy system,
- To implement a multi-criteria optimisation within a traditional single objective linear programming model,
- To show, for a chosen application case, the additional perspectives that a multi-criteria optimisation can provide in the analysis of an energy system, in particular when looking for a green solution.

In a first step, we were interested in the **characterisation of the energy system** (see **chapter 2**).

To this end, a life cycle assessment (LCA) approach was chosen in order to account for the impacts of the energy system from cradle to cradle (including thus waste disposal and recycling). For assessing that cumulative environmental impact, an LCA study involves a thorough inventory of the energy and materials required across the whole cycle and its multiple sub-processes.

Existing databases offering this level of information for all energy sectors (electricity, heat and mobility) were therefore explored and the scope of *ecoinvent* database was found to be the most adequate, with its extensive data, good structure and information on the methodology behind its content. Amongst the modelling possibilities offered by *ecoinvent* for the allocation of impacts (or “burdens”), the cut-off approach was adopted. To extract and process the data from *ecoinvent*, we made use of the *SimaPro* software tool.

Since the challenges of an energy system are of an economic (micro and macro), technical and also environmental nature, we selected three key performance indicators (KPIs) tackling these various aspects: the cost of the whole energy system, the global warming potential (GWP) and the energy invested E_{inv} (as appearing in the ratio of the energy return on investment (EROI)). These KPIs are the object of the optimisation effort to find an effective and clean energy system. In order to portray even better the energy system, some complementary metrics, such as land use and environmental prices, were also looked at.

Given the comprehensive view we wanted to have on the system through the LCA approach, and owing to the number of targeted metrics, the data collection effort was substantial. Some metrics were hard to obtain or their origin and the underlying rationale were sometimes difficult to verify. Also, like in every model, a number of assumptions and simplifications were necessary, as detailed throughout the report. It is on these aspects that we believe that some further improvements could be made in future works.

As an example, in the mobility sector, due to the scarcity of data related to freight and public transport, we had to obtain data on trucks and buses by extrapolation or analogy with other technologies. So, we would recommend a reassessment of those data if more information becomes available in the future. Also, for the criteria considered in addition to the KPIs, in order to ensure the pertinence of the results obtained, the data

could also be re-examined. For instance, for the land use, the lifetime of the technology plays a role, but it was not always possible to find the lifetime considered in the *ecoinvent* database to verify its consistency with the energy system model.

After the selection of the key indicators for the evaluation of the energy system and the determination of a data collection methodology, the second part of our thesis (see **chapter 3**) dealt with the introduction of a **multi-criteria optimisation** into the existing *EnergyScope TD* model that is currently single objective, but that offers a multi-sector coverage (electricity, heat and mobility), an hourly resolution, a reasonable computation time and, furthermore, has the advantage to be open source.

First, the architecture of original *EnergyScope TD* model was explained, as well as its computation of the objective function (for cost optimisation) and its calculation of the constrained criterion (GWP). Then, possible multi-criteria optimisation techniques were discussed. Amongst them, the goal programming method was selected because, in its non pre-emptive formulation, it is a generalisation of a linear programming problem formulation and it allows to stay with a single objective function, which makes the modifications to be made to *EnergyScope TD* more straightforward. That single objective function is built using a weighted sum of the deviations of each criterion with respect to its goal. The new *EnergyScope TD Multi-Criteria* version can be found in repository [56].

If one would wish to optimise the criteria considering different priority levels, several objective functions would be required and the optimisation would proceed in several steps, in the order of priority of the objective functions. The introduction of that pre-emptive goal programming approach into *EnergyScope TD Multi-Criteria* could be pursued as a model enhancement, especially if the number of parameters to be optimised is growing and the decision-maker wants to put different degrees of emphasis on them. In that case, more in-depth modifications to the model would obviously be required.

In the last part of our thesis, the Belgian energy system in 2035 is used as a **case study** (see **chapter 4**) to understand the additional perspectives that multi-criteria optimisation can offer in the analysis of energy systems.

In **chapter 5, single-criterion optimisations**, performed for each KPI separately, provided great insight into the strategies used to optimise the energy system with respect to one or the other of the KPIs. But they also showed that none of the single-criterion optimised solution is acceptable for the ensemble of the criteria (KPIs and additional metrics) and that a multi-criteria optimisation is necessary to obtain a compromise solution.

These **multi-criteria optimisations performed for the Belgian energy system in 2035** are presented in **chapter 6**. Multiple cases with varying weights between the KPIs were analysed and the cloud of solutions obtained was explored through maps illustrating the choice of resources and the mix of technologies applied, strongly dependent on the set of weights selected. One trade-off solution has been further illustrated and commented. The value of a multi-criteria optimisation to obtain a balanced solution for an energy system with conflicting KPIs at hand has been demonstrated. The additional perspectives offered by the complementary metrics have been shown. Therefore, both the choice of the weights to be assigned to the KPIs and the surveillance of the additional criteria need to be part of the decision-making process to ensure that a robust solution is adopted for the energy system in the prospect of a carbon-free country.

Two remarks can be done concerning the selected case study. First, although its focus was on Belgium, the associated conclusions can be generalised to other countries with similar challenges. Second, the constraints and assumptions considered in the model will need to be revisited in function of the evolution of the policy context or technological innovations.

Also, it must be reminded that the non-energy demand, which corresponds to fuels that are used as raw materials in different sectors, has not been treated in our model. Future studies could consider adding this aspect to the end-use demand in order to have a complete picture of the fuel needs in the system.

In summary, this thesis, by introducing several metrics, with their underlying data, and by implementing a multi-criteria optimisation capability in *EnergyScope TD*, opens new avenues to explore future energy systems in the transition towards climate neutrality. The case study performed with *EnergyScope TD Multi-*

Criteria has demonstrated the value of a multi-criteria approach and has provided interesting insights into how the Belgian energy system should look like in the year 2035. Even if Belgium was selected as application case, the learnings can be extended to other countries facing the same challenges. As we have seen, the model could be enhanced with a pre-emptive goal programming approach. Also, the application case could be further developed, conceivably by including the non-energy demand and certainly by incorporating refined data or new technologies once more knowledge becomes accessible or if the political context evolves.

Appendix A

Data collection

The methodology chapter on data (chapter 2) has expressed the general method used to obtain data from the *ecoinvent* database. In this section, we look at the data into more details and explain the calculations and assumptions made for the more complicated cases.

In the tables summarising the data, the names of the indicators have been shortened:

C	Cost
GWP	Global warming potential
Env	Energy invested
Agri Land	Agricultural land use
Urban Land	Urban land use
DamToHH	Damage to human health
DamToEcosys	Damage to ecosystems
DamToRes	Damage to resource availability
EP	Environmental prices
CRM	Critical raw materials

1 LCIA methods

The life cycle impact assessment (LCIA) methods used are the following:

- European Environmental Prices (2015): The midpoint impact of GWP was collected with this impact method; it corresponds to the values for IPCC 2013 100-year [24]. The endpoint environmental price was also collected in €₂₀₁₅. The other midpoint impacts collected are agricultural land use and urban land use (with the characterisation factors of ReCiPe 2008). We have chosen these as we liked the distinction between the types of land used, whereas this distinction is not made in ReCiPe 2016 where all land uses are reported as annual crop land use equivalents.
- ReCiPe 2016 Endpoint: The endpoint impact on ecosystems, human health and resource scarcity were collected.
- Cumulative Energy Demand (based on LHV) to calculate the energy invested.
- Critical raw materials: custom made (see section 1.1)

1.1 Critical raw materials

The goal of this method was to have an additional insight into the critical materials used by the system. To do so, a link was to be established between the LCI materials and the critical materials defined by the EU in 2020 (see table A.1).

Antimony	Cobalt	Heavy rare earths	Natural rubber	Silicon metal
Baryte	Coking coal	Indium	Niobium	Strontium
Bauxite	Fluorspar	Light rare earths	Phosphate rock	Tantalum
Beryllium	Gallium	Lithium	Phosphorus	Titanium
Bismuth	Germanium	Magnesium	Platinum group metals	Tungsten
Borates	Hafnium	Natural graphite	Scandium	Vanadium

Table A.1: List of the critical raw materials as defined by the EU in 2020 [12]

Category of materials are usually not defined in *SimaPro* and substances were added individually. In case a critical raw material's exact name could not be found in *SimaPro*, more research was made to find its match (or matches) and the correspondences can be found in table A.2. The characterisation factors of the method are all set at $1 \text{ kg}_{\text{critical raw material}}/\text{kg}_{\text{substance}}$.

Critical Raw Material	Substance in <i>SimaPro</i>	Comment
Borates	Boran, Borax	
Coking Coal	/	Not possible to differentiate coking coal from other coals, the enormous quantities of coal used in the life cycles would overwhelm this impact assessment method.
Natural Graphite	Graphite	
Natural Rubber	/	Not in <i>SimaPro</i> .
Phosphate rock	Phosphate ore	
Silicon metal	Silicon	No distinction between grades of silicon.

Table A.2: Link between substances in *SimaPro* and some critical raw materials

2 Resources

As has been explained in the data computation methodology (chapter 2 section 4), data collection presents a couple of challenges:

- Accounting for direct and indirect impacts
- Calculation of the energy invested with the CED method
- Converting data to the *EnergyScope TD* format
- Missing data in *ecoinvent*

The general solutions to these challenges have been presented in the data computation methodology section as well. In this appendix, we will go into more details for the calculations, hypotheses and results found for the different resources.

Let us first remind the tools available for the data collection again, as detailed in the appendix E providing a quick user guide for *SimaPro*:

- We have access to the results of life cycle impact assessment (LCIA) methods. From these, we can extract the total impact of a product for a given impact category (i.e. the different indicators).
- We have also access to the contributions of all the unit processes involved in the life cycle of the said product: their respective impacts that, when summed together, give the total impact aforementioned.
- Additionally, we can navigate in the network of processes and see how the impact propagates through them.

The process contribution tool in *SimaPro* is very useful to obtain the E_{inv} criterion based on the CED method. Indeed as explained in the data collection methodology, to obtain the energy invested, some contributions have just to be subtracted from the CED (such as the energy content of the resources).

With these tools, let us now analyse the different resources available. Most of the explanations will be for the E_{inv} criterion as it is the most complicated. The choice of market and combustion activity to evaluate the environmental impacts are given in appendix D.

The resulting data are summarised in tables A.4 and A.5 at the end of this section.

2.1 Petroleum products

The petroleum products considered as resources in *ESTD* are gasoline, diesel and light fuel oil (LFO). In the case of petroleum products, the CED distribution tool cannot be used to obtain the E_{inv} . Indeed petroleum and its refined products are used extensively for heat and transport purposes. The difference cannot be made between the energy content of petroleum ending up in the refined fuels and the indirect energy uses for petroleum (extraction, transport and refining). As such we explored the CED propagation through the network processes by hand.

The final CED contribution for imported petroleum products in Belgium is spread across the various extraction sites around the world. To simplify calculations, we have decided to only look at the 4 biggest contributors: the middle east (RME) (29% of the market), the rest of the world (RoW) on-shore prod (31.5% of the market), the RoW off-shore (15% of the market) and Russia (14% of the market). Each extraction site is different and the LHV of petrol, the energy invested for the extraction and losses differ for each of these contributors. To illustrate this, let us look at the EROI of extraction of petrol (LHV of petrol / energy required for the extraction) in two locations: the EROI of extraction is 27.4 for RoW on-shore, whereas, in RME, the EROI of extraction is 60.9. The distribution of the different energy contributions to the CED of extraction of 1 kg of petroleum can be found in table A.3. The data for Russia (EROI of extraction of 8.4) was ignored as it seems false and does not fit with either the EROI of the other regions or the EROI of 30 found by A. Safronov and A. Sokolov [68].

Contribution [MJ]	RME	RoW onshore	RoW offshore	Russia
Petroleum LHV	43.4	43.2	43.2	44.3
Petroleum extraction	0.713	1.5774	0.78	5.3
Losses	0.587	0.4226	0.22	2.2
Total CED	44.7	45.2	44.2	51.8

Table A.3: Breakdown of the CED for petroleum extraction

With this market mix, we obtain an average energy invested and LHV for petrol; the corresponding mean EROI of extraction is 39.9. To obtain the energy invested of the refined products, the energy required for the refinery operation is needed. For this operation, a SOUP is used. It takes, among other inputs, $1+x$ kg of petroleum as input to produce 1 kg of petroleum product at the output. We assume that x kg of petrol are used for energy purposes and obtain the required energy investment. Finally, the chosen values for the resources LHV are 42.8, 42.5 and 42.6 MJ/kg for diesel, gasoline and LFO respectively [31].

2.2 Coal

Similarly to petrol, the energy content of fossil fuels varies with the extraction sites. This is even more so for coal. The LHV chosen is that of the combustion activity as mentioned in chapter 2 section 4 and is of 24.096 MJ/kg.

To obtain the energy invested for the extraction, we use the CED distribution tool. This gives us the LHV of coal at all the extraction sites. Part of this coal is used to produce electricity that will be used in the mining of coal; however this quantity is small (it amounts for example to 0.15% of the coal energy in Austria) and has thus been neglected. The final energy invested is obtained by removing the sum of the coal LHV at the extraction site from the total CED. The energy invested for coal extraction is very small. If import from EU is assumed, the energy invested for coal extraction and transport in the EU is around 0.03 MJ per MJ of coal. However the coal market for Belgium mostly consists of oversea imports and the transport of coal from abroad requires a lot of energy, which increases the energy invested by 400% compared to EU coal.

2.3 Uranium

When looking at the energy use in the conversion chain of uranium ore to nuclear fuel, most of the energy use comes from the enrichment stage. We assume that the other energy uses in the chain can be neglected. Depending on the enrichment method (diffusion/centrifuge), the contribution of the enrichment stage ranges from 0.00215% to 0.6% of the total CED of the enriched uranium. We neglect the contribution of centrifugal enrichment and obtain the energy invested for diffusion enrichment, that is done in enrichment facilities in the US and France.

The energy content of 1 kg of nuclear fuel used is 53 MWd (4.5792 TJ), that is the burnup rate of pressure water reactors in *ecoinvent*. With this and the energy invested, we find an EROI of extraction of 58 for the Belgian nuclear fuel market. If all uranium was enriched in France with the diffusion method however, the EROI would be 23.

In terms of environmental impact, although uranium has no combustion emissions, the EoL treatment of the spent fuel does have its impacts. The impacts are included in the resource impact and have been obtained with the same methodology as for combustion impacts as described in chapter 2 section 4.

2.4 NG

In the case of natural gas, the import market is more specific to Belgium. The same approach as for petroleum was used for NG. The chosen LHV is from the combustion activity.

2.5 Electricity and hydrogen imports

The import mixes have been described extensively in the case study (see chapter 4 section 2.1.2). An additional electricity mix was also calculated for 2050 see appendix B.

2.6 Bio-fuels

In the case of bio-fuels, direct emission impacts are neglected and only the bio-fuels production impacts are taken into account.

To obtain the energy invested, the process contribution tool was used to subtract the LHV of the biomass at the production site from the total CED. The available impacts are those of:

- bio-ethanol produced from grass (66%) and from sugar beet (33%) as in Switzerland,
- bio-diesel produced from rapeseed oil,
- wet biomass corresponding to grass,
- woody biomass corresponding to woodchips,
- SNG produced from manure, bio-waste, sewage sludge and vegetable cooking oil.

2.7 Waste

The impacts of waste are obtained from the incineration process; the energy content of waste is assumed to be 12.348 MJ/kg as in S. Moret's thesis [55]. From a cut-off approach point of view, heat and electricity from waste are burden free; however this poses a problem in collecting data as we use waste as a resource for the energy system. Consequently we have decided to attribute the recycling process impacts to the waste, which includes the transport of waste, the direct emissions, the production of chemicals used in the incineration facility and the land fill of the residual materials.

Resource	C_{op} [$\frac{M\text{€}_{2015}}{\text{TWh}}$]	GWP_{op} [$\frac{\text{ktCO}_2\text{eq}}{\text{TWh}}$]	$E_{inv_{op}}$ [$\frac{\text{TWh}}{\text{TWh}}$]	EP_{op} [$\frac{M\text{€}_{2015}}{\text{TWh}}$]	$DamToRes_{op}$ [$\frac{M\text{€}_{2015}}{\text{TWh}}$]
Electricity Import	84	72	123	26	10.61
Gasoline	82	346	281	37	37.16
Diesel	80	302	210	45	35.20
Light Fuel Oil	60	315	204	32	35.28
Natural Gas	44	260	61	25	27.56
Woody Biomass	33	12	49	112	1.30
Wet Biomass	6	33	56	53	1.20
Waste	23	150	58	24	0.75
Coal	18	400	121	185	7.71
Uranium	4	3	43	11	0.18
Bio-diesel	240	174	432	259	7.65
Bio-ethanol	226	68	316	47	4.69
Synthetic Liquid Fuel	211	120	492	223	7.10
Synthetic Natural Gas	197	154	269	26	3.13
Hydrogen	177	45	579	31	3.94

Table A.4: Resources data. Abbreviation: operational (op)

Resource	$Agri\ Land_{op}$ [$\frac{\text{km}^2\ y}{\text{TWh}}$]	$Urban\ Land_{op}$ [$\frac{\text{km}^2\ y}{\text{TWh}}$]	$DamToHH_{op}$ [$\frac{\text{DALY}}{\text{TWh}}$]	$DamToEcosys_{op}$ [$\frac{\text{species}\ y}{\text{TWh}}$]	CRM_{op} [$\frac{\text{t}}{\text{TWh}}$]
Electricity Import	58.09	5.76	146	0.50	46.39
Gasoline	1.25	0.60	459	1.16	414.37
Diesel	0.55	0.54	461	1.19	401.21
Light Fuel Oil	0.52	0.48	418	1.06	74.08
Natural Gas	0.10	0.07	283	0.80	480.36
Woody Biomass	860.57	7.78	23	2.39	401.78
Wet Biomass	151.36	0.35	210	1.24	88.28
Waste	0.14	0.28	487	0.52	28.94
Coal	3.59	3.03	1 504	3.20	14.69
Uranium	0.07	0.04	14	0.03	15.98
Bio-diesel	603.25	9.96	638	6.30	24.36
Bio-ethanol	165.45	0.93	185	1.41	9.24
Synthetic Liquid Fuel	1 452.18	10.21	408	4.53	405.25
Synthetic Natural Gas	10.82	0.76	296	0.67	196
Hydrogen	3.73	35.66	276	0.67	60.93

Table A.5: Resources data (continuation of table A.4).

3 Technologies

In the case of technologies, GWP is obtained with the GWP impact assessment method; E_{inv} is assumed equal to CED and is obtained with the CED impact assessment method. The challenges linked to resources are thus linked to sizing the technologies. The quantity of technologies is also a challenge and data for all technologies was not obtained. To fill the data gaps, the construction impacts of some technologies in the same sector were assumed to be the same, extrapolated from similar technologies or obtained from independent studies.

3.1 Electricity sector

The electricity sector is very complete in *ecoinvent*; however no distinction could be made for the different coal technologies. The energy invested and GWP values from *ecoinvent* for PV have been halved to obtain more up to date values. This was done following a study on evolution of PV LCA impacts by [13].

The resulting data are summarised in tables A.6 and A.7.

Technology	C_{inv} [$\frac{\text{M€}_{2015}}{\text{GW}}$]	C_{maint} [$\frac{\text{M€}_{2015}}{\text{GW}}$]	GWP_{cstr} [$\frac{\text{ktCO}_2\text{eq}}{\text{GW}}$]	$\text{Einv}_{\text{cstr}}$ [$\frac{\text{GWh}}{\text{GW}}$]	EP_{cstr} [$\frac{\text{M€}_{2015}}{\text{GW}}$]	$\text{DamToRes}_{\text{cstr}}$ [$\frac{\text{M€}_{2015}}{\text{GW}}$]
Nuclear	4 846	102.93	670	2 609	222	30.16
CCGT	772	19.55	157	615	72	10.63
U-S Coal	2 517	29.38	280	914	114	13.72
IGCC	3 246	48.42	280	914	114	13.72
PV	870	9.94	1 109	4 468	860	101.69
On. Wind Turbine	1 040	2.83	557	2 868	223	36.24
Off. Wind Turbine	4 975	9.57	764	2 743	282	44.36
Hydro River	5 045	50.44	2 810	8 256	1 059	139.28
Geothermal	7 488	139.11	23 328	89 474	5 961	818.26

Table A.6: Electricity sector data. Abbreviations: investment (inv), maintenance (maint), construction (cstr), combined cycle gas turbine (CCGT), ultra-supercritical (U-S), integrated gasification combined cycle (IGCC), photovoltaic (PV), onshore (On.), offshore (Off.).

Technology	$\text{Agri Land}_{\text{cstr}}$ [$\frac{\text{km}^2 \text{ y}}{\text{GW}}$]	$\text{Urban Land}_{\text{cstr}}$ [$\frac{\text{km}^2 \text{ y}}{\text{GW}}$]	$\text{DamToHH}_{\text{cstr}}$ [$\frac{\text{DALY}}{\text{GW}}$]	$\text{DamToEcosys}_{\text{cstr}}$ [$\frac{\text{species y}}{\text{GW}}$]	CRM_{cstr} [$\frac{\text{t}}{\text{GW}}$]
Nuclear	54.72	16.68	2 420	3.51	193
CCGT	12.65	5.56	742	1.01	84
U-S Coal	7.51	11.31	1 266	1.59	98
IGCC	7.51	11.31	1 266	1.59	98
PV	105.93	1 081	7 387	19.13	2 500
On. Wind Turbine	15.21	51.91	2 557	3.37	301
Off. Wind Turbine	22.96	10.37	3 343	4.11	455
Hydro River	61.05	43.14	9 476	13.08	1 238
Geothermal	578	254	65 660	105	185 139

Table A.7: Electricity sector data (continuation of table A.6).

3.2 Heating sector

The heating sector is composed of two main types of technologies: boilers and co-generation plants. The former are not the source of any particular difficulty in the data collection as they are widely used and simple in nature. The latter however is the link between the electricity and heat sectors, leading to a higher level of difficulty in sizing. Indeed many CHP configurations are possible depending on the applications; this variety in configurations is reflected in the available technologies in *ecoinvent* and the chosen technologies in *ESTD*. To link both sets of technologies, the closest technological configurations between both models have been identified and are used. This identification has been done both on the type of CHP (ICE, CCGT etc), on the ratio between electrical and thermal efficiencies and on the power of the installation. The efficiencies are higher in *ESTD* as opposed to those in *ecoinvent* due to time considerations as the efficiencies in the *ESTD* model are suited for 2035 while those of *ecoinvent* date back to the early 2000s. We deal with this in a simplified manner by assuming the construction impacts per plant from *ecoinvent* to be valid for 2035 while considering the plant efficiencies to have improved to those of *ESTD*.

Most of industrial and district heating technologies are assumed to have the same construction impacts as they have similar powers.

In addition to the main fuel burning types of technologies explained above, other plants are implemented such as geothermal and solar thermal collectors. More hypotheses were necessary to establish the impacts of these technologies and are explained below.

The resulting data are summarised in tables A.8 and A.9 at the end of this section.

3.2.1 Geothermal

No datasets are available for deep geothermal district heating facilities in *ecoinvent*. However an electric geothermal power plant is implemented. From this plant, we discovered that 99% of the construction impacts are linked to the drilling of the wells. Consequently we have used the deep well drilling impacts to model the deep geothermal heating plant construction. Five 2 km wells are used for the infrastructure of the plant and we thus link the impacts to 10 000 m of deep well drilling. This could be perfected as drilling impacts vary with the depth of drilling as well as the ground composition; however not much geothermal potential for Belgium has been proven so we have decided to place our efforts elsewhere.

3.2.2 Solar thermal collectors

For solar collector panels, the difficulty lies in quantifying the peak thermal power of said panels. The total lifetime heat production for the panels is given in *ecoinvent*; to obtain the power, this value was divided by the time the panels have been in use and by the capacity factor.

Technology	C_{inv} [$\frac{M\text{€}_{2015}}{GW}$]	C_{maint} [$\frac{M\text{€}_{2015}}{GW}$]	GWP_{cstr} [$\frac{ktCO_2eq}{GW}$]	$Einvcstr$ [$\frac{GWh}{GW}$]	EP_{cstr} [$\frac{M\text{€}_{2015}}{GW}$]	$DamToRes_{cstr}$ [$\frac{M\text{€}_{2015}}{GW}$]
Ind. Cogen Gas	1 408	90.51	515	2 013	174	22.81
Ind. Cogen Wood	1 080	39.57	169	759	92	8.90
Ind. Cogen Waste	2 928	107.94	578	1 820	145	33.76
Ind. Boiler Gas	59	1.18	13	46	4	0.57
Ind. Boiler Wood	115	2.30	79	277	31	4.46
Ind. Boiler Oil	55	1.18	13	46	4	0.57
Ind. Boiler Coal	115	2.30	42	149	16	2.38
Ind. Boiler Waste	115	2.30	79	277	31	4.46
Ind. Direct Elec	332	1.51	2	6	1	0.08
DHN HP Elec	345	11.69	145	212	68	3.55
DHN Cogen Gas	1 254	36.68	157	615	72	10.63
DHN Cogen Wood	1 080	39.57	169	759	92	8.90
DHN Cogen Waste	2 928	107.94	578	1 820	145	33.76
DHN Cogen Wet Biomass	1 374	111.86	578	1 820	145	33.76
DHN Cogen Bio-hydrolysis	4 537	221.69	578	1 820	145	33.76
DHN Boiler Gas	59	1.18	13	46	4	0.57
DHN Boiler Wood	115	2.30	79	277	31	4.46
DHN Boiler Oil	55	1.18	13	46	4	0.57
DHN Deep Geo	1500	56.20	2 292	8 649	575	79.91
DHN Solar	362	0.43	213	781	197	12.00
Dec. HP Elec	492	20.52	145	212	69	3.55
Dec. THHP Gas	316	9.23	357	1 299	162	18.25
Dec. Cogen Gas	1 408	90.51	343	1 404	92	14.85
Dec. Cogen Oil	1 306	80.10	343	1 404	92	14.85
Dec. Adv. Cogen Gas	7 242	134.97	211	4 413	62	16.70
Dec. Adv. Cogen H ₂	7 242	134.97	211	4 413	62	16.70
Dec. Boiler Gas	159	4.76	46	162	27	2.22
Dec. Boiler Wood	462	16.18	69	237	22	2.83
Dec. Boiler Oil	142	8.54	46	147	27	2.22
Dec. Solar	719	7.98	519	1 947	393	28.51
Dec. Direct Elec	40	0.17	2	6	1	0.08

Table A.8: Heating sector data. Abbreviations: investment (inv), maintenance (maint), construction (cstr), industrial (Ind.), district heating network (DHN), decentralised (Dec.), electricity (Elec), heat pump (HP), thermal heat pump (THHP), geothermal (Geo), advanced (Adv.).

Technology	Agri Land _{cstr} [$\frac{\text{km}^2 \cdot \text{y}}{\text{GW}}$]	Urban Land _{cstr} [$\frac{\text{km}^2 \cdot \text{y}}{\text{GW}}$]	DamToHH _{cstr} [$\frac{\text{DALY}}{\text{GW}}$]	DamToEcosys _{cstr} [$\frac{\text{species} \cdot \text{y}}{\text{GW}}$]	CRM _{cstr} [$\frac{\text{t}}{\text{GW}}$]
Ind. Cogen Gas	59.82	6.04	1 838	2.82	162
Ind. Cogen Wood	297.06	98.64	461	2.17	82
Ind. Cogen Waste	8.45	13.23	1 689	2.55	295
Ind. Boiler Gas	0.37	0.15	63	0.06	3
Ind. Boiler Wood	1.92	3.70	416	0.46	31
Ind. Boiler Oil	0.37	0.15	63	0.06	3
Ind. Boiler Coal	3.52	4.08	166	0.27	22
Ind. Boiler Waste	1.92	3.70	416	0.46	31
Ind. Direct Elec	0.08	0.03	7	0.01	0.36
DHN HP Elec	2.09	1.12	699	0.9	503
DHN Cogen Gas	12.65	5.56	742	1.01	84
DHN Cogen Wood	297.06	98.64	461	2.17	82
DHN Cogen Waste	8.45	13.23	1 689	2.55	295
DHN Cogen Wet Biomass	8.45	13.23	1 689	2.55	295
DHN Cogen Bio-hydrolysis	8.45	13.23	1 689	2.55	295
DHN Boiler Gas	0.37	0.15	63	0.06	3
DHN Boiler Wood	1.92	3.70	416	0.46	31
DHN Boiler Oil	0.37	0.15	63	0.06	3
DHN Deep Geo	51.95	20.59	6 341	10.24	10 383
DHN Solar	16.65	4.83	1 900	2.03	195
Dec. HP Elec	2.09	1.12	699	0.90	503
Dec. THHP Gas	14.55	5.81	1 681	2.19	209
Dec. Cogen Gas	51.02	3.52	968	1.76	101
Dec. Cogen Oil	51.02	3.52	968	1.76	101
Dec. Adv. Cogen Gas	6.65	1.86	785	1.11	4 875
Dec. Adv. Cogen H ₂	6.65	1.86	785	1.11	4 875
Dec. Boiler Gas	2.40	0.73	306	0.32	16
Dec. Boiler Wood	2.11	0.86	305	0.33	16
Dec. Boiler Oil	2.40	0.73	306	0.32	16
Dec. Solar	67.11	11.51	3 965	4.32	703
Dec. Direct Elec	0.08	0.03	7	0.01	0.36

Table A.9: Heating sector data (continuation of table A.8)

3.3 Mobility sector

3.3.1 Private mobility

The construction and EoL impacts of passenger cars are modelled in *ecoinvent* as the weight combination of glider, combustion engine, electrical powertrain and Li-ion battery (114 Wh/kg) in addition to a manual dismantling activity. The weight distribution of these elements for the different car technologies are given in table A.10; cars were studied with the same glider size.

Components [kg]	Gasoline	Diesel	NG	HEV	PHEV	BEV	FCEV
Glider	1091 ^a	1091 ^a	1091 ^a	1091 ^a	1091 [43]	1091 [43]	1091 ^a
Engine	290.7 ^a	401 ^b	290.7 ^a	290.7 ^a	290.7 [43]		
Electrical Powertrain				82.2 ^c	82.2 [43]	82.2 [43]	64.5
Li-ion Battery					132 [43]	263 [43]	
NiMH Battery				53.3 ^d			15.4
Fuel Cell Stack							39.1
H ₂ tanks							156.9
BoP and PCU							45.1
Total	1381.7	1492	1381.7	1517.2	1595.9	1436.2	1412.1

Table A.10: Car components weight per vehicle category

^a Taken as value for internal combustion engine vehicle (ICEV) in [43]

^b Diesel engine weight used in *ecoinvent* for diesel passenger car

^c assumed to be the same as PHEV and BEV vehicle, the Toyota Prius powertrain is indeed in this range

^d 120 cells NiMH battery as in the Yaris hybrid (53.3kg)

The data were gathered on the basis of the already implemented *ecoinvent* datasets for gasoline, diesel and battery electric cars. The components of these cars were then used to model hybrid technologies. On the other hand, fuel cell vehicles are very different and so, an LCA of the Toyota Mirai (2017) was reproduced based on the master thesis of G. Santesteban and A.Jesko ([69], 2020) with a slight modification to the powertrain and scaled back to the same glider weight as other technologies.

3.3.2 Public mobility

The inventory for train and tramway transport can be found in appendix D. As for the buses, data in *ecoinvent* is available for a classic diesel bus. The impacts of hybrid diesel buses (HYDIESEL), of compressed natural gas buses (CNG_STOICH) and fuel cell hybrid buses (FC_HYBRIDH2) were estimated based on this classic bus and the data of the different car technologies.

For hybrid diesel buses, the additional impact of an electric powertrain and batteries were added to the classic diesel bus impacts. These impacts are those of the powertrain and battery of HEV cars scaled to the power of a bus. The impacts of a CNG bus are assumed the same as those of a diesel one. Finally, for hybrid electric hydrogen buses, the impacts of the fuel cell car as well as the battery of a HEV car were scaled with the glider weight of a bus.

The resulting data for passenger transport are provided in tables A.11 and A.12.

Technology	C_{inv} [$\frac{M\text{€}_{2015}}{\text{Mpkm/h}}$]	C_{maint} [$\frac{M\text{€}_{2015}}{\text{Mpkm/h}}$]	GWP_{cstr} [$\frac{\text{ktCO}_2\text{eq}}{\text{Mpkm/h}}$]	$E_{inv_{cstr}}$ [$\frac{\text{GWh}}{\text{Mpkm/h}}$]	EP_{cstr} [$\frac{M\text{€}_{2015}}{\text{Mpkm/h}}$]	$DamToRes_{cstr}$ [$\frac{M\text{€}_{2015}}{\text{Mpkm/h}}$]
Gasoline Car	420	13.8	180	677	63	9.44
Diesel Car	434	14.7	197	738	69	10.25
NG Car	429	17.8	180	677	63	9.44
HEV	429	9.0	228	857	108	12.26
PHEV	456	9.5	229	868	103	12.04
BEV	450	6.9	204	788	106	11.09
FC Car	435	6.9	280	1023	103	14.82
Tram & Trolley	625	12.5	18	73	13	0.92
Diesel Bus	611	30.6	95	380	34	5.67
Diesel HEV Bus	833	33.3	119	470	57	7.09
NG Bus	611	30.6	95	370	34	5.67
FC Bus	1042	31.3	137	505	54	7.32
Train Pub.	1506	54.4	82	305	47	4.15

Table A.11: Passenger mobility data. Abbreviations: investment (inv), maintenance (maint), construction (cstr), natural gas (NG), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV), fuel cell (FC), public (Pub.).

Technology	$AgriLand_{cstr}$ [$\frac{\text{km}^2 \text{ y}}{\text{Mpkm/h}}$]	$UrbanLand_{cstr}$ [$\frac{\text{km}^2 \text{ y}}{\text{Mpkm/h}}$]	$DamToHH_{cstr}$ [$\frac{\text{DALY}}{\text{Mpkm/h}}$]	$DamToEcosys_{cstr}$ [$\frac{\text{species y}}{\text{Mpkm/h}}$]	CRM_{cstr} [$\frac{\text{t}}{\text{Mpkm/h}}$]
Gasoline Car	6.60	2.55	697	0.96	72.5
Diesel Car	7.05	2.76	760	1.05	79.8
NG Car	6.60	2.55	697	0.96	72.5
HEV	8.37	3.44	1179	1.52	733.9
PHEV	8.61	3.7	1080	1.37	624.9
BEV	8.34	3.63	1084	1.31	1070
FC Car	10.38	3.26	1080	1.51	371.8
Tram & Trolley	1.91	0.3	130	0.15	7.1
Diesel Bus	3.58	1.31	387	0.52	45.5
Diesel HEV Bus	4.47	1.76	630	0.8	379
NG Bus	3.58	1.31	387	0.52	45.5
FC Bus	5.16	1.69	560	0.77	321
Train Pub.	8.00	1.25	474	0.57	25.6

Table A.12: Passenger mobility data (continuation of table A.11).

3.3.3 Freight

Freight technologies include trucks, trains and barges. The NG and diesel barge are assumed to have the same impacts. In the case of trucks, the same methodology as for hybrid electric hydrogen buses is used. The impact of trucks are thus scaled with weight from their car counter parts. In the case of electric trucks, a battery of 500 kWh battery pack was considered. Finally for trains, data are available for locomotives as well as goods wagons. An average train is considered to be composed of 1 locomotive and 24 wagons. This value of 24 wagons per train was obtained based on a journalistic article and verified with our own calculation based on the average tonnage per train and tonnage per wagon. Data are summarised in tables A.13 and A.14.

Technology	C_{inv} [$\frac{M\text{€}_{2015}}{\text{Mtkm/h}}$]	C_{maint} [$\frac{M\text{€}_{2015}}{\text{Mtkm/h}}$]	GWP_{cstr} [$\frac{\text{ktCO}_2\text{eq}}{\text{Mtkm/h}}$]	$E_{inv_{cstr}}$ [$\frac{\text{GWh}}{\text{Mtkm/h}}$]	EP_{cstr} [$\frac{M\text{€}_{2015}}{\text{Mtkm/h}}$]	$DamToRes_{cstr}$ [$\frac{M\text{€}_{2015}}{\text{Mtkm/h}}$]
Train Freight	104	2.1	49	190	21	2.18
Boat Diesel	76	3.8	31	109	11	1.35
Boat NG	76	3.8	31	109	11	1.35
Truck Diesel	371	18.6	71	265	25	4.87
Truck FC	402	12.1	101	368	37	7.05
Truck Elec.	771	23.1	142	570	101	10.70
Truck NG	371	18.6	65	243	23	4.49

Table A.13: Freight mobility data. Abbreviations: investment (inv), maintenance (maint), construction (cstr), natural gas (NG), fuel cell (FC), electrical (Elec.).

Technology	$Agri\ Land_{cstr}$ [$\frac{\text{km}^2\ y}{\text{Mtkm/h}}$]	$Urban\ Land_{cstr}$ [$\frac{\text{km}^2\ y}{\text{Mtkm/h}}$]	$DamToHH_{cstr}$ [$\frac{\text{DALY}}{\text{Mtkm/h}}$]	$DamToEcosys_{cstr}$ [$\frac{\text{species}\ y}{\text{Mtkm/h}}$]	CRM_{cstr} [$\frac{\text{t}}{\text{Mtkm/h}}$]
Train Freight	8.16	0.73	253	0.29	15.1
Boat Diesel	3.65	0.41	122	0.17	9.1
Boat NG	3.65	0.41	122	0.17	9.1
Truck Diesel	2.53	0.99	273	0.38	28.7
Truck FC	3.73	1.17	388	0.54	133.6
Truck Elec.	6.25	3.04	990	1.12	2025
Truck NG	2.37	0.92	250	0.34	26.03

Table A.14: Freight mobility data (continuation of table A.13)

3.4 Storage

Storage technologies consist in PHS, battery storage and thermal storage. The impacts of PHS have been assimilated to the construction of a dam, battery storage to Li-ion batteries and low temperature thermal storage to a water container heat storage. Resulting data are shown in tables A.15 and A.16.

Technology	C_{inv} [$\frac{\text{M€}_{2015}}{\text{GWh}}$]	C_{maint} [$\frac{\text{M€}_{2015}}{\text{GWh}}$]	GWP_{cstr} [$\frac{\text{ktCO}_2\text{eq}}{\text{GWh}}$]	$E_{\text{inv}_{\text{cstr}}}$ [$\frac{\text{GWh}}{\text{GWh}}$]	EP_{cstr} [$\frac{\text{M€}_{2015}}{\text{GWh}}$]	$\text{DamToRes}_{\text{cstr}}$ [$\frac{\text{M€}_{2015}}{\text{GWh}}$]
Battery LI	302	0.47	66	274	61	3.93
BEV Battery	-	-	-	-	-	-
PHEV Battery	-	-	-	-	-	-
PHS	59	-	6	16	2	0.24
TS Dec. HP Elec	18.97	0.13	6	23	2	0.29
TS Dec. THHP	18.97	0.13	6	23	2	0.29
TS Dec. Cogen Gas	18.97	0.13	6	23	2	0.29
TS Dec. Cogen Oil	18.97	0.13	6	23	2	0.29
TS Dec. Adv. Cogen Gas	18.97	0.13	6	23	2	0.29
TS Dec. Adv. Cogen H ₂	18.97	0.13	6	23	2	0.29
TS Dec. Boiler Gas	18.97	0.13	6	23	2	0.29
TS Dec. Boiler Wood	18.97	0.13	6	23	2	0.29
TS Dec. Boiler Oil	18.97	0.13	6	23	2	0.29
TS DHN Daily	18.97	0.13	6	23	2	0.29
TS DHN Seasonal	0.54	0	1.41	7	0.34	0.16
TS High Temperature	28.03	0.30	184	342	31.87	5.8
Seasonal NG	0.05	0.001	-	-	-	-
Seasonal H ₂	6.19	0.39	-	-	-	-
CO ₂ Storage	49.50	0.49	-	-	-	-
SLF Storage	0.01	0.0004	-	-	-	-

Table A.15: Storage technologies data. Abbreviations: investment (inv), maintenance (maint), construction (cstr), lithium-ion (LI), battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), pumped hydro storage (PHS), thermal storage (TS), decentralised (Dec.), heat pump (HP), electrical (Elec), thermal heat pump (THHP), advanced (Adv.), district heating network (DHN), natural gas (NG), synthetic liquid fuel (SLF).

Technology	$\text{Agri Land}_{\text{cstr}}$ [$\frac{\text{km}^2 \text{ y}}{\text{GWh}}$]	$\text{Urban Land}_{\text{cstr}}$ [$\frac{\text{km}^2 \text{ y}}{\text{GWh}}$]	$\text{DamToHH}_{\text{cstr}}$ [$\frac{\text{DALY}}{\text{GWh}}$]	$\text{DamToEcosys}_{\text{cstr}}$ [$\frac{\text{species y}}{\text{GWh}}$]	CRM_{cstr} [$\frac{\text{t}}{\text{GWh}}$]
Battery LI	3.11	1.66	574	0.62	1 570
BEV Battery	-	-	-	-	-
PHEV Battery	-	-	-	-	-
PHS	0.15	0.09	15	0.03	2
TS Dec. HP Elec	1.54	0.13	30	0.03	16
TS Dec. THHP	1.54	0.13	30	0.03	16
TS Dec. Cogen Gas	1.54	0.13	30	0.03	16
TS Dec. Cogen Oil	1.54	0.13	30	0.03	16
TS Dec. Adv. Cogen Gas	1.54	0.13	30	0.03	16
TS Dec. Adv. Cogen H ₂	1.54	0.13	30	0.03	16
TS Dec. Boiler Gas	1.54	0.13	30	0.03	16
TS Dec. Boiler Wood	1.54	0.13	30	0.03	16
TS Dec. Boiler Oil	1.54	0.13	30	0.03	16
TS DHN Daily	1.54	0.13	30	0.03	16
TS DHN Seasonal	0.01	0.01	3.44	0.01	1
TS High Temperature	3.88	1.2	380	0.77	64
Seasonal NG	-	-	-	-	-
Seasonal H ₂	-	-	-	-	-
CO ₂ Storage	-	-	-	-	-
SLF Storage	-	-	-	-	-

Table A.16: Storage technologies data (continuation of table A.15)

3.5 Synthetic fuels technologies

A lot of data are missing for the synthetic fuels technologies. We have been able to gather data for biofuels and hydrogen production. Data on synthetic fuels production from hydrogen facilities are missing however due to the immaturity of the technologies. Resulting data are shown in tables A.17 and A.18.

Technology	C_{inv} [$\frac{\text{M€}_{2015}}{\text{GW}}$]	C_{maint} [$\frac{\text{M€}_{2015}}{\text{GW}}$]	GWP_{cstr} [$\frac{\text{ktCO}_2\text{eq}}{\text{GW}}$]	$\text{Einv}_{\text{cstr}}$ [$\frac{\text{GWh}}{\text{GW}}$]	EP_{cstr} [$\frac{\text{M€}_{2015}}{\text{GW}}$]	$\text{DamToRes}_{\text{cstr}}$ [$\frac{\text{M€}_{2015}}{\text{GW}}$]
H ₂ Electrolysis	696	19.15	159	3 334	47	12.61
H ₂ _NG	681	62.87	964	4 443	654	46.39
H ₂ _Biomass	2 525	177.91	169	547	67	8.67
Gasification SNG	2 744	137.75	169	547	67	8.67
Pyrolysis	1 344	61.10	294	982	153	16.10
Atm. CCS	5 160	128.09	-	-	-	-
Industry CCS	2 580	64.04	-	-	-	-
Syn. Methanolation	1 680	47.76	-	-	-	-
Syn. Methanation	262	66.99	-	-	-	-
Bio-methanation	986	13.66	631	5 614	514	40.47
Bio-hydrolysis	1 592	108.54	631	5 614	514	40.47
Methane To Methanol	958.58	41.92	-	-	-	-
SLF To Diesel	-	-	-	-	-	-
SLF To Gasoline	-	-	-	-	-	-
SLF To LFO	-	-	-	-	-	-

Table A.17: Synthetic fuels technologies data. Abbreviations: investment (inv), maintenance (maint), construction (cstr), natural gas (NG), synthetic natural gas (SNG), atmospheric (Atm.), carbon capture and storage (CCS), synthetic (Syn.), synthetic liquid fuel (SLF), light fuel oil (LFO).

Technology	$\text{Agri Land}_{\text{cstr}}$ [$\frac{\text{km}^2 \text{ y}}{\text{GW}}$]	$\text{Urban Land}_{\text{cstr}}$ [$\frac{\text{km}^2 \text{ y}}{\text{GW}}$]	$\text{DamToHH}_{\text{cstr}}$ [$\frac{\text{DALY}}{\text{GW}}$]	$\text{DamToEcosys}_{\text{cstr}}$ [$\frac{\text{species y}}{\text{GW}}$]	CRM_{cstr} [$\frac{\text{t}}{\text{GW}}$]
H ₂ Electrolysis	5.02	1.40	593	0.84	3 683
H ₂ _NG	308.33	41.36	6 120	7.98	983
H ₂ _Biomass	6.26	69.94	652	1.34	74
Gasification SNG	6.26	69.94	652	1.34	74
Pyrolysis	11.17	143.81	1 452	2.73	143
Atm. CCS	-	-	-	-	-
Industry CCS	-	-	-	-	-
Syn. Methanolation	-	-	-	-	-
Syn. Methanation	-	-	-	-	-
Bio-methanation	2 303.56	64.59	2 305	9.67	313
Bio-hydrolysis	2 303.56	64.59	2 305	9.67	313
Methane To Methanol	-	-	-	-	-
SLF To Diesel	-	-	-	-	-
SLF To Gasoline	-	-	-	-	-
SLF To LFO	-	-	-	-	-

Table A.18: Synthetic fuels technologies data (continuation of table A.17)

Appendix B

Foreseen European electricity mix for 2050

If further studies are done until 2050 for Belgium or another European country, we recommend the following 2050 electricity import mix, based on the trends of electricity production from 2016 to 2050 as projected by the EU in 2016 [17] as well as future clean and green scenarios identified by McKinsey [75]. It is illustrated on figure B.1.

The EU projection corresponds to the projection of the current trends up to 2050 under the assumption that the legally binding GHG and renewable energy sources (RES) targets for 2020 were reached and that the policies agreed at EU and Member State level until December 2014 will be implemented. This projection serves as a guide for further policies and does not however mean that the EU goals in 2050 will be reached. We use this EU electricity mix as a basis for our 2050 mix, with the following adjustments:

- In the EU projection, still 23% of the mix was supposed to be produced by conventional fossil plants. This is modified in order to reach climate neutrality by 2050.
- In both scenarios by McKinsey, 13% of electricity is produced by hydropower, 2% more than in the EU projection. In line with McKinsey, we will assume a contribution of 13% for hydropower.
- In the green scenario of McKinsey, 66% of power is produced by renewables. We assume that this value will be reached. Since wind power is already projected to be very well developed, we double the solar production projected by the EU to reach 22% of solar.
- The 34% left are assumed produced by clean technologies: 6% generated by fossil and carbon capture and storage (CCS) plants, a percentage in between the green and clean scenarios by McKinsey, and the rest achieved by nuclear power.

This results in a final electricity mix of 22% solar, 4% wind offshore, 21% wind onshore, 6% biomass, 13% hydropower, 6% fossil+CCS and 28% nuclear. It must be noted that a new projection by the EU for 2020-2050 has been published since the start of our thesis, but has not been accounted for in the above, by lack of time.

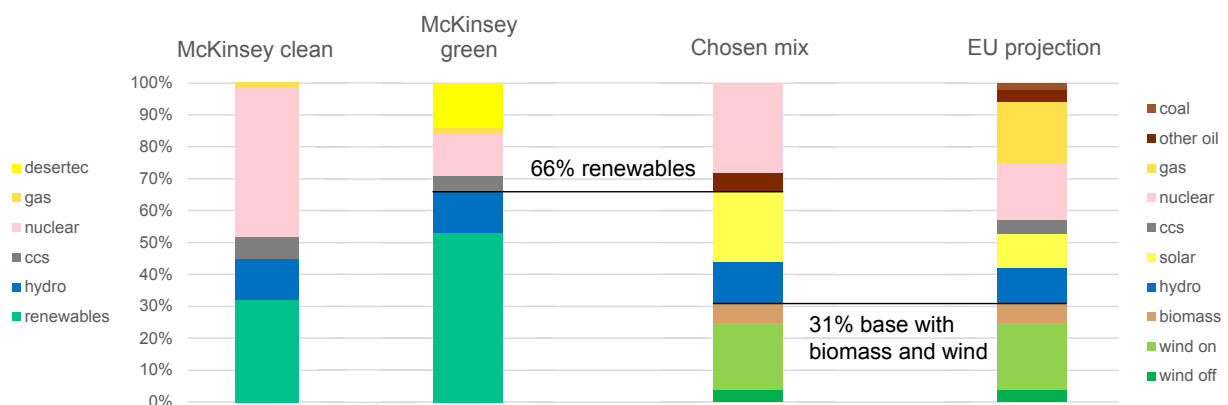


Figure B.1: Foreseen European electricity mix for 2050

Appendix C

Additional criteria impact maps for Belgium in 2035

This appendix contains the maps of the additional criteria impacts in the case of the low GWP solution (weights: 60% for GWP, 20% for cost and 20% for energy invested) analysed for the Belgian energy system in 2035. This solution is described in chapter 6 section 2.1. The KPIs and some selected additional criteria have been discussed in chapter 6 section 2.2. The maps for all the additional criteria are presented hereafter.

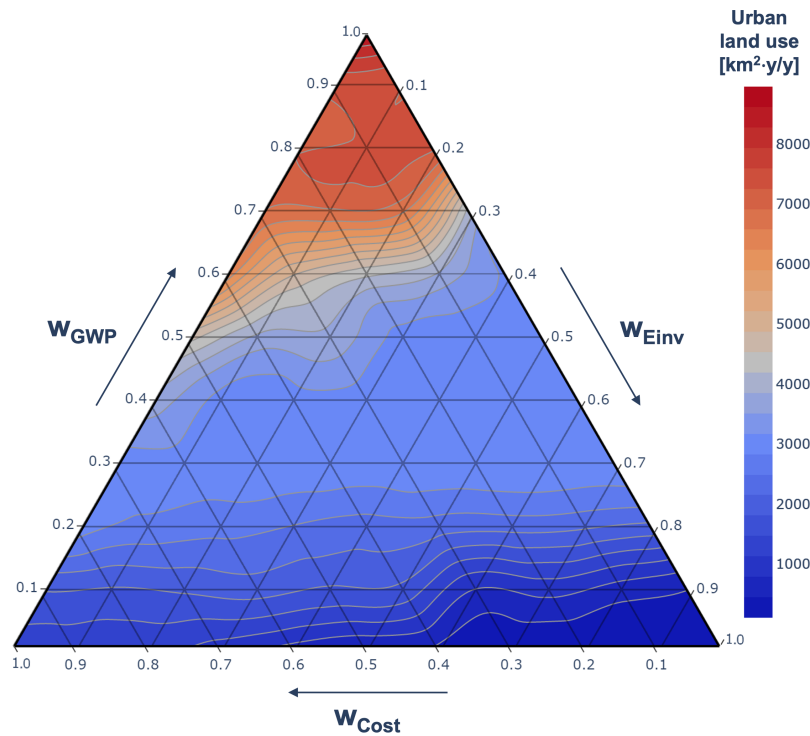


Figure C.1: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the urban land use indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

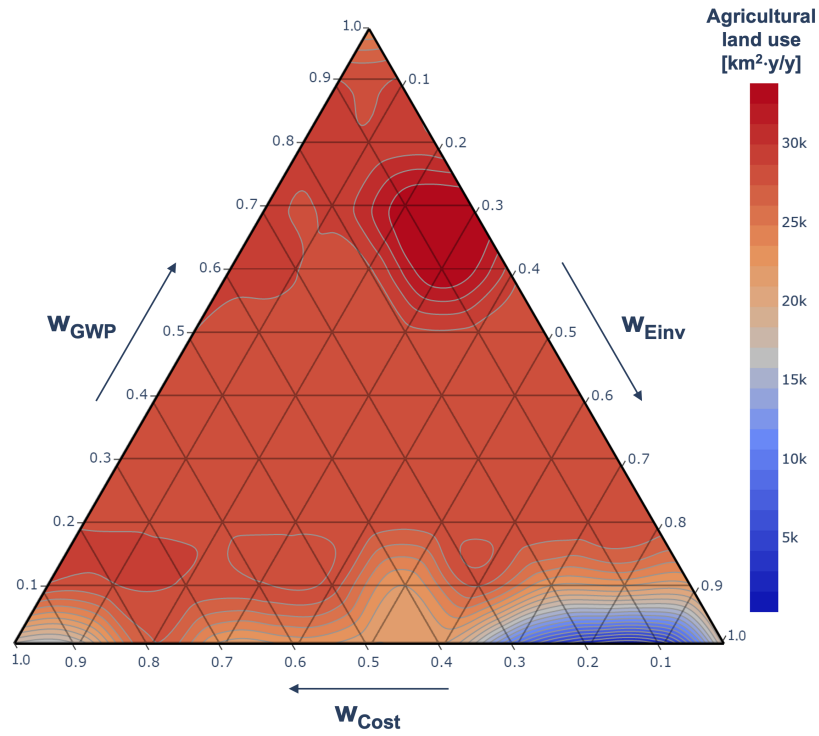


Figure C.2: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the agricultural land use indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

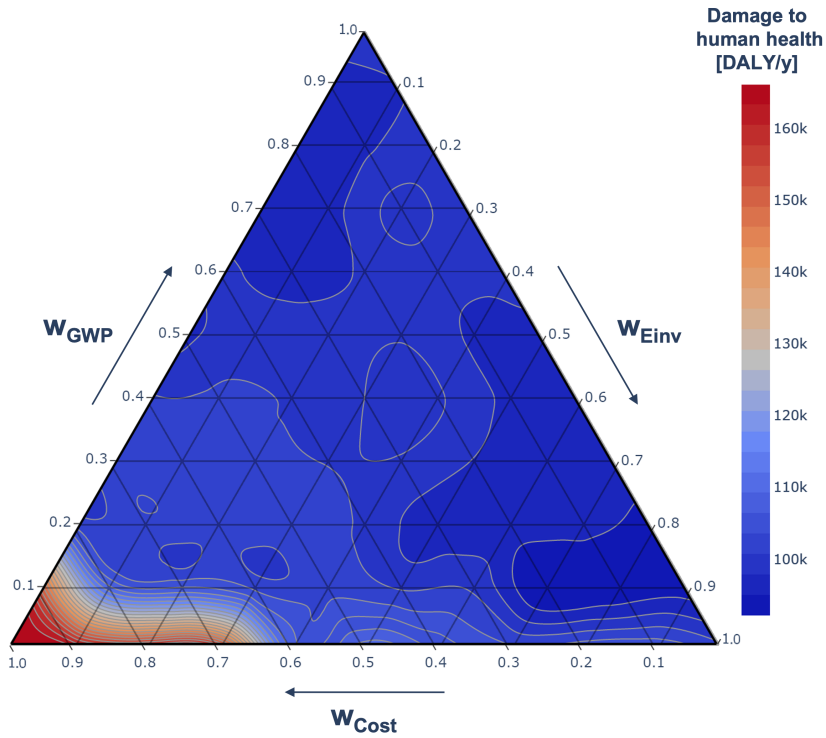


Figure C.3: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the damage to human health indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

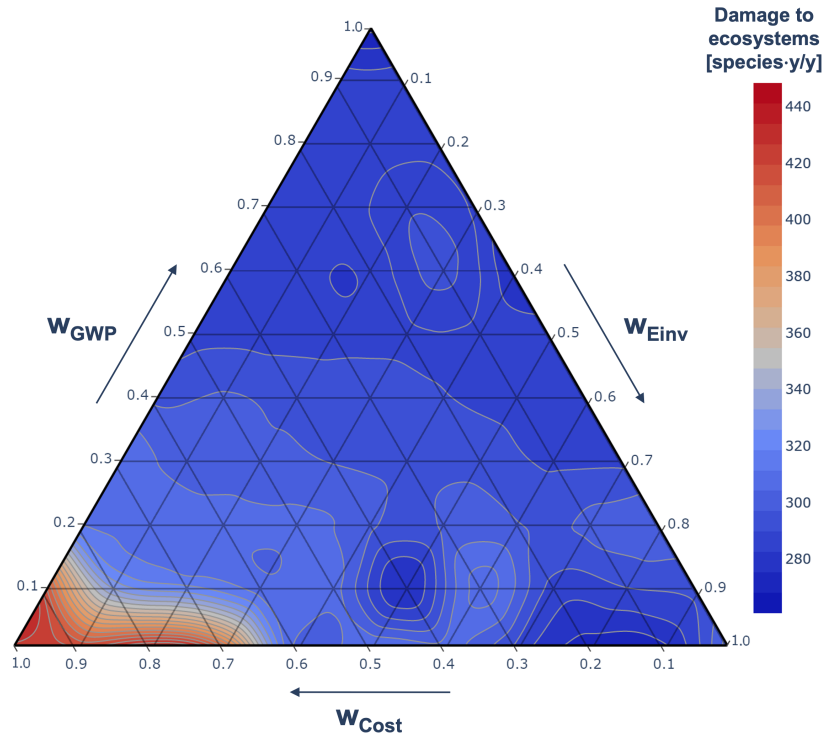


Figure C.4: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the damage to ecosystems indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

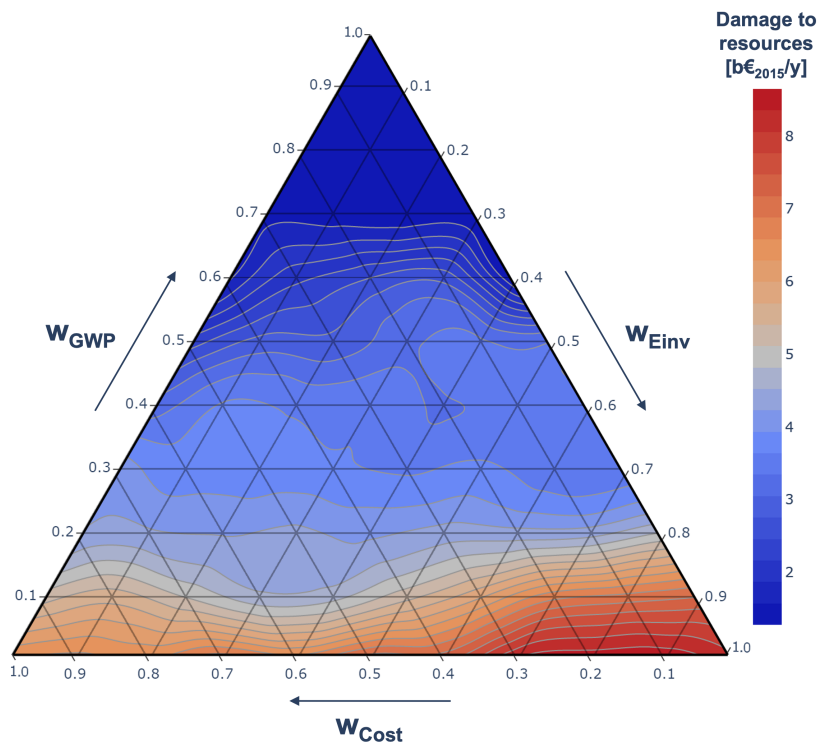


Figure C.5: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the damage to resource availability indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

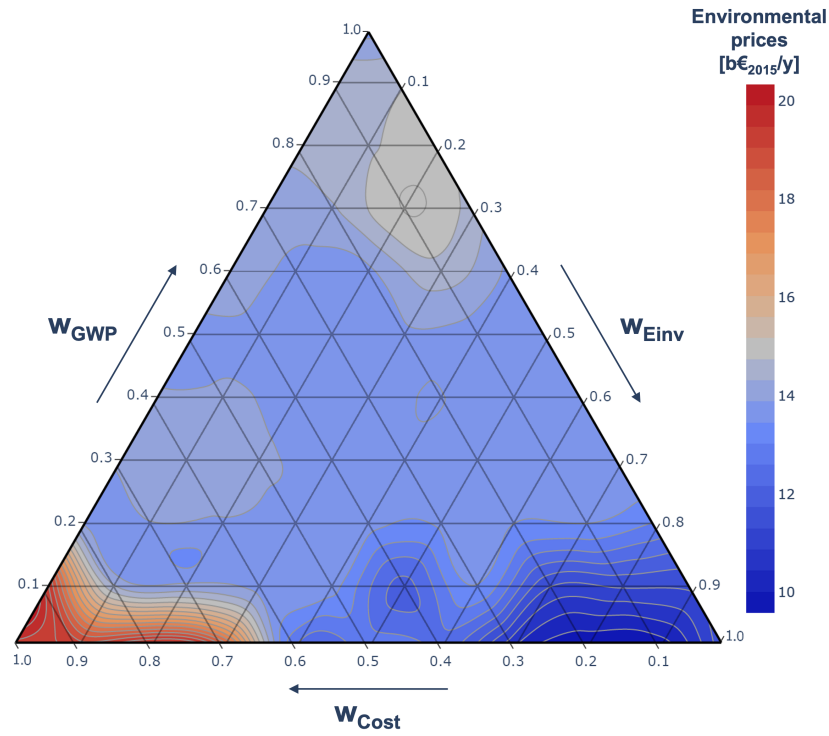


Figure C.6: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the environmental prices indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

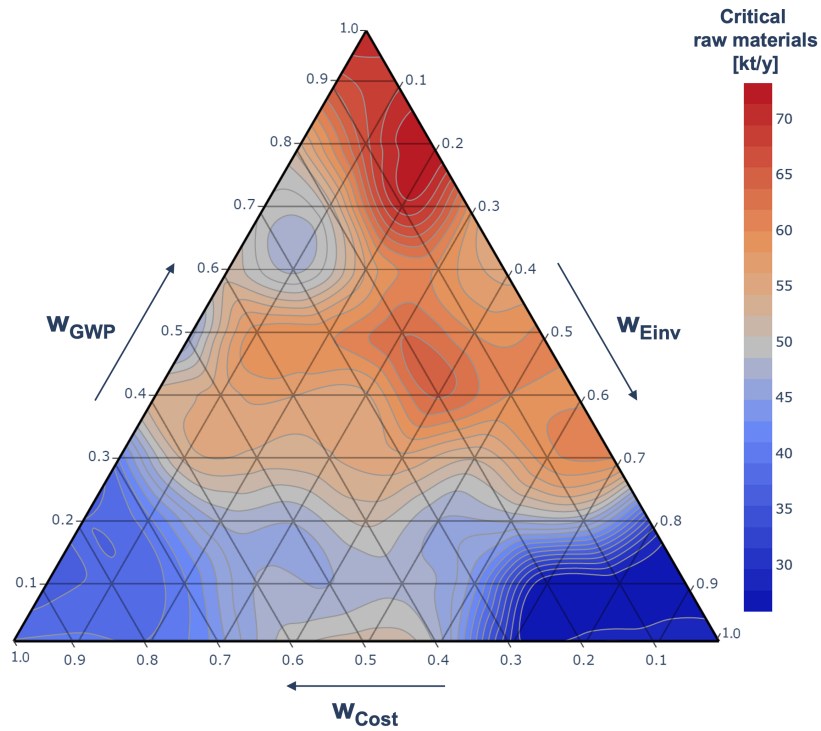


Figure C.7: Multi-criteria optimisations of the 2035 Belgian energy system: Map of the critical raw materials indicator based on the choice of weights for the GWP, cost and energy invested (w_{GWP} , w_{Cost} , w_{Einv})

Appendix D

Links between technologies and resources in *EnergyScope TD* and processes in *ecoinvent*

1 Resources

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
Electricity Imp.	1 kWh Electricity, low voltage ES electricity production, photovoltaic, 570kWp open ground installation, multi-Si	Electricity by fuel\Photovoltaic \Transformation
	1 kWh Electricity, high voltage DK electricity production, wind, 1-3MW turbine, offshore	Electricity by fuel\Wind\Transformation
	1 kWh Electricity, high voltage DK electricity production, wind, 1-3MW turbine, onshore	Electricity by fuel\Wind \Transformation
	1 kWh Electricity, high voltage CH electricity production, hydro, reservoir, alpine region	Electricity by fuel\Hydro \Transformation
	1 kWh Electricity, high voltage NL electricity production, natural gas, combined cycle power plant	Electricity by fuel\Gas \Transformation
	1 kWh Electricity, high voltage FR electricity production, nuclear, pressure water reactor	Electricity by fuel\Nuclear\PWR \Transformation
Gasoline	Petrol, low-sulfur Europe without Switzerland market for transport, passenger car, medium size, petrol, EURO 5	Fuels\Oil\Petrol\Market Road\Transformation
Diesel	Diesel, low sulfur Europe without Switzerland market for Transport, passenger car with internal combustion engine RER processing	Material\Fuels\Oil\Diesel\Market Road\Transformation
Bio-ethanol	Ethanol, without water, in 99.7% solution state, from fermentation, at service station CH	Fuels\Biofuels\Ethanol\Market
Bio-diesel	Vegetable oil methyl ester Europe without Switzerland esterification of rape oil	Fuels\Biofuels\Others\Transformation
Light Fuel Oil	Light fuel oil Europe without Switzerland petroleum refinery operation	Fuels\Oil\Fuel oil\Transformation
	Heat, central or small-scale, other than natural gas Europe without Switzerland heat production, light fuel oil, at boiler 10kW, non-modulating	Heat\Oil\Transformation
Natural Gas	Natural gas, high pressure BE	Fuels\Natural gas\Market
	Electricity, high voltage BE electricity production, natural gas, combined cycle power plant	Electricity by fuel\Gas\Transformation
Synthetic Natural Gas	Methane, 96% by volume RoW biogas purification to methane 96 vol-%	Fuels\Biofuels\Methane\Transformation
Woody Biomass	Wood chips, wet, measured as dry mass Europe without Switzerland	Wood\Extraction\Market
Wet Biomass	Grass, Swiss integrated production CH grass production, Swiss integrated production, intensive	Agricultural\Animal feed\Transformation
Coal	Hard coal Europe, without Russia and Turkey	Fuels\Coal\Market
	Electricity, high voltage BE electricity production, hard coal	Electricity by fuel\Coal\Transformation
Uranium	Nuclear fuel element, for pressure water reactor, UO ₂ 4.2% & MOX GLO	Fuels\Uranium\Fuel element\Market
Waste	Municipal solid waste BE treatment of, incineration	Waste treatment\incineration\MSW\Transformation
Hydrogen	1 kWh Electricity, high voltage DK electricity production, wind, 1-3MW turbine, offshore	Electricity by fuel\Wind \Transformation
	1 kWh Electricity, high voltage ES electricity production, wind, 1-3MW turbine, onshore	Electricity by fuel\Wind \Transformation
	1 kWh Electricity, low voltage PT electricity production, photovoltaic, 570kWp open ground installation, multi-Si	Electricity by fuel\Photovoltaic \Transformation
	1 kWh Electricity, low voltage AU electricity production, photovoltaic, 570kWp open ground installation, multi-Si	Electricity by fuel\Photovoltaic \Transformation
Synthetic Liquid Fuel	Methanol, from biomass RoW	Fuels\Biofuels\Others\Market

Table D.1: *Ecoinvent* processes used to model *ESTD* resources

2 Technologies

2.1 Electricity sector

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
Nuclear	Nuclear power plant, pressure water reactor 1000MW RoW construction	Electricity by fuel\Nuclear\PWR\Transformation\Infrastructure
CCGT	Gas power plant, combined cycle, 400MW electrical RER	Cogeneration\Gas\Transformation\Infrastructure
U-S Coal	Hard coal power plant GLO construction, 500MW	Electricity by fuel\Coal\Transformation\Infrastructure
IGCC	same as U-S Coal	
PV	Photovoltaic plant, 570kWp, multi-Si, on open ground GLO	Electronics\Photovoltaic\Market\Infrastructure
Off. Wind Turbine	Wind power plant, 2MW, offshore, fixed parts GLO construction Wind power plant, 2MW, offshore, moving parts GLO	Electricity by fuel\Wind\Transformation\Infrastructure Electricity by fuel\Wind\Transformation\Infrastructure
On. Wind Turbine	Wind turbine, 4.5MW, onshore GLO Wind turbine network connection, 4.5MW, onshore GLO	Electricity by fuel\Wind\Transformation\Infrastructure Electricity by fuel\Wind\Transformation\Infrastructure
Hydro River	Hydropower plant, run-of-river Europe without Switzerland	Electricity by fuel\Hydro\Flow through\Transformation\Infrastructure
Geothermal	Geothermal power plant, 5.5MWel CH geothermal power plant construction	Electricity by fuel\Geothermal\Transformation\Infrastructure

Table D.2: *Ecoinvent* processes used to model *ESTD* electricity sector technologies

2.2 Industrial heating sector

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
Ind. Cogen Gas	Heat and power co-generation unit, 200kW electrical, common components for heat+electricity RER	Cogeneration\Gas\Transformation\Infrastructure
	Heat and power co-generation unit, 200kW electrical, components for electricity only RER	Cogeneration\Gas\Transformation\Infrastructure
	Heat and power co-generation unit, 200kW electrical, components for heat only RER	Cogeneration\Gas\Transformation\Infrastructure
Ind. Cogen Wood	Heat and power co-generation unit, organic Rankine cycle, 1400kW thermal, building RoW construction	Cogeneration\Wood\Transformation\Infrastructure
Ind. Cogen Waste	Municipal waste incineration facility GLO	Transport\Waste\Infrastructure\Market
Ind. Boiler Gas	Industrial furnace, natural gas RER	Heat\Gas\Transformation\Infrastructure
Ind. Boiler Wood	Furnace, wood chips, with silo, 1000kW CH	Heat\Wood\Transformation\Infrastructure
Ind. Boiler Oil	Industrial furnace, 1MW, oil RoW production	Heat\Oil\Transformation\Infrastructure
Ind. Boiler Coal	Industrial furnace, coal, 1-10MW RER	Heat\Coal\Transformation\Infrastructure
Ind. Boiler Waste	Same as Ind. Boiler Wood	
Ind. Direct Elec.	Auxiliary heating unit, electric, 5kW RoW	Heat\Solar\Transformation\Infrastructure

Table D.3: *Ecoinvent* processes used to model *ESTD* industrial heating sector technologies

2.3 District heating sector

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
DHN HP Elec.	Heat pump, 30kW RER	Heat\Heat pump\Transformation\Infrastructure
DHN Cogen Gas	Same as CCGT	
DHN Cogen Wood	Same as Ind. Cogen Wood	
DHN Cogen Waste	Same as Ind. Cogen Waste	
DHN Cogen Wet Biomass	Same as Ind. Cogen Waste	
DHN Cogen Bio-hydrolysis	Same as Ind. Cogen Waste	
DHN Boiler Gas	Same as Ind. Boiler Gas	
DHN Boiler Wood	Same as Ind. Boiler Wood	
DHN Boiler Oil	Same as Ind. Boiler Oil	
DHN Depp Geo	Deep well, drilled, for geothermal power RoW deep well drilling, for deep geothermal power	Electricity by fuel\Geothermal\Transformation\Infrastructure
DHN Solar	Solar collector system, Cu flat plate collector, multiple dwelling, hot water RoW	Heat\Solar\Transformation\Infrastructure

Table D.4: *Ecoinvent* processes used to model *ESTD* district heating sector technologies

2.4 Decentralised heating sector

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
Dec. HP Elec.	Heat pump, brine-water, 10kW RoW	Heat\Heat pump\Transformation\Infrastructure
Dec. THHP	Heat pump, diffusion absorption, 4kW, future RoW	Heat\Heat pump\Transformation\Infrastructure
Dec. Cogen Gas	Same as Ind. Cogen Gas	
Dec. Cogen Oil	Same as Ind. Cogen Oil	
Dec. Adv. Cogen Gas	Fuel cell, stack solid oxide, 125kW electrical, future RoW	Cogeneration\Gas\Transformation\Infrastructure
Dec. Adv. Cogen H ₂	Fuel cell, stack solid oxide, 125kW electrical, future RoW	Cogeneration\Gas\Transformation\Infrastructure
Dec. Boiler Gas	Gas boiler RER production	Heat\Gas\Transformation\Infrastructure
Dec. Boiler Wood	Furnace, logs, 6kW RoW	Heat\Wood\Transformation\Infrastructure
Dec. Boiler Oil	Oil boiler, 10kW RoW	Heat\Oil\Transformation\Infrastructure
Dec. Solar	Solar collector system, Cu flat plate collector, one-family house, combined system RoW	Heat\Solar\Transformation\Infrastructure
Dec. Direct Elec.	same as Ind. Direct Elec.	

Table D.5: *Ecoinvent* processes used to model *ESTD* decentralised heating sector technologies

2.5 Public mobility sector

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
Tramway & Trolley	Tram RER production	Rail\Transformation\Infrastructure
Bus Coach Diesel	Bus RER production	Road\Transformation\Infrastructure
Bus Coach Hybrid Diesel	Extrapolated from Bus Diesel and private mobility	
Bus Coach CNG Stoich	Extrapolated from Bus Diesel and private mobility	
Bus Coach Hybrid H ₂	Extrapolated from Bus Diesel and private mobility	
Train Pub.	Train, passenger, regional RoW	Rail\Transformation\Infrastructure

Table D.6: *Ecoinvent* processes used to model *ESTD* public mobility sector technologies

2.6 Private mobility sector

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
Glider	Glider, passenger car GLO	Electronics\Component\Market
Engine	Internal combustion engine, for passenger car GLO	Road\Market\Infrastructure
Dismantling	Manual dismantling of used passenger car with internal combustion engine GLO	Processing\Others\Market
Elec. Powertrain	Powertrain, for electric passenger car GLO	Electronics\Component\Market
Li-ion Battery	Battery, Li-ion, rechargeable, prismatic GLO	Electronics\Module\Transformation
NiMH Battery	Battery, NiMH, rechargeable, prismatic GLO	Electronics\Module\Transformation
FCEV	Recreated from the study [69]	

Table D.7: *Ecoinvent* processes used to model *ESTD* private mobility sector technologies

2.7 Freight sector

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
Train Freight	Locomotive RER production	Rail\Transformation\Infrastructure
	Goods wagon RER production	Rail\Transformation\Infrastructure
Boat Freight Diesel	Barge RER production	Water\Transformation\Infrastructure
Boat Freight NG	Same as Boat Freight Diesel	
Truck Diesel	Lorry, 28 metric ton RER	Road\Transformation\Infrastructure
Truck Fuel Cell	Extrapolated from Truck Diesel and private mobility	
Truck Elec.	Extrapolated from Truck Diesel and private mobility	
Truck NG	Extrapolated from Truck Diesel and private mobility	

Table D.8: *Ecoinvent* processes used to model *ESTD* freight sector technologies

2.8 Storage

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
Battery LI	Battery, Li-ion, rechargeable, prismatic GLO	Electronics\Module\Transformation
BEV Battery	Same as Battery LI	
PHEV Battery	Same as Battery LI	
PHS	Hydropower plant, reservoir, non-alpine regions RER	Electricity by fuel\Hydro\Reservoir\Transformation\Infrastructure
TS Dec. Direct Elec.	Heat storage, 2000l RoW	Heat\Solar\Transformation\Infrastructure
TS Dec. HP Elec.	Same as TS Dec. Direct Elec.	
TS Dec. THHP	Same as TS Dec. Direct Elec.	
TS Dec. Cogen Gas	Same as TS Dec. Direct Elec.	
TS Dec. Cogen Oil	Same as TS Dec. Direct Elec.	
TS Dec. Adv. Cogen Gas	Same as TS Dec. Direct Elec.	
TS Dec. Adv. Cogen H ₂	Same as TS Dec. Direct Elec.	
TS Dec. Boiler Gas	Same as TS Dec. Direct Elec.	
TS Dec. Boiler Wood	Same as TS Dec. Direct Elec.	
TS Dec. Boiler Oil	Same as TS Dec. Direct Elec.	
TS DHN Daily	Same as TS Dec. Direct Elec.	
TS DHN Seasonal	Borehole heat exchanger, 150m RoW	Heat\Heat pump\Transformation\Infrastructure
TS High Temperature	Thermal storage system, solar thermal parabolic trough, 50 mw ZA	Electricity by fuel\Photovoltaic\Transformation\Infrastructure
Seasonal NG	-	
Seasonal H ₂	-	
CO ₂ Storage	-	
SLF Storage	-	

Table D.9: *Ecoinvent* processes used to model *ESTD* storage technologies

2.9 Synthetic fuels technologies

<i>ESTD</i> name	<i>Ecoinvent</i> process	Location in database
H ₂ Electrolysis	Same as Dec. Adv. Cogen H ₂	
H ₂ _NG	Chemical factory, organics RER	Chemicals\Organic\Transformation\Infrastructure
H ₂ _Biomass	Same as Gasification SNG	
Gasification SNG	Industrial furnace, natural gas RER Synthetic gas factory CH	Fuels\Biofuels\Others\Transformation\Infrastructure Fuels\Biofuels\Others\Transformation\Infrastructure
Pyrolysis	Methanol factory GLO	Chemicals\Organic\Market\Infrastructure
Atm. CCS	-	
Industry CCS	-	
Syn. Methanolation	-	
Syn. Methanation	-	
Bio-methanation	Anaerobic digestion plant, agriculture, with methane recovery CH Chemical factory, organics RER	Fuels\Biofuels\Others\Transformation\Infrastructure Chemicals\Organic\Transformation\Infrastructure
Bio-hydrolysis	Same as Bio-methanation	
Methane To Methanol	-	
SLF To Diesel	-	
SLF To Gasoline	-	
SLF To LFO	-	

Table D.10: *Ecoinvent* processes used to model *ESTD* synthetic fuels technologies

Appendix E

SimaPro: Quick user guide

In this section, a quick guide to use the *SimaPro* software for data collection is presented. This is not a very in-depth *SimaPro* manual, but just a simple guide specific to the tips and tricks, tools and methods used throughout this thesis to help future students who would work on a similar topic. More general and in-depth manuals are available online.

This guide starts with guidance when using the software for the first time, before looking at the structure of *SimaPro* and the important tabs for data collection. Finally we explain how to navigate the database to find the desired process and how to evaluate its impacts.

1 First use

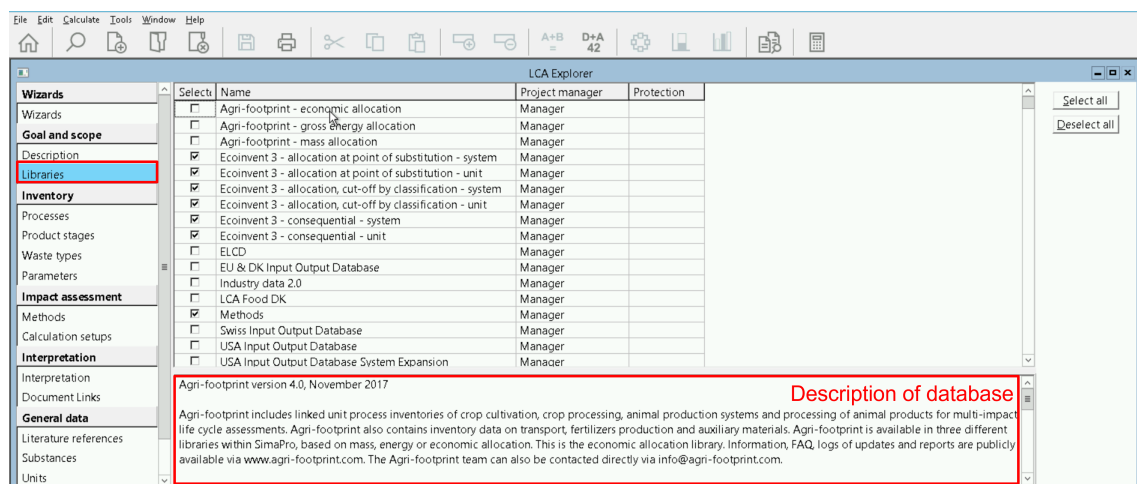
Select the "Professional" Database name and click "Open". Select your name in the listed available users and click "Ok". A menu with your projects will appear. This menu should be empty of any personal projects. There is however an "introduction to *SimaPro*" project that we recommend to open before creating your own projects. When opened, choose the "Guided Tour (with coffee)" wizard that will guide you through the most important features of *SimaPro* in 15-45 minutes.

2 Structure

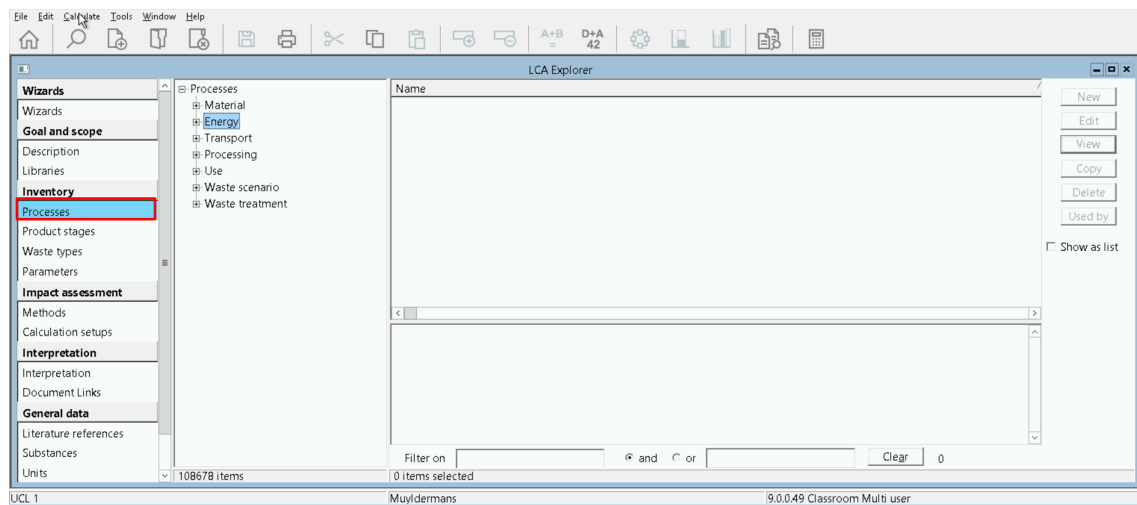
SimaPro is structured with the different steps of an LCA analysis. This is however not what we are doing. We are just collecting data and we will therefore skip all parts of the software unnecessary for this purpose.

The 3 sections that we are interested in are:

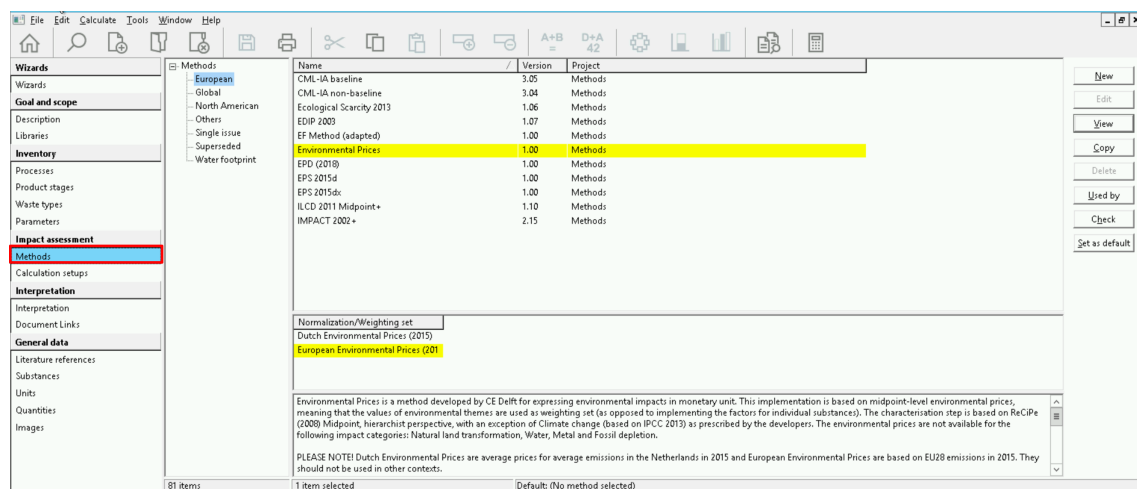
- Libraries: It contains the available databases to choose from.



- Processes: It contains the processes from the selected libraries.



- Methods: It contains the available impact methods. It is also where one can add, create and modify LCIA methods as we have done for critical raw materials in this thesis.



3 Finding a process

Once the desired libraries have been selected, the goal is to find the wanted processes. The databases are arranged in a tree-like fashion with different sections and subsections. This is very helpful, although some processes are not stored in instinctive sections. An open ground PV plant, for example, is in the electronic materials section and not in the infrastructure for photovoltaic electricity production section. As such the first step in finding a process is to verify if the technology that we are searching for is available in the *ecoinvent* database. To do so, with *ecoinvent*, the best way is to access the online platform *ecoQuery* (accessible with a free guest account) and to search the database. Be careful with the search engine, it is very sensitive to the search query: different formulations for the same technology should be tested.

Search in Activity Name, Reference Product Names and Synonyms

CHP

System Model

☒ Undefined

These are the unlinked, multi-product activity datasets that form the basis for all the other system models. This is the way the datasets are obtained and entered by the data providers. These activity datasets are useful for investigating the environmental impacts of a specific activity (gate-to-gate), without regard to its upstream or downstream impacts.

☐ Allocation, cut-off by classification

☐ Allocation at the point of substitution

☐ Substitution, consequential, long-term

☐ Allocation, cut-off, EN15804

[Switch to Advanced Search](#)

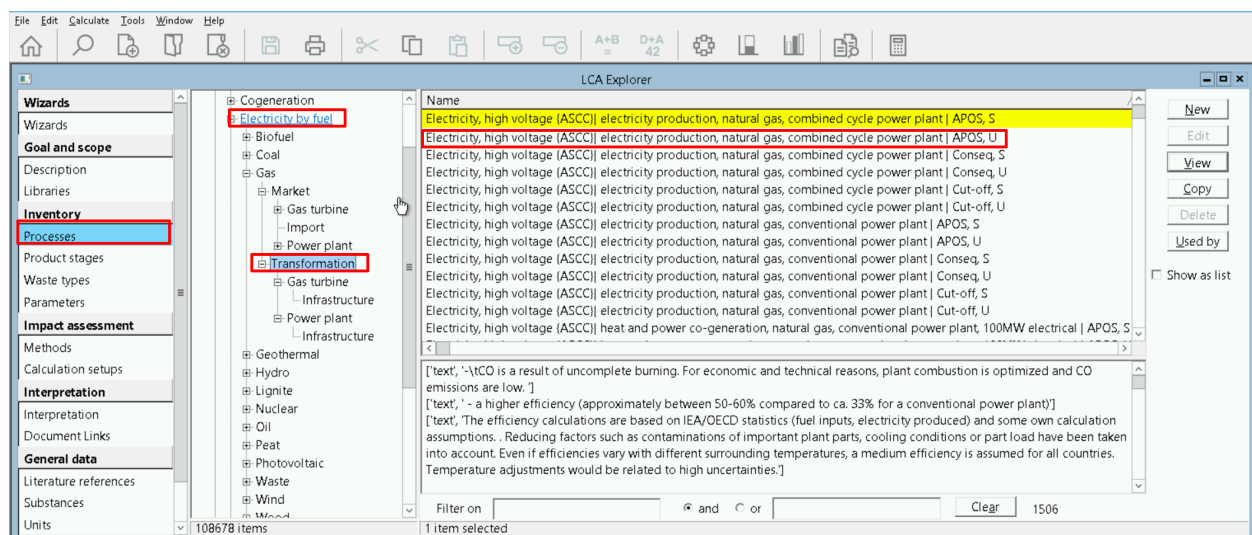
Guest and subscription users are not allowed to download datasets. Please order a licence to access all features of the ecoinvent database.

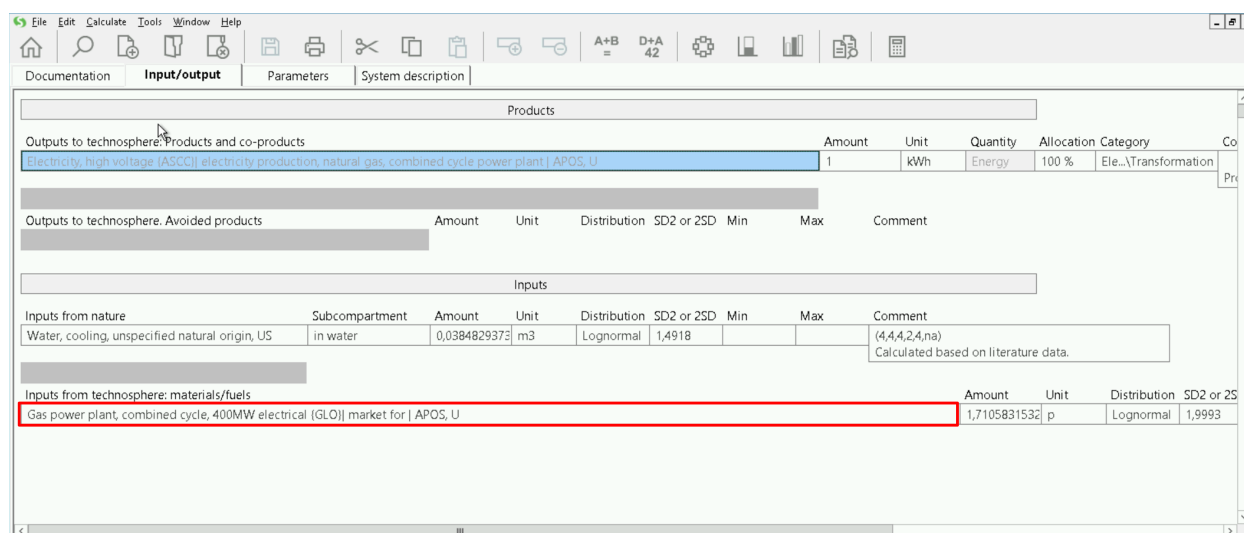
#		Name	Reference Product	Loc.	Time Period	Synonyms	View
15	☐	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	heat, district or industrial, natural gas [MJ]	BE	1/1/2000 - 12/31/2015	CCPP//CCGT //GCC//CHP //GuD//cogeneration	UPR
54	☐	heat and power co-generation, natural gas, conventional power plant, 100MW electrical	heat, district or industrial, natural gas [MJ]	BE	1/1/1990 - 12/31/2015	cogeneration//CHP	UPR

Show 10 entries Showing 1 to 2 of 2 entries (filtered from 138 total entries)

Guest and subscription users are not allowed to download datasets. Please order a licence to access all features of the ecoinvent database.

Another effective way to find a given technology is to navigate the sections related to the energy produced by this technology. Taking electricity production from gas for example, go to electricity by fuel, then select gas: electricity produced from different gas technologies are available. Open a unit process and then find the technology's infrastructure in the inputs of the unit process. Right click to navigate to that process.





Finally another tool is the lookup tool (the magnifying glass in the top left corner next to the home icon). It searches the database for a given keyword but it is very very slow. So we recommend it only as a last resort.

4 Evaluating the process impacts

Once a process is found, we can evaluate its impacts. To do so, let us first explain the difference between unit processes and system processes. System processes are an aggregated LCI for the product from the cradle to the process's point in the life cycle and the associated results are calculated very quickly. A unit process is a single process linked to other products and processes. Evaluating a unit process takes a lot of time, but it is well worth it as you obtain information on the different contributions of life cycle stages. The first evaluation of the impacts of a unit process after opening the software is particularly slow (15 min). Consequently we mostly used system processes to batch export data and unit processes to explore and understand unusual values.

To evaluate the data, two tools are available: a single- and a multi-process tool (called "analyse" and "compare" respectively in *SimaPro*).



4.1 Batch save data

Due to the high number of technologies and process data to gather, we mostly used the multi-process tool. To use this tool effectively, it is necessary to have a good grasp on the location of the process in the database. So, we recommend to first make a list of all the process names and locations in the database as has been done in appendix D.

General

Name:

Comment:

Calculation function:

- ☐ Network
- ☐ Tree
- ☐ Analyse
- ☒ Compare

Method: **IPCC 2013 GWP 100a V1.03**

Product	Amount	Unit	Project	Comment
Gas power plant, combined cycle, 400MW electrical [RoW] construction Cut-off, S	1	p	Ecoinvent 3 - allocation, cu	
Nuclear power plant, pressure water reactor 1000MW [RoW] construction Cut-off, S	1	p	Ecoinvent 3 - allocation, cu	
Hard coal power plant [GLO] construction, 500MW Cut-off, S	1	p	Ecoinvent 3 - allocation, cu	
Photovoltaic plant, 570kWp, multi-Si, on open ground [GLO] construction Cut-off, S	1	p	Ecoinvent 3 - allocation, cu	

Current library: Suffix:

Replacing library: Suffix:

Switches:

- ☐ Exclude infrastructure processes
- ☐ Exclude long-term emissions

Calculate **Close**

All the processes are to be added in the "Product" fields and the wanted LCIA method is chosen in "Method" field. When everything has been added, click the "calculate" button. The impact assessment for all the selected processes are obtained and can be copy-pasted in an Excel sheet.

Impact assessment

Characterisation

Skip categories: **Never**

Se	Impact category	Unit	Gas power plant, combined cycle, 400MW electrical [RoW] construction Cut-off, S	Nuclear power plant, pressure water reactor 1000MW [RoW] construction Cut-off, S	Hard coal power plant [GLO] construction, 500MW Cut-off, S	Photovoltaic plant, 570kWp, multi-Si, on open ground [GLO] construction Cut-off, S
☒	IPCC GWP 100a	kg CO2 eq	7,18E7	6,9E8	1,4E8	1,26E6

To repeat an LCIA on these processes, go to "Calculate" and find the last calculation that you have performed, this saves a lot of time.

Calculate

Wizards:

- ☐ Network
- ☐ Analyse
- ☐ Compare

Goal and scope:

- ☐ Specification per Substance
- ☐ Specification per Process

Description:

- ☐ Show Expression Results
- ☒ Auto Update Expression Results
- ☐ Update Expression Results

Libraries:

- ☐ Inventory
- ☒ Processes

Product stages:

- ☐ Biofuel
- ☐ Coal
- ☐ Gas
- ☐ Geothermal
- ☐ Hydro
- ☐ Lignite
- ☐ Nuclear
- ☐ Oil
- ☐ Peat
- ☐ Photovoltaic
- ☐ Infrastructure
- ☐ Market
- ☐ Transformation

Waste types:

- ☐ Waste
- ☐ Wind
- ☐ Wood

Parameters:

- ☐ Electricity country mix
- ☐ Fuels
- ☐ Heat
- ☐ Mechanical
- ☐ Others

Impact assessment:

- ☐ Methods
- ☐ Calculation setups

Interpretation:

- ☐ Document Links
- ☐ Literature references
- ☐ Substances
- ☐ Units
- ☐ Quantities
- ☐ Images

Calculate

Name: Unit: Project: Comment:

Name	Unit	Project	Comment
Liquid crystal display [CH] treatment of, municipal waste incineration Cut-off, S	kg	Ecoinvent 3 - allocation, cut-off by classifi	
Liquid crystal display [CH] treatment of, municipal waste incineration Cut-off, U	kg	Ecoinvent 3 - allocation, cut-off by classifi	
Liquid crystal display [RoW] treatment of, municipal waste incineration APOS, S	kg	Ecoinvent 3 - allocation at point of subste	
Liquid crystal display [RoW] treatment of, municipal waste incineration Conseq, S	kg	Ecoinvent 3 - consequential - system	
Liquid crystal display [RoW] treatment of, municipal waste incineration Cut-off, S	kg	Ecoinvent 3 - allocation, cut-off by classifi	
Liquid crystal display [RoW] treatment of, municipal waste incineration Cut-off, U	kg	Ecoinvent 3 - allocation, cut-off by classifi	
Municipal solid waste [AT] treatment of, incineration APOS, S	kg	Ecoinvent 3 - allocation at point of subste	
Municipal solid waste [AT] treatment of, incineration Conseq, S	kg	Ecoinvent 3 - consequential - system	
Municipal solid waste [AT] treatment of, incineration Cut-off, S	kg	Ecoinvent 3 - allocation, cut-off by classifi	
Municipal solid waste [AT] treatment of, incineration Cut-off, U	kg	Ecoinvent 3 - allocation, cut-off by classifi	
Municipal solid waste [BE] treatment of, incineration APOS, S	kg	Ecoinvent 3 - allocation at point of subste	
Municipal solid waste [BE] treatment of, incineration Conseq, S	kg	Ecoinvent 3 - consequential - system	
Municipal solid waste [BE] treatment of, incineration Cut-off, S	kg	Ecoinvent 3 - allocation, cut-off by classifi	
Municipal solid waste [BE] treatment of, incineration Cut-off, U	kg	Ecoinvent 3 - allocation, cut-off by classifi	
Municipal solid waste [BG] treatment of, incineration APOS, S	kg	Ecoinvent 3 - allocation at point of subste	
Municipal solid waste [BG] treatment of, incineration Conseq, S	kg	Ecoinvent 3 - consequential - system	
Municipal solid waste [BG] treatment of, incineration Cut-off, S	kg	Ecoinvent 3 - allocation, cut-off by classifi	

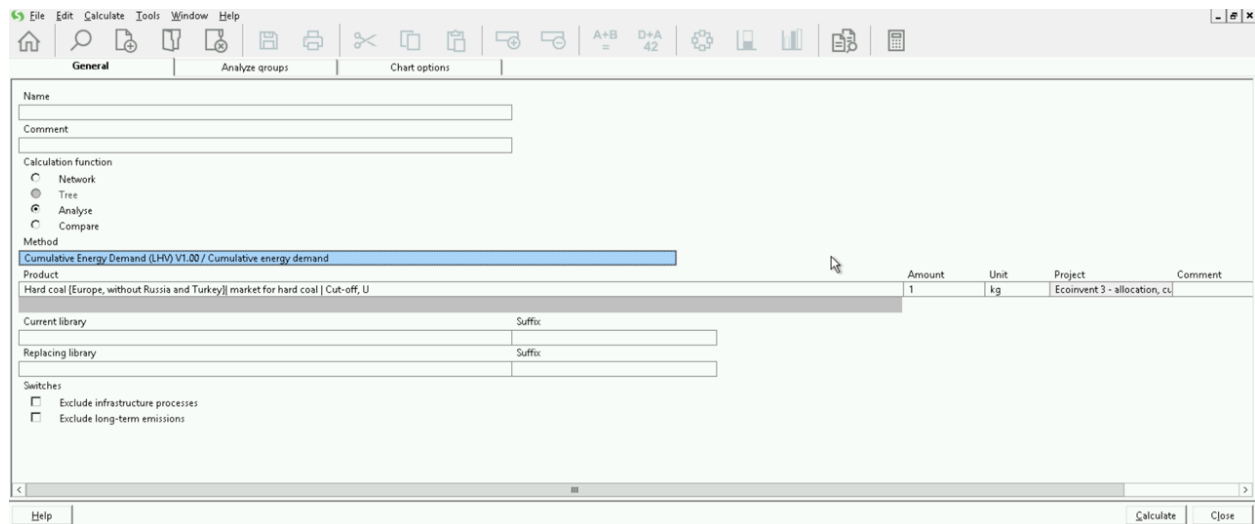
This dataset represents the activity of waste disposal of municipal solid waste in a municipal solid waste incinerator (MSWI). // Recommended use of this dataset: For average municipal/communal waste mixture. Not suitable to represent any single specific waste material, like plastics, paper, cardboard. If your waste is a specific mixture of waste materials, inventory the respective waste materials individually. // Inventoried waste contains 92.8% average municipal solid waste, burnable part; 7.23% average municipal solid waste, unburnable (inert) part. // Waste composition (wet, in ppm): upper heating value 13.05 MJ/kg; lower heating value 11.7 MJ/kg; H2O 25260; O 261060; H 41105; C 339800; S 15323; N 75742; B 73876; Cl 6670; Br 12932; F 36639; I 0.01418; Ag 0.73279; As 1.4061; Ba 15296; Cd 8.0053; Co 1.3807; Cr 13919; Cu 93047; Hg 0.6664; Mn 26619; Mo 3.0065; Ni 52342; Pb 413.61; Sb 53368; Se 0.3201; Sn 99353; V 94572; Zn 11279; Be 47005; Sc n.a.; Sr n.a.; Ti 26164; Tl n.a.; W n.a.; Si 49786; Fe 23628; Ca 18946; Al 11395; K 2132.7; Mg 2568.9; Na 4741.6; // Share of carbon in waste that is biogenic 61.1%. // Share of metals in waste not oxidized and bulk-recyclable (exclude very small or thin parts) Iron: 72.06%; Al: 38.71%; Copper: 45.44%. // One kg of this waste produces 0.2221 kg of slag and 0.02224 kg of residues, which are landfilled. Additional solidification with 0.008896 kg of cement. // Net energy production: 1.39MJ/kg electric energy and 2.85MJ/kg thermal energy. // Recovery of metal scrap to recycling: 9.7909g iron scrap, 1.2166g aluminium scrap, 0.12319g copper scrap.

Filter on: ☐ and ☐ or **Clear** 731

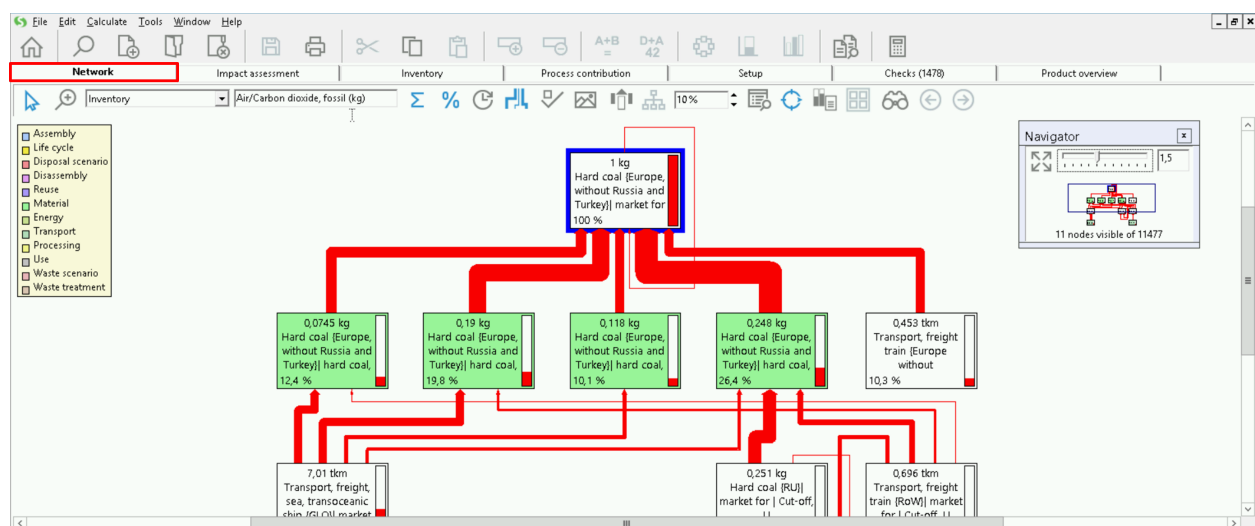
UCL 1 71676 items 1 item selected Maydemars 9.0.0.49 Classroom Multi user

4.2 Investigating the different process contributions

To obtain the energy invested from the CED LCIA method, the unit process was analysed with the single-process tool. Let us take coal for example:



The total CED is given in the "impact assessment" tab. Notice that there is now a "Network" tab as we evaluate a unit process. The processes displayed are those whose cumulative contribution from cradle to gate is higher than the threshold set.



As there are many contributors to the market for coal, the network is complicated to read. Another tool that can be used to help us analyse the process contributions to the coal market is the "Process contribution" tool. In this case, the contribution of each individual process (not a cumulative contribution) is given and can be sorted from biggest to lowest.

Network		Impact assessment	Inventory	Process contribution	Setup	Checks (1478)	Product overview
Indicator	Single score	Cut-off	0%	☐ Default units ☐ Exclude long-term emissions ☐ Per impact category	☒ Standard ☐ Group		
Category							
No	Process	Project	Unit	Hard coal (Europe)			
	Total of all processes		MJ	28,5			
1	Hard coal [Europe, without Russia and Turkey] hard coal mine operation and hard coal preparation Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	8,25			
2	Hard coal [RU] hard coal mine operation and hard coal preparation Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	5,75			
3	Hard coal [RLA] hard coal mine operation and hard coal preparation Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	3,41			
4	Hard coal [RNA] hard coal mine operation and hard coal preparation Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	3,4			
5	Hard coal [AU] hard coal mine operation and hard coal preparation Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	2,47			
6	Hard coal, run-of-mine [ZA] hard coal mine operation, open cast, dragline Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,826			
7	Hard coal [ID] hard coal mine operation and hard coal preparation Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,605			
8	Petroleum [RoW] petroleum and gas production, on-shore Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,513			
9	Petroleum [RME] production, onshore Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,481			
10	Hard coal, run-of-mine [ZA] hard coal mine operation, open cast, truck and shovel Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,452			
11	Hard coal, run-of-mine [ZA] hard coal mine operation, underground Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,287			
12	Petroleum [RoW] petroleum and gas production, off-shore Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,255			
13	Petroleum [RU] production, onshore Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,21			
14	Natural gas, high pressure [RU] natural gas production Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,204			
15	Hard coal [CN] hard coal mine operation and hard coal preparation Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,139			
16	Uranium, in yellowcake [GL] uranium production, in yellowcake, in-situ leaching Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,134			
17	Sawlog and veneer log, hardwood, measured as solid wood under bark [DE] hardwood forestry, beech, sustainable forest management Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,107			
18	Lignite [RoW] mine operation Cut-off, U	Ecoinvent 3 - allocation, c,	MJ	0,0798			

Analysing 1 kg 'Hard coal [Europe, without Russia and Turkey] market for hard coal | Cut-off, U'; Method: Cumulative Energy Demand (LHV) V1.00 / Cumulative energy demand / Single score

This tool was very useful for the evaluation of the energy invested as was mentioned in appendix A.

This is all for the quick guide on data collection from *ecoinvent* with *SimaPro*. Feel free to contact the authors of this thesis if further information is required.

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