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Implementation of the Energy Return on Investment (EROI) into the EnergyScope TD model.

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Abstract

In the coming years, the countries of the European Union must prepare for a transition to more decarbonised societies. A society with zero net greenhouse gas emissions is expected to be achieved by 2050, although reaching this goal seems far off and complicated.

To achieve this transition, energy system modelling will play an indispensable role. It is expected that these models will be able to guide the policies to be implemented, thanks to accurate simulations of scenarios. One of the most promising models is the open-source EnergyScope TD model. This model allows working with a multi-sector model that takes into account all societal demands, optimising both the investment and the operating strategy for a target year.

To help develop the model, we try to include the concept of Energy Return on Investment (EROI). The EROI refers to the ratio of energy produced to the energy required for its production. This concept has been developed over several decades but is rarely included in energy system models. Although it is an old concept, it still needs to be further developed, as technologies advance and new technologies appear.

In this work, the EnergyScope TD model has been compared with a version that takes into account the EROI to find out what impact it has and whether it needs to be taken into account in future analyses. To carry out this comparison, the Belgian 2035 energy system proposed by both models has been analysed for different carbon emission targets.

This report presents the results of the simulations made with each model, as well as the sensitivity study of the EROI values. The results and the impact of the EROI are discussed below, as well as the limitations of the model and the proposed scenarios. Finally, the conclusions of the study are presented, and improvements for further work are proposed.

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Glossary

BEV : Battery electric vehicle

CCGT: Combined cycle gas turbine

Coal US: Coal ultra-supercritical

CO_2: Carbon dioxide

EnergyScope TD : EnergyScope Typical Days

EROI: Energy return on investment

EU: European Union

EUD: End-use demand

EUT: End-use type

FEC: Final energy consumption

GHG: Greenhouse gas

GWP : Global warming potential

H2: Hydrogen

HTH: High temperature heat

HP: Hheat pumps

IEA: International Energy Agency

IGCC: Integrated gasification combined cycle

LFO: Light fuel oil

LTH: Low temperature heat

LP: Linear programming

Mpkm: Million passenger-kilometre

NG: Natural gas

PHEV: Plug-in hybrid electric vehicle

PHS: Pumped hydro storage

PV: Photovoltaic

RE: Renewable energy

SLF: Synthetic liquid fuel

SNG: Synthetic natural gas

TD: Typical day

TS: Thermal storage

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1 Introduction

1.1 Thesis Motivation

The EU aims to be climate neutral by 2050: an economy with zero net greenhouse gas emissions. This objective is at the heart of the European Green Pact and in line with the EU's commitment to global climate action under the Paris Deal. The transition to a climate-neutral society is an urgent challenge. All parts of society and economic sectors will have a role to play, from the energy sector to industry, mobility, buildings, agriculture and forestry. The EU can lead the way by investing in realistic technological solutions, empowering citizens and aligning action in key areas such as industrial policy, financing and research, while ensuring social equity for a just transition. This transition is expected to take place by 2050 in more than 100 countries outside the EU [1]. Although, a recent Emissions Gap Report by the United Nations Environment Programme (UNEP) points out the difference between the projected situation for greenhouse gas emissions in 2030 and what would be needed to reach the 2050 targets.[2]

In the coming years, the importance of increasingly accurate simulations and modelling scenarios will grow in order to prepare countries for the transition to a 100% renewable energy system. Despite the need for this transition, fossil fuel consumption continues to increase to supply most of the current and growing energy demand, despite the negative impact of fossil fuels on air pollution and climate change. A major shift is needed to achieve such a transition. Moreover, currently, according to standard energy use scenarios, global primary energy is expected to continue to grow by 30% between now and 2040.[3]

A growing number of scenarios have now been developed to model the disruptive changes needed to achieve this transition with simulation intervals of one hour. The feasibility of the proposed solutions for a 100% renewable energy system scenario has been questioned by other scholars who cite oversimplified assumptions [4]. One of the main claims is that 100% renewable energy scenarios assume too rapid technological progress and scaling up of renewable energy infrastructure, without a thorough assessment of the underlying physical and engineering constraints, such as the available renewable energy potential that can be harnessed in a sustainable way, by taking into account land use constraints [5], physical availability constraints and limitations of the energy efficacy of generating systems to deliver energy to society [6].

It is within this framework that this project is born, which seeks to provide a different way of approaching this problem. This study aims to use EnergyScope Typical Days (EnergyScope TD), a novel open source energy planning model, available on GitHub. The model optimises both the investments and the operation of the entire energy system by taking into account all energy flows within its boundaries, including electricity, heating, transport and non-energy use. This is the main reason why this model has been chosen. Traditionally, energy models focus only on a particular sector without taking into account cross-sectoral interactions. Examples of such models are Dispa-SET or SciGRID which, like many others, model only the electricity system, other models artificially take into account the heating, electricity and mobility sectors. A large part of these models consider cross-sectoral interactions in a simplified way and/or represent only a part of the energy system. In addition, many of the more comprehensive models are not open source, such as Plexos Open EU or EnergyPLAN.[7]. To this model, the Energy return on investment concept, a concept developed in the 1970s, will be implemented, and which with the emergence of renewable technologies is gaining weight again. EROI is the ratio of the total amount of energy that an energy source is capable of producing to the amount of energy that needs to be used or supplied to exploit that energy resource.[8]

1.2 Thesis Objective

As mentioned above, the proposed solutions for a 100% renewable energy system scenario have been questioned as taking overly simplified assumptions. This study takes a less common approach to this constraint. As mentioned above, the EnergyScope TD model will be used. This model is able to account for the GWP derived from the construction of the different technologies in the system. This is where the concept of EROI comes into play, this concept offers an alternative way of taking into account the new technologies installed, putting the focus more on the energy needed for the construction than on the GWP.

The main objective of the study is to provide a comparison of the optimal systems proposed by the model depending on whether GWP or EROI is taken into account. The objective is to find out if these two approaches cause the optimal systems to show large differences in the way demand is supplied. And which of these approaches is more limiting when proposing an energy transition for the system. For this purpose, different scenarios will be proposed for the Belgian energy system in 2035 with different CO2 targets and under different assumptions.

Furthermore, this study also aims to assess the importance of EROI in the simulations. The goal is to identify which of the different technologies is more interesting to install depending on the EROI value used, since there is no consensus on the EROI of the different technologies as will be shown in this document.

This study does not intend to draw definitive conclusions on what the Belgian system will or should look like in 2035. Nor does it aim to determine the EROI values of the technologies, but rather to use the values provided by other studies. The model tries to give a picture and trends of what these systems would look like. However, the model has its limitations, which are developed in the discussion section.

1.3 Thesis Outline

After this chapter, this report is structured in five more chapters, in which the work carried out during the master thesis is presented. The next chapter covers the theoretical background necessary to understand the work carried out in this master thesis, this also includes an extensive literature review, and a short approach to the EnergyScope TD program. The chapter 3 details the methodology used in this study, describing the mathematical model, the presentation of the 2015 Belgian system as well as the needs of the 2035 system, the proposed scenarios to be studied and finally the hypotheses that have been put forward. The chapter 4 presents the results of the simulations, followed by the discussion in chapter 5, where the different results are discussed. The last chapter concludes the report with ideas for further development.

1.4 State of the art: EROI Implementation in Modelling.

This section lists the latest developments, including the most recent work on models incorporating EROI in their design. Although this concept is strongly linked to the energy sector, it can also be approached in other areas.

The study [9], carried out at the University of Surrey, UK, is a good example. The aim of the work is to understand the impact of declining EROI on the modelling of energy transition scenarios. To achieve this, they use a conceptual input-output model (TranSim) consistent with the stock flow (SFC) that is able to simulate a reduction in the EROI. In the work, the EROI reduction is assumed to be triggered by a transition from relatively high EROI fossil fuels to relatively low EROI green energy sources. The study focuses on the interactions between the real and financial sides of the economy as the potential interaction between the capital transformations associated with an energy technology transition and the financial flows needed to finance these transformations. As can be seen, the study is framed in terms of the economic sector, without paying attention to the technologies used for the transition.

More focused on the energy sector, we have studies carried out on a small scale, one example is the study [10]. This study uses the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) to estimate energy use and greenhouse gas emissions from "upstream" oil operations (activities between initial exploration and crude oil passing through the refinery gate) using data from more than forty global oilfields.

Finally, what is most similar to what we do in this study is the MEDEAS model [11]. This open-source model has been designed applying system dynamics by the Energy, Economics and System Dynamics Group of the University of Valladolid (Spain). The MEDEAS models are structured in nine main modules that interact with each other. The modules are economics, energy demand, energy availability, energy infrastructure and EROI, minerals, land use, water, climate/emissions and social and environmental impact indicators. Unlike EnergyScope, the MEDEAS model uses the expected population and per capita income to estimate the mix, and the different country systems are interrelated and depend on the systems in which they are included (e.g. World System or Eu system). Simulations typically run from 1995 to 2060, although the horizon can be extended to 2100 for long-term strategic sustainability analyses. In this model, the EROI is included in the same module as infrastructure, which represents electricity and heat generation capacities. Energy investments for electricity production are modelled endogenously and dynamically, which allows the calculation of the energy return on investment (EROI) of individual technologies and the EROI of the energy system as a whole. Energy demand is affected by the variation of the EROI of the system.

2 Theoretical Background

This section focus on the theoretical background of the paper. First, the origin of the term EROI is explained, as well as the different ways of calculating it. A summary of the EROI values offered by the different studies that have been found for the most important electricity producing technologies is also given. This is followed by an overview of the most important features of the program used to carry out the simulations, EnergyScope TD.

2.1 Energy Return on Investment (EROI)

In the 1970's ecologist Charles Hall coined the term "Energy Return on Investment" (EROI), with originally a focus on migrating fish. In the 1980s, Hall, working with Cutler Cleveland, Robert Kaufmann and others[12], extended the concept to seeking oil and other fuels. The concept had been around in the anthropological , economic , and ecological literature for some time, although it was expressed as "net energy" [13]. The difference is that EROI is a means of measuring the quality of various fuels by calculating the ratio between the energy delivered by a particular fuel to society and the energy invested in the capture and delivery of this energy, and net energy is the difference left over after the costs have been subtracted from the gains. The EROI is a more useful parameter because it allows to classify the different forms of energy generation and an estimate of the changing in their ease of extraction over time, which can also be interpreted as the difference between the effects of technology (which would be expected to increase EROI) and depletion (which would be expected to decrease it). One important idea is that as this ratio approaches 1:1 the fuel is no longer useful to society.[14]

The original papers on EROI (e.g., Hall and Cleveland [15]), were mostly received with interest, but that interest waned in the late 1980s and 1990s as fuel prices declined. More recently as energy prices have again been increasing the interest in EROI has increased too. In fact, despite the growing interest in EROI, little new data is available today. Most of these efforts have consisted of refining the EROI of certain oils and fuels, but few have focused on the new methods of energy generation that have been emerging and growing in importance in our society, such as renewable energies or nuclear energy.

In addition, depending on the methodology used to calculate the EROI of the different technologies, the values obtained differ from one study to another. The difference in the results of , in theory, a simple equation as is the EROI are mainly due to the choice of the direct and indirect costs associated with energy production/extraction included (i.e. the limits of the denominator).

Four different methods for calculating the EROI and their limitations are detailed, according to the equations presented by Lambert et al. 2013 [16]

1. Standard EROI (EROI st): A standard EROI approach divides the energy output of a project, region or country by the sum of the direct (i.e. on-site) and indirect energy (i.e. the energy required to manufacture the products used on-site) used to generate that output. It does not include, for example, energy associated with support labour, financial services and similar. This approach allows different fuels to be compared even when analysts disagree on the rest of the methodology to be used. (Eq. 2.1)

2. Point of Use EROI (EROI pou): The EROI at the point of use is a more comprehensive EROI that additionally includes the costs associated with transporting the fuel. As the boundaries of the analysis are extended, the energy cost of reaching that point increases, resulting in a reduction of the EROI .(Eq. 2.2)

3. Extended EROI (EROI ext): This expanded analysis considers the energy required not only to get but also to use a unit of energy. (Eq. 2.3)

4. Societal EROI (EROI soc): Societal EROI is the overall EROI that might be derived for all of a nation's or society's fuels by summing all gains from fuels and all costs of obtaining them. Currently, this calculation has yet to be undertaken because it is difficult, if not impossible, to include all the variables necessary to generate an all-encompassing societal EROI value .(Eq. 2.4)

$$EROI_{st} = \frac{Energy\ Returned\ to\ Society}{Direct\ and\ Indirect\ energy\ required\ to\ get\ that\ energy} \tag{2.1}$$

$$EROI_{pou} = \frac{Energy\ Returned\ to\ Society}{Energy\ required\ to\ get\ and\ deliver\ that\ energy} \tag{2.2}$$

$$EROI_{ext} = \frac{Energy\ Returned\ to\ Society}{Energy\ required\ to\ get,\ deliver\ and\ use\ that\ energy} \tag{2.3}$$

$$EROI_{soc} = \frac{Energy\ Returned\ to\ Society\ from\ all\ economic\ activity}{Energy\ required\ to\ perform\ all\ economic\ activity} \tag{2.4}$$

With this knowledge, in order to carry out this study, first of all, it was decided to go through the different studies that have been done in recent years to obtain the EROI values for the different technologies. We have tried to use values derived from the same calculation whenever it has been possible to identify, the equation we have most commonly use is the EROI st equation as it is the simplest. As mentioned above, a wide range of values has been found for each of the electricity producing technologies used by the programme. These values and a short explanation of why they differ from study to study is shown below.

2.1.1 Nuclear

Nuclear power is the use of controlled fission reactions to produce electricity. There are currently 439 commercial nuclear power plants around the world using variations of generally the same technology .

The analysis of EROI values for nuclear energy fails to expose a clear value. Older and more pessimistic studies suggest an average EROI of approximately 15:1 but these values may not adequately reflect current technology or ore grades. Reviewing more recent studies, it has been concluded that the most reliable information gives nuclear power an EROI of around 50-60:1 (with much of the variability depending on whether electricity is corrected for quality), with the most optimistic reporting EROIs as high as 75:1.

The studies note that differences in EROI can sometimes be attributed to differences in system boundaries and technologies. However, empirical information on the subject is generally lacking. The three main factors influencing nuclear EROI are the huge upfront capital costs required, the environmental costs and the grade of uranium ore available.The continuing use of increasingly depleted geological deposits could lead to a decrease in EROI. At present, some of the ore is obtained from decommissioned nuclear warheads; on the other hand, there are possible new, but unproven, technologies using smaller reactors or even thorium, which could lead to safer reactors with higher EROI.

References : [14], [17], [18] and [19].

2.1.2 Natural Gas

Currently, we know of almost no published and reviewed studies on the EROI of plants using unconventional natural gas for electricity production. Studies tend to focus specifically on natural gas production. The studies estimated that in 2005 the EROI of a not conventional gas field is 10:1. Several studies predict that these sources will have lower EROIs than conventional gas, and as they gain market share in the global energy matrix, the EROI of natural gas could decrease dramatically, but we desperately need real analysis on this issue with solid data.

According to a study of an operating plant in Bulgaria the EROI of CCGT [20] fluctuates between 13-19:1 . A great advantage of CCGT is the ability to work in constant mode, as well as the short technological time in managing the mode of operation - on/off, ramp-up and production. The CCGT allows for great flexibility and the ability to immediately cover shortfalls in production fluctuations. But the use of natural gas as a fuel is also not without problems. First of all, the combustion of gas also emits greenhouse gases, even if they are half as much as coal and fuel oil, and this can lead to penalties in the future, which is why gas is considered a temporary solution.

More importantly, while coal-fired power plants have reserves for weeks (even months) at full capacity, gas-fired power plants have reserves for hours and depend on a constant external supply. The EU imports most of the quantities needed, so clearly the EROI of these plants will be lower the further away the gas has to be transported and the smaller the plant is.

References : [13], [14], [17] and [21].

2.1.3 Coal

Unfortunately, as for the Natural Gas,there is no recent studies published, the last one dates from 1987. They have calculated the EROI for coal, including estimates of labour and transport, from 1930 to the late 1970s, and found that it was relatively constant at about 30:1 until the 1960s, when it increased to about 35:1, and then after a small drop in the 1970s, increased again to around 50:1 in 1987.

The increase in EROI during the 1960s is attributed to increased mining efficiency as production shifted to western surface coal, while the decrease in EROI during the 1970s is mainly attributed to the decline in the quality of coal being mined. Quality-corrected values are 4 times lower. To obtain more recent values, some assumptions can be made. In the case of the USA, there are forces driving down the EROI in the future. Bituminous coal reached its peak production around 1992 and its quality (BTU per tonne) has been gradually declining since the 1950s. In addition, increasing environmental regulations in the industry would have a negative impact on EROI.

It is unclear whether over time the decrease in resource quality would be greater or less than the increased impact of technology. This is why some studies currently estimate an EROI value for coal of between 20-40:1.

References : [13], [14], [17] and [22].

2.1.4 Solar

The use of Solar photovoltaic (PV) are increasing almost as rapidly as wind systems, although they too represent far less than 5% of the primary energy consumed in the world [23]. Similarly, they are a renewable source of energy and thus the EROIs are also calculated using the same idea. Although there are very few studies which perform "bottom up" analysis of the PV systems we are familiar with today, we can calculate the EROI by dividing the lifetime of a module by its energy payback time. PV energy payback time can vary depending on the location of production and installation. It can also be affected by the materials used to make the modules, and the efficiency with which it operates - especially under extreme temperatures.

An examination of the EROI literature on solar photovoltaic or PV energy generation shows differences in the assumptions and methodologies employed and the EROI values calculated. The values, assumptions, and parameters included are often ambiguous and differ from study to study, making comparisons between PV and other energy EROI values difficult and fraught with potential pitfalls. Nevertheless, the mean EROI value assume in differents publications spanning several decades is approximately 10:1 for the PV.Some studies examine the actual energy costs and benefits of a number of installation and suggest that the actual operating EROI may be considerably lower than suggested by developers, giving the PV EROI values of around 3:1.

In contrast, for installations using concentrated solar power technologies, an EROI of approximately 6:1 is calculated for some theoretical modules, reaching even ranges between 8-20:1 for the biggest and most modern plants. Much promotional literature gives higher estimates but these values could not be validated.

Factors contributing to the increase of EROI include increasing efficiency in production, increasing efficiency of the module, and using materials that are less energy intensive than those available today. Factors contributing to lower EROI include lower ore grades of rare metals used in production (from either depletion in the ground or competition from other industries) and lower than projected lifetimes and efficiencies, problems with energy storage and intermittence.

References : [13], [14], [24], [25], [26], [27] and [28].

2.1.5 Wind

Wind energy is one of the fastest growing renewable energies in the world today, although it still represents also far less than 5% of global primary energy use [23]. Since it is renewable energy, EROI is not calculated the same as for finite resources. The energy cost for such renewable systems is mostly the very large capital cost per unit output and the backup systems needed, for two thirds of the time the wind is not blowing. As a result, the input for the EROI equation is mostly upfront, and the return over the lifetime of the system—which largely is not known well.

The studies show an average EROI for all systems studied is 24:1 and that for all operational studies is 18:1. The operational studies provide lower EROIs because the simulations run in conceptual models appear to assume conditions to be more favourable than actually experienced on the ground. For the offshore , even if theses systems would experience more reliable winds but have greater maintenance costs associated with them, so a very similar EROI of around 18-25:1 can be assumed. However, according to a study carried out in Germany on an Enercon E-82 wind turbine on a 98 m concrete tower (with a life expectancy of 20 years), it was able to achieve an EROI of 35.4:1 for inland locations and 51:1 if it was located directly on the coast.

The studies found that the EROI tends to increase with the size of the turbine. They conclude that there are three reasons for this. First, that smaller turbines are of older design and can be less efficient, so despite a larger initial capital investment larger systems compensate with larger energy outputs; second that larger models have larger rotor diameters so they can operate at lower wind speeds and capture more wind energy at higher efficiencies year round; and finally because of their size, larger models are taller and can take advantage of the higher wind speeds farther above ground.

Aspects of wind energy which can lower the EROI include the location of manufacture and installation but have greater construction and maintenance costs as they can add to the initial capital investment of a wind turbine or limit the use of recycled materials. Also, energy storage and grid connection dynamics could potentially reduce EROI where applicable.

References : [13], [14], [17], [29], [30] and [31].

2.1.6 Hydropower

Hydroelectric power generation systems have the highest mean EROI value, 84:1, of the electric power generation systems . The EROI of hydropower is extremely variable, although the best sites in the developed world were developed long ago .

Hydropower plants vary greatly in size and scope, and therefore so do the power output and the inputs required to construct and maintain the facilities. Large-scale hydropower projects, often involving reservoirs, are the best researched. For hydropower, the EROI is calculated in the same way as for other renewable energy sources, i.e. the total energy production over the lifetime of the plant is divided by the energy costs of setting up and maintaining it. It is unclear whether decommissioning plants are part of the analysis, which would reduce the EROI.

Reviewing older studies of existing facilities the author's proposed EROI values ranged from 11.2-96:1 due to the extreme variability of geography and technology. The most recent estimates put the EROI value at 84:1 (the most widely accepted value). Hydropower generation systems have the highest average EROI value.

It is noted in the studies that environmental and social costs, which can be substantial, are not incorporated into the figures. Given that all of these costs and benefits are location sensitive, it is clear that determining an overall EROI for hydropower would be meaningless and that each project would have to be examined separately. However, given the range of EROIs in the study, it appears that hydropower, when available, is often a good energy return on investment.

For smaller hydropower plants, studies propose an EROI between 41-78:1. These smaller hydropower plants are typically used to produce power from smaller flows, such as rivers. It should be noted that the EROI of mini-hydro plants are even more sensitive to the transport of the materials needed to build the plant and the construction processes. to obtain the highest EROI values, more attention should be paid, in a localised area, to using less energy-intensive materials and reducing the distances to move the parts. Furthermore, this implies that, from an environmental perspective, construction managers should pay attention to the site selection of mini-hydro projects to reduce energy waste and improve project design and execution.

References : [14], [17], [17], [21] and [32].

2.1.7 Geothermal

Geothermal energy uses heat from inside the Earth to do work by transferring heat to a gas, such as steam, or to a liquid. This can be used to produce electricity or heat. The most suitable locations are close to plate boundaries and are therefore not equally available to all countries. Currently, only hydrothermal resources are used for commercial energy. Here, heat is transferred to groundwater at depths that can be drilled. It is believed that enhanced geothermal systems, also known as Hot Dry Rock (HDR), can exploit heat deeper underground where there is no groundwater, although there are none in commercial use. It should be noted that there is currently no consensus on estimates of the resource base for geothermal energy.

That is why studies are not able to give concrete EROI values for this technology. Early studies on hydrothermal resources carried out between 1975 and 1991 [33], estimated an EROI for electricity generation from hydrothermal resources in the range of 2-13:1. Corrected for quality as a source of electricity, it recalculates to approximately 6-39:1. Some theoretical EROI values have been calculated for HDR ranging from 1.9-13:1 or 5.7-39:1 when corrected for quality. .

The author attributes the large ranges to the lack of a unified methodology for EROI analysis and disagreements about system boundaries, quality correction and future expectations. No EROI values have been found for the direct use of geothermal energy. Energy can be extracted from normal soils and groundwater with an EROI of about 5:1, although the input is electricity and the output is heat, so the output with quality correction may not be very high.

References : [14], [17] and [17],

2.1.8 Brief summary

As we can see in Table 2.1, nearly all renewable energy systems appear to have relatively low EROI values when compared with conventional fossil fuels. A question remains as to the degree to which total energy costs can be reduced in the future, but as it stands most "renewable" energy systems appear to be still heavily supported by fossil fuels. Nevertheless they are considerably more efficient at turning fossil fuels into electricity than are thermal power plants, although it takes many years to get all the energy back.

A positive aspect of most renewable energies is that the output of these fuels is high quality electricity. A potential drawback is that the output is far less reliable and predictable. EROI values for renewable alternatives are generally computed without converting the electricity generated into its "primary energy-equivalent" but also without including any of the considerable cost associated with the required energy backups or storage. EROI calculations of renewable energy technology appear to reflect some disagreement on the role of technological improvement. Some studies attribute the low EROI values published to the use of outdated data and direct energy output data that represents obsolete technology that is not indicative of more recent changes and improvements in renewable technology. EROI values that do reflect technological improvements are calculated by combining "top-of-the-line" technological specifications from contemporary commercially available modules with the energy out- put values obtained from experimental field data. Other researchers contend that values derived using this methodology do not represent adequately the "actual" energy cost to society and the myriad energy costs associated with this delivery process.

Technologies	**EROI$_{min}$ (X:1)**	**EROI$_{max}$ (X:1)**	**EROI (X:1)**	
Nuclear	15	75	60	[14]
CCGT	7	28	19	[20]
Coal US	20	50	35	[14]*
PV	3	10	10	[26]
Solar Thermal	6	20	8	[24]
Wind Onshore	18	50	18	[29]
Wind Offshore	18	50	22	[31]
Hydropower	11	96	84	[17]
Mini Hydro	41	78	60	[21]*
Geothermal	6	39	20	[14]*

Table 2.1 – Summary of the EROI values of the different technologies found in the different studies. EROI$_{min}$ represents the minimum value attributed to the technology, while EROI$_{max}$ represents the maximum. EROI represents the most accepted value among the studies, the most normalised value. **:Intermediate value between max. and min.*

2.2 EnergyScope TD

This chapter aims to explain the basic principles of the existing version of EnergyScopeTD used for this study. The changes and improvements made to the model during this thesis are explained in Section 3.1.2.

EnergyScopeTD is a novel open source energy system model suitable for optimising the entire regional energy system, including high shares of renewables. It was developed by G. Limpens et al. and is the result of collaboration between UCLouvain and EPFL. This model is a linear programming model that optimises the investment and operation strategy through hourly resolution in a multi-sector energy system. EnergyScope TD represents with the same level of detail the heating, mobility and electricity sectors, although we will focus especially on the latter. The model has a constraint on greenhouse gas emissions. The calculation time is minimised by the use of Typical Days, which will be explained later in this chapter.

The main features are:

1. Meeting the end-use demand of the system, accounting for electricity, heat and transport;
2. Optimisation of both system design and operation, minimising overall system cost;
3. An hourly resolution (time step) that makes the model suitable for analysing the integration of intermittent RE and storage;
4. A short calculation time (1-5 minutes) as a result of using typical days and a reconstructed method to represent a year with an hourly resolution.

The operating principles of EnergyScope TD are based on 3 basic building blocks: resources, energy conversion and demand. (as depicted in Figure 2.1). Resources represent primary energy, which can be imported or locally produced. In the end, energy demand is imposed. Contrary to modelling practice, we use end-use demand (EUD) instead of final energy consumption (FEC). EUD is the actual end-user demand, while FEC is the energy consumed by a technology to supply the end-user demand. As an example, the end-user does not need gasoline for his car, but needs passenger mobility (which has as unit the passenger-kilometre). Between resources and demand, there are technologies that can convert one energy into another, such as a heat pump that converts electricity into heat. The energy system encompasses all the energy conversion technologies needed to transform the resources and supply EUD.

EnergyScopeTD implements 5 different EUDs, also called End Uses Categories (EUC): electricity, heating, cooling, mobility and non-energy demand. Non-energy demand is defined by the International Energy Agency as "fuels that are used as feedstock in different sectors and are neither consumed as fuel nor transformed into another fuel". As examples, the European Commission includes as non-energy the following materials "chemical feedstocks, lubricants and asphalt for road construction". These EUDs are divided into more precise demands that are called End Use Types (EUTs). For example, heating is divided into three TUEs: low temperature heat for hot water, low temperature heat for space heating and high temperature heat for industry. Mobility is divided into two TUEs: passenger and freight mobility (passenger transport activity of aviation is counted in passenger mobility (excluding international aviation outside the EU).To cover each of these EUCs, the program assigns each of the technologies according to the EUT they can satisfy. For example, Trains can be used to cover the EUT Mobility Freight. Figure 2.2 provides a more accurate visual representation of all the assemblies used by the program, including resources and storage.

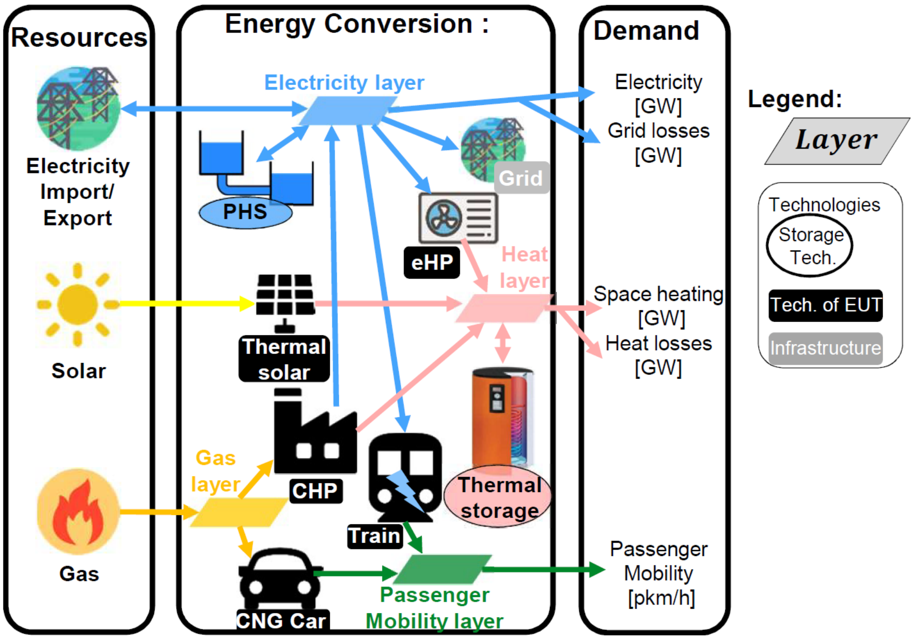

Figure 2.1 – Conceptual example of an energy system with 3 resources, technologies (of which 2 storage and 1 infrastructure) and 4 end use demand (of which 1 losses). Abbreviations: pumped hydro storage (PHS), electrical heat pump (eHP), combined heat and power (CHP), compressed natural gas (CNG). [33]

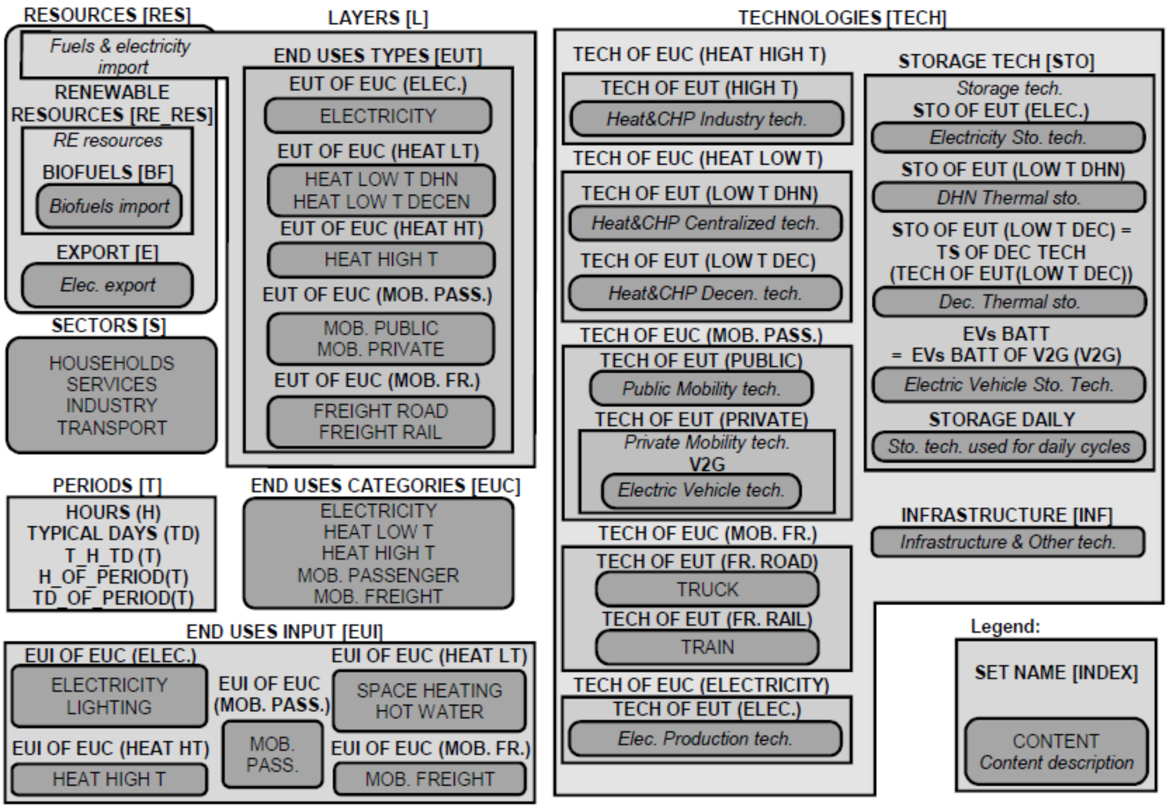

Figure 2.2 – Visual representation of the LP frame sets and indices used in the EnergyScope TD. The model uses the following nomenclature: *SETS* are in italic capital letters, *parameters* are in italic lower letters and **Variables** are bold in lower letter, with the first letter in capital (e.g. **Ctot**) [33]

The objective of the model is to minimise the total annual cost of the system (or greenhouse gas emissions) by optimising its design over a year and its operation with an hourly resolution. The model belongs to the "snapshot" category, in the sense that the energy system is completely rebuilt in a target year with no relation to the existing one. To identify the optimal system, EnergyScopeTD works with an hourly resolution such that the hourly demand is satisfied with the appropriate hourly production throughout the year. An hourly time-scale resolution is required to verify how the system handles high shares of intermittent renewable production, while a one-year horizon is needed to operate long-term storage. However, as many days have similar profiles, such as solar, wind or electricity demand, they provide redundant information. Therefore, by matching 365 days of the year with 12 typical days, the calculation time can be reduced by three orders of magnitude, while verifying consistent accuracy. Twelve typical days have been selected because it is a good compromise between accuracy and computational time. This typical days can be classified as follows : 5 winter days with high heat demand; 3 cold intra-season days; 2 hot intra-season days; and 2 warm summer days [7].

3 Methodology

In this section the methodology used throughout this study is presented. The performance indicators of the systems are shown, both those used in the *Original* model (which is the current model of the programme), as well as those used in the model in which we have implemented different equations as will be explained. Afterwards, the Belgian data used for the different simulations is presented, as well as the different scenarios that have been created to check the differences between the models. At the end, a summary of the assumptions that have been taken into account to create the models and scenarios is be presented.

3.1 Performance Indicators

As described in the previous section, the EnergyScope TD program uses different technologies to transform system resources into final demand. The energy system implemented in the model includes 28 layers, 9 types of end-use demand and 96 technologies, including new technologies such as those used for the production of synthetic fuels, energy storage or new forms of mobility such as fuel cell cars. Figure 3.1 shows that energy system.

In addition, the program is composed of 42 equations that mark the different constraints that must be met to validate the proposed response. These equations and their explanation can be read in the Appendix A. As mentioned in section 2.2, the optimal solution is found by minimising the annual cost (Millions of €/y) or the total GWP emitted by the system in a year ($MtCO_2$ eq/y). For all the simulations carried out in this study, only the annual costs of the system have been minimised. The annual system cost (Equation 3.1) is defined as the sum of the annualised investment cost (C_{inv}) of the technologies, the cost of operating and maintaining the technologies (C_{maint}) and the cost of exploiting the resources (C_{op}).

$$min\ \mathbf{C_{tot}} = \sum_{j \in TECH} (\tau(j)\mathbf{C_{inv}}(j) + \mathbf{C_{maint}}(j)) + \sum_{i \in RES} \mathbf{C_{op}}(i) \tag{3.1}$$

The CO_2 annual emissions have been used as a limiting factor in the model. During the different scenarios studied, the maximum value of GWP that the system was allowed to emit has been modified. These maximum values were based on the annual GWP in Belgium in 2015. The equations used by the programme to calculate the GWP change depending on the model used. On the one hand we have the model that we have called the *Original* model, this model corresponds to the model that is available for download on GitHub. And on the other hand we have the model where the EROI has been included, we will call this model the *EROI* model.

The differences between the two models will be detailed below, but these differences focus exclusively on the technologies responsible for producing electricity from different resources. These technologies are a total of 12 of the 96 technologies that make up the models. These technologies and some of the abbreviations used in the model are: nuclear (Nuclear), natural gas combined cycle (CCGT), carbon ultra-super-critical (Coal US), integrated gasification natural gas and coal combined cycle (Coal IGCC), photovoltaic (PV), onshore and offshore Wind, Geothermal, mini-hydro (Hydro River) and Solar Thermal (ST Power). All these technologies have been briefly explained, when their EROI values have been presented.

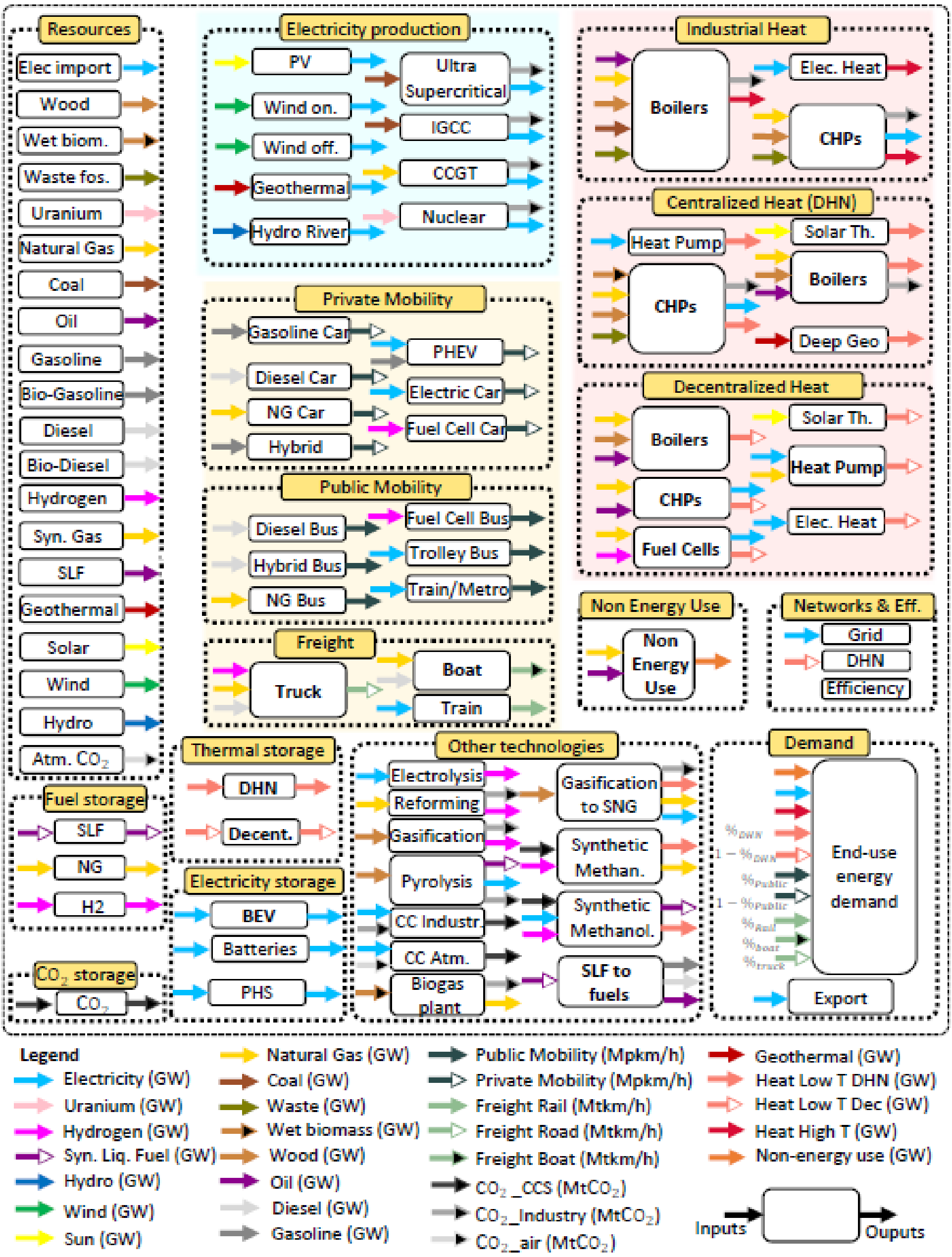

Figure 3.1 – Application of the LP modelling framework to the Belgian energy system. Technologies (in **bold**) represent groups of technologies with different energy inputs. Abbreviations: synthetic liquid fuel (SLF), Atm. (atmospheric), hydrogen (H_2), photovoltaic (PV), integrated gasification combined cycle (IGCC), combined cycle gas turbine (CCGT), carbon capture and storage (CCS), combined 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.). [34]

3.1.1 *Original* model

In this model, the total annual system emissions (GWP_{tot}) are calculated, as shown in Equation 3.2, as the sum of the resource-related emissions (GWP_{op}) and the emissions associated with the construction of the electricity-producing technologies (GWP_{constr}). The first term takes into account the production, transport and combustion of resources. The second term is obtained by studying the life cycle (LCA) of the different technologies, to obtain the CO_2 emissions in the construction of 1 GW, and then dividing it by the lifetime of the technology. Table 3.1 summarises the CO_2 emissions specific to each resource, it is assumed that resources not present in the table, such as wind, geothermal, etc., have negligible CO_2 emissions, while Table 3.2 shows the different GWP_{constr} values used for the different technologies.

$$\mathbf{GWP_{tot}} = \sum_{j \in TECH\ OF\ EUT["ELECTRICITY"]} \frac{\mathbf{GWP_{constr}}(j)}{lifetime(j))} + \sum_{i \in RES} \mathbf{GWP_{op}}(i) \tag{3.2}$$

Resources	**gwp_{op} [ktCO$_2$ /MWh]**
Electr.(import)	482
Gasoline	345
Diesel	315
LFO	312
NG	267
Biomass	12
Waste	150
Coal	401
Uranium	4

Table 3.1 – The CO_2 equivalent emissions for different fuels and metrics. The emissions are given for the impact of the production, transport and combustion of the resources. CO_2 emissions related to the production of the electricity imported are accounted for in the country producing. No difference is made between wood and wet biomass. Based on GWP100a—IPCC2013.

Technologies	gwp_{constr} [ktCO$_2$ /GW]	lifetime [year]
Nuclear	707.9	60
CCGT	183.8	25
Coal US	331.6	35
Coal IGCC	331.6	35
PV	2081.4	25
Wind Onshore	622.9	30
Wind Offshore	622.9	30
Mini-Hydro	1 262.8	40
Geothermal	24 929.1	30

Table 3.2 – GWP$_{constr}$ values used for the different technologies. Global warming potential (GWP) emissions for the construction of technologies [kgCO$_2$-eq./kW], with respect to main output of the technology. Greenhouse gas emissions including the technology construction only. For GHG emissions, LCA data are taken from the EcoInvent database v3.2 using the 'allocation at the point of substitution' method. GWP is assessed with the 'GWP100a - IPCC2013' indicator.

Only the emissions associated with the construction of these technologies have been taken into account, since in the *EROI* model, this value is replaced by the energy necessary for their manufacture, and therefore the GWP$_{constr}$ of the rest of the technologies is considered in both cases and, since it is the same, it is omitted for the rest of the study.

3.1.2 *EROI* model

As stated above, the GWP$_{constr}$ of the technologies that produce electricity have been replaced by the energy invested in that construction. Therefore, the total emissions (GWP$_{tot}$) of the system would be equal to the emissions associated with the resources (GWP$_{op}$), as seen in Equation 3.3.

$$\mathbf{GWP_{tot}} = \sum_{i \in RES} \mathbf{GWP_{op}}(i) \tag{3.3}$$

On the other hand, the concept of energy invested (e$_{inv}$) is introduced into the model. This is the way we introduce the EROI. Invested energy refers to the energy, in our case it is all counted as electricity, needed for the production, transport and installation of the technologies (and in some cases demolition). These values have been very difficult to find, as most LCA databases do not show the energy invested in construction processes. For the technologies for which values have been found, detailed values can be found in the Appendix B, for the rest of the values the EROI value (Eq.3.4) and the usual capacity factor (cp) of the technology in Belgium have been used to obtain them, the values can be found in Table 3.3.

$$\mathbf{EROI} = \frac{Lifetime\ energy\ generation}{Energy\ invested} \tag{3.4}$$

Technologies	$\mathbf{e}_{inv}$ [GWhe/GW]
Nuclear	7 236
CCGT	6 648
Coal US	7 258
Coal IGCC	7 158
PV	2 143
ST Power	4 979
Wind Onshore	3 665
Wind Offshore	4 032
Mini Hydro	712
Geothermal	19 030

Table 3.3 – e_{inv} values used for the different technologies. The energy invested of the PV, Solar Thermal and Wind technologies have been obtained from studies on their LCA (presented in Appendix B), while for the rest they have been taken from their most widely accepted EROI values (EROI) presented in Table 2.1. For the Coal IGCC technology, the same EROI has been used as for Coal US, due to the lack of data.

Once the values of the energy invested have been obtained, they are used to calculate the extra electricity demand that the installation of these technologies would imply in the final demand (EUD). As shown in Equation 3.5, the energy invested (e_{inv}) is multiplied by the installed capacity of each technology (**F**) and divided by its lifetime. In this way the extra system demand is spread evenly over the lifetime of the technology, as is the investment cost (C_{inv}) and the construction emissions (GWP_{constr}) of the technology.

$$\mathbf{ExtraDemand}("ELECTRICITY") = \sum_{j \in TECH\ OF\ EUT\ "ELECTRICITY"} \frac{\mathbf{F}(j) * e_{inv}(j)}{lifetime(j)} \quad (3.5)$$

Before including the extra demand in Equation 3.6, it had to be divided by 8 760 hours (total hours in a year), so that the programme can include it in the hourly calculations it carries out. In this way we obtain the extra demand variable as a function of the typical day (td) and hour (h).This equation expresses the balance for each layer: all outputs from resources and technologies (including storage) are used to satisfy the EUD (l) or as inputs to other resources and technologies.

$$\sum_{i \in RES \cup TECH \setminus STO} f(i,l)\mathbf{F_t}(i,h,td) + \sum_{j \in STO} (\mathbf{STO_{out}}(j,l,h,td) - \mathbf{STO_{in}}(j,l,h,td)) - \mathbf{EndUses}(l,h,td) - \mathbf{ExtraDemand}("ELECTRICITY", h, td) = 0 \quad \forall l \in L, \forall h \in H, \forall td \in TD \quad (3.6)$$

3.2 Case Study: Belgium

Long-term planning models cannot be validated, as they model an unknown future. However, the performance and consistency of these models can be demonstrated by representing the past or present state of the system. It has been decided to choose Belgium as the study country, and as the validation and reference system, the Belgian system in the year 2015. The validation and study has been previously carried out by Gauthier Limpens [35]. For the scenarios that have been simulated a in this study, the data projected for Belgium in 2035 have been used.

3.2.1 Belgium System 2015

The Belgian energy system in 2015 is a fossil-based system, with traditional fuels accounting for more than 93% of primary energy, with low electrification of heat (6.6%) and transport (1.3%) and marginal deployment of promising technologies such as district heating network (2%) and heat pumps (0%) (Eurostat and Belgian Heat Roadmap data). In addition to fossil fuels, uranium (18.6%), waste (1.3%) and electricity imports (3.3%) are counted as traditional fuels.

In Table 3.4, a comparison between the model outputs obtained in Gauthier Limpens' study and the values reported for the year 2015 from Eurostat can be seen. Overall, the ESTD model gives an accurate picture of the primary energy demand and GWP emissions of the Belgian energy system.

For energy consumption, the model provides an accurate approximation to the reported 2015 values. The ESTD slightly underestimates primary energy consumption. Small variations may come from minor unaccounted contributions or differences in the accounting method. These differences are explained more precisely in the previously mentioned study.

Total GWP emissions from fuel combustion in 2015 were between 92.5 (IEA) and 97.8 $MtCO_2$ (Eurostat). Emissions from fuel combustion are accurately estimated by the model (96.9 $MtCO_2$). However, as for the GWP_{constr} calculation, if emissions related to fuel production and transport are taken into account (IPCC2013- GWP100a metric), the Belgian emissions increase to 156 $MtCO_2$ /y.

Technology	2015	Model	Δ	Δ rel.
Gasoline		22.16		
Diesel		59.91		
Oil		110.01		
N.E. oil	84.84	84.65		
Total Oil	**280.93**	**276.72**	4.2	1.5%
Gas	150.56	153.02		
N.E. gas	11.45	13.78		
Total Gas	**162.02**	**166.8**	**4.78**	**2.95%**
Coal	34.5	33.35		
N.E. coal	2.49			
Total Coal	**36.98**	**33.35**	3.63	9.81%
Nuclear	**78.11**	**65.78**	12.32	15.78%
Elec. Imp.	**20.94**	**20.97**	**0.03**	**0.13%**
Solar PV	3.05	3.38	0.33	10.86%
Solar th	0.26	0.27	0.01	5.37%
Wind	5.56	5.01	0.55	9.9%
Hydro	0.32	0.37	0.01	15.06%
Geothermal	0.04	0.03	0.12	18.58%
Wood	15.34	16.12		5.05%
Biogas	2.66	2.53		4.58%
Biofuels	3.33	3	0.33	9.95%
Total RE	**30.55**	**30.71**	**0.16**	**0.51%**
RE.	4.39			
non RE.	6.32			
Total Waste	**10.71**	**8.97**	**-1.74**	16.28%
Total Energy	**620.24**	**603.31**	16.94	2.73%

Table 3.4 – Model verification: model outputs vs. actual 2015 values for the Belgian energy system. Δ rel stands for the relative difference. Abbreviations: non-energy (N.E.), electricity imports (Elec. Imp.). Results from the study [35].

3.2.2 Belgium System 2035

In order to carry out the study of the Belgian system in 2035, some simplifications have also been necessary to represent complex sectors or demands, and some technologies have also been added. The main simplifications are as follows: non-energy demand has been simplified to natural gas energy demand; aviation demand has been simplified to mobility demand and non-EU aviation mobility is not accounted for; synthetic fuel production is aggregated into three molecules: H_2, methane and methanol.

Additional constraints are added and some parameters of the energy system are modified respect to the model used for 2015. Firstly,the mobility shares with those expected in 2035 have been updated. The fuel and technology efficiencies have also been updated, the new values correspond to the expected future improvements of those technologies. Also, certain technologies that are considered to be irrelevant in 2035 have been removed, as more efficient technologies are currently available, e.g. oil turbine, incinerator and woody biomass power plant. An additional EUD, cooling, has been added. This EUD has been divided into two EUTs, space cooling and process cooling.

Finally, the expected end-use demand (EUD) values for 2035 have been updated. The European Commission published a report giving an overview of numerical values of the future energy system, such as annual final energy consumption or fuel used per sector in 2035. Based on the final energy consumption, we estimate the annual end-use demand used as input parameter in the model. Table 3.5 summarises the differences between the EUD in 2015 and in 2035. Demand increases, except for the heating sectors. This growth is related to the increase in population (+19.2%) and gross domestic product (GDP) (+44.2%) over the same time period.

End Use Demand	2015	2035	Δ	Units
Electricity	81.6	83.2	1.6	TWh
High Temp. Heat	84.7	51.8	-32.9	TWh
Low Temp. Heat	136.2	151.9	15.7	TWh
Cooling	-	20	20	TWh
Mobility Passenger	158	194	36	Mpkm
Mobility Freight	66	98	32	Mpkm
Non-Energy	98.4	102.3	3.9	TWh

Table 3.5 – Comparison of EUD for the years 2015 and 2035. The value of cooling in the 2015 data is included in the electricity EUD . Abbreviations : temperature (Temp.),millions of passenger-km (Mpkm).

3.3 Scenarios 2035

As mentioned above, the different scenarios that have been studied have been constructed on the basis of limiting the CO_2 emissions (GWP_{tot}) of the system. The emissions that have been limited are the 2015 emissions, which were 156 $MtCO_2$-eq. A total of four scenarios have been proposed for 2035: a 50% reduction, a 75% reduction and an 85% reduction. This would equate to total emissions of 79 $MtCO_2$/y, 39 $MtCO_2$/y and 23.4 $MtCO_2$/y respectively. All scenarios have been simulated with the *Original* model and the *EROI* model. In addition, the 75% reduction scenario will be studied twice as detailed below. The critical input parameters for each of the scenarios to be studied, such as the renewable energy potential and the maximum capacity which can be install of each of the technologies, also are detailed in the section below.

3.3.1 Energy Potential

The energy transition relies on renewable energies, which makes their deployment potential a critical parameter. Therefore, assessing the country's renewable resource potential in 2035 becomes a key factor in the study. The main resources are expected to be wind, solar and biomass.

Research on geothermal potential in Belgium is in its early stages. A study conducted by VITO assesses the potential in Belgium at 3.1 GW_e, although others extend it to 4 GW_e. However, due to the lack of reliable sources, we consider the maximum potential to be 3.1 GW_e [36].

As for PV, the biggest obstacle to calculating its maximum potential is to make an approximation of the space available in the territory for its installation. The same assumptions as in the study by G. Limpens have been used to carry out the study. Assuming that there are currently 250

km^2 of well oriented roof space available (which represents almost one hundredth of the surface of Belgium (28 635 km^2) and that the efficiency in 2035 will be 23% with an average daily total irradiation - similar to historical values - of 2 820 Wh/m^2 in Belgium. If we add land-based PV to this estimation, the upper limit becomes 59.2 GW of installed capacity. This limit is in line with a study carried out by the Belgian transmission grid operator (TSO) which proposes 40 GW [35].

Studies on Wind energy potential have been carried out in both the Flemish and Walloon regions to assess the maximum onshore wind capacities (ICEDD, 2009 and VITO, 2011). These studies give a potential of slightly less than 9 GW. However, if some constraints were relaxed, such as the exclusion of forested areas, or if some social priorities were to change (e.g. prioritising energy production over co-visibility constraints), the maximum onshore capacity could be more significant. In this study, land-based potential is assumed to increase to 20 GW [37].

Different studies have tried to estimate the offshore potential of the Belgian maritime area. The theoretical potential is estimated in the range of 12.6-16.8 GW, considering an average density of 6-8 MW/km2. This maximum energy potential estimates that the Belgian continental shelf is covered by wind turbines except for some specific areas reserved for maritime navigation, military exercises and some visual constraints. This estimate should be considered as a theoretical potential, as other uses (secondary shipping routes, aquaculture, exploration of natural areas) and constraints (seabed soil properties) have not yet been taken into account. As the available potential provided by the study is not very "realistic" for the contiguous Belgian shelf, it has been decided to limit, by hypothesis, the potential to 8 GW [37].

For the other technologies, less precise assumptions have been made. Since the hydropower potential is very limited and almost fully exploited, the potential has not been modified. As for the maximum capacity of natural gas and coal-fired installations, they have been given an infinite limit, but instead it will be left to the programme to decide how much to install.[35]

Finally, for the maximum capacity of nuclear power, two scenarios have been considered. The first scenario takes into consideration that the lifetime of the nuclear power plants has been extended. The potential would be 5.92 GW, as it represents the installed capacity at Doel and Tihange. This assumption has been taken into account in the scenarios where a reduction of 50%, 75% and 85% of CO_2 emissions has been taken into account. While the scenario where the plants are closed as planned in 2025, only a 75% reduction will be realised. Extending their life would entail an economic, energy and CO_2 cost. A brief summary can be found in the Table 3.6.

For Coal, as for imported electricity, it has been decided to limit the amount of resources that can be imported into the system. For the former it has been limited to 33 TWh, the amount imported in 2015. For electricity, it has been limited to 5.8 TWh, the historical average of net electricity imports in Belgium between 2003 and 2010. The maximum resources of Wet-Biomass, Wood and Waste will also be the same as in 2015. In addition, imports of RE-Fuels such as Biodiesel, H_2 or SNG will be restricted to zero. For the rest of Renewable resources and Natural Gas, there is an unlimited amount that the system is able to import. A brief summary can be found in the Table 3.7.

Technologies	f_{min} [GW]	f_{min} [GW]
Nuclear	0	5.92
CCGT	0	∞
Coal US	0	∞
Coal IGCC	0	∞
PV	2.916	59
Wind Onshore	1.249	20
Wind Offshore	0.712	8
Hydroelectric	0	0.001
Mini-Hydro	0.171	0.172
Geothermal	0	3.1

Table 3.6 – Summary of the maximum capacity in 2035 of the technologies used in the 50%, 75% and 85% CO_2 emission reduction scenarios (except for the 75% reduction scenario with no nuclear energy). f_{min} represents the current installed capacity of each of the renewable technologies. For the rest, the value is 0, as extending their life would imply an extra cost in terms of energy, CO_2 and money.

3.3.2 Sensitivity Analysis of EROI

As a wide variety of EROI values for different technologies were found when searching for EROI values, it was decided to carry out a sensitivity study. This would give a better insight into the impact of the EROI when deciding which technologies to use for the optimal system.

For this purpose, it has been decided to use the most extreme values of EROI, which we have previously called $EROI_{min}$ and $EROI_{max}$ in the Table 2.1 , to obtain new values of e_{inv} . These values, according to the Equation, are inversely proportional to the initial EROI value, i.e. for $EROI_{min}$ the value of the energy invested will be maximum, and the opposite for $EROI_{max}$ where the value of e_{inv} will be minimum.

Using the values of the Table 3.8 in the *EROI* model, all the simulations of the previously mentioned study have been repeated. This adds another eight new simulations to the study.

Resources	Potential [TWh]
Electr.import	5.8
Gasoline	∞
Diesel	∞
Bioethanol	0
Biodiesel	0
LFO	∞
NG	∞
SLF	0
SNG	0
Wood	23.43
Wet Biomass	38.88
Coal	33
Uranium	∞
Waste	17.83
H_2	0
Wind	∞
Solar	∞
Hydro.	∞
Geo.	∞

Table 3.7 – Maximum quantities of each resource that the system is able to import in 2035 for all scenarios.

Tech	$\mathbf{e}_{inv\ max}$ [GWh/GW]	$\mathbf{e}_{inv\ min}$ [GWh/GW]
Nuclear	29 749	5 950
CCGT	26 593	6 648
Coal US	13 306	5 323
Coal IGCC	13 122	5 249
PV	7 300	2 190
Solar Thermal	5 475	1643
Wind Onshore	3 650	1 314
Wind Offshore	4 088	1 472
Mini Hydro	855	449
Geothermal	30 660	4 717

Table 3.8 – $E_{inv,max}$ and $E_{inv,min}$ use for the sensitivity analysis. As mentioned above, the value of $E_{inv,max}$ is obtained from $EROI_{min}$ and the value of $E_{inv,min}$ from $EROI_{max}$.

3.4 Hypothesis of the Study

Before presenting the results of the study and discussing them, this section provides a brief summary of all the hypothesis that have been taken into account for the simulations. All of these have been discussed throughout this report.

The sixteen simulations carried out (four with the *Original* model, and four more with the *EROI* model, plus the eight belonging to the sensitivity study) are subjected to these hypotheses.

In both models:

1. Emissions associated with the construction (GWP_{constr}) of technologies that do not produce electricity are taken into account.
2. The possibility of making electricity through cogeneration has been blocked, due to a lack of EROI values.
3. Imports of electricity and coal have been limited to those of 2015. Imports of some resources have also been restricted.
4. The EUDs of 2035 and the maximum capacities of the technologies in that year have been assumed.
5. The non-energy EUD will be supplied by natural gas only.
6. The aviation demand has been simplified to mobility demand and the extra-EU aviation mobility is not accounted for.

In the *EROI* model:

1. Only the EROI of technologies that produce electricity is used.
2. All energy invested for the production of new technologies will be accounted for in the EUD of electricity.
3. The extra demand from this production of technologies will be spread evenly over the hours of the year.
4. The energy invested for Nuclear, CCGT, Coal, Geothermal and Hydro technologies have been obtained from the EROI values (as no more accurate values have been found).

4 Results

The results of the simulations for each of the scenarios are presented below. The first results presented are the scenarios that take into account only the reduction of GWP, without taking into account the different EROI values. Then a comparison is made between *Scenario 75* with and without nuclear energy. Finally, the results of the simulations carried out with different EROI values are presented.

From this section until the end of the study, the different scenarios are referred to as follows in order not to be repetitive. The scenario where emissions are limited to 50% is referred to as *Scenario 50*, likewise the scenarios where the reductions are 75% and 85% are called *Scenario 75* and *85* respectively.

A more detailed version of the results obtained can be found in the Appendix D.

4.1 CO_2 Emissions Reduction

First, we examine the CO_2 emissions of each model, as this is the factor we have constrained to differentiate the scenarios. In the only scenario where the imposed emissions limit is not reached is *Scenario 50* (78 $MtCO_2$ -eq/y); in this scenario the emissions are 60.4 $MtCO_2$ in the *EROI* model, and 61.5 $MtCO_2$ for the *Original* model, of which 3.5 $MtCO_2$ corresponds to emissions from the construction of technologies (GWP_{constr}). In the remaining scenarios the limit is reached, with GWP_{constr} rising from 3.5 $MtCO_2$ to 7 $MtCO_2$ (18% of GWP_{tot}) in the *Scenario 75*, and to 8 $MtCO_2$ for the *Scenario 85*, where the limit is 23.4 $MtCO_2$ (35% of GWP_{tot}). Figure 4.1 shows in detail the CO_2 emissions of each scenario and the technologies that cause them.

If we look at the costs, which are minimised in each of the simulations. We see that between *Scenario 50* and 85 there is a cost increase of 99 000 Million € (220%) for the *Original* model and 24 000 Million € (53%) for the *EROI* model, with the cost of the first scenario being 45 000 Million €. In *Scenario 50*, the difference between the two costs is only a 1.1% increase for the *EROI* model; whereas in *Scenario 85*, it is the *EROI* model that is 51.6% cheaper. This may come as a surprise, but although the cost of the electricity sector is higher for the *EROI* model, the cost overrun of the Low Temp. Heat sector and the Freight Mobility sector in the *Original* model is much higher. This suggests that the more emissions are reduced, the greater the difference between the costs of the *Original* and *EROI* models. And also that the lower the emissions, the more expensive the optimal system proposed by the *Original* model, largely due to the installation of solar power plants to produce Heat and the use of low polluting technologies for Mobility, as explained below. In Tables D.1-D.12-D.23, the cost of the technologies installed in each of the sectors is detailed.

In terms of the resources used by the proposed systems, the first thing that strikes us is that only the systems with emissions of 23.4 $MTCO_2$ use more resources than the 2015 system, and it should also be noted that none of the proposed systems use fossil fuels such as oil or gasoline. These two facts are largely related; while in 2015 276 TWh of fossil energy (Oil, Diesel and Gasoline) are used, in 2035, they are replaced by other technologies with lower Primary Energy consumption, based on lower-emission sources such as Nuclear, Natural Gas and Renewable Energies. Only in *Scenario 85*, where a large part of the NG has to be replaced by Solar energy, is when the system consumes more Primary Energy than in 2015. So, a certain pattern can be seen between the different proposed systems for 2035: the lower the CO_2 emissions, the higher the primary energy consumption, with the maximum in the *Scenario 85* with 675 TWh for the *Original* model and 663 TWh for the *EROI* model, this is accompanied by a notable increase in the use of solar resources in these cases. Specifically, the CCGT has been replaced by PV panels, in addition to the installation of decentralised solar thermal heating for the Low Temperature Heat demand. The minimum is in *Scenario 50* where primary energy consumption amounts to 474 TWh in the *Original* and 491 TWh in the *EROI* model, a reduction of 21% and 18% compared to 2015 consumption respectively. It is the only scenario where less resources are used by *Original* model than by *EROI* model. In this case, fossil fuels are offset by +53 TWh from Nuclear and +63 TWh from renewable compared to 2015. The resources used by the electricity sector are detailed in Table 4.2, and those used by the other sectors can be found in Table D.10-D.21-D.32.

Below is a small breakdown of how the different demands have been met in the different systems proposed, a more detailed picture of the different technologies deployed can be seen in the Appendix D. Figure 4.2 shows the total Primary Energy consumed in each of the scenarios.

	Model\Scenario	**50**	**75**	**85**	
Cost	**Original**	**45 349**	**51 353**	**144 121**	**[M€]**
	EROI	**45 860**	**50 072**	**69 769**	
GWP_{op}	Original	58 011	31 995	15 228	[ktCO_2 -eq]
	EROI	60 443	39 000	23 400	
GWP_{constr}	Original	3 496	7 005	8 172	[ktCO_2 -eq]
	EROI	0	0	0	
GWP_{tot}	**Original**	**61 507**	**39 000**	**23 400**	**[ktCO_2 -eq]**
	EROI	**60 443**	**39 000**	**23 400**	

Table 4.1 – Summary of costs and emissions for each of the models in each of the scenarios. As explained above, scenarios *50*, *75* and *85* refer to the percentage reduction in CO_2 emissions. The *Original* model is the current ESTD model, and the *EROI* model is the one that incorporates our modifications. Finally, the GWP_{constr} and GWP_{op} are the emissions of CO_2 gases in the construction and operation of the different technologies. Figure 4.1 shows in detail the CO_2 emissions of each scenario and the technologies that cause them.

Electricity Demand: 83.2 TWh

Electricity demand is the most complex to meet of all the scenarios. The maximum import of electricity occurs in *Scenario 50*, the only scenario where the imposed limit of 5.8 TWh is reached. For *Scenario 75*, the *Original* model and the *EROI* model continue to import electricity with 1.7 TWh and 5 TWh respectively. While in *Scenario 85*, this possibility is discarded. What remains constant throughout all scenarios and models is the use of nuclear power, which always reaches the maximum capacity of 5.92 TWh and produces 44 TWh while consuming 118 TWh of Uranium, is the first source of electricity in the first two scenarios, and the second in *Scenario 85*. CCGT and coal-fired power plants vary the most across scenarios and models. In

Scenario 50, both models rely on these plants, installing 0.9 GW in the *Original* model (2.84 TWh) and 1.92 GW in the *EROI* model (8.59 TWh), in *Scenario 75* only 0.5 TWh are produced with CCGT in the *Original* model, while none are produced in the *EROI* model. This is due to the high CO_2 emissions that this technology emits when operating (GWP_{op}), although the construction emissions (GWP_{constr}) and energy invested (e_{inv}) is lower than the replacement technologies. The same is true for coal-fired plants, which are only present in *Scenario 50*. Finally, renewable technologies are gaining more and more weight as CO_2 emissions decrease, while wind and geothermal technology installations are at their highest in all optimal systems, solar energy technologies increase considerably. These go from using 6.7 TWh and 14.4 TWh for the *Original* and *EROI* models respectively in *Scenario 50*, to approximately 190TWh for both models in *Scenario 85*. This implies that the system goes from not installing any new solar technologies compared to 2015, to reaching the maximum limit of 59.2 GW. Throughout the scenarios, PV technology is the least interesting to install in the *Original* model due to its high cost in construction emissions. Similarly, the *EROI* model favours other renewable technologies over solar, as they are cheaper and more productive. It should also be noted that in *Scenario 85*, the models propose systems where the maximum capacity of all electricity producing technologies is installed, with 100.6 GW installed. Figure 4.3 shows the amount of electricity produced and the amount of electricity used for the EUD of Electricity. A summary of the primary energy consumed by the electricity sector is given in the Table 4.2. Appendix D.1, D.2 and D.3 provides a complete picture of the electricity sector for scenarios *50*, *75* and *85* respectively.

	Scenario 50		**Scenario 75**		**Scenario 85**	
Model	*Original*	*EROI*	*Original*	*EROI*	*Original*	*EROI*
Elect. Import	5.8	5.8	1.71	4.67	0	0
NG	4.51	13.64	0.86	0	0	0
Coal	6.39	6.39	0	0	0	0
Uranium	119	119	119	119	119	119
Wind	63.45	63.47	63.53	62.68	63.53	63.53
Solar	6.72	14.37	101.77	98.98	195	191.03
Hydro	0.117	0.117	0.117	0.117	0.118	0.118
Geo.	23.35	23.35	23.35	23.35	23.35	23.35
TOTAL	**229.35**	**246.15**	**310.34**	**308.80**	**401**	**397.03**

Table 4.2 – Summary of the Primary Energy consumed by the electricity sector in the different scenarios. It can be seen that as CO_2 emissions are reduced, the optimal systems stop importing NG, Coal and Electricity. On the other hand, the use of Solar Energy increases considerably, thus increasing the total energy consumption. All values are in TWh.

High Temperature Heat Demand: 51.8 TWh

All models use all the Waste that the system imports (17.83 TWh) to cover 28% of the total demand. The use of wood is also common, in the *Scenario 75*, all the imported wood (23.4 TWh) is used to cover a total of 39% of the demand, while the remaining 33% is covered by electricity. In the rest of the scenarios less wood is consumed for this purpose prioritising electricity, except for the *Scenario 50* where it is the only scenario that uses wood waste and coal which covers 42% of the EUD. In the *Scenario 85* there is a big difference between the *Original* model and the EROI, while in the latter the use of wood is maintained, in the *Original* model 21 TWh of electricity is used to cover 72% of the demand, so we have a clearly electrified and less polluting system.

Low Temperature Heat Demand: 151.9 TWh

Only two resources are used for this demand: electricity and solar. In the first scenario (*Scenario 50*), the system is fully electrified and 47 TWh are used. For the other scenarios, solar is the predominant resource in the *Original* model, reaching 90% of the EUD in *Scenario 85*, with a total of 151 TWh used. In contrast, in the *EROI* model it is only 10% in *Scenario 75* (42% in the *Original* model) and becomes a consumption of 113 TWh in the *Scenario 85* (66% of the EUD). This is due to the fact that in the *Original* model, electricity is used for other purposes, such as High Temp. Heat (previous paragraph), as in these cases there is no less polluting method to meet the demand. That is why for Low Temp. Heat it is necessary to switch to solar energy instead of electricity, even the technologies are more expensive and require much more resources. The Table 4.3 shows this transition, as well as the values of Primary Energy consumed in each scenario.

Resource	Scenario 50	Scenario 75		Scenario 85	
		Original	*EROI*	*Original*	*EROI*
	P.E. (%EUD)	P.E. (%EUD)	P.E. (%EUD)	P.E. (%EUD)	P.E. (%EUD)
Electr.	47.34 (100%)	32.19 (58.6%)	44.52 (89,9%)	5.41 (9.7%)	19.19 (33.7%)
Solar	0	68.16 (41.4%)	16.31 (10,1%)	151.34 (90.3%)	113.29 (66.3%)
Total	**47.34 (100%)**	**100.36 (100%)**	**60.84 (100%)**	**156.75 (100%)**	**132.49 (100%)**

Table 4.3 – Summary of the Primary Energy consumed by the low temp. heat sector in the different scenarios. As discussed, there is a transition from a 100% electrified system to a mostly solar system. This change is much more extreme in the *Original* model. The value in parenthesis represents the percentage of EUD covered by that Primary Energy. All values are in TWh. Abbreviations: Primary Energy (P.E).

Passenger Mobility Demand: 194 Mpkm

One of the main resources used to cover the EUD is H_2 , this resource is not imported but produced by the system, through the reforming of Natural Gas or by Electrolysis using electricity. More about the procurement of Synthetic Fuels can be found in the Appendix C. H_2 covers 80% of the demand with 28 TWh. Electricity accounts for only 6% (2 TWh) as does Natural Gas (3.5 TWh), and the remaining 8% is covered by Diesel (3.7 TWh). Diesel is imported in *Scenario 75*, while in the other two scenarios it is obtained from Syntetic Liquid Fuel (SLF) which is produced by burning wood in Pyrolysis (5TWh). The only different system is the one obtained in the *Original* model in *Scenario 85*, in which H_2 is simply 55% (19.5 TWh) of the demand, while electricity is 45% (10TWh). This is due to the fact that natural gas imports are minimal and Diesel cannot be obtained from Pyrolysis (SLF) as wood is put to another use as explained below.

Freight mobility Demand: 98 Mpkm

In all optimal systems that have been found, 2 TWh of electricity is used to supply 25% of the demand. In *Scenario 50*, the remaining 75% is supplied by Natural Gas (29.7 TWh).

This is repeated in *Scenario 75* for the *EROI* model, while for the *Original* model 3.3 TWh of Natural Gas (30%) and 19.4 TWh of H_2 (45%) are used. This same configuration is used by the system proposed by the *EROI* model in *Scenario 85*. In this same scenario, the *Original* model proposes a system using 3 TWh of Diesel instead of natural gas. This Diesel is obtained from SLF, which is produced this time from the Synthetic Methanolation of H_2 and CO_2 (and electricity). This method makes it possible to use the CO_2 that has been produced and thus reduce the total emissions of the system to reach the set limit.

Non Energy Demand: 102.3 TWh

The entire EUD has been satisfied with Natural Gas. In most systems, the imported Natural Gas and Synthetic Natural Gas (SNG) obtained through Bio-methanation of the 38.88 TWh of Wet Biomass is sufficient, giving the system an extra 36.31 TWh. In *Scenario 85*, the system proposed by the *Original* model, imports and Bio-methanation cover 77% of the EUD, the rest is obtained by other methods. These methods are the gasification of SGN from all the wood that the system did not use for the High Temp. Heat, this method gives the system an extra 17 TWh and Methanation provides 6 TWh of SNG from H_2 and CO_2.

The electricity consumption by sector, explained in the previous paragraphs, is shown in the Table 4.4. Also in Appendix D.9, D.20 and D.31, the technologies installed for each sector and the resources used to meet the demands are shown in detail.

	Scenario 50		**Scenario 75**		**Scenario 85**	
	Original	*EROI*	*Original*	*EROI*	*Original*	*EROI*
Elect. Export	0	0	0.55	0.21	0	0
High Temp. Heat	0	0	17.02	16.96	37.37	21.04
Low Temp. Heat	47.34	47.28	32.19	44.52	5.41	19.19
Cooling	2.95	2.95	2.95	2.95	2.95	2.95
Mobility Passenger	1.91	1.91	1.91	1.91	10.15	1.91
Mobility Freight	1.67	1.67	1.67	1.67	1.67	1.67
Other	0	0	36.15[a]	16.72[a]	61.03[b]	58.39[a]
Storage[c]	0.28	0.25	0.25	0.31	0.06[d]	0.07
Total	**54.17**	**54.09**	**92.73**	**85.29**	**118.66**	**105.25**

Table 4.4 – Summary of electricity usage by sector in the different scenarios. It can be seen that as CO_2 emissions are reduced, the system is more electrified. The *Original* model allocates more electricity in the Passenger Mobility and High Temp. Heat sectors, as well as for Other functions. Although less in the Low Temp. Heat sector as shown in the Table 4.3. All values are in TWh.
[a] *Electrolysis*
[b] *Electrolysis + Syn. Methanolation + Syn. Methanation*
[c] *Hydro Pump Storage*
[c] *Storage in Lithium Batteries*

Finally, the total electricity produced in *Scenario 50* is 146.3 TWh for the *Original* model compared to 154 TWh (+5%) in the *EROI* model. This increase is exclusively due to the extra demand, since, as mentioned above, the electricity consumed to cover the rest of the EUDs is

54 TWh (the variations are exclusively due to electricity storage). The losses of both systems are between 8.9 TWh and 9.4 TWh, leaving 83.21 TWh (*Original*) and 90.56 TWh (EROI), i.e. approximately 57%, 59%, of the electricity produced is used to cover the EUD, i.e. 43% of the system proposed by the *Original* model and 41% of the *EROI* model is electrified.

For *Scenario 75*, the electricity produced amounts to 187.4 TWh for the *Original* model and 191.4 TWh in the *EROI* model (+2.11%). The differences are smaller between the models than in the previous scenario, and it is noteworthy that the *Original* model produces the least electricity although it uses the most for the rest of the EUD, with a consumption of 92 TWh compared to 85TWh for the *EROI* model. System losses are 11 TWh for both, leaving 83.21 TWh (*Original*) and 94.36 TWh (EROI). With the inclusion of the EUD HHT, the *Original* system is 56% electrified, compared to 51% for the EROI system, because the *EROI* model has to cover the extra electricity demand of just over 11 TWh.

In the last scenario, *Scenario 85*, although the installed capacity is the same, we observe small differences; the electricity produced is 214 TWh in the *Original* model (+14% compared to *Scenario 75*), 213 TWh in EROI (+12%). This time the *Original* model produces the most electricity, this is due to the fact that in this model the majority of the system is electrified, whereas for the *EROI* model there is an extra demand to be covered. The difference in the electricity produced is produced by solar thermal, even though the same capacity (3.8 GW) is installed, more ST collectors and storage are installed, allowing more heat to be captured and then converted into electricity. The *Original* system consumes 118 TWh while the EROI system consumes 105 TWh, this added to losses of around 13 TWh, means that each model uses 83.21 TWh (*Original*) and 95.14 TWh (EROI) of the electricity produced to cover the EUD of electricity. Thus the system proposed by the *Original* model is 62% electrified by 55% of the *EROI* model. The extra demand in this scenario also amounts to 12 TWh, with the extra demand caused by PV (5.2 TWh) and onshore wind (2.5 TWh) being the most important.

Further details on the extra demand values will be given in the EROI sensitivity study.

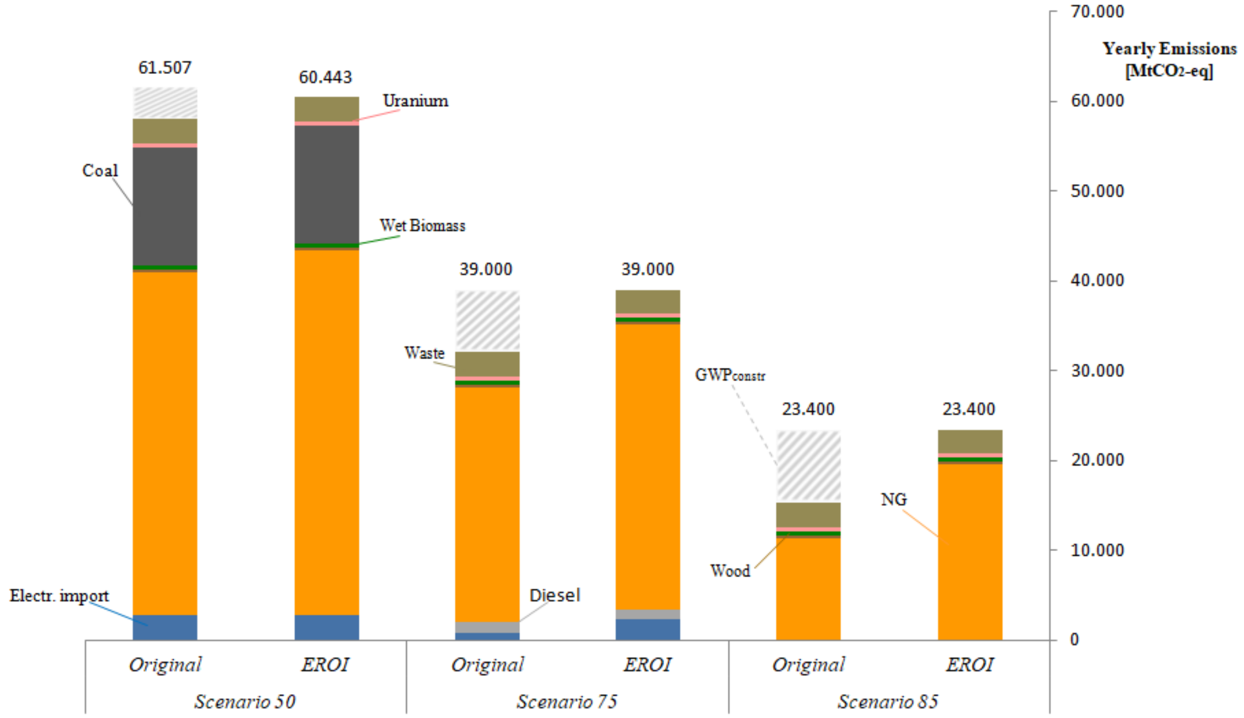

Figure 4.1 – Total CO_2 Emissions in each of the scenarios. As mentioned above, the *Original* model has lower operating CO_2 emissions (GWP_{op}). However, when these are added to the GWP_{constr} they are equal or even higher (Scenario 50). The Emissions due to Nuclear, Wood, Wet Biomass and Waste are constant in all scenarios with a total of 3.87 $MtCO_2$-eq/y. The value above each bar indicates the total yearly emissions of each model in $MtCO_2$-eq/y. Abbreviations: Electricity (Electr). A resource breakdown of the GWP_{op} for each scenario can be found in Tables D.2-D.13-D.24.

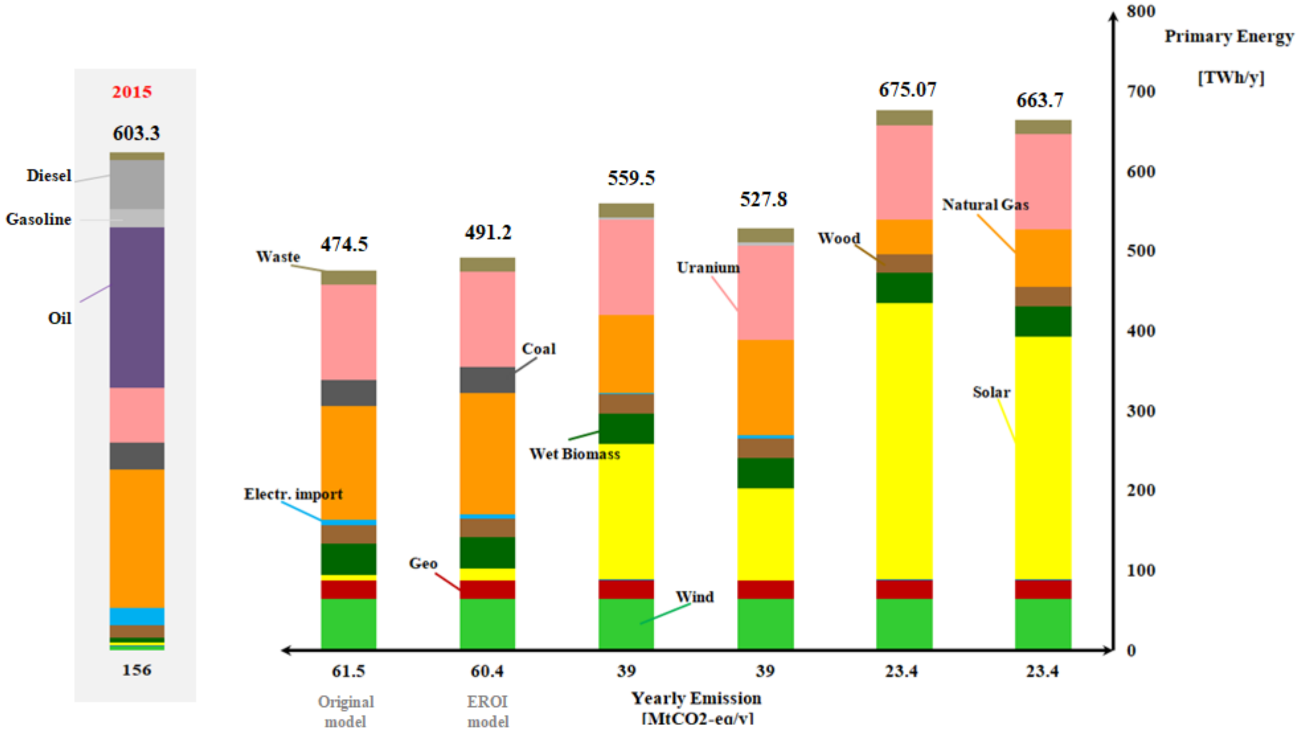

Figure 4.2 – Total Primary Energy consumed in each of the scenarios. The values on the horizontal axis represent the GWP_{tot} of each scenario. The models are ordered from the highest CO_2 emissions to the lowest, in case of having the same emissions, the values of the *Original* model are presented first, followed by the *EROI* model. The value above each bar indicates the total Primary Energy consumed in TWh/y. Abbreviations: Geothermal (Geo).

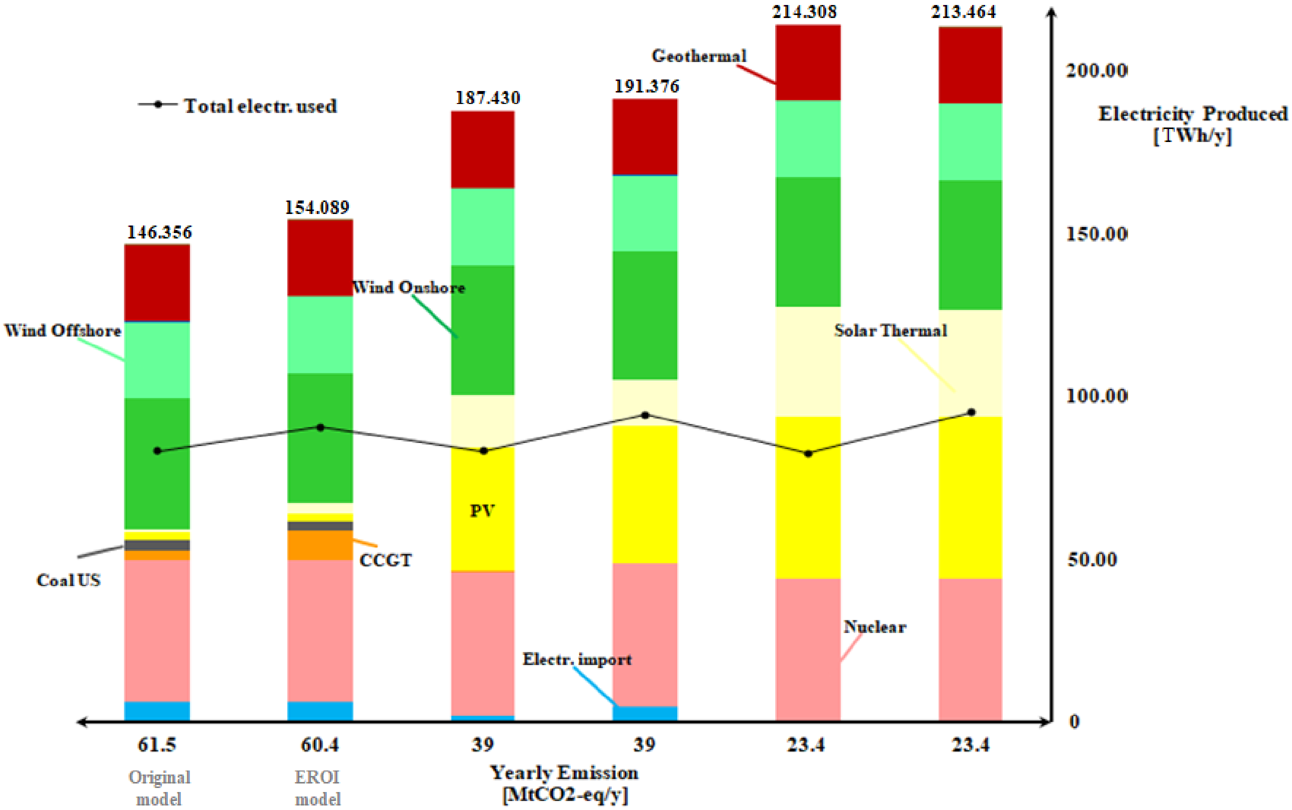

Figure 4.3 – Amount of electricity produced by each technology and amount of electricity used for the EUD of Electricity. The values on the horizontal axis represent the GWP_{tot} of each scenario. The models are ordered from the highest CO_2 emissions to the lowest, in case of having the same emissions, the values of the *Original* model are presented first, followed by the *EROI* model. The value above each bar indicates the electricity produced in TWh/y. The black line represents the amount of electricity used for the EUD of Electricity, also in TWh/y. The electricity not used to cover the demand and the extra demand of the Electricity sector is explained in the Table 4.4.

4.2 Nuclear Energy System

In order to assess the results of the *non − nuclear Scenario 75*, these will be compared with its nuclear counterpart, *Scenario 75*.

As in the other scenario, both models reach the imposed GWP limit of 39 MtCO_2. On this occasion, the *Original* model emits 21% of these gases due to the construction of the electricity production technologies, with a total of 8 MtCO_2 , which is 1 MtCO_2 more than in *Scenario 75*.

As for the cost of the optimal systems in the *non − nuclear scenario*, these costs are 73 000 Million € for the *Original* model and 65 590 Million € for the *EROI* model, which represents cost overruns of 22 000 Million € and 14 500 Million € compared to the same models in *Scenario 75*. Although the cost overrun for nuclear power plants is higher than for CCGT plants, the cost overrun is mainly due to the fact that not all the electricity produced by nuclear power can be covered by natural gas, but that other technologies using solar energy, which has a very high cost, must be used. These technologies consume between 1.8 and 2.4 times more energy than the same models in *Scenario 75*, this energy is mainly consumed by photovoltaic (PV), which have a maximum capacity (from the 45 GW and 50 GW that were installed in the *Original* and *EROI* models in *Scenario 75*), and in the case of the *EROI* model, this energy is also consumed in supplying 46% of the EUD of Low Temp. Heat.

For the rest of the resources used by the system, although the *non − nuclear scenario* stops consuming 118 TWh of uranium, there is an increase in the total energy consumed. The total energy consumed is 580 TWh in the *Original* model and 574 TWh in the *EROI* model, compared to 560 TWh and 528 TWh in *Scenario 75*. This increase is due, as mentioned above, to the increase in solar energy consumption, which is 331 TWh and 277 TWh, as the increase in natural gas consumption is barely 5 TWh in both models. The diesel consumed is imported in both scenarios, although it decreases by just over 1.5 TWh in the *EROI* model, this diesel is replaced by technologies that use electricity. On the other hand, H_2 is still produced within the system by means of Electrolysis and by the transformation of Natural Gas. Figure 4.4 illustrates this difference between the two scenarios.

Although the primary energy consumption is higher in the *non − nuclear scenario*, the electricity production is lower, which makes the optimal systems in this scenario less electrified. The difference in electricity production is approximately 12 TWh in both models, while the difference between the *Original* and the *EROI* model is only 3 TWh. Of the 174 TWh and 179 TWh produced, 50 TWh are produced by PV and 33 TWh by solar thermal, compared to only 54 TWh in the *Scenario 75* models. This, together with the 4.6 TWh produced by the CCGT plants in the *Original* model and 7.8 TWh in the model, and the 1.7 TWh lower electricity imports, makes the difference between the scenarios, taking into account the 44 TWh produced by nuclear. It is also interesting to note that the *non − nuclear scenario* systems find it more interesting to invest as little as possible in mini-hydropower than in CCGT plants.

The *Original* system consumes 81 TWh compared to 92 TWh for its 75 scenario counterpart, while the *EROI* model consumes 73 TWh compared to 85 TWh. This, together with losses of around 11 TWh, means that each model uses 83.21 TWh (*Original*) and 95.04 TWh (EROI) of the electricity produced to cover the EUD of electricity. Thus the proposed system, in the *non − nuclear scenario*, is 52% electrified in the *Original* model and 47% in the *EROI* model, 4% less than in *Scenario 75*. All these differences can be seen in the Figure 4.5.

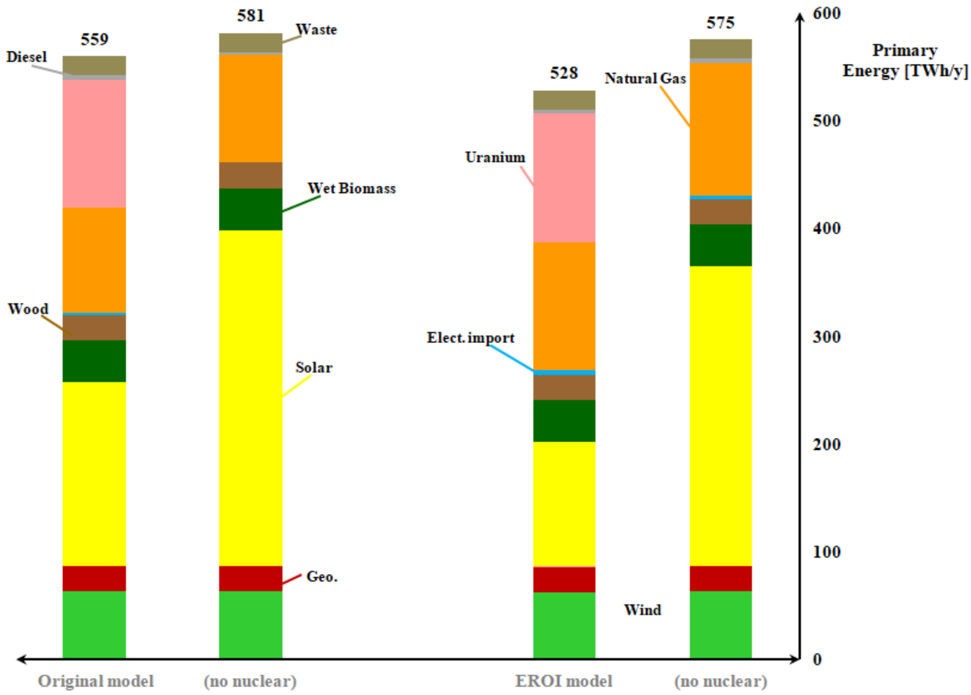

Figure 4.4 – Difference of Primary Energy consumed between the *Scenario 75* and the no nuclear scenario. On the left we have the values of the *Original* model for *Scenario 75*, on the right the values of the scenario without nuclear for the same model. The same is the case for the values on the right.The value above each bar indicates the total Primary Energy consumed in TWh/y. Abbreviations: Geothermal (Geo).

The extra demand in this scenario is almost identical to the other scenario at 11.8 TWh, with a difference of 700 GWh. This highlights the importance of nuclear power plants in the context of the *EROI* models, as they provide a large amount of electricity with very little extra consumption, as the 5.92 GW of nuclear equals the 9 GW of PV installed in the $non - nuclear\ scenario$.

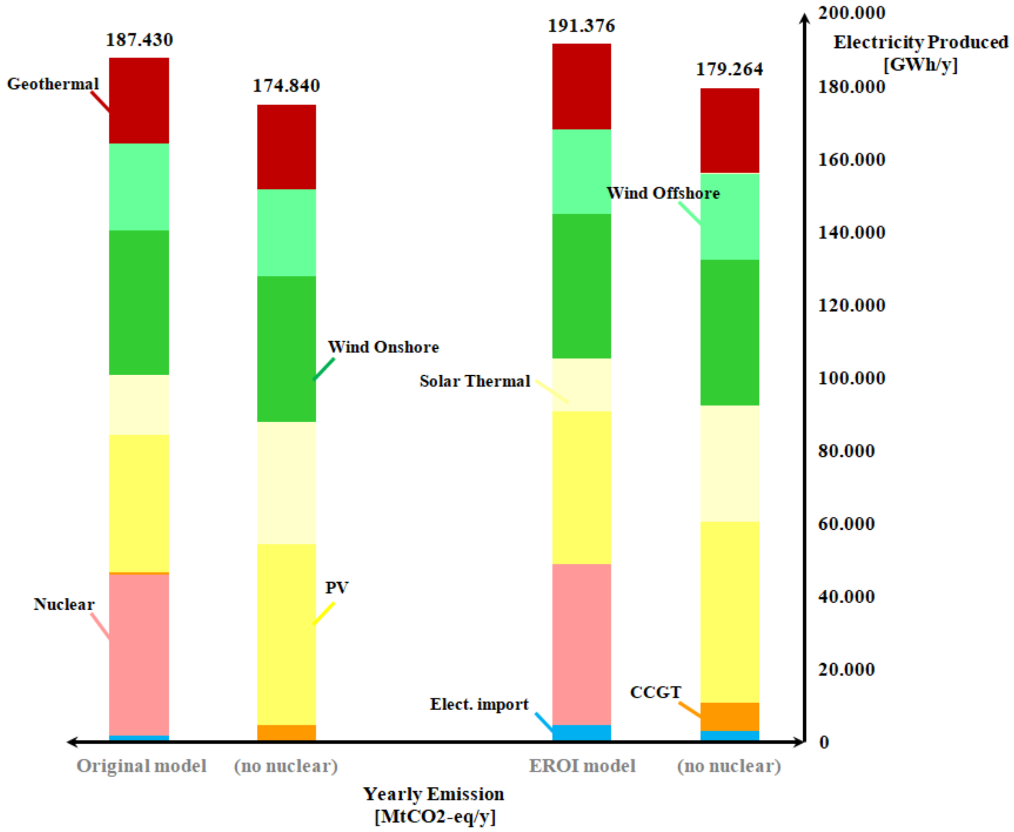

Figure 4.5 – Difference of electricity produced and the amount of electricity used for the EUD of Electricity between the *Scenario 75* and the no nuclear scenario. On the left we have the values of the *Original* model for *Scenario 75*, on the right the values of the scenario without nuclear for the same model. The same is the case for the values on the right. The value above each bar indicates the electricity produced in GWh/y. The black line represents the amount of electricity used for the EUD of Electricity, also in GWh/y .

4.3 Different EROI Systems

Scenario 50

There are no major differences between the different *EROI* models. There is only a 1% cost increase in the $EROI_{max}$ model and the $EROI_{min}$ model system is 0.7% cheaper compared to the *EROI* model. With regard to the GWP emissions of the systems, the variations are +/- 3%, with minimum emissions of 58.7 $MtCO_2$ occurring in the $EROI_{min}$ model.

The variations in emissions and cost are exclusively due to the difference in extra demand and the different EROI values used. This extra demand is supplied exclusively with energy from Natural Gas, as in the $EROI_{min}$ model, the programme considers it to be the most profitable technology in terms of Elect. Produced/ Electr. Invested over Coal US and PV plants. In contrast, for the $EROI_{min}$ model system, it is the Coal US plants that are considered to be the most interesting to invest in, and a greater amount of Coal is reserved to make electricity to the detriment of High Temp. Heat.

The rest of the variations in primary energy consumed and electricity produced are also caused by the differences in extra demand. The extra demand for the *EROI* model is 7.3 TWh ,double for model the $EROI_{min}$ model(14.5 TWh) and half for the $EROI_{max}$ model(3.7 TWh). This difference corresponds to the difference of electricity produced between each of the models.

There is a large difference between the extra demand values for each of the EROI values. With respect to Nuclear we see a variation of 2.2 TWh between the EROI normalised and the minimum. Regarding renewable technologies, we see a big difference between the extra demand for Wind Onshore when the EROI is maximum (2.48 TWh) and when it is minimum (0.893 TWh) and for geothermal, where we go from an extra demand of 0.487 TWh for the minimum, to 1.96 TWh for the normalised and 3.17 TWh for the maximum. Thus we have a total extra demand of 7.35 TWh for the EROI, 14.11 TWh for the $EROI_{max}$ (almost double) and only 3.21 TWh for the $EROI_{min}$.

Scenario 75

In this scenario there is a greater difference in the cost of each of the systems. In the *EROI* model, the total cost is 50 000 M€, for the $EROI_{min}$ model the cost amounts to 53 800 M€, 7.5% more expensive; while in the $EROI_{max}$ model the cost of the model is only 1.6% cheaper, with a total cost of 49 251 M€. This time the variations are not exclusively due to the difference in the extra electricity demand to be covered, but also to the different technologies that the system uses for each of the demands.

The main difference is observed in the high consumption of solar energy by the $EROI_{min}$ model, which is 190 TWh, 75 TWh more than the *EROI* model and 86 TWh more than the $EROI_{max}$ model. This remarkable difference is due to the fact that the system decides to invest 68 TWh to cover 42% of the Low Temp. Heat demand, compared to the 10% used by the *EROI* model (16 TWh) and the 2.25% (3.75 TWh) covered by the $EROI_{max}$ model. This use of solar energy clashes with the fact that the optimal system of the *EROI* model is the one that installs the least PV, with 25% less installed capacity than the others. This lack of capacity means that the $EROI_{min}$ system has the lowest installed capacity with a total of 79 GW compared to the 90 GW and 91 W of the *EROI* and $EROI_{max}$ models, although it is the only system that uses CCGT plants (0.5 GW installed) and the mini-Hydro, and also increases the solar collectors to increase the production of solar thermal energy.

The electricity produced is 191.4 TWh in *EROI*, 192.2 TWh in $EROI_{max}$ and 189.5 TWh in $EROI_{min}$. The differences between the models are smaller than in the previous scenario, and it is also striking that the "normal" and $EROI_{max}$ models produce the least electricity, which is exclusively due to the use of this electricity. In the *EROI* system, 85 TWh are consumed, of which the most important are the 45 TWh used to cover 90% of the EUD Low Temp. Heat and the 16 TWh used for the production of 14 TWh of H_2 by means of electrolysis. In terms of $EROI_{min}$, these values are transformed into 27 TWh for the remainder of EUD Low Temp. Heat and 21 TWh for the production of 18 TWh of H_2 through Electrolysis, for a total consumption of 73 TWh. The consumption of $EROI_{max}$ is very similar to the *EROI* model, with minor differences, the most notable being that the system is able to export 2 TWh of electricity.

The extra demand is very similar to the previous scenario as the installed capacity of most technologies does not change. It should be noted in this scenario that although the amount of PV installed for the $EROI_{min}$ model is almost 13 GW less than in the *EROI* model, this represents an extra demand of 10 TWh compared to 4.4 TWh in the *EROI* model. It is clearly seen how PV is a very unprofitable technology with low EROI values (you need to invest a lot of energy for little return), even comparing the extra demand of one scenario and another it is observed that the increase is due to the need to install many GW of PV to compensate for the limited Coal and NG installations due to the CO_2 limitation, which although they need a greater energy input per GW installed, less is required. The total extra demand is 11 TWh for *EROI* compared to 22 TWh for $EROI_{min}$ (+96%) and 6.884 TWh for $EROI_{max}$ (-38.2%) (difference in Wind technologies).

Scenario 85

In this scenario, as in *Scenario 50*, there are no major differences between the *EROI* model and the $EROI_{max}$ model, these are exclusively caused by the difference in the extra demand. We will therefore focus exclusively on the differences between the *EROI* model and the $EROI_{min}$ model. These differences are in the way resources are allocated.

In this scenario, the cost of the $EROI_{min}$ model skyrockets. It reaches 137 031 million €, almost three times the costs of the previous scenarios. This is also an increase of 105% over the cost of the *EROI* model, which is 66 635 Million €. Most of this cost overrun is in the technologies used to meet the demand for Low Temp. Heat and Mobility.

In terms of primary energy used, there is a considerable increase in the resources used in this scenario compared to the previous one, with *EROI* spending 663 TWh and $EROI_{min}$ 689 TWh (+7.25%). Less differences are observed between the different models than in the previous scenario. Natural Gas is a point of difference as there is a 4.5 TWh difference which means that the $EROI_{min}$ model can only cover 20% of the EUD for Freight Mobility, 10% less than the *EROI* model. There are also differences in H_2 consumption. In the $EROI_{min}$ model, 38TWh are used, obtained through Electrolysis, divided into 17 TWh for the EUD of passenger mobility (50% of the EUD) and another 19.5 TWh for Freight Mobility (45%). The remaining H_2 is stored. In contrast, in the *EROI* model, 49 TWh are produced by Electrolysis (very little of the NG) and the use in Passenger Mobility is increased to 27 TWh for the EUd of (80% of the EUD). Finally, as for solar energy, the *EROI* model uses 304 TWh, 191 TWh are distributed to produce 45% of the resources destined for this purpose and 37.5% of the electricity produced, and 113 TWh to cover 66% of the EUD of Low Temp. Heat. As far as the $EROI_{min}$ model is concerned, 332 TWh are used, 194 TWh to produce 38% of the electricity and 138 TWh to cover 80% of the EUD of Low Temp. Heat, 25 TWh more.

The installed capacity of the electricity system in all models is the same: 100 GW, this capacity is equivalent to the maximum capacity of all technologies, except for CCGT and coal-fired plants. As for the electricity produced we observe small differences; the electricity produced is 213 TWh in $EROI$ and 217 TWh in $EROI_{min}$. The differences are small, moreover the $EROI_{min}$ model is the one that produces more electricity, this is due to the fact that there is a higher extra demand to be covered. The difference in electricity produced is produced by Solar Thermal even though the same capacity (3.8 GW) is installed, this is due to the fact that in the $EROI_{min}$ model more ST collectors are installed to produce electricity when the sun is not enough, plus the $EROI_{min}$ model imports 2.6 TWh electricity. This together with the use of electricity to cover the Passenger Mobility EUD is the cause of the high cost of the system. The difference between the electricity consumed between the two models is 13 TWh more in the $EROI$ model with 105 TWh, making it the more electrified system with 55%.

In this scenario where the installed capacity is the same for the different models, the difference in the EROI values used is especially accentuated. For the same capacity we have an extra demand of 11.9 TWh for the $EROI$ model, 27.8 TWh for the $EROI_{min}$ model (+ 130%) and 7.8 TWh for the $EROI_{max}$ model (-35%). The big difference between the $EROI$ model and $EROI_{min}$ is due to the PV technology, which accounts for 63% of the extra demand of the latter with almost 17.3 TWh. This demonstrates what has been seen throughout all the scenarios, technologies using solar energy are very unattractive for the system but necessary to achieve the imposed emissions.

Figure 4.6 shows the different extra demands in each of the scenarios.

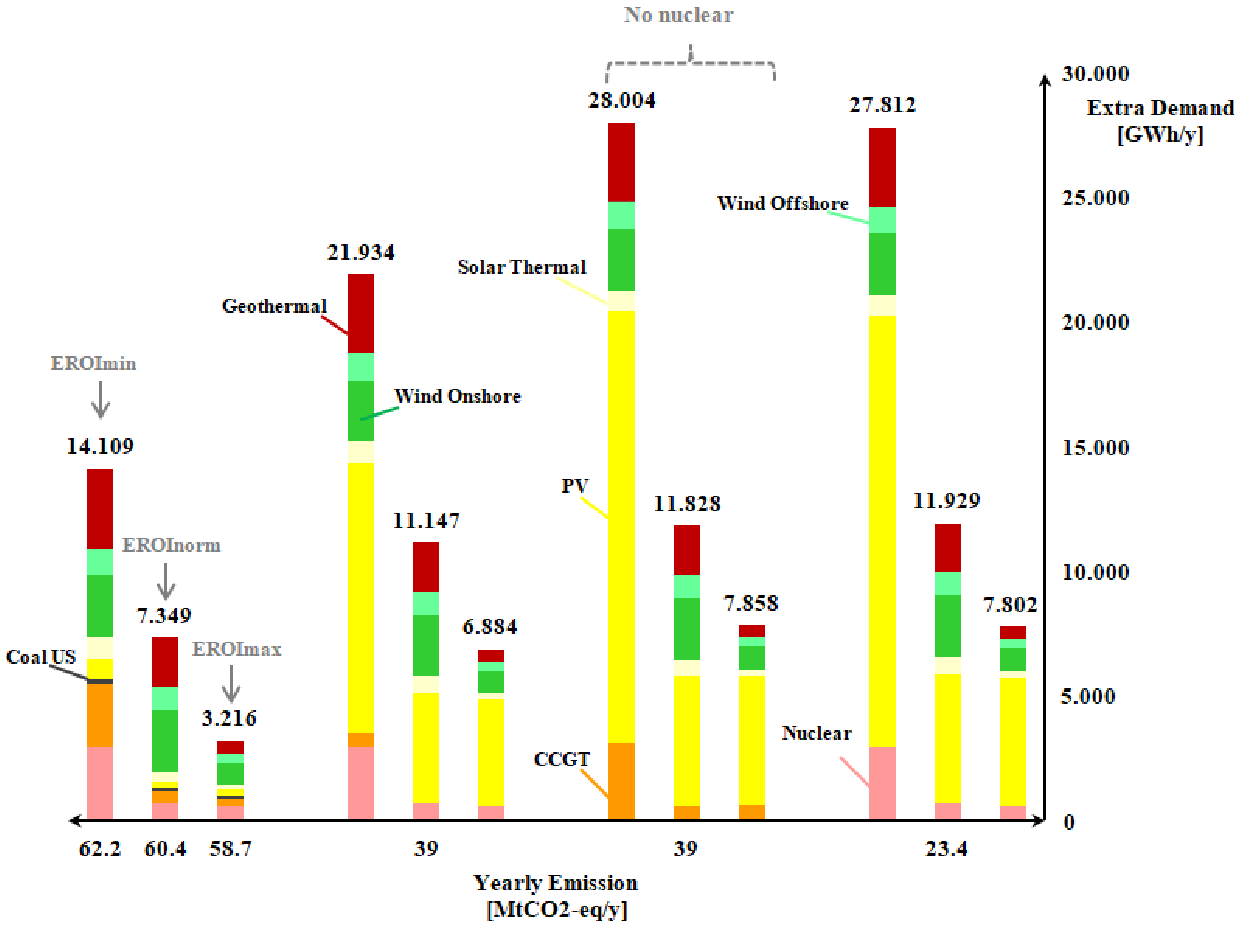

Figure 4.6 – Different extra demands in each of the scenarios and the technology that produces them. The results are ordered on the horizontal axis according to their emissions, in case they are the same, the results of the model $EROI_{min}$, $EROI$ and $EROI_{max}$ are presented first.In the case of the 75 and $non-nuclear\ scenario$, the results of the 75 scenario are presented first. The values above each bar represent the total extra demand in GWh/y.

5 Discussion

In this section the results of the results presented above is discussed. First, the systems proposed by the different models for the transition of the Belgian system towards a lower CO_2 emitting system will be presented. A brief comparison between *Original* and *EROI* is presented. Then the importance of specifying the EROI values of the different technologies for future analyses is discussed. Finally, the limitations of the study are discussed.

5.1 Transition to a Low-Emission System

Regarding the results, we see two different types of results: *Scenario 50* where the imposed CO_2 limits are not reached; and the other scenarios where this limit is reached and therefore the systems are influenced. The reason why the limit is not reached is because the models are able to provide the cheapest system with lower emissions than those imposed.

As for *Scenario 50*, there are no major differences between the *Original* model and the *EROI* model. In both systems, there is a drastic change in the use of fossil fuels such as oil, petrol and diesel, which cease to represent 45% of the primary energy used by the system and become practically insignificant, as the little diesel consumed comes from pyrolysis and is not imported. These fossil fuels are replaced by renewable energies, which had hardly any value in the 2015 system, and now represent 20% of the energy consumed and are used exclusively for electricity production. The rest of the energy used in the system comes from Uranium, Natural Gas and Coal. These last two resources have more use than electricity production, such as for High Temp. Heat in the case of Coal or for mobility, especially for Freight Mobility and non-Energy in the case of Natural Gas. Natural Gas is also used for the production of H_2 which is used exclusively for Passenger Mobility. The use of these resources is what differentiates the Original and *EROI* models. While the former proposes a system where more coal is used for electricity production because it is cheaper, the latter prioritises CCGT plants and solar thermal plants because of the lower extra demand for electricity. For both models, PV technology is unattractive to install because of its high cost in CO_2 and energy invested, for its low performance.

As for the other scenarios, more changes take place once the CO_2 limit is reached. The first, and most obvious, is the clear increase in the cost of the systems as emissions are reduced, as the use of more modern technologies such as fuel cell vehicles or solar heat production systems cause the cost of the systems to increase. Especially in the *Original* model.

The second is the fact that the system no longer consumes carbon and imports less and less natural gas. Natural gas is increasingly less used in freight and passenger mobility in both models, to the point where it has no use in *Scenario 85* of the *Original* model, it is only used in the non-Energy demand. To meet this demand, the system needs to produce SGN through Gasification (Wood), Biomethanation (Wet Biomass) and Methanation (CO_2 and H_2); the latter method also serves to reduce CO_2 by using it as a resource.

Another of the most notable changes is the way in which the models supply heat demand. In *Scenario 50*, this demand is mostly covered by fossil resources for the High Temp. Heat and is 100% electrified for the Low Temp. Heat demand. As CO_2 emissions are reduced, the *Original* model opts to use solar energy instead of electricity to cover the Low Temp. Heat EUD. On the other hand, the High Temp. Heat system is increasingly electrified, which is a change from the

EROI system, which maintains the use of electricity over solar for HLT demand, and wood over electricity for HHT. This is explained by the fact that the *EROI* model needs more electricity to supply the extra electricity demand.

Finally, the *Original* model proposes more electrified systems than the *EROI* model systems, although both models produce an almost identical amount of electricity. One of the main reasons is due to the high need of H_2 obtained by Electrolysis. This H_2 is used to make SNG, to cover a large part of the demand for Freight Mobility (up to 45%) and Passenger Mobility (up to 80%), as well as being used for Synthetic Methanolation of Diesel, also used for mobility. To get all this H_2 the method used is Electrolysis, so it is necessary to use a large part of the electricity that is produced.

5.2 Comparison between the *Original* model and the *EROI* model

When comparing the two models, it should be considered that each model has a limiting factor as discussed in Section 3.1. The Original model is constrained by the CO_2 emissions from the construction of the electricity-producing technologies. The *EROI* model is constrained by the electricity needed to build these technologies. One increases annual emissions while the other increases electricity demand.

These constraints, although they only apply to technologies in the electricity sector, cause the proposed systems to differ in their ability to supply the rest of the system's demands. These differences increase as CO_2 emissions are reduced. A great example is *Scenario 85*. In this scenario in order, to meet the emissions targets, both models have to install the maximum capacity of renewable technologies, and also the maximum capacity of nuclear power. With this capacity, the system can largely cover the final electricity demand. Why is so much electricity capacity being installed? And how does each model distribute the surplus?

On the one hand, we have the *Original* model. As mentioned above, the system commits part of its emissions to the construction of electricity-producing technologies, which means that the model has less room for manoeuvre when it comes to using more polluting technologies for the rest of the demand.

The clearest example is when it comes to meeting non-energy demand, which is 100% NG. Since the model cannot import all of this NG, it needs the means to produce a less polluting substitute within the system: SNG. This gas is obtained by three different methods such as gasification from wood, biomethanation of wet biomass, or synthetic methanation. Of these three methods, the only one that does not produce CO_2 is the latter (it even eliminates it), but it requires H_2 and electricity. This H2 is obtained from electrolysis, so more electricity is required. With all this and the installation of electricity-producing technologies, the system has reached 90% of the limit to cover two demands.

To cover the rest of the demand, the system needs to use renewable resources. And the existing technologies are very limited. High-temperature heat can only be covered by electricity (and waste). For the two mobility' sectors, three resources are mainly used: H_2, electricity, and bio-diesel (Diesel and NG are very polluting). But because the system has already used H_2 to obtain SNG (also SLF to make the bio-diesel), it has to be substituted by electric technologies in the passenger mobility sector, which are much more expensive. Last and most important is the low-temperature heat sector. This sector can be supplied by electricity and solar energy which is immensely more expensive and requires much more resources. But due to all the electricity use previously explained, the entire surplus has already been used, we have a sector that is under-electrified and very expensive.

On the other hand, in the *EROI* model, because it installs so much electrical capacity, there is a high extra demand for electricity. Therefore, the proposed system cannot electrify the different sectors as much or rely excessively on resources obtained from electricity. But the system can use a larger amount of more polluting resources, as it does not have CO_2 emissions from construction.

In the case of non-energy demand, this is simply completed by imported NG and SNG obtained by biomethanation of wet biomass. Therefore the system can use part of the wood that is saved in the high-temperature heat sector, and in the pyrolysis that allows making SLF (future bio-diesel) and to a minor measure, electricity. This is coupled with the saving of H_2, which is fully invested in passenger and freight mobility, avoiding the use of expensive electric technologies. Thus, making the low-temperature heat sector have more electricity to cover its demand, surprising as it may seem, and therefore not having to install as much solar thermal heat which is responsible for the high prices and high primary energy consumption in the *Original* model.

Therefore, we see that although the difference between the models is in the electricity sector, by working with a whole energy system, these changes have strong repercussions in other sectors of the energy system. These repercussions may be less pronounced in more flexible scenarios, but when the room for manoeuvre is limited (i.e CO_2 emission reduced), there are important differences between the two models that cannot be ignored.

More about the procurement of Synthetic Fuels can be found in the Appendix C.

5.3 Importance of the EROI values

As in the previous section, in *Scenario 50*, there is no major difference between the systems, the only difference being the amount of electricity produced and consumed by each of the systems. This is exclusively due to the difference in the EROI values used. The differences in the extra electricity demand amount to twice as much between the $EROI_{max}$ and *EROI* model, and between $EROI_{max}$ and $EROI_{min}$. This difference in the $EROI_{min}$ model is essentially made up by CCGT and Solar Thermal over and above the PV.

In *Scenario 75*, something similar happens, as the $EROI_{min}$ model invests less PV than the other systems, and also invests in CCGT even though the system has strong CO_2 emission limitations. It is also more interesting to install as little hydroelectric power as possible in the rivers, which is not the case for the other systems in this scenario, which prioritise low emissions over invested energy and rely on PV. As a consequence, the $EROI_{min}$ system is less electrified, which leads to a higher use of H_2 to cover mobility and a higher use of solar energy for the EUD of Low Temp. Heat. The cost of this system does not become too expensive as it is partly compensated by the difference in installed PV.

In *Scenario 85*, it is the system where the difference between the EROI values used is best seen, as the maximum capacity is the same for all systems. Although the capacity is the same, the costs of the $EROI_{min}$ system are much higher than the costs of the other models. Mainly, this is due to the use of less electricity in the HLT EUD and instead more in technologies covering Passenger Mobility, this is because less H_2 is produced by Electrolysis, as it is a method that uses too much electricity and this is needed to cover the Electricity EUD. The extra demand difference in this case is accentuated due to the deployment of the full PV capacity by the $EROI_{min}$ model.

As seen, the wide range of EROI values causes the optimal systems to be affected depending on the model. The difference in extra demand increases as CO_2 emissions are reduced. This is because these differences are more important for renewable energy technologies such as PV, Wind Onshore and Geothermal. This is because for the same amount of electricity produced, these technologies need more installed capacity.

5.4 Limits of the Study

The study is based on several assumptions that need to be discussed. In the following, we question the fixed energy demand, the CO_2 metric, the scenario approach, the reliability of the inputs and other assumptions.

The energy demand and cost is based on the European Commission's forecast in 2035 and is assumed as an input parameter. However, economics taught us that demand and supply are related. An increase in system cost, and thus in end-use energy prices, results in a decrease in end-use energy demand; and a new equilibrium will be reached. In addition, the emergence of new or improved technologies in the future may significantly change their cost or the capacity that can be installed.

As introduced in the section above, only CO_2 emissions and extra electricity investment related to the construction of the electricity producing technologies are taken into account, not the other technologies, and the end of life of all technologies is not taken into account. This is because if they were taken into account it would be impossible to reduce CO_2 levels to the values that have been done. In the case of the energy invested, the fact that only the value of electricity-producing technologies is used is an important constraint. Due to this assumption, imposed by the lack of data on the other technologies, certain restrictions have to be imposed on the system, such as limiting the import of electricity or blocking the possibility of making electricity by cogeneration. Without these restrictions, the model would tend to supply a large part of the electricity demand using these methods, as they would not lead to extra demand. Furthermore, as with CO_2 construction, if the values for all technologies are introduced, it would be impossible to achieve the scenarios proposed in this study unless we start from the exact capacities currently installed for all technologies, which is very difficult to achieve.

Another limiting factor has been the fact that all the energy invested in the construction of the technologies is electricity, which is not 100% true, as other demands such as freight and passenger mobility would also increase. This would mean that the demands of the other sectors would be updated, and it would be more complicated to meet them in the low-CO_2 scenarios of this study. Since with the proposed data, it can be seen that the models are quite tightly bounded in the optimal solutions while maintaining admissible costs.

The use of EnergyScope TD also leads to certain limitations. First, it does not take into account the current design of the energy system. Secondly, some simplifications have been necessary to represent complex sectors or demands, and some technologies have also been added. The main simplifications are the following: (i) CHP processes have been blocked; (ii) non-energy demand has been simplified to natural gas energy demand; (iii) aviation demand has been simplified to mobility demand and extra-EU aviation mobility is not taken into account; (iv) synthetic fuel production is aggregated into three molecules: H_2, methane and methanol; (v) extra energy demand is only electricity, extra freight mobility is not taken into account.

Also the wide range of EROI values, and the lack of precise studies for all technologies, means that theoretical values have had to be used, which can be very different from the real values in Belgium.

This means that the uncertainty of the input parameters makes the numerical values approximate but the trends valid.

6 Conclusion

EnergyScope TD has been used in this study to analyse the Belgian energy system in 2035, using the *Original* model, which is currently in []; and the EROI model, which is the model where the equations that take into account the energy invested for the construction of new technologies have been implemented. In order to carry out this study, the Belgian energy system in 2015 was used as a starting point, and different scenarios with different CO_2 emission reduction targets were created.

The 2015 system uses a large amount of fossil fuels to cover energy needs, with total CO_2 emissions of 156 $MtCO_2$. A 50%, 75% and 85% reduction in GWP emissions is decided for this system, using both models. The scenarios that have been analysed propose an increase in renewable potential, based on additional offshore wind concessions or geothermal potential, or even that existing nuclear power plants have an extended lifetime.

Are there major differences between the systems found by each of the models?

In the models where the imposed CO_2 limit is not reached, the systems are very similar with the small difference being the extra electricity demand. These systems switch from fossil fuels to renewable energies, especially wind and geothermal energy, while remaining dependent on uranium, coal and imported natural gas. As the scenarios place stricter limits, the *EROI* model and the *Original* model propose systems that differ in the way primary energy is used, such as the way low-temperature heat demand is supplied (electricity vs. solar), the demand for mobility (natural gas vs. H_2) or even the way electricity is produced (PV vs. CCGT). These changes make the *Original* model a much more expensive model, even at a price much higher than that proposed by the *EROI* model.

Also at very low emissions, the use of synthetic fuels becomes competitive to eliminate fossil fuels in the mobility sector, and the two models differ in the way they are produced. The fact that the *EROI* model has an extra demand for electricity means that it varies its way of obtaining RE fuels such as BioDiesel, SNG or H_2, to obtain them the model prioritises methods that emit CO_2 but do not use electricity, such as pyrolysis or the transformation of natural gas. On the other hand, the *Original* model makes a lot of use of methods such as electrolysis, or even in scenarios where CO_2 emissions are minimal, the system is interested in methods such as methanation (SNG) or synthetic methanolation (SLF) which use electricity, H_2 and CO_2, capturing the CO_2 emissions of the model.

These changes make the *Original* model much more expensive, with a price tag almost double that of the *EROI* model. This cost could be approached if precise EROI values of all technologies were used in the *EROI* model.

And how does the value of EROI affect the models?

EROI values have proven to be a determining factor in the choice of one technology over another. The range of EROI values causes even greater differences between one model and another. In low-emission scenarios, certain models continue to favour technologies with considerable emissions, such as CCGT, over PV, or more expensive technologies such as hydro. This is why the study demonstrates an urgent need to update the EROI values of the technologies, as well as to carry out new exhaustive studies for new technologies and non-electricity producing technologies.

In future work, it is proposed to address the two main weaknesses of the model: the lack of precise values for electricity production technologies or EROI values for certain technologies such as cogeneration, mobility or heat production technologies; and the more accurate estimation of energy demand, price and availability of resources and technologies, especially renewables, by the future Belgian system.

Supplementary materials: The models used and all results can be found on GitHub.

A Original Model Formulation [33]

The energy system is formulated as a linear programming (LP) problem. It optimises the design by computing the installed capacity of each technology, as well as the operation in each period, to meet the energy demand and minimise the total annual cost of the system. In the following, we present the complete formulation of the model. It accounts for sets, parameters, variables, constraints and the objective function. The model formulation is expressed by the equations in Figure A.1 and Eqs. (1)-(42).

End-use demand

We use the end-use demand (EUD) instead of the final energy consumption (FEC) to characterise the demand. According to the definition of the European commission, FEC is defined as "*the energy which reaches the final consumer's door*" [3]. In other words, the FEC is the amount of input fuel needed to satisfy the EUD in energy services. As an example, in the case of decentralised heat production with a gas boiler, the FEC is the amount of NG consumed by the boiler; the EUD is the amount of heat produced by the boiler, i.e. the heating service needed by the final user. This modelling choice has two advantages. First, it introduces a clear distinction between demand and supply. On the one hand, the demand concerns the definition of the end-uses, i.e. the requirements in energy services (e.g. the mobility needs). On the other hand, the supply concerns the choice of the energy conversion technologies to supply these services (e.g. the types of vehicles used to satisfy the mobility needs). Based on the technology choice, the same EUD can be satisfied with different FEC, depending on the efficiency of the chosen energy conversion technology. Second, it facilitates the inclusion in the model of electric technologies for heating and transportation.

The hourly end-use demand (**EndUses**) is computed based on the yearly end-use demand (*endUsesInput*), distributed according to a normalised time series.

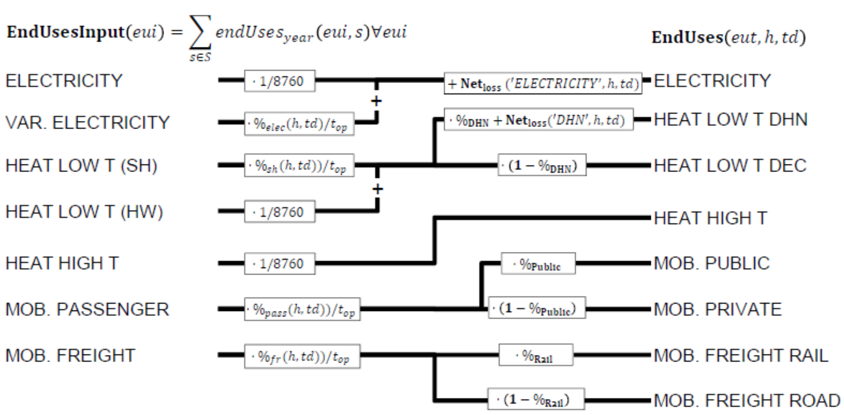

Figure A.1 – **EndUses** calculation starting from yearly demand model inputs (*endUsesInput*). Adapted from [6]. Abbreviations: space heating (sh), district heating network (DHN), hot water (HW), passenger (pass) and freight (fr).

Figure A.1 graphically presents the constraints associated to the hourly end use demand (**EndUses**), e.g. the public mobility demand at time t is equal to the hourly passenger mobility demand times the public mobility share ($\%_{Public}$).

Electricity end-uses result from the sum of the electricity-only demand, assumed constant throughout the year, and the variable demand of electricity, distributed across the periods according to $\%_{elec.}$. Low-temperature heat demand results from the sum of the yearly demand for hot water (HW), evenly shared across the year, and space heating (SH), distributed across the periods according to $\%_{sh}$.

The percentage repartition between centralised (DHN) and decentralised heat demand is defined by the variable $\%_{DHN}$. High temperature process heat and mobility demand are evenly distributed across the periods. Passenger mobility demand is expressed in passenger-kilometers (pkms), freight transportation demand is in ton-kilometers (tkms). The variables $\%_{Public}$ and $\%_{Rail}$ define the penetration of public transportation in passenger mobility and of train in freight, respectively.

Cost, emissions and objective function

The objective Eq. A.1 is the minimisation of the total annual cost of the energy system ($\mathbf{C}_{tot}$), defined as the sum of the annualised investment cost of technologies (τ $\mathbf{C}_{inv}$), the operating and maintenance cost of technologies ($\mathbf{C}_{maint}$) and the operating cost of the resources ($\mathbf{C}_{op}$). The total investment cost ($\mathbf{C}_{inv}$) of each technology results from the multiplication of its specific investment cost (c_{inv}) and its installed size ($\mathbf{F}$), the latter defined with respect to the main end-uses output type Eq. A.3. $\mathbf{C}_{inv}$ is annualised with the factor τ, calculated based on the interest rate (i_{rate}) and the technology lifetime (*lifetime*) Eq. A.2. The total operation and maintenance cost is calculated in the same way Eq. A.4. The total cost of the resources is calculated as the sum of the end-use over different periods multiplied by the period duration (t_{op}) and the specific cost of the resource (c_{op}) Eq. A.5. Note that, in Eq. A.5, summing over the typical days using the set T_H_TD is equivalent to summing over the 8 760 h of the year.

$$min\ \mathbf{C_{tot}} = \sum_{j \in TECH} (\tau(j)\mathbf{C_{inv}}(j) + \mathbf{C_{maint}}(j)) + \sum_{i \in RES} \mathbf{C_{op}}(i) \tag{A.1}$$

$$s.t \quad \tau(j) = \frac{i_{rate} * (i_{rate} + 1)^{lifetime(j))}}{(i_{rate} + 1)^{lifetime(j)-1)}} \quad \forall j \in TECH \tag{A.2}$$

$$\mathbf{C_{inv}}(j) = c_{inv}(j) * \mathbf{F}(j) \quad \forall j \in TECH \tag{A.3}$$

$$\mathbf{C_{maint}}(j) = c_{maint}(j) * \mathbf{F}(j) \quad \forall j \in TECH \tag{A.4}$$

$$\mathbf{C_{op}}(i) = \sum_{t \in T | \{h,td\} \in THTD(t)} c_{op}(i) * \mathbf{F_t}(i,h,td) t_{op}(h,td) \quad \forall i \in RES \tag{A.5}$$

The global annual greenhouse gas (GHG) emissions are calculated using a life cycle assessment (LCA) approach, i.e. taking into account emissions of technologies and resources "from cradle to grave". For climate change, the natural choice as indicator is the global warming potential (**GWP**), expressed in ktCO_2-eq./year. In Eq. A.6, the total yearly emissions of the system ($\mathbf{GWP}_{tot}$) are defined as the sum of the emissions related to the construction and end-of-life of the energy conversion technologies ($\mathbf{GWP}_{constr}$), allocated to one year based on the technology lifetime (*lifetime*), and the emissions related to resources ($\mathbf{GWP}_{op}$). Similarly to the costs, the total emissions related to the construction of technologies are the product of the specific emissions (gwp_{constr}) and the installed size (**F**), Eq. A.7. The total emissions of resources are the emissions associated to fuels (from cradle to combustion) and imports of electricity (gwp_{op}) multiplied by the period duration (t_{op}) (Eq A.8).

$$\mathbf{GWP_{tot}} = \sum_{j \in TECH} \frac{\mathbf{GWP_{constr}}(j)}{lifetime(j))} + \sum_{i \in RES} \mathbf{GWP_{op}}(i) \quad \text{(A.6)}$$

$$\mathbf{GWP_{constr}}(j) = gwp_{constr}(j)\mathbf{F}(j) \quad \forall j \in TECH \quad \text{(A.7)}$$

$$\mathbf{GWP_{op}}(i) = \sum_{t \in |T\{h,td\} \in THTD(t))} gwp_{op}(i)\mathbf{F_t}(i,h,td)t_{op}(h,td) \quad \forall i \in RES \quad \text{(A.8)}$$

System design and operation

The installed capacity of technologies (**F**) is constrained between upper and lower bounds (f_{max} and f_{min}), Eq. A.9. This formulation allows accounting for old technologies still existing in the target year (lower bound), but also for the maximum deployment potential of a technology. As an example, for hydroelectric power plants, f_{min} represents the existing installed capacity (which will still be available in the future), while f_{max} represents the maximum potential.

$$f_{min}(j) \leq \mathbf{F}(j) \leq f_{max}(j) \quad \forall j \in TECH \quad \text{(A.9)}$$

The operation of resources and technologies in each period is determined by the decision variable $\mathbf{F}_t$. The capacity factor of technologies is conceptually divided into two components: a capacity factor for each period ($c_{s,t}$) depending on resource availability (e.g. renewable) and a yearly capacity factor (c_p) accounting for technology downtime and maintenance. For a given technology, the definition of only one of these two is needed, the other one being fixed to the default value of 1. Eqs. A.10 and A.11 link the installed size of a technology to its actual use in each period ($\mathbf{F}_t$) via the two capacity factors. The total use of resources is limited by the yearly availability ($avail$), Eq. A.12.

$$\mathbf{F_t}(j,h,td) \leq \mathbf{F}(j)c_{p,t}(j,h,td) \quad \forall j \in TECH, \forall h \in H, \forall td \in TD \quad \text{(A.10)}$$

$$\sum_{t \in T|\{h,td\} \in THTD(t)} \mathbf{F_t}(j,h,td)t_{op}(h,td) \leq \mathbf{F}(j)c_p(j) \sum_{t \in T|\{h,td\} \in THTD(t)} t_{op}(h,td) \quad \forall j \in TECH \quad \text{(A.11)}$$

$$\sum_{t \in T|\{h,td\} \in THTD(t)} \mathbf{F_t}(i,h,td)t_{op}(h,td) \leq avail(i) \quad \forall i \in RES \quad \text{(A.12)}$$

The matrix f defines for all technologies and resources outputs to (positive) and inputs (negative) layers. Eq. A.13 expresses the balance for each layer: all outputs from resources and technologies (including storage) are used to satisfy the EUD or as inputs to other resources and technologies.

$$\begin{aligned}\sum_{i \in RES \cup TECH \setminus STO} f(i,l)\mathbf{F_t}(i,h,td) + \sum_{j \in STO} (\mathbf{STO_{out}}(j,l,h,td) - \\ \mathbf{STO_{in}}(j,l,h,td)) - \mathbf{EndUses}(l,h,td) &= 0 \\ \forall l \in L, \forall h \in H, \forall td \in TD\end{aligned} \tag{A.13}$$

Storage

The storage level ($\mathbf{Sto}_{level}$) at a time step (t) is equal to the storage level at t-1 (accounting for the losses in t-1), plus the inputs to the storage, minus the output from the storage (accounting for input/output efficiencies A.14). The storage systems which can only be used for short-term (daily) applications are included in the STO DAILY set. For these units, Eq. A.15 imposes that the storage level be the same at the end of each typical day. Adding this constraint drastically reduces the computational time. For the other storage technologies, which can also be used for seasonal storage, the capacity is bounded by Eq A.16. For these units, the storage behaviour is thus optimised over 8 760h, as explained in the methodology Section of the paper.

$$\begin{aligned}\mathbf{Sto_{level}}(j,t) = \mathbf{Sto_{level}}(j,t-1) \cdot (1 - \%_{sto_{loss}}(j)) + t_{op}(h,td) \cdot (\sum_{l \in L | \eta_{sto,in(j,l)>0)}} \\ \mathbf{Sto_{in}}(j,l,h,td)\eta_{sto,in}(j,l) - \sum_{l \in L | \eta_{sto,out(j,l)>0)}} \mathbf{Sto_{out}}(j,l,h,td)\eta_{sto,out}(j,l)) \\ \forall j \in STO, \forall t \in T \mid \{h,td\} \in THTD(t)\end{aligned} \tag{A.14}$$

$$\mathbf{Sto_{level}}(j,t) = \mathbf{F_t}(j,h,td) \quad \forall j \in STODAILY, \forall t \in T \mid \{h,td\} \in THTD(t) \tag{A.15}$$

$$\mathbf{Sto_{level}}(j,t) = \mathbf{F}(j) \quad \forall j \in STO \setminus STODAILY, \forall t \in T \tag{A.16}$$

Eqs. A.17-A.18 force the power input and output to zero if the layer is incompatible. As an example, a PHS will only be linked to the electricity layer (input/output efficiencies $>$ 0). All other efficiencies will be equal to 0, to impede that the PHS exchanges with incompatible layers (e.g. mobility, heat, etc). Eq. A.19 limits the power input/output of a storage technology based on its installed capacity ($\mathbf{F}$) and three specific characteristics. First, storage availability ($\%_{sto,avail}$) is defined as the ratio between the available storage capacity and the total installed capacity (default value is 1). This parameter is required to realistically represent V2G, for which we assume that only a fraction of the fleet can charge/discharge at the same time. Second and third, the charging/discharging time ($t_{sto,in}$, $t_{sto,out}$), which are the time to complete a full charge/discharge from empty/full storage5. As an example, a daily thermal storage can be fully discharged in minimum 4 hours ($t_{sto,out}$ = 4 [h]), and fully charged in maximum 4 hours ($t_{sto,in}$ = 4 [h]).

$$\mathbf{Sto_{in}}(j,l,h,td) \cdot (\lceil \eta_{sto,in}(j,l) \rceil - 1) = 0 \quad \forall j \in STO, \forall l \in L, \forall h \in H, \forall td \in TD \tag{A.17}$$

$$\mathbf{Sto_{out}}(j,l,h,td) \cdot (\lceil \eta_{sto,out}(j,l) \rceil - 1) = 0 \quad \forall j \in STO, \forall l \in L, \forall h \in H, \forall td \in TD \tag{A.18}$$

$$(\mathbf{Sto_{in}}(j,l,h,td) t_{sto_{in}}(j) - \mathbf{Sto_{out}}(j,l,h,td) t_{sto_{out}}(j)) \leq \mathbf{F}(j).\%_{sto_{avail}}(j) \\ \forall j \in STO, \forall l \in L, \forall h \in H, \forall td \in TD \tag{A.19}$$

Infrastructure

Eq. A.20 calculates network losses as a share ($\%_{net,loss}$) of the total energy transferred through the network. As an example, losses in the electricity grid are estimated to be 7% of the energy transferred6. Eqs. A.21-A.23 define the extra investment for networks. Integration of intermittent renewable energies (iRE) implies an additional investment costs for the electricity grid ($c_{grid,extra}$). As an example, the needed investments are expected to be 2.5 billions CHF_{2015} for the high voltage grid and 9.4 billions CHF_{2015} for the medium and low voltage grid. Eq. A.22 links the size of DHN to the total size of the installed centralised energy conversion technologies. The power-to-gas storage data is implemented as in Al-musleh et al.. It is implemented in the model with two conversion units and a liquified natural gas (LNG) storage tank. $PowerToGas_{in}$ converts electricity to LNG, $PowerToGas_{out}$ converts LNG back to electricity. The investment cost is associated to the PowerToGas unit, whose size is the maximum size of the two conversion units, Eq. A.23 here displayed in a compact non-linear formulation.

$$\mathbf{Net_{loss}}(eut,h,td) = (\sum_{i \in RES \cup TECH \setminus STO \,|\, f(i,eut)>0} f(i,eut) \mathbf{F_t}(i,h,td)).\%_{net_{loss}}(eut)) \\ \forall eut = EUT, \forall h \in H, \forall td \in TD \tag{A.20}$$

$$\mathbf{F}(Grid) = \frac{c_{grid,extra}}{c_{inv}(Grid)} \cdot \frac{\mathbf{F}(Wind) + \mathbf{F}(PV)}{f_{max}(Wind) + f_{max}(PV)} \tag{A.21}$$

$$\mathbf{F}(DHN) = \sum_{j \in TECH\ OF\ EUT(HeatLowTDHN)} \mathbf{F}(j)(22) \tag{A.22}$$

$$\mathbf{F}(PowerToGas) = max(\mathbf{F}(PowerToGas_{in}), \mathbf{F}(PowerToGas_{out}))(23) \tag{A.23}$$

Additional Constraints

Nuclear power plants are assumed to have no power variation over the year A.24. If needed, this equation can be replicated for all other technologies for which a constant operation over the year is desired.

$$\mathbf{F_t}(Nuclear, h, td) = \mathbf{P_{Nuc}} \quad \forall h \in H, \forall td \in TD \tag{A.24}$$

Eq. A.25 imposes that the share of the different technologies for mobility ($\%_{MobPass}$) be the same at each time step. In other words, if 20% of the mobility is supplied by train, this share remains constant in the morning or the afternoon. The addition of this constraint is motivated by the fact that the investment cost of passenger and freight transport technologies is not accounted for in the model ($c_{inv} = 0$ for these technologies).

$$\mathbf{F_t}(j, h, td) = \%_{\mathbf{MobPass}}(j) \sum_{l \in EUT\ of\ EUC(MobPass)} \mathbf{EndUses}(l, h, td)$$
$$\forall j \in TECH\ OF\ EUC(MobPass), \forall h \in H, \forall td \in TD \tag{A.25}$$

Decentralised heat production

Thermal solar is implemented as a decentralised technology. It is always installed together with another decentralised technology, which serves as backup to compensate for the intermittency of solar thermal. Thus, we define the total installed capacity of solar thermal $\mathbf{F}(Dec_{Solar})$ as the sum of $\mathbf{F}_{sol}$(j) (A.27), where $\mathbf{F}_{sol}$(j) is the solar thermal capacity associated to the backup technology j. Eq. A.26 links the installed size of each solar thermal capacity ($\mathbf{F}_{sol}$(j)) to its actual production $\mathbf{F}_{sol,t}$(j; h; td)) via the solar capacity factor ($c_{p,t}$ (Dec_{Solar},h,td)).

$$\mathbf{F_{t_{sol}}}(j, h, td) \leq \mathbf{F_{sol}}(j) c_{p,t}(Dec_{Solar}, h, td)$$
$$\forall j \in TECH\ OF\ EUT(HeatLowTDec) \setminus \{Dec_{Solar}\}, \forall h \in H, \forall td \in TD \tag{A.26}$$

$$\mathbf{F}(Dec_{Solar}) = \sum_{j \in TECH\ OF\ EUT(HeatLowTDec) \setminus \{Dec_{Solar}\}} \mathbf{F_{sol}}(j) \tag{A.27}$$

A thermal storage i is defined for each decentralised heating technology j, to which it is related via the set TS OF DEC TECH, i.e. i=TS OF DEC TECH(j). Each thermal storage i can store heat from its technology j and the associated thermal solar $\mathbf{F}_{sol}$(j). Similarly to the passenger mobility, Eq. A.28 makes the model more realistic by defining the operating strategy for decentralised heating. In fact, in the model we represent decentralised heat in an aggregated form; however, in a real case, residential heat cannot be aggregated obviously. A house heated by a decentralised gas boiler and solar thermal panels should not be able to be heated by the electrical heat pump and thermal storage of the neighbours, and vice-versa. Hence, Eq. A.28 imposes that the use of each technology ($\mathbf{F}_t$(j; h; td)), plus its associated thermal solar

($\mathbf{F}_{t_{sol}}$ (j, h, td)) plus its associated storage outputs ($\mathbf{Sto}_{out}$ (i, l, h, td)) minus its associated storage inputs ($\mathbf{Sto}_{in}$(i, l, h, td)) should be a constant share ($\%_{HeatDec}$(j)) of the decentralised heat demand (**EndUses**(HeatLowT; h; td)). Figure A.2 shows, through an example with two technologies (a gas boiler and a heat pump (HP)), how decentralised thermal storage and thermal solar are implemented.

$$\begin{aligned} \mathbf{F_t}(j,h,td) + \mathbf{F_{t_{sol}}}(j,h,td) + \sum_{l \in L} (\mathbf{Sto_{out}}(i,l,h,td) - \mathbf{Sto_{in}}(i,l,h,td)) \\ = \%_{\mathbf{HeatDec}}(j)\mathbf{EndUses}(HeatLowT,h,td) \\ \forall j \in TECH\ OF\ EUT(HeatLowTDec) \setminus \{Dec_{Solar}\}, \\ \forall i \in TS\ OF\ DEC\ TECH(j), \forall h \in H, \forall td \in TD \end{aligned} \tag{A.28}$$

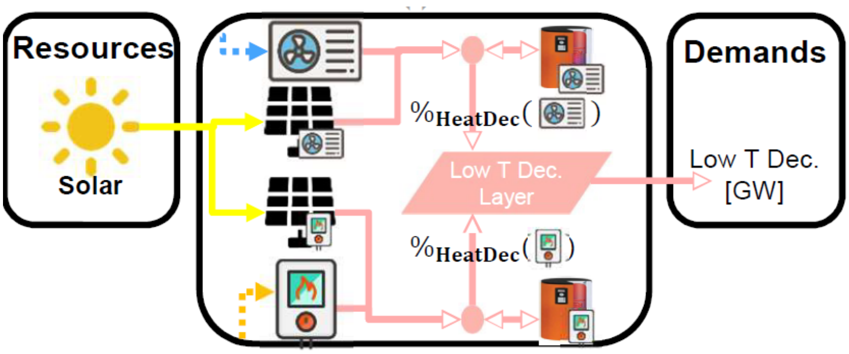

Figure A.2 – Illustrative example of a decentralised heating layer with thermal storage, solar thermal and two conventional production technologies, gas boilers and electrical HP. In this case, Eq. A.28 applied to the electrical HPs becomes the equality between the two following terms: left term is the heat produced by: the eHPs ($\mathbf{F}_t$('eHPs')), the solar panel associated to the eHPs ($\mathbf{F}_{t_{sol}}$('eHPs')) and the storage associated to the eHPs; right term is the product between the share of decentralised heat supplied by eHPs ($\%_{HeatDec}$('eHPs')) and heat low temperature decentralised demand (**EndUses**(HeatLowT, h, td)).

Hydroelectric dams

Hydroelectric dams are implemented here as the combination of two components: a storage unit (the reservoir, or dam storage (*DamSto*) and a power production unit (*HydroDam*). It has to be noted that, in this implementation, we differentiate between PHS and the storage unit with river inflow *DamSto*. PHS has a lower and upper reservoir without inlet source; *DamSto* has an inlet source, i.e. a river inflow, but cannot pump water from the lower reservoir. The power production technology *HydroDam* accounts for all the dam hydroelectric infrastructure cost and emissions. Eqs. A.29-A.31 regulate the reservoir (*DamSto*) based on the production (*HydroDam*). Eq. A.29 linearly relates the reservoir size with the power plant size (**F**(*HydroDam*)). Eq. A.30 imposes the storage input power ($\mathbf{Sto}_{in}$) to be equal to the water inflow term ($\mathbf{F}_t$(*HydroDam*, h, td)). This latter is constrained by Eq. A.10 and represents the water in ow in the dam ($\mathbf{Sto}_{in}$). Eq. A.31 ensures that the storage output ($\mathbf{Sto}_{out}$) be lower than the installed capacity (**F**

(*HydroDam*)). Figure A.3 shows how the reservoir (*DamSto*) and the power unit (*HydroDam*) are implemented.

$$\mathbf{F}(DamSto) \leq f_{min}(DamSto)+(f_{max}(DamSto)-f_{min}(DamSto))\cdot\frac{\mathbf{F}(HydroDam)-f_{min}(HydroDam)}{f_{max}(HydroDam)-f_{min}(HydroDam)} \quad (A.29)$$

$$\mathbf{Sto_{in}}(DamSto, Elec, h, td) = \mathbf{F_t}(HydroDam, h, td) \quad \forall h \in H, \forall td \in TD \quad (A.30)$$

$$\mathbf{Sto_{out}}(DamSto, Elec, h, td) = \mathbf{F}(HydroDam) \quad \forall h \in H, \forall td \in TD \quad (A.31)$$

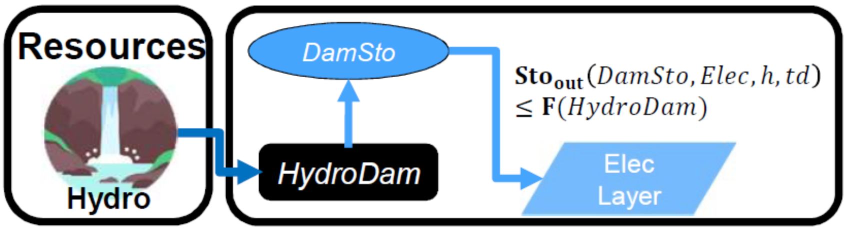

Figure A.3 – Visual representation of hydro dams implementation in the model. The storage (*DamSto*) is filled by river inflows and can produce electricity through the *HydroDam* technology.

Vehicle-to-grid

Vehicle-to-grid dynamics are included in the model via the V2G set. For each vehicle $j \in$ V2G, a battery i (i EVs BATT) is associated using the set EVs BATT OF V2G (i EVs BATT OF V2G(j)). Each type j of V2G has a different size of battery per car ($ev_{Batt,size}$(j)), e.g. the first generation battery of the Nissan Leaf (ZE0) has a capacity of 24 kWh. To estimate the number of vehicles of a given technology, we use the share of mobility covered supplied by this technology ($\%_{MobPass}$) and the number of cars required if all the mobility was covered with private cars n$_{car,max}$. Thus, the energy that can be stored in batteries **F**(i) of V2G(j) is the product of the maximum number of cars (n$_{car,max}$) multiplied by the share of the mobility covered by the type of vehicle j ($\%_{MobPass}$(j)) and the size of battery per car ($ev_{Batt,size}$(j)) A.32. As an example, if all the drivers of Switzerland (5.8 millions [10]) owned a car and 5% of the mobility was supplied by Nissan Leaf (ZE0), then the energy that could be stored by this technology would be 6.76 GWh.

Eq. A.33 forces batteries of electric vehicle to supply, at least, the energy required by each associated electric vehicle technology. This lower bound is not an equality; in fact, according to the V2G concept, batteries can also be used to support the grid. Figure **??** shows through an example with only battery electric vehicles (BEVs) how Eq.A.33 simplifies the implementation of V2G. In this illustration, a battery technology is associated to a BEV. The battery can either supply the BEV needs or restore electricity to the grid.

$$\mathbf{F}(i) = \eta_{car,max}.\%_{\mathbf{MobPass}}(j)ev_{Batt,size}(j) \quad \forall j \in V2G, \forall i \in EVs\ BATT\ OF\ V2G(j) \quad (A.32)$$

$$\mathbf{Sto_{out}}(i, Elec, h, td) \geq -f(j, Elec)\mathbf{F_t}(j, h, td) \quad \forall j \in V2G, \forall i \in EVsBATTOFV2G(j), \forall h \in H, \forall td \in TD \tag{A.33}$$

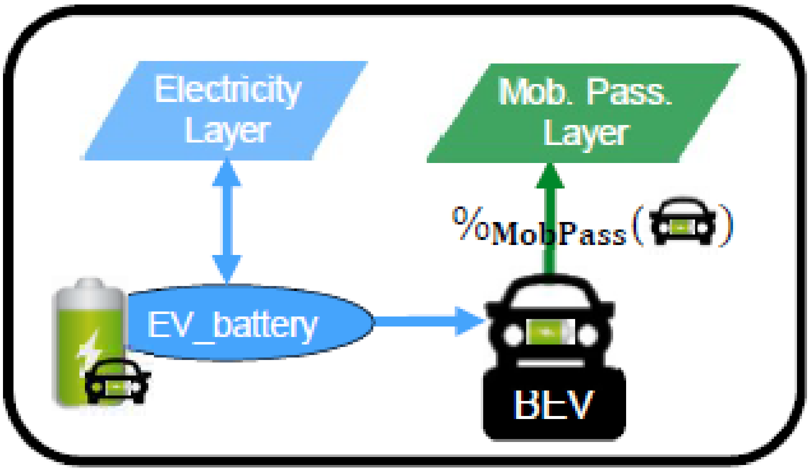

Figure A.4 – Illustrative example of a V2G implementation. The battery can interact with the electricity layer. The V2G takes the electricity from the battery to provide a constant share ($\%_{MobPass}$) of the passenger mobility layer ($Mob.Pass.$).

Peak demand

Finally, Eqs. A.34-A.35 constrain the installed capacity of low temperature heat supply. Based on the selected typical days (TDs), the ratio between the yearly peak demand and the TDs peak demand is defined for space heating ($\%_{Peak,sh}$). Eq. A.34 imposes that the installed capacity for decentralised technologies covers the real peak over the year. Similarly, Eq. A.35 forces the centralised heating system to have a supply capacity (production plus storage) higher than the peak demand.

$$\mathbf{F}(j) \geq \%_{Peak_{sh}} \max_{h\in H, td \in TD} \{\mathbf{F_t}(j, h, td)\} \quad \forall j \in TECH\ OF\ EUT(HeatLowTDec) \setminus \{Dec_{Solar}\} \tag{A.34}$$

$$\sum_{j\in TECH\ OF\ EUT(HeatLowTDHN, i\in STO\ OF\ EUT(HeatLowTDHN)} (\mathbf{F}(j) + \mathbf{F}(i)/t_{sto_{out}}(i, HeatLowTDHN)) \geq \%_{Peak_{sh}} \max_{h\in H, td\in TD} \{\mathbf{EndUses}(HeatLowTDHN, h, td)\} \tag{A.35}$$

Adaptation for the case study

Additional constraints are required to implement the scenarios and the Swiss hydroelectric power plants. Scenarios require four additional constraints (A.36-A.39) to impose a limit on the GWP emissions, the minimum share of renewable energies (RE) primary energy, the relative shares of some technologies, such as gasoline cars in the private mobility and the cost of energy efficiency measures. Due to the high penetration of hydropower in Switzerland and the good availability of data, the hydro potential has been split into old and new hydro plants and that changes three constraints (A.40-A.42). Eq. A.36 imposes a limit on the GWP (gwp_{limit}). Eq. A.37 fixes the minimum renewable primary energy share. Eq. A.38 is complementary to Eq.A.9 , as it expresses the minimum ($f_{min,\%}$) and maximum ($f_{max,\%}$) yearly output shares of each technology for each type of EUD. In fact, for a given technology, assigning a relative share (e.g. boilers providing at least a given percent of the total heat demand) is more intuitive and close to the energy planning practice than limiting its installed size. $f_{min,\%}$ and $f_{max,\%}$ are fixed to 0 and 1, respectively, unless otherwise indicated. Eq. A.39 imposes the cost of energy efficiency.

$$\mathbf{GWP_{tot}} \leq gwp_{limit} \tag{A.36}$$

$$\sum_{j \in RES_{re}, t \in T | \{h,td\} \in THTD(t)} \mathbf{F_t}(j,h,td) \cdot t_{op}(h,td) \geq re_{share} \sum_{j \in RES, t \in T | \{h,td\} \in THTD(t)} \mathbf{F_t}(j,h,td) \cdot t_{op}(h,td) \tag{A.37}$$

$$\begin{aligned} f_{min,\%}(j) \sum_{j' \in TECH\ OF\ EUT(eut), t \in T | \{h,td\} \in THTD(t)} \mathbf{F_t}(j',h,td) \cdot t_{op}(h,td) \leq \\ \sum_{t \in T | \{h,td\} \in THTD(t)} \mathbf{F_t}(j,h,td) \cdot t_{op}(h,td) \\ \leq f_{max,\%}(j) \sum_{j'' \in TECH\ OF\ EUT(eut), t \in T | \{h,td\} \in THTD(t)} \mathbf{F_t}(j'',h,td) \cdot t_{op}(h,td) \\ \forall eut \in EUT, \forall j \in TECH\ OF\ EUT(eut) \end{aligned} \tag{A.38}$$

$$\mathbf{F}(Efficiency) = \frac{1}{1 + i_{rate}} \tag{A.39}$$

Due to the high penetration of hydropower in Switzerland and the good availability of data, the hydro potential has been split into old and new hydro plants. The old power plants have a fixed capacity and a known cost. Compared to the existing plants, the new power plants have a different price. As a consequence, Eqs. A.29-A.31 are modified to integrate the potential of new hydro dams and became, respectively, Eqs A.40-A.42.

$$\begin{aligned} \mathbf{F}(DamSto) \leq f_{min}(DamSto) + (f_{max}(DamSto) - \\ f_{min}(DamSto)) \frac{\mathbf{F}(NewHydroDam) - f_{min}(NewHydroDam)}{f_{max}(NewHydroDam) - f_{min}(NewHydroDam)} \end{aligned} \tag{A.40}$$

$$\mathbf{Sto_{in}}(DamSto, Elec, h, td) = \mathbf{F_t}(HydroDam, h, td) + \mathbf{F_t}(NewHydroDam, h, td) \quad \forall h \in H, \forall td \in TD \tag{A.41}$$

$$\mathbf{Sto_{out}}(DamSto, Elec, h, td) \leq \mathbf{F}(HydroDam) + \mathbf{F}(NewHydroDam) \quad \forall h \in H, \forall td \in TD \tag{A.42}$$

Linearisation of integer variables

Equations (A.25 and A.28) multiply two variables among which **EndUses**. The latter is a dependent variable depending only on parameters, and thus it can be rewritten as a sum and products of parameters as shown in Figure A.1.

Compared to the previous version of EnergyScope reported by Moret , the integer variables have been removed. They had the following use: (i) forcing the number of technologies to be an integer multiple of a reference size (e.g. one could only install 0.5, 1, 1.5, etc GW of CCGT if reference size is 0.5 GW); (ii) forcing that storage cannot charge and discharge at the same time; (iii) defining backup decentralised production technologies for thermal solar. These variables were removed to reduce the computational time. As a consequence, (i) we accepted to have continuous size for installed capacities, such as 732 MW of CCGT; (ii) we systematically verify during the post treatment that a storage technology is not charging and discharging at the same time, which removes the need of using a binary variables. This change was also required to implement V2G, which can both charge and discharge. Complementarily, Eq. 19 verifies that the power charging and discharging are not higher than the maximum capacity. For example, assuming a case with 100 electric cars with a battery of 10kWh each, with an energy to power ratio of 10 (charging) and 5 (discharging) and with 20% of the cars are available to drive or charge. In this case, the charge and discharge powers are limited to a maximum of 20 or 40 kW, respectively, or a mix of the two. Finally, (iii) as illustrated in Section 1.3, the thermal solar implementation has been improved; the new formulation is more realistic and does not require the use of binary/integer variables.

B Energy Invested

B.1 PV and Solar Thermal

	poly-Si-PV	
	[GJ/GW]	Share [%]
Raw material extraction & processing	12,211,500	65
Raw & intermediary material transport	33,930	0.2
Power plant manufacturing	4,394,480	23
, Construction material transport	303,480	2
Facility construction	71,650	0.4
Facility maintenance	1,322,800	7
Facility decommissioning	71,650	0.4
Decommissioning material transport	315,520	2
Total Energy Inputs [GJ/GW]	18,725,010	100
Facility operation [GJ/GJ]	0.0097	

Figure B.1 – The table shows in detail the summary of life cycle energy inputs for solar-PV technologies. [24]

	ST-Salt-TES	
	[GJ/GW]	Share [%]
Raw material extraction & processing	24,891,800	67
Raw & intermediary material transport	108,510	0.3
Power plant manufacturing	3,642,820	10
Construction material transport	1,222,840	3
Facility construction	220,160	1
Facility maintenance	5,511,600	15
Facility decommissioning	237,600	1
Decommissioning material transport	1,049,220	3
Total Energy Inputs [GJ/GW]	36,884,540	100
Facility operation [GJ/GJ]	0.073	

Figure B.2 – The table shows in detail the summary of life cycle energy inputs for Solar Thermal technologies. [24]

B.2 Wind Onshore and Offshore

	Onshore	Offshore
Manufacturing primary energy [GJ] for 1 GW turbine generators		
Wind turbine	7,869,000	8,523,000
Park cabling (183 km)	52,128	66,030
Substation	16,632	16,632
Cables to shore (1 km)	583	1282

Figure B.3 – The table shows in detail the manufacturing primary energy [GJ] for a 1 GW wind farm.[29]

Component	Material	Weight [tonnes]		Electricity [GJ]		Diesel [GJ]	
		Onshore	Offshore	Onshore	Offshore	Onshore	Offshore
Embodied energy in materials for 1 GW turbine generators							
Tower	Steel	52,920	27,500	123,282	64,064	1,184,350	615,450
	Coating	420	331	18,783	14,791	9074	7146
Nacelle	Steel	19,993	46,502	46,576	108,331	447,451	1,040,718
	Copper	1250	1754	95,358	125,726	14,634	19,294
	Aluminum	770	484	96,113	19,294	17,764	60,373
	Coating	17	7	810	323	361	144
Hub and blades	Steel	6643	13,562	15,476	31,595	148,678	303,525
	Fibre glass	4013	7217	143,838	258,639	64,213	115,464
	Epoxy resin	2810	5054	251,776	452,847	112,400	202,164
	Coating	21	38	1035	1861	462	831
Foundation	Concrete	380,000	7813	502,208	16,173	786,600	10,326
	Steel	12,000	155,375	27,955	361,962	268,560	3,477,293
Embodied energy in materials for substation and cables							
Park cabling (183 km)	Steel	0	1502	0	3604	0	33,633
	Copper	266	846	20,419	64,974	2925	9306
	Aluminium	1358	0	181,420	0	31,349	0
	Other	1471	1463	70,648	70,242	29,437	29,267
Substation	Steel	337	337	808	808	7540	7540
	Copper	88	88	6758	6758	968	968
	Other	214.5	214.5	10,296	10,296	4290	4290
Cables to shore (1 km)	Steel	n/a	25.3	n/a	61	n/a	567
	Copper	n/a	19.8	n/a	1517	n/a	217
	Other	n/a	34.1	n/a	1637	n/a	682

Figure B.4 – The table shows in detail the invested energy in materials for a 1 GW wind farm.[29]

Transport	Material	Mode	Weight [tonnes]		Distance [km]		Diesel [GJ]	
			Onshore	Offshore	Onshore	Offshore	Onshore	Offshore
Raw materials	Cement	Truck	380,000	7813	20	20	9500	195
	Steel	Truck	91,557	242,939	150	150	17,167	45,551
	Copper	Truck	1330	1754	430	430	715	943
	Aluminium	Truck	770	484	60	60	58	36
	Other	Truck	7282	12,647	20	20	182	316
	Copper	Ship	1330	1754	4200	4200	161	212
	Aluminium	Ship	455	484	3000	3000	39	42
	Other	Ship	7282	12,647	4000	4000	839	1457
Factory to site	Cement	Truck	380,000	7813	250	250	118,750	2442
	Steel	Truck	91,557	242,939	600	600	57,223	182,204
	Copper	Truck	1330	1754	600	600	416	1316
	Aluminium	Truck	770	484	600	600	667	363
	Other	Truck	7282	12,647	600	600	5462	9485
	Steel	Ship	91,557	242,939	10,000	10,000	26,368	69,966
	Copper	Ship	1330	1754	10,000	10,000	383	505
	Aluminium	Ship	770	484	10,000	10,000	222	139
	Other	Ship	7282	12,647	10,000	10,000	2097	3642
Decommissioning	All	Truck	480,939	265,637	350	350	210,411	116,216
	All	Ship	96,188	53,127	5000	5000	138,510	76,503

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Figure B.5 – The table shows in detail the transport energy inputs for a 1 GW wind farm.[29]

		Onshore	Offshore
Installation - Primary energy [GJ]	Wind turbine	129,660	1,709,830
	Park cabling (168 km)	13,159	33,338
	Substation	10,603	34,991
	Cabling to shore (1 km)	n/a	4681
Operation - Electricity [GJ/GJ]		0.035	0.007
Maintenance - Diesel [GJ/GW/year]		1656	65,587
Decommissioning - Primary energy [GJ]		6450	1,283,000

Figure B.6 – The table shows in detail Other energy inputs for a 1 GW wind farm.[29]

C Technologies Related to Synthetic Fuels [35]

Synthetic fuels are expected to play a key role to phase out fossil fuels. Figure C.1 offers an overview of the technology related to synthetic fuels, including the carbon dioxide layers. Synthetic fuels can be imported (Bio-ethanol, Bio-Diesel, H_2 , SNG or SLF) or produced by converting biomass and/or electricity. The wet biomass - usually organic waste - can be converted through the *biogas plant* technology to SNG. This technology combines anaerobic digestion and cleaning processes. Woody biomass can be used to produce H_2 through *gasification*, SLF through *pyrolysis* or SNG through *gasification to SNG*. The synthetic liquid fuel can later be converted into LFO, gasoline or diesel. The other processes to produce synthetic fuels are based on the water electrolysis, where the *electrolysers* convert electricity to H_2 . Then, the H_2 can be combined with CO_2 and upgraded to SNG through the *methanation* technology, or methanol through *methanolation* technology. For these latter, the processes require CO_2 . It can either be captured from large scale emitters, such as the industries and centralised heat technologies, or directly captured from the air but at a higher energetic and financial cost.

The characteristics of each technology with their numerical values and sources can be found in the Supplementary Materials.

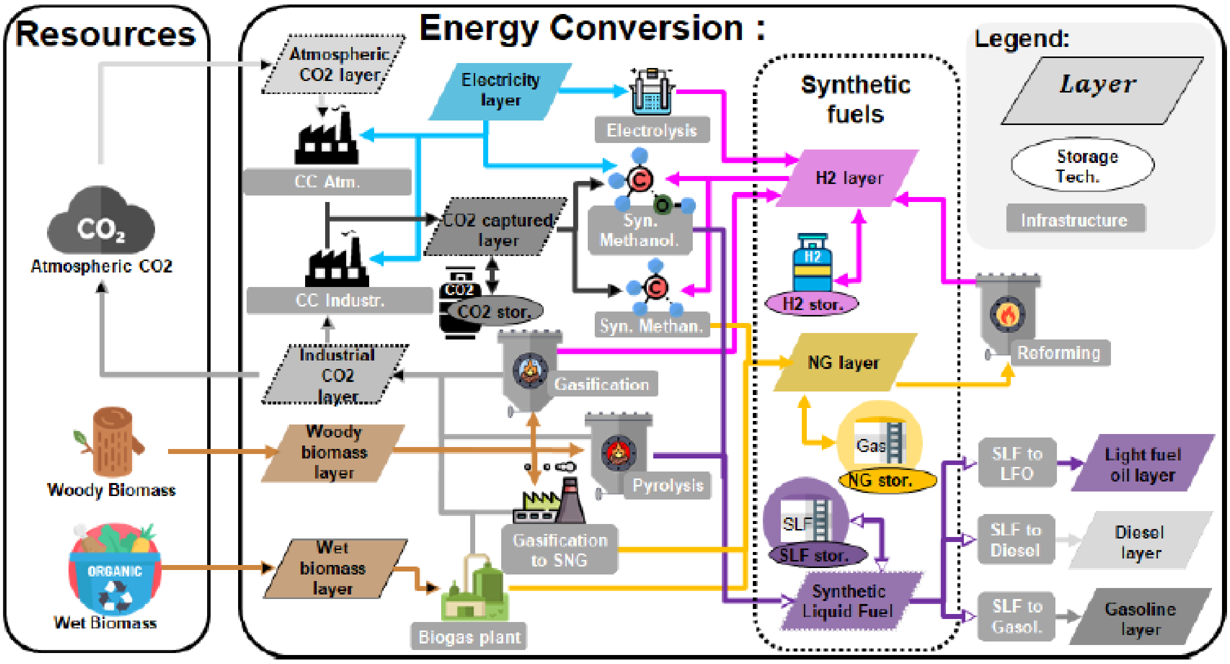

Figure C.1 – Illustration of the technologies and processes to produce synthetic fuels. For clarity, only the most relevant flows are drawn

D Results

D.1 *Scenario 50*

General Overview

	Original	*EROI*	*EROImin*	*EROImax*	
		$\mathbf{C}_{op}$			
Electricity	489	489	489	489	
NG	6 302	5 923	6 583	6 032	
Wood	334	334	334	334	
Wet Biomass	97	97	97	97	
Coal	582	582	582	582	
Uranium	461	461	461	461	
Waste	179	179	179	179	
Total	**8 444**	**8 066**	**8 725**	**8 175**	**M€**
		$\mathbf{C}_{maint} + \mathbf{C}_{inv}$			
Electricity	4 778	4 741	4 821	4 762	
High Temp. Heat	66	66	66	66	
Low Temp. Heat	1 830	1 829	1 820	1 828	
Cooling	348	348	348	348	
Mobility Passenger	21 196	21 196	21 196	21 196	
Mobility Freight	2 565	2 565	2 565	2 565	
Other	6 358	6 266	6 489	6 347	
Storage	275	273	337	92	
Total	**37 415**	**37 283**	**37 641**	**37 203**	**M€**
Total	**45 860**	**45 349**	**46 366**	**45 378**	**M€**

Table D.1 – Annual costs for each of the models in *Scenario 50*. The operating cost (C_{op}) only takes into account resources. The maintenance (C_{maint}) and investment cost (C_{inv}) applies to installed technologies. All values are given in Millions of €.

	Original	*EROI*	*EROImin*	*EROImax*	
Electricity	2.794	2.794	2.794	2.794	
NG	38.094	40.527	42.334	38.792	
Wood	0.277	0.277	0.277	0.277	
Wet Biomass	0.459	0.459	0.459	0.459	
Coal	13.246	13.246	13.246	13.246	
Uranium	0.464	0.464	0.464	0.464	
Waste	2.676	2.676	2.676	2.676	
GWP_{op}	**58.011**	**60.443**	**62.250**	**58.708**	**$MtCO_2$-eq**
GWP_{constr}	**3.496**	**0**	**0**	**0**	**$MtCO_2$-eq**
GWP_{tot}	**61.507**	**60.443**	**62.250**	**58.708**	**$MtCO_2$-eq**

Table D.2 – Yearly CO_2 emissions for each of the models in *Scenario 50*. GWP_{op} takes into account the CO_2 emitted by all technologies in the system during operation. While GWP_{constr} only includes the CO_2 from the construction of electricity-producing technologies, and is only used in the *Original* model. All values are given in $MtCO_2$-eq.

	Original	*EROI*	*EROImin*	*EROImax*	
Electr. imported	5.80	5.80	5.80	5.80	
NG	142.89	152.01	158.79	145.51	
Wood	23.43	23.43	23.43	23.43	
Wet Biomass	38.88	38.88	38.88	38.88	
Coal	33	33	33	33	
Uranium	119	119	119	119	
Waste	17.83	17.83	17.83	17.83	
Wind	63.45	63.47	63.50	63.45	
Solar	6.72	14.38	25.98	13.59	
Hydro	0.12	0.12	0.12	0.12	
Geo	23.35	23.35	23.35	23.35	
Total	**474.48**	**491.28**	**509.69**	**483.96**	**TWh**

Table D.3 – Total Primary Energy import for each of the models in *Scenario 50*. Energy produced within the system itself is not taken into account. All values are given in TWh.

Electricity Sector

	Original	*EROI*	*EROImin*	*EROImax*	
Electr. imported	5.8	5.8	5.8	5.8	
NG	4.515	13.638	20.415	7.132	
Coal	6.395	6.395	6.395	6.395	
Uranium	118.996	118.996	118.996	118.996	
Wind	63.449	63.473	63.501	63.450	
Solar	6.725	14.376	25.985	13.595	
Hydro	0.117	0.117	0.117	0.117	
Geo	23.354	23.354	23.354	23.354	
Total	**229.351**	**246.149**	**264.563**	**238.839**	**TWh**

Table D.4 – Breakdown of the Resources consumed by the electricity sector of the system in *Scenario 50.*

	Original	*EROI*	*EROImin*	*EROImax*	
Nuclear	5.920	5.920	5.920	5.920	
CCGT	0.899	1.925	2.414	1.207	
Coal U.S	0.668	0.412	0.454	0.593	
PV	2.916	2.916	2.916	2.916	
Solar Thermal	1.159	2.431	3.838	2.857	
Wind Onshore	20.379	20.379	20.379	20.379	
Wind Offshore	8	8	8	8	
Mini-Hydro	0.171	0.171	0.171	0.171	
Geothermal	3.1	3.1	3.1	3.1	
Total	**43.213**	**45.255**	**47.193**	**45.144**	**GW**

Table D.5 – Capacity installed in the electricity sector for each of the models in *Scenario 50.* In this scenario, the installed capacity is almost the same for all technologies except for CCGT, Coal U.S. and Solar Thermal. This difference is due to the values of EROI chosen. All values are given in GW.

	Original	*EROI*	*EROImin*	*EROImax*	
Electr. imported	5.8	5.8	5.8	5.8	
Nuclear	44.028	44.028	44.028	44.028	
CCGT	2.844	8.592	12.862	4.493	
Coal U.S	3.134	3.134	3.134	3.134	
PV	2.441	2.443	2.443	2.443	
Solar Thermal	1.098	3.058	6.030	2.859	
Windo Onshore	39.887	39.839	39.867	39.816	
Wind Offshore	23.562	23.634	23.634	23.634	
Mini-Hydro	0.117	0.117	0.117	0.117	
Geothermal	23.354	23.354	23.354	23.354	
Pyrolysis	0.090	0.090	0.090	0.090	
Total	**146.356**	**154.089**	**161.359**	**149.768**	**TWh$_e$**
Losses	8.963	9.436	9.881	9.172	TWh$_e$

Table D.6 – Distribution of the electricity produced by the different technologies in each model. It can be seen that the electricity produced is higher than the demand, this is because the extra demand, the losses and the electricity consumed by other sectors have not yet been removed. All values are given in TWh$_e$.

	Original	*EROI*	*EROImin*	*EROImax*	
Elect. Export	0	0	0	0	
Heat High Temp.	0	0	0	0	
Heat Low Temp	47.344	47.286	47.315	47.343	
Cooling	2.956	2.956	2.956	2.956	
Mobility Passenger	1.914	1.914	1.914	1.914	
Mobility Freight	1.673	1.673	1.673	1.673	
RE fuels	0	0	0	0	
Storage	0.283	0.250	0.293	0.278	
Total	**54.178**	**54.089**	**54.153**	**54.165**	**TWh$_e$**

Table D.7 – Breakdown of the electricity consumed by each of the sectors of the system, except for the electricity sector. The values of RE fuels correspond to the electricity used for the production of these fuels. All values are given in TWh$_e$. Abbreviations Renewables (RE)

	Original	*EROI*	*EROImin*	*EROImax*	
Nuclear	0	0.714	2.935	0.587	
CCGT	0	0.512	2.568	0.321	
Coal U.S	0	0.085	0.172	0.090	
PV	0	0.255	0.851	0.255	
Solar Thermal	0	0.423	0.841	0.188	
Wind Onshore	0	2.480	2.480	0.893	
Wind Offshore	0	0.910	1.090	0.392	
Geothermal	0	1.966	3.168	0.487	
Extra Demand	**0**	**7.349**	**14.109**	**3.216**	**TWh**$_e$
Demand	**83.216**	**83.216**	**83.216**	**83.216**	**TWh**$_e$
Total	**83.216**	**90.565**	**97.325**	**86.432**	**TWh**$_e$

Table D.8 – Summary in detail of each technology's extra demand, and the fixed demand of electricity. The sum represents the total electricity consumed by the electricity sector of the system. The extra demand of the Original model is always 0. all values are given in TWh$_e$.

Other Sectors

	Original	*EROI*	*EROImin*	*EROImax*	
		High Temperature Heat			
Boiler Coal (IND)	21.82	21.82	21.82	21.82	
Boiler Wood (IND)	15.35	15.35	15.35	15.35	
Boiler Waste (IND)	14.62	14.62	14.62	14.62	
Total	**51.79**	**51.79**	**51.79**	**51.79**	**TWh$_t$**
		Low Temperature Heat			
Electric Heat Pump (DHN)	61.103	61.029	61.215	61.124	
Electric Heat Pump (DEC)	96.216	96.095	96.044	96.195	
Total	**157.319**	**157.124**	**157.260**	**157.319**	**TWh$_t$**
		Mobility Passengers			
Tram and Trolley Bus	11.582	11.582	11.582	11.582	
Diesel Bus and Coach	11.582	11.582	11.582	11.582	
Diesel HEV Bus and Coach	3.861	3.861	3.861	3.861	
NG Bus and Coach	11.582	11.582	11.582	11.582	
Fuel Cell Car	155.394	155.394	155.394	155.394	
Total	**194.000**	**194.000**	**194.000**	**194.000**	**Mpkm**
		Mobility Freight			
Train	24.500	24.500	24.500	24.500	
NG Boat	29.400	29.400	29.400	29.400	
NG Truck	44.100	44.100	44.100	44.100	
Total	**98.000**	**98.000**	**98.000**	**98.000**	**Mpkm**
		Re fuels			
		H_2			
NG (Reforming)	28.707	28.707	28.707	28.707	TWh
		SNG			
Biomethanation	36.313	36.313	36.313	36.313	TWh
		Bio-diesel (SLF)			
Pyrolysis	3.780	3.780	3.780	3.780	TWh

Table D.9 – Breakdown of the technologies installed in each of the sectors of the system, except for the electricity sector. The values correspond to the amount of demand they cover, not to the installed capacity. In the case of RE fuels, the technologies represent the method used to obtain them. The values for heat are given in TWh$_t$, for mobility in Mpkm, and for RE fuels in TWh. Abbreviations: Industrial (Ind), Decentralised (DEC), District Heating Network (DHN) and Renewables (RE).

	Original	*EROI*	*EROImin*	*EROImax*	
			High Temperature Heat		
Wood	17.76	17.76	17.76	17.76	
Waste	17.84	17.84	17.84	17.84	
Coal	26.60	26.60	26.60	26.60	
TOTAL	**62.19**	**62.19**	**62.19**	**62.19**	**TWh**
			Low Temperature Heat		
Electricity	47.344	47.286	47.315	47.343	TWh
			Mobility Passengers		
Electricity	1.914	1.914	1.914	1.914	
Bio-Diesel	3.781	3.781	3.781	3.781	
NG/SNG	3.546	3.546	3.546	3.546	
H_2	27.878	27.878	27.878	27.878	
TOTAL	**37.119**	**37.119**	**37.119**	**37.119**	**TWh**
			Mobility Freight		
Electricity	1.673	1.673	1.673	1.673	
NG/SNG	29.635	29.635	18.776	29.635	
TOTAL	**31.308**	**31.308**	**28.548**	**31.308**	**TWh**
			Cooling		
Electricity	2.95	2.95	2.95	2.95	TWh
			Non Energy		
NG/SNG	102.33	102.33	102.33	102.33	TWh
			Re fuels		
			H_2		
NG/SNG	39.174	39.174	39.174	39.174	TWh
			Bio-diesel (SLF)		
Wood	5.677	5.677	5.677	5.677	TWh
			SNG		
Wet Biomass	38.879	38.879	38.879	38.879	TWh

Table D.10 – Breakdown of the Resources consumed by each of the sectors of the system, except for the electricity sector. The values correspond to the amount of resources consumed, they can be imported energy, in which case it would be accounted for in Table D.3, or resources produced in the system such as electricity or RE fuels. All values are given in TWh. Abbreviations: Renewables (RE).

Storage

	Original	*EROI*	*EROImin*	*EROImax*	
		Electricity			
Pumped Hydro Storage	282	380	293	278	GWh_e
		Low Temperature Heat			
Electrical Heat Pump (DEC)	502	380	330	481	
Seasonal Storage (DHN)	613	544	717	632	
Total	**1 114**	**925**	**1 048**	**1 113**	$\mathbf{GWh}_t$
		Cooling			
Cold Storage	56	57	57	37	GWh_t
		RE fuels			
Seasonal H_2 Storage	830	830	830	830	GWh
Solar Thermal Storage	0	7	23	2	GWh

Table D.11 – System power storage for each sector. The sectors that do not appear is because there is no excess demand. The values for heat are given in GWh_t, Electricity in GWh_e, and for RE fuels in TWh. Abbreviations: Decentralised (DEC), District Heating Network (DHN) and Renewables (RE).

D.2 *Scenario 75*

General Overview

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
		C_{op}			
Electricity	144	394	489	438	
NG	4 059	4 927	4 842	4 888	
0	301	301	301	301	
Wood	334	334	334	334	
Wet Biomass	97	97	97	97	
Coal	0	0	0	0	
Uranium	461	461	461	461	
Waste	179	179	179	179	
Total	**5 576**	**6 693**	**6 704**	**6 698**	**M€**
		C_{maint} + C_{inv}			
Electr. imported	6 889	7 130	6 463	7 048	
High Temp. Heat	542	578	574	571	
Low Temp. Heat	2 778	2 253	3 774	2 021	
Cooling	348	348	348	348	
Mobility Passenger	21 196	21 196	21 196	21 196	
Mobility Freight	2 691	2 565	2 618	2 565	
Other	9 644	8 148	10 329	7 799	
Storage	1 689	1 162	1 812	1 005	
Total	**45 776**	**43 378**	**47 112**	**42 553**	**M€**
Total	**51 353**	**50 072**	**53 816**	**49 251**	**M€**

Table D.12 – Annual costs for each of the models in *Scenario 75*. The operating cost (C_{op}) only takes into account resources. The maintenance (C_{maint}) and investment cost (C_{inv}) applies to installed technologies. All values are given in Millions of €.

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$
Electricity	0.824	2.251	2.794	2.502
Diesel	1.190	1.190	1.190	1.190
NG	26.105	31.683	31.140	31.433
Wood	0.277	0.277	0.277	0.277
Wet Biomass	0.459	0.459	0.459	0.459
Uranium	0.464	0.464	0.464	0.464
Waste	2.676	2.676	2.676	2.676
GWP_{op}	**31.995**	**39.000**	**39.000**	**39.000**
GWP_{constr}	**7.005**	**0**	**0**	**0**
GWP_{tot}	**39.000**	**39.000**	**39.000**	**39.000**

Table D.13 – Yearly CO_2 emissions for each of the models in *Scenario 75*. GWP_{op} takes into account the CO_2 emitted by all technologies in the system during operation. While GWP_{constr} only includes the CO_2 from the construction of electricity-producing technologies, and is only used in the *Original* model. All values are given in $MtCO_2$-eq.

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
Electricity	1.71	4.67	5.80	5.19	
Diesel	3.78	3.78	3.78	3.78	
NG	97.92	118.84	116.80	117.90	
Wood	23.43	23.43	23.43	23.43	
Wet Biomass	38.88	38.88	38.88	38.88	
Uranium	119.00	119.00	119.00	119.00	
Waste	17.83	17.83	17.83	17.83	
Wind	63.53	62.68	63.53	63.53	
Solar	169.94	115.30	190.02	103.78	
Hydro	0.12	0.12	0.12	0.12	
Geo.	23.35	23.35	23.35	23.35	
Total	**560.05**	**528.10**	**602.64**	**518.51**	**TWh**

Table D.14 – Total Primary Energy import for each of the models in *Scenario 75*. Energy produced within the system itself is not taken into account. All values are given in TWh.

Electricity Sector

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
Electr. imported	1.711	4.672	5.800	5.192	
NG	0.862	0	3.606	0	
Uranium	118.996	118.996	118.996	118.996	
Wind	63.531	62.682	63.528	63.528	
Solar	101.776	98.983	107.469	100.129	
Hydro	0.117	0.116	0.118	0.117	
Geothermal	23.354	23.354	23.354	23.354	
Total	**310.346**	**308.802**	**322.870**	**311.316**	**TWh**

Table D.15 – Breakdown of the Resources consumed by the electricity sector of the system in *Scenario 75*.

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
Nuclear	5.920	5.920	5.920	5.920	
CCGT	0.522	0	0.560	0	
PV	45.170	50.298	37.056	48.744	
Solar Thermal	3.838	3.838	3.838	3.838	
Wind Onshore	20.379	20.379	20.379	20.379	
Wind Offshore	8	8	8	8	
Mini-Hydro	0.171	0.171	0.172	0.171	
Geothermal	3.1	3.1	3.1	3.1	
Total	**87.101**	**91.706**	**79.026**	**90.153**	**GW**

Table D.16 – Capacity installed in the electricity sector for each of the models in *Scenario 75*. All values are given in GW.

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
Electr. imported	1.711	4.672	5.800	5.192	
Nuclear	44.028	44.028	44.028	44.028	
CCGT	0.543	0	2.271	0	
PV	37.868	41.999	31.065	40.864	
Solar Thermal	16.278	14.525	19.369	15.108	
Wind Onshore	39.897	39.375	39.897	39.894	
Wind Offshore	23.634	23.307	23.631	23.634	
Mini-Hydro	0.117	0.116	0.118	0.117	
Geothermal	23.354	23.354	23.354	23.354	
Total	**187.430**	**191.376**	**189.534**	**192.192**	**TWh$_e$**
Losses	11.478	11.72	11.607	11.77	TWh$_e$

Table D.17 – Distribution of the electricity produced by the different technologies in each model. It can be seen that the electricity produced is higher than the demand, this is because the extra demand, the losses and the electricity consumed by other sectors have not yet been removed. All values are given in TWh$_e$.

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
Elect. Export	0.557	0.211	0.01	1.713	
Heat High Temp.	17.024	16.969	17.014	17.027	
Heat Low Temp	32.197	44.528	27.550	47.339	
Cooling	2.955	2.955	2.956	2.956	
Mobility Passenger	1.914	1.914	1.914	1.914	
Mobility Freight	1.673	1.673	1.673	1.673	
RE fuels	36.159	16.729	21.400	17.415	
Storage	0.257	0.313	0.173	0.286	
Total	**92.737**	**85.294**	**72.779**	**90.323**	**TWh$_e$**

Table D.18 – Breakdown of the electricity consumed by each of the sectors of the system, except for the electricity sector. The values of RE fuels correspond to the electricity used for the production of these fuels. All values are given in TWh$_e$. Abbreviations Renewables (RE)

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
Nuclear	0	0.714	2.935	0.587	
CCGT	0	0	0.596	0	
PV	0	4.406	10.820	4.270	
Solar Thermal	0	0.668	0.841	0.252	
Wind Onshore	0	2.480	2.480	0.893	
Wind Offshore	0	0.910	1.090	0.392	
Geothermal	0	1.966	3.168	0.487	
Extra Demand	**0**	**11.147**	**21.934**	**6.884**	$\mathbf{TWh}_e$
Demand	**83.216**	**83.216**	**83.216**	**83.216**	$\mathbf{TWh}_e$
Total	**83.216**	**94.362**	**105.149**	**90.099**	$\mathbf{TWh}_e$

Table D.19 – Summary in detail of each technology's extra demand, and the fixed demand of electricity. The sum represents the total electricity consumed by the electricity sector of the system. The extra demand of the Original model is always 0. all values are given in TWh_e.

Other Sectors

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
High Temperature Heat					
Boiler Gas (IND)	0	0.057	0	0	
Boiler Wood (IND)	20.257	20.258	20.258	20.258	
Boiler Waste (IND)	14.620	14.620	14.620	14.620	
Direct Electric Heating	17.024	16.969	17.014	17.027	
Total	**51.902**	**51.904**	**51.892**	**51.904**	**TWh$_t$**
Low Temperature Heat					
Electric Heat Pump (DHN)	0	49.034	0	60.259	
Solar (DHN)	68.167	16.317	68.167	3.654	
Electric Heat Pump (DEC)	96.600	96.818	82.658	96.831	
Solar (DEC)	0	0	14.382	0	
Total	**164.767**	**162.170**	**165.208**	**160.744**	**TWh$_t$**
Mobility Passengers					
Tram and Trolley Bus	11.582	11.582	11.582	11.582	
Diesel Bus and Coach	11.582	11.582	11.582	11.582	
Diesel HEV Bus and Coach	3.861	3.861	3.861	3.861	
NG Bus and Coach	11.582	11.582	11.582	11.582	
Fuel Cell Car	155.394	155.394	155.394	155.394	
Total	**194.000**	**194.000**	**194.000**	**194.000**	**Mpkm**
Mobility Freight					
Train	24.500	24.500	24.500	24.500	
NG Boat	29.400	29.400	29.400	29.400	
Fuel Cell Truck	44.100	0	18.405	0	
NG Truck	0	44.100	25.695	44.100	
Total	**98.000**	**0**	**98.000**	**98.000**	**Mpkm**
RE fuels					
H_2					
Electrolysis	30.734	14.219	18.190	14.802	
NG (Reforming)	17.496	14.348	18.215	13.705	
Total	**48.230**	**28.568**	**36.405**	**28.507**	**TWh**
SNG					
Biomethanation	36.313	36.313	36.313	36.313	TWh

Table D.20 – Breakdown of the technologies installed in each of the sectors of the system, except for the electricity sector. The values correspond to the amount of demand they cover, not to the installed capacity. In the case of RE fuels, the technologies represent the method used to obtain them. The values for heat are given in TWh$_t$, for mobility in Mpkm, and for RE fuels in TWh. Abbreviations: Industrial (Ind), Decentralised (DEC), District Heating Network (DHN) and Renewables (RE).

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
High-Temperature Heat					
Electricity	17.024	16.969	17.014	17.027	
WOOD	23.434	23.434	23.434	23.434	
WASTE	17.829	17.829	17.829	17.829	
Total	**58.288**	**58.232**	**58.277**	**58.290**	**TWh**
Low Temperature Heat					
Electricity	32.197	44.528	27.550	47.339	
Solar	68.167	16.317	82.550	3.654	
Total	**100.364**	**60.845**	**110.100**	**50.992**	**TWh**
Mobility Passengers					
Electricity	1.914	1.914	1.914	1.914	
Diesel	3.781	3.781	3.781	3.781	
NG	3.546	3.546	3.546	3.546	
H2	27.878	27.878	27.878	27.878	
Total	**37.119**	**37.119**	**37.119**	**37.119**	**TWh**
Mobility Freight					
Electricity	1.673	1.673	1.673	1.673	
Diesel	0	0	0	0	
NG	3.616	29.635	18.776	29.635	
H_2	19.404	0	8.098	0	
Total	**24.693**	**31.308**	**28.548**	**31.308**	**TWh**
Cooling					
Electricity	2.95	2.95	2.95	2.95	TWh
Non-Energy					
NG	102.33	102.33	102.33	102.33	TWh
RE fuels					
H_2					
Electricidad	36.159	16.729	21.400	17.415	TWh
NG	23.875	19.580	24.856	18.702	TWh
SNG					
Wet Biomass	38.879	38.879	38.879	38.879	TWh

Table D.21 – Breakdown of the Resources consumed by each of the sectors of the system, except for the electricity sector. The values correspond to the amount of resources consumed, they can be imported energy, in which case it would be accounted for in Table D.14, or resources produced in the system such as electricity or RE fuels. All values are given in TWh. Abbreviations: Renewables (RE).

Storage

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
		Electricity			
Pumped Hydro Storage	257	313	173	286	GWh$_e$
		High-Temperature Heat			
Molten Salt	116	118	106	118	GWh$_t$
		Low Temperature Heat			
Electrical Heat Pump	886	1.104	1.327	1.117	
Seasonal Storage (DHN)	7.182	4.564	7.182	3.226	
Total	**8.068**	**5.668**	**8.509**	**4.343**	**GWh$_t$**
		Cooling			
Cold Storage	46	50	52	57	GWh$_t$
		RE fuels			
Seasonal H_2 Storage	948	690	429	630	GWh
Solar Thermal Storage	423	337	865	344	GWh

Table D.22 – System power storage for each sector. The sectors that do not appear is because there is no excess demand. The values for heat are given in GWh$_t$, Electricity in GWh$_e$, and for RE fuels in TWh. Abbreviations: Decentralised (DEC), District Heating Network (DHN) and Renewables (RE).

D.3 *Scenario 85*

General Overview

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
		C_{op}			
Electricity	0	0	222	0	
NG	1 765	3 036	2 839	3 036	
Wood	334	334	334	334	
Wet Biomass	97	97	97	97	
Uranium	461	461	461	461	
Waste	179	179	179	179	
Total	**2 837**	**4 107**	**4 132**	**4 107**	**M€**
		C_{maint} + C_{inv}			
Electricity	7 602	7 602	7 602	7 602	
High Temp. Heat	609	620	725	618	
Low Temp. Heat	65 250	8 107	59 087	7 758	
Cooling	557	348	442	348	
Mobility Passenger	36 737	21 589	36 284	21 589	
Mobility Freight	2 691	2 691	2 691	2 691	
Other	16 556	13 415	14 024	12 233	
Storage	11 282	10 935	12 045	9 689	
Total	**141 284**	**65 662**	**132 899**	**62 527**	**M€**
Total	**144 121**	**69 769**	**137 031**	**66 635**	**M€**

Table D.23 – Annual costs for each of the models in *Scenario 85*. The operating cost (C_{op}) only takes into account resources. The maintenance (C_{maint}) and investment cost (C_{inv}) applies to installed technologies. All values are given in Millions of €.

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
Electricity	0	0	1.26	0	
NG	11.35	19.52	18.25	19.52	
Wood	0.27	0.27	0.27	0.27	
Wet Biomass	0.46	0.46	0.46	0.46	
Uranium	0.46	0.46	0.46	0.46	
Waste	2.67	2.67	2.67	2.67	
GWP$_{op}$	**15.23**	**23.40**	**23.40**	**23.40**	**MtCO$_2$-eq**
GWP$_{constr}$	**8.17**	**0**	**0**	**0**	**MtCO$_2$-eq**
GWP$_{tot}$	**23.40**	**23.40**	**23.40**	**23.40**	**MtCO$_2$-eq**

Table D.24 – Yearly CO_2 emissions for each of the models in *Scenario 85*. GWP$_{op}$ takes into account the CO_2 emitted by all technologies in the system during operation. While GWP$_{constr}$ only includes the CO_2 from the construction of electricity-producing technologies, and is only used in the *Original* model. All values are given in MtCO$_2$-eq.

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
Electr. imported	0	0	3	0	
Natural Gas	43	73	68	73	
Wood	23	23	23	23	
Wet Biomass	39	39	39	39	
Uranium	119	119	119	119	
Waste	18	18	18	18	
Wind	64	64	64	63	
Solar	346	304	332	283	
Hydro	0.12	0.12	0.12	0.12	
Geothermal	23	23	23	23	
Total	675	664	689	643	**TWh**

Table D.25 – Total Primary Energy import for each of the models in *Scenario 85*. Energy produced within the system itself is not taken into account. All values are given in TWh.

Electricity Sector

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
Electr. imported	0	0	2.63	0	
Uranium	119	119	119	119	
Wind	63.53	63.54	63.55	63.56	
Solar	195	191.03	193.73	174.31	
Hydro	0.12	0.12	0.12	0.12	
Geothermal	23.35	23.35	23.35	23.35	
Total	**401**	**397.03**	**402.36**	**380.27**	**TWh**

Table D.26 – Breakdown of the Resources consumed by the electricity sector of the system in *Scenario 85*.

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
Nuclear	5.92	5.92	5.92	5.92	
PV	59.23	59.23	59.23	59.23	
Solar Thermal	3.84	3.84	3.84	3.84	
Wind Onshore	20.38	20.38	20.38	20.38	
Wind Offshore	8.00	8.00	8.00	8.00	
Mini-Hydro	0.172	0.172	0.172	0.172	
Geothermal	3.10	3.10	3.10	3.10	
Total	**100.64**	**100.64**	**100.64**	**100.64**	**GW**

Table D.27 – Capacity installed in the electricity sector for each of the models in *Scenario 85*. In this scenario, the installed capacity is maximum for all technologies except for CCGT and Coal U.S. (highly polluting). All values are given in GW.

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
Electr. imported	0	0	2.632	0	
Nuclear	44.028	44.028	44.028	44.028	
PV	49.653	49.626	49.653	49.640	
Solar Thermal	33.624	32.732	33.624	29.153	
Wind Onshore	39.897	39.897	39.897	39.879	
Wind Offshore	23.634	23.634	23.634	23.618	
Mini-Hydro	0.12	0.12	0.12	0.12	
Geothermal	23.354	23.354	23.354	23.354	
Pyrolysis	0	0.075	0.066	0.080	
Total	214.308	213.464	217.007	209.871	**TWh$_e$**
Losses	13.169	13.072	13.289	12.852	TWh$_e$

Table D.28 – Distribution of the electricity produced by the different technologies in each model. It can be seen that the electricity produced is higher than the demand, this is because the extra demand, the losses and the electricity consumed by other sectors have not yet been removed. All values are given in TWh$_e$.

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
Elect. Export	0	0	0	0.021	
High Temp. Heat	37.377	21.046	20.550	21.336	
Low Temp. Heat	5.414	19.196	11.545	19.783	
Cooling	2.949	2.953	2.952	2.953	
Mobility Passenger	10.147	1.914	10.147	1.914	
Mobility Freight	1.673	1.673	1.673	1.673	
RE fuels	61.038	58.393	45.181	58.231	
Storage	0.064	0.070	0.0641	0.089	
Total	**118.662**	**105.247**	**92.690**	**106.001**	**TWh$_e$**

Table D.29 – Breakdown of the electricity consumed by each of the sectors of the system, except for the electricity sector. The values of RE fuels correspond to the electricity used for the production of these fuels. All values are given in TWh$_e$. Abbreviations Renewables (RE)

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
Nuclear	0	0.714	2.935	0.587	
PV	0	5.188	17.294	5.188	
Solar Thermal	0	0.668	0.841	0.252	
Wind Onshore	0	2.480	2.480	893	
Wind Offshore	0	0.910	1.090	0.392	
Mini-Hydro	0	0.03	0.04	0.02	
Geothermal	0	1.966	3.168	0.487	
Extra Demand	**0**	**11.929**	**27.812**	**7.802**	**TWh**$_e$
Demand	**83.216**	**83.216**	**83.216**	**83.216**	**TWh**$_e$
Total	**83.216**	**95.145**	**111.027**	**91.018**	**TWh**$_e$

Table D.30 – Summary in detail of each technology's extra demand, and the fixed demand of electricity. The sum represents the total electricity consumed by the electricity sector of the system. The extra demand of the Original model is always 0. all values are given in TWh$_e$.

Other Sectors

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
		High Temperature Heat			
Boiler Wood (IND)	0	16.179	16.650	15.903	
Boiler Waste (IND)	14.620	14.620	14.620	14.620	
Direct Electric Heating	37.377	21.046	20.550	21.336	
Total	**51.997**	**51.845**	**51.820**	**51.858**	**TWh$_t$**
		Low Temperature Heat			
Solar (DHN)	63.226	68.167	68.167	68.167	
Electric Heat Pump (DEC)	16.243	57.593	34.639	59.356	
Solar (DEC)	88.118	45.128	70.290	40.896	
Total	**219.584**	**222.733**	**224.916**	**220.277**	**TWh$_t$**
		Mobility Passengers			
Tram and Trolley Bus	29.100	11.582	29.100	11.582	
Diesel Bus and Coach	0	3.861	0	4.663	
Diesel HEV Bus and Coach	0	11.582	9.700	11.582	
NG Bus and Coach	0	11.582	0	10.780	
Fuel Cell Bus and Coach	9.700	0	0	0	
Train/Metro	58.200	0	58.200	0	
Fuel Cell Car	97.000	155.394	97.000	155.394	
Total	**194.000**	**194.000**	**194.000**	**194.000**	**Mpkm**
		Mobility Freight			
Train	24.500	24.500	24.500	24.500	
Diesel Boat	29.400	0	9.404	0	
NG Boat	0	29.400	19.996	29.400	
Fuel Cell Truck	44.100	44.100	44.100	44.100	
Total	**98.000**	**98.000**	**98.000**	**98.000**	**Mpkm**
		RE fuels			
		H_2			
Electrolysis	49.846	49.633	38.403	49.495	
NG (Reforming)	0	0	0	219	
Total	**49.846**	**49.633**	**38.403**	**49.714**	**TWh**
		Bio-diesel (SLF)			
Syn. Methanolation.	3.146	0	0	0	
Pyrolysis	0	3.142	2.779	3.355	
Total	**3.146**	**3.142**	**2.779**	**3.355**	**TWh**
		SNG			
Gasification	17.341	0	0	0	
Biomethanation	36.313	36.313	36.313	36.313	
Syn. methanation	6.094	0	0	0	
Total	**42.407**	**36.313**	**36.313**	**36.313**	**TWh**

Table D.31 – Breakdown of the technologies installed in each of the sectors of the system, except for the electricity sector. The values correspond to the amount of demand they cover, not to the installed capacity. In the case of RE fuels, the technologies represent the method used to obtain them. The values for heat are given in TWh$_t$, for mobility in Mpkm, and for RE fuels in TWh. Abbreviations: Industrial (Ind), Decentralised (DEC), District Heating Network (DHN) and Renewables (RE).

	Original	*EROI*	*EROI$_{min}$*	*EROI$_{max}$*	
		High Temperature Heat			
Electricity	37.37	21.05	20.55	21.33	
Wood	0	18.71	19.26	18.39	
Waste	17.83	17.83	17.83	17.83	
TOTAL	**55.2**	**57.59**	**57.64**	**57.56**	**TWh**
		Low Temperature Heat			
Electricity	5.41	19.2	11.54	19.78	
Solar	151.34	113.29	138.46	109.06	
TOTAL	**156.75**	**132.49**	**150**	**128.84**	**TWh**
		Mobility Passengers			
Diesel/Bio-diesel	0	3.14	1.77	3.35	
NG/SNG	0	3.56	0	3.3	
H_2	19.59	27.88	17.4	27.88	
TOTAL	**29.74**	**36.48**	**29.32**	**36.45**	**TWh**
		Mobility Freight			
Electricity	1.67	1.67	1.67	1.67	
Diesel/Bio-diesel	3.14	0	1.01	0	
NG/SNG	0	3.61	2	3.61	
H_2	19.4	19.4	19.4	19.4	
TOTAL	**24.22**	**24.69**	**24.54**	**24.69**	**TWh**
		Cooling			
Electricity	2.95	2.95	2.95	2.95	TWh
		Non Energy			
NG/SNG	102.33	102.33	102.33	102.33	TWh
		Re fuels			
		H_2			
Electricity	58.643	58.393	45.181	58.231	TWh
NG/SNG	0	0	0	0.299	TWh
		Bio-diesel (SLF)			
H_2	2.347	0	0	0	TWh
Electricity	2.265	0	0	0	TWh
CO_2	0.777	0	0	0	TWh
Wood	0	4.719	4.174	5.038	TWh
		SNG			
Wood	23.434	0	0	0	TWh
Wet Biomass	38.879	38.879	38.879	38.879	TWh
H_2	2.347	0	0	0	TWh
Electricity	0.130	0	0	0	TWh
CO_2	1.207	0	0	0	TWh

Table D.32 – Breakdown of the Resources consumed by each of the sectors of the system, except for the electricity sector. The values correspond to the amount of resources consumed, they can be imported energy, in which case it would be accounted for in Table D.25, or resources produced in the system such as electricity or RE fuels. All values are given in TWh. Abbreviations: Renewables (RE).

Storage

	Original	*EROI*	$EROI_{min}$	$EROI_{max}$	
		Electricity			
Pumped Hydro Storage	0	70	24	89	
Lithium Batteries	64	0	618	0	
Total	**64**	**70**	**641**	**89**	**GWh$_e$**
		High Temperature Heat			
Molten Salt	211	59	34	72	GWh$_t$
		Low Temperature Heat			
Electrical Heat Pump	8 647	7 007	9 215	4 538	
Seasonal Storage (DHN)	6 985	7 182	7 182	7 182	
Total	**15 632**	**14 189**	**16 397**	**11 720**	**GWh$_t$**
		Cooling			
Cold Storage	10	38	30	37	GWh$_t$
		RE fuels			
Seasonal H_2 Storage	705	2 391	1 597	2 433	GWh
Solar Thermal Storage	14 215	13 751	12 941	10 969	GWh

Table D.33 – System power storage for each sector. The sectors that do not appear is because there is no excess demand. The values for heat are given in GWh$_t$, Electricity in GWh$_e$, and for RE fuels in TWh. Abbreviations: Decentralised (DEC), District Heating Network (DHN) and Renewables (RE).

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