UCLouvain

École polytechnique de Louvain

Integration of the SMR Technology into the Belgian Energy Mix: a Cost Optimisation Approach

Authors: **Matteo Brevi, Axel Diriken**
Supervisor: **Hervé Jeanmart, Antoine Laterre, Paolo Thiran**
Reader: **Thomas Pardoen**
Academic year 2021–2022
Master [120] in Mechanical Engineering

Abstract

The fight against climate change is the great challenge of the 21st century. To achieve this, Europe has decided to reduce its use of primary fossil fuels. In addition, it is increasingly turning to renewable energies, which seems to be indispensable to the future energy mix. Alongside these technologies is nuclear power, which had a heyday in the 1970s. However, this major source of decarbonised energy is very controversial. Belgium, a Western European country, is following the German trend away from nuclear power. It is planning to shut down some of its reactors from 6 [GW] of nuclear power to 2 [GW]. This loss of power is planned to be temporarily replaced by the construction of Combined Cycle Gas Turbines (CCGTs) until sufficient renewable energy is installed. On the other hand, many new projects around nuclear energy are emerging, including Small Modular Reactors (SMRs). These are very similar to conventional reactors but claim to have certain advantages, including higher flexibility.

This thesis studies the relevance of nuclear energy (under conventional or SMR form) in the Belgian energy mix. The tool used to carry out this study is EnergyScope Typical Days (ESTD), an energy system modelling tool based on cost optimisation. First, the case of the conventional NPPs is studied. Then the alternative solution of SMRs is studied as well.

The results show that the installation of nuclear power under either form. The latter suggests putting a lot of nuclear, around 42 [GW] coupled with 10 [GW] of Wind Turbines (WT). It is obvious that the installation of this nuclear capacity in Belgium is not feasible. However, results from a Global Sensitivity Analysis (GSA) show that on average, ESTD recommends 12 [GW] of nuclear power. This is more than double the current Belgian nuclear fleet. Moreover, the annual cost of the energy mix decreases when nuclear is increasingly present. All in all, nuclear seems to be a viable ecological and economical way to reach carbon neutrality by mid-century.

Acknowledgements

First of all we would like to express our deepest gratitude to our supervisors. Professor Hervé Jeanmart for making the theme of this thesis possible and for his availability during the year. Then, Antoine Laterre and Paolo Thiran, who joined us along the way and without whom the present work would have been even more tedious. All of these people made it possible to finalise this work successfully thanks to their priceless advice.

We thank our reviewer, Professor Thomas Pardoen, for his interest in our subject and for his valuable time.

We would like to thank Diederik Coppitters and Xavier Rixhon who gave us their time to answer our many questions.

A big thank you goes to Gauthier Limpens, who provided us with EnergyScope Typical Days, an essential tool in our work.

A big thank you to Éléonore Lieffrig, Justine Lebrun, Simon Van Brussel and Quentin Hagen, who took the time to proofread our work and gave us valuable feedback.

Special thanks go to our loved ones. Our families and friends who have been there from the beginning to the end, for better or for worse, during these few years spent at the EPL.

We would like to direct the greatest thanks to each other. This work is the result of a special collaboration and will only strengthen our deep friendship.

Contents

List of Figures

List of Tables

List of abbreviations

- **BPA** : Bonneville Power Administration
- **CCGT** : Combined cycle gas turbine
- **CEPCI** : Chemical Engineering's Plant Cost Index
- **CI** : Confidence interval
- **CLT** : Central limit theorem
- **CO_2e** : CO_2 equivalent
- **ESTD** : Energyscope Typical Days
- **EU** : European Union
- **FOAK** : First-of-a-kind
- **GhG** : Greenhouse gases
- **GSA** : Global sensitivity analysis
- **GWe** : Gigawatt electric
- **GWP** : Global warming potential
- **IAEA** : International Atomic Energy Agency
- **IEA** : International Energy Agency
- **IQR** : Interquartile range
- **LCOE** : Levelized cost of energy
- **LOO** : Leave-one-out error
- **LRL** : Licensing readiness level
- **MC** : Monte Carlo
- **MMR** : Micro modular reactor
- **MYRRHA** : Multi-purpose hYbrid Research Reactor for High-tech Applications
- **NEA** : Nuclear Energy Agency
- **NED** : Non-energy Demand
- **NG** : Natural gas

- **NOAK** : N-th of a kind
- **NPP** : Nuclear power plant
- **ONDRAF** : Organisme national des déchets radioactifs et des matières fissiles enrichies
- **PCE** : Polynomial chaos expansion
- **PDF** : Probability density function
- **PHS** : Pumped hydro storage
- **PV** : Photovoltaic
- **PWR** : Pressurised water reactor
- **RE** : Renewable energies
- **SMR** : Small modular reactors
- **SNG** : Synthetic natural gas
- **TRL** : Technology readiness level
- **TD** : Typical day
- **WNA** : World Nuclear Association
- **WT** : Wind turbines

Introduction

Europe wants to achieve carbon neutrality by 2050. To achieve this, many countries are increasingly turning to renewable energies. However, due to their intermittency, the energy mix has to be supplemented with other more flexible resources, which are often more polluting. This is one of the reasons why there are still gas, oil and even coal-fired power stations in Europe.

Nuclear power enjoyed a prosperous era in the 1970s. However, nowadays many European countries are trying to move away from this technology. Indeed, with the current power plants reaching the end of their life, the Chernobyl and Fukushima incidents and the management of nuclear waste, nuclear power is a very controversial energy. Nevertheless, nuclear power seems to be a good solution for achieving carbon neutrality by the middle of the century.

Belgium is following this European trend to move away from nuclear power. It plans to reduce its nuclear fleet by 66%, from the original 6 [GWe] to 2 [GWe]. This power shortfall is planned to be filled by CCGTs until sufficient renewables are installed, but is this the best choice to make?

Belgium has been modelled in a numerical tool called EnergyScope Typical Days (ESTD) [1]. This tool optimises the cost of the Belgian energy system while respecting a constraint on operational greenhouse gas emissions. Although this optimisation is linear, it gives an idea of what kind of energy system Belgium should turn to in order to minimise its cost and respect the constraint on emissions.

ESTD was chosen among other optimisation programmes for the following reasons:

- Open source energy model,
- Hourly resolution,
- Optimisation of the investment and operation cost,
- Reasonable computational time for uncertainty analysis [2].

From this model, the aim is to analyse how ESTD incorporates nuclear power into the Belgian energy mix and to understand why this is the case.

This thesis is structured as follows:

- In Chapter 1, the Belgian nuclear context is discussed. Furthermore, ESTD is explained followed by the methodology used throughout this thesis.
- In Chapter 2, the case of conventional nuclear power in Belgium is studied using ESTD.

- In Chapter 3, Small modular reactors (SMRs), a new technology similar to conventional nuclear power is presented
- In Chapter 4, the implementation of SMRs in the Belgian energy mix is studied using ESTD.
- Finally, in Chapter 5 a discussion is proposed to step back from the results presented earlier.

It is important to note that the power units (kW, MW, GW) as well as the energy units (kWh, MWh, GWh) always represent an electric power or energy output respectively unless mentioned otherwise.

Thorough this thesis, the following conventions are used:

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

Briefly

All the conclusion paragraphs are written in boxes.

Chapter 1

Contextualisation

First of all, it is necessary to set the context of the card in which the study is conducted. The situation in Europe and more precisely in Belgium must be clarified before understanding the issues that lead to this work. It is also crucial to introduce the tools and the data on which they are based. This allows for a better understanding of the results obtained, which will be presented in the following chapters. All this is the subject of this first introductory chapter.

> First, this chapter introduces the European nuclear context (section 1.1), and then more specifically that of Belgium (section 1.2). After that, the modelling tool EnergyScope Typical Days (ESTD) is introduced. Explanations of its working, its parameters as well as the input data it is relying on are presented (section 1.3). The explanation and motivation of a sensitivity analysis (section 1.4) are addressed and finally, the methodology followed throughout this thesis is exposed (section 1.5).

1.1 European Nuclear Context

Nuclear energy is widely used in Europe, especially in Western Europe. However, the reactors currently in use date from the 1970s and are slowly coming to the end of their designed lifetime. Indeed, Figure 1.1 shows that nuclear energy production will drastically decrease in the incoming decades[3] since the current reactors are reaching the end of their life. Today, on a European scale, this energy source represents 120 gigawatts [GW], which will have to be replaced. In 2020, nuclear energy represented 24.6% of the total electricity produced in the EU according to Eurostat[4].

It is possible to extend the operation of the plants or to replace them with new ones. In both cases, the problem remains the cost. Maintaining an existing reactor can cost between 1 and 4 billion € while building a new one costs between 3.2 and 20 billion €, furthermore, a new nuclear power plant takes about 10 [years] to build[3]. To replace 120 [GW] of nuclear power by 2050, 150 medium-sized plants would have to be built over the next 30 [years]. This means building 5 plants per year. However, between the beginning of the 21st century and 2014, only 8 new plants have been commissioned[3].

To replace nuclear power with another decarbonised energy source, one option is renewable energy. However, significant improvements in energy storage systems and the electricity grid are needed before renewables can take on an equivalent role to nuclear due to their

intermittency. Given their greenhouse gas emissions, coal, gas and oil are not long-term solutions if the European Union (EU) wants to reach its climate goals unless costly carbon capture technology is added to each power plant. On the other hand, the reduction in energy consumption should make it easier to meet Europe's energetic needs. The EU plans to reduce its energy consumption by 30% by 2030, which should reduce the number of power plants needed[3].

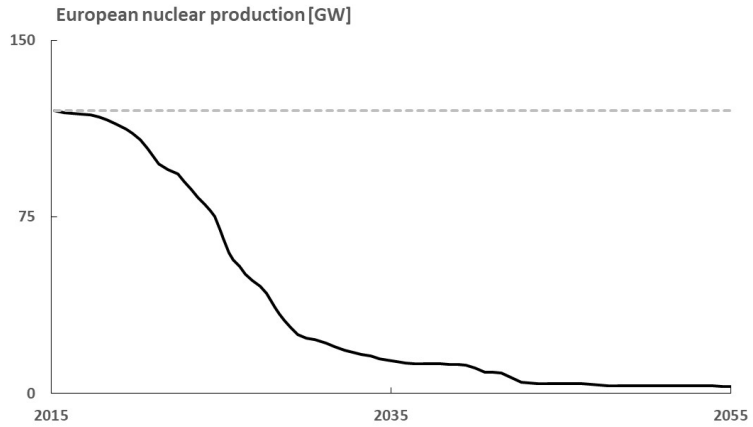

Figure 1.1: Predictions of the installed capacity of nuclear in Europe show that it will decrease from 120 [GW] in 2015 to nearly 0 [GW] in 2055 [3]

1.2 The Case of Belgium

Briefly

Belgium is a country in Western Europe with high energy needs. The Belgian energy mix relies on many sources of energy including nuclear power. However, Belgium still depends a lot on fossil fuels. Indeed, Figures 1.4, to 1.8 give an insight into Belgium's situation and its urge to find solutions to decarbonise its energy system. Coal has nearly disappeared as of today, but the remaining part of it still is responsible for a non-negligible part of the CO_2 emissions (Figure 1.6). While there is nearly no oil in electricity production anymore, it is still used a lot for other purposes such as transportation or industrial uses. It is responsible for a very big part of Belgium's emissions. Natural gas (NG) is one of the three dominant electricity production sources and it too is responsible for a big part of the country's emissions. On the other hand, Renewable energy (RE) sources are gaining in importance in the electricity mix, now representing about a fifth of its production, but this is still a very small part of the energy production. Nuclear power represented around 40% of the electricity production in 2020, but Belgium plans to shut down 5 of its 7 reactors (Table 1.1), only keeping around 2 [GW] out of its current 6 [GW]. It plans to fill the gap by opening new combined cycle gas turbines (CCGTs)[5].

Belgium is located north of France and south of the Netherlands (see Figure 1.2). It has existed since 1831 and has been part of the European Union since the latter's creation in 1993. With

its 11 500 000 inhabitants and 30700 [km^2], it is the 6^{th} most densely populated country in Europe and the 22^{nd} in the world with a population density of 375 [people/km^2] [6]. The fact that Belgium has a dense population leads to big energy needs with little space for RE sources which take up much space. Nuclear power is a very dense energy source ($\approx$ 35 times more than solar and $\approx$ 130 times more than wind [7]), which might look like a suitable solution for the dense population of Belgium, but in fact, a high population density can be a problem for nuclear power. In April 2020, ONDRAF (l'organisme national des déchets radioactifs et des matières fissiles enrichies) was looking for a place to bury the nuclear waste. The province of Luxembourg seemed to be the best location for this purpose, but public opinion was not in favour [8]. Furthermore, this province is located in the south of Belgium and close to borders with Germany and Luxembourg. This proximity to neighbouring countries led them to also oppose this decision[9].

Figure 1.2: Belgium is located in the centre of Western Europe.

1.2.1 Nuclear Power

According to the World Nuclear Association (WNA)[10], Belgium started to use its first nuclear reactor, Doel 1, in 1974. Since then, 6 other ones have been built. Table 1.1 regroups the seven nuclear power plants of Belgium. All of them are pressurised water reactors (PWR). A PWR consists of two circuits, a primary circuit and a secondary circuit. The primary one is closed. The water that it contains is heated by the heat released by nuclear fission in the reactor core. The pressure in the primary circuit is sufficient so that at this temperature the water remains in its liquid phase. This water will heat the water in the secondary circuit which will then evaporate and pass through a steam turbine to produce electricity. PWRs are the most widespread type of reactor according to the WNA[11], there are around 300 operable reactors for power generation worldwide.

As reported by the World NuclearAassociation [10], Forum Nucléaire commissioned annual surveys from Kantar TNS from 2010 on to track the sentiment of the Belgian population towards nuclear energy. Figure 1.3 shows the results of the 2019 survey that demonstrates that the Belgian population has an increasingly growing interest in keeping nuclear power as an electricity production. To the question, of whether Belgium should continue to produce electricity thanks to nuclear power, 83% of the participants turned out to be in favour, compared to 80% in 2017. On the other hand, 46% of the participants were in favour of extending the

current nuclear power plants (NPPs) compared to 30% two years earlier. Despite this, one can see in Table 1.1 that all NPPs are planned to be shut down before the end of 2025[1]. This will, according to the European Commission [13], increase the import dependency on electricity from 71% in 2020 to 86% in 2030.

Reactor	**Type**	**Net capacity** [MWe]	**First power**	**Licence to**	**Shutdown date**
Doel 1	PWR	445	1974	Feb 2025	Feb 2025
Doel 2	PWR	445	1975	Dec 2025	Dec 2025
Doel 3	PWR	1006	1982	2022	Oct 2022
Doel 4	PWR	1038	1985	2025*	2025*
Tihange 1	PWR	962	1975	2025	Oct 2025
Tihange 2	PWR	1008	1982	2022	Feb 2023
Tihange 3	PWR	1038	1985	2025*	2025*
Total		5942			

Table 1.1: List of nuclear power plants in Belgium as of March 2018[10].
*2 reactors have been extended further than 2025 according to *Le Soir*[12]. Their shut-down date is to be announced.

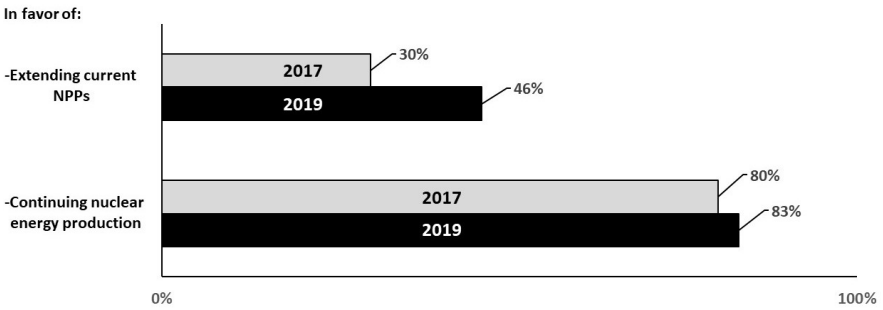

Figure 1.3: The Belgian population gains in interest of keeping nuclear energy for its electricity production. The survey asked two questions: The first one is about continuing with an electricity production based on nuclear power (in any kind). The second asks if the participants are in favour of maintaining current NPPs beyond 2025 [10].

Concerning nuclear waste, Belgium still does not agree to use a geological repository [8], which is contrary to what is internationally agreed and imposed by law. Nowadays landfill is the best method to treat nuclear waste because taking no action is the worst thing to do[14]. Currently, nuclear waste in Belgium is stored in cooling pools, which can not be seen as a sustainable solution.
Nowadays, it is already possible to recycle parts of spent nuclear fuel and convert them into mixed oxide fuel (MOX)[2]. This type of fuel can be reused in most reactors. Reprocessing does not solve the issue of highly toxic, heat-generating waste though. Because of the half-life of several hundreds of thousands of years of the radioisotopes contained in this waste, geological

[1]By the time of publishing, the government has decided to extend 2 of the 7 reactors further than 2025 [12].
[2]Mixed Oxide: plutonium and uranium nuclear fuel

disposal seems to be the best solution[14].

It is worth mentioning that currently a Belgian nuclear transmutation project, called MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), is under development. The MYRRHA reactor would allow this nuclear waste to be processed through transmutation. Transmutation makes it possible to isolate the most heat-emitting and long-living elements, called minor actinides, from spent nuclear fuel. The reactor would then be able to break down these particles to reduce their half-life time[15].

1.2.2 The Energy System

With the dense population of Belgium comes concentrated energy needs. The following set of figures (Figures 1.4 to 1.8) has been produced thanks to data provided by the *IEA Data browser*[16]. The distribution of the energy consumption can be observed in Figure 1.4. The industry, transport and residential parts are the ones that come to mind first when thinking about energy use. Public and commercial services represent a small part of the energy consumption as well, the last part is represented by what is called "Other final consumption". Under this category falls for example the non-energy demand (NED)[3].
The non-energy demand (NED) represents a big part of Belgian energy consumption. This is due to the fact that Flanders (the northern region of Belgium) hosts Europe's largest (and the world's second largest) integrated petrochemical cluster[18]. Belgium also is at the world's top of the list for the most selling plastic per capita[18].

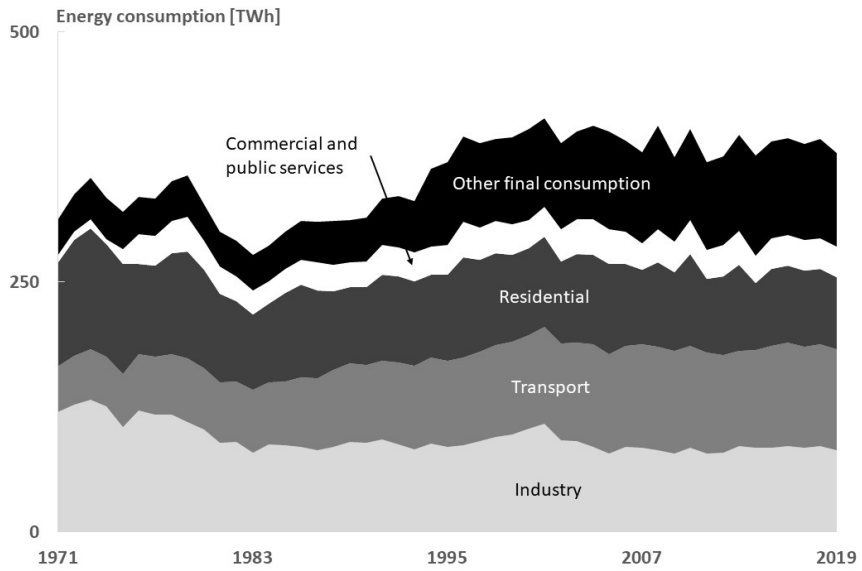

Figure 1.4: The Belgian energy consumption is distributed fairly evenly around 5 sector categories. The NED, included in black share, is an important part of Belgium's energy consumption The total consumption seems to have reached an equilibrium since the 21^{st} century. Data from the *IEA Data browser*[16]

[3] (or non energy use) "Non energy use includes energy products used as raw materials in the different sectors; that is not consumed as a fuel or transformed into another fuel. For example most lubricants and bitumen are used for non-energy purposes. Similarly natural gas is used as a raw material for the petrochemical industry, etc."[17]

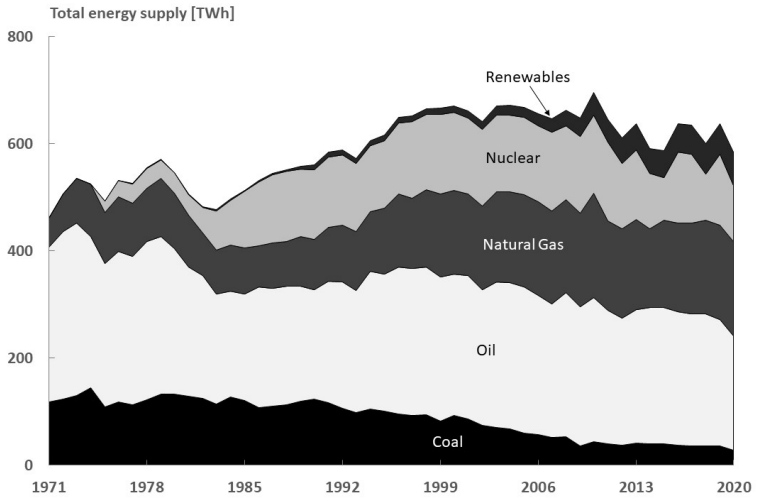

Figure 1.5: The Belgian energy production relies on a lot of fossil fuels. Coal is slowly falling away, but is still present in 2020. Natural gas and oil are very predominant in the energy mix. Data from the *IEA Data browser*[16]

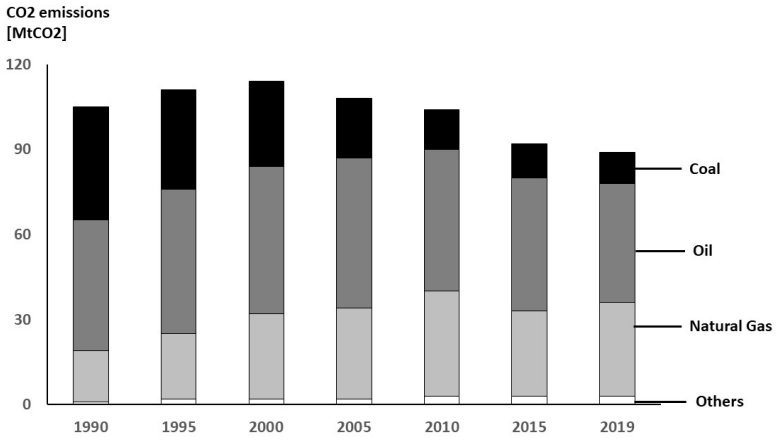

Figure 1.6: Belgian CO_2 emissions seem to be on a decreasing trend since the beginning of the 21^{st} century, but fossil fuels are still accounting for nearly 100% of the CO_2 emissions. Data from the *IEA Data browser*[16]

Figure 1.5 shows the produced energy in Belgium by source. One can observe that still today the majority of the energy comes from fossil sources, mostly oil or natural gas (NG). Nuclear energy also plays an important role in the Belgian energy mix, while coal and renewable energy (RE) sources complete the share.
Figure 1.6 shows Belgium's CO_2 emissions by source from 1990 to 2019. It is clear that when it comes to emissions that fossil fuels are standing out the most. While Belgium has nearly completely cut away coal (Figure 1.5) it still represents a non-negligible part of its emissions (Figure 1.6). Oil and gas imports are still on a rising trend in 2020 as can be observed in Figure 1.7. Therefore, very strong efforts need to be made to cut them away just like it has been the tendency for coal.

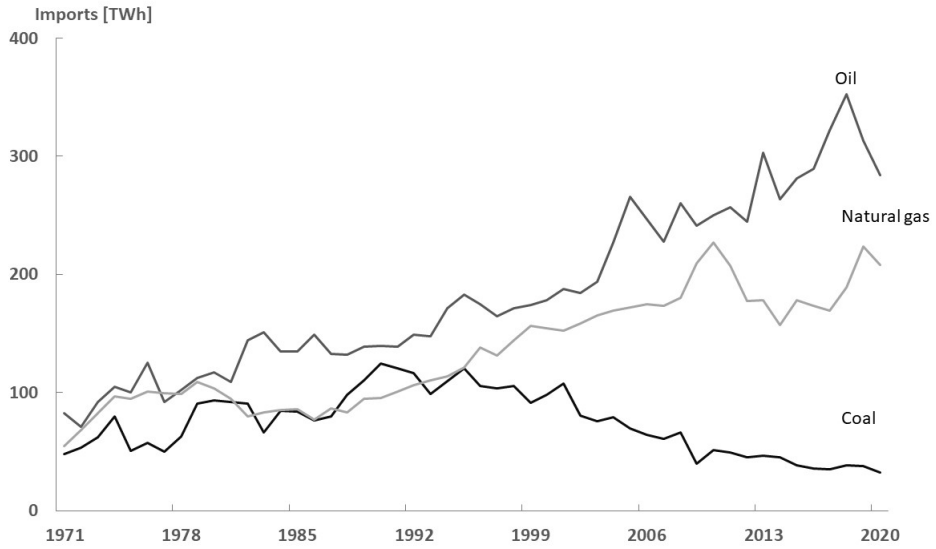

Figure 1.7: Oil and gas imports are still increasing, while coal imports are falling off. Data from the *IEA Data browser*[16]

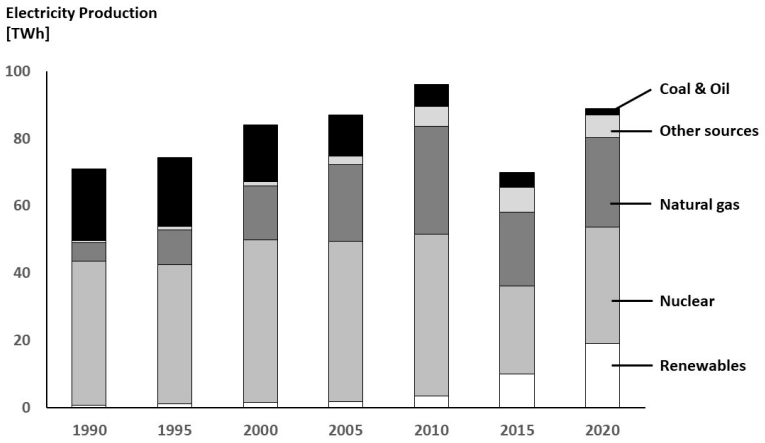

Figure 1.8: Belgium relies mostly on natural gas, nuclear power and RE sources for its electricity production in 2020. Coal and oil have nearly disappeared from the electricity system while a clear rising tendency is observed for the renewable part. Data from the *IEA Data browser*[16]

Today, oil is mostly used for transport, NED and domestic heating, according to the *IEA Data browser*[16]. As for NG, the country plans to open new combined cycle gas turbines (CCGTs) in order to replace the NPPs that are supposed to be shut down for 2025 [5], which runs counter to the emission reductions expected by the Paris Agreements (See Appendix A)[19].

Turning to the electricity production, one can see in Figure 1.8 that the majority of Belgium's production is insured via nuclear, NG and RE sources (39%, 30% and 22% in 2020 respectively). Nearly no coal or oil is used for electricity production anymore (2% in 2020). A small part is produced via so-called "other sources" (7.73% in 2020). Under these fall, among others, biofuels and waste-based production. While coal and oil are on a decreasing trend, RE sources have a rising tendency. In 2010, RE sources accounted for around 3 – 4% of the electricity

production. In only 10 [years] they have shifted from a very small part of the electricity system to a significant part of it. This comes from the will to decarbonise the electricity mix and one can see in Figure 1.6 that it seems to pay off as the emissions have reduced since the beginning of the 21^{st} century. The catch is that RE sources operate in a different way than most of the other sources because they rely on weather conditions to operate. To a well-balanced system, other more flexible sources are required.

Currently, Belgium relies on NG and the imports from its neighbours to cover the remaining demand while the nuclear fleet provides a safe baseload production. Figure 1.9 shows the hourly electricity production from 15-16 May 2022 and one can clearly see that nuclear power in Belgium varies very little in one day, while the intermittency of RE sources is pretty obvious. Other sources such as NG, pumped hydro storage (PHS) and imports cover the remaining part of the electricity demand.

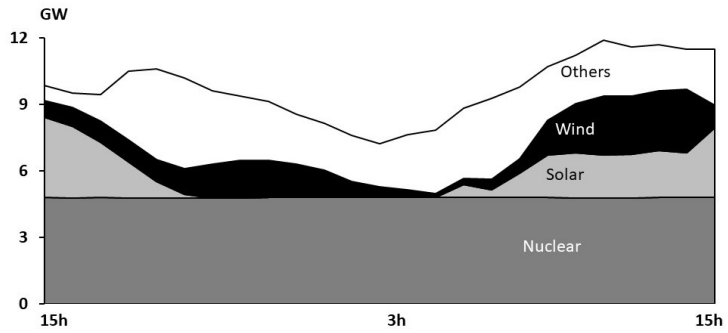

Figure 1.9: The Belgian hourly electricity production on 15-16 May 2022 according to *ElectricityMap* [20]. Nuclear plays the role of a safe baseload. Photovoltaic (PV) and wind turbines (WT) depend on the weather conditions. Other sources (Natural gas, pumped hydro storage and imports from France, the Netherlands and Germany) cover the remaining electricity demand and adapt depending on RE sources' intermittency.

1.3 EnergyScope Typical Days : A Cost Optimisation Model

Briefly

EnergyScope Typical Days (ESTD) is an energy system optimisation program. Based on linear programming, it enhances the system such that it represents the cheapest possible solution respecting a set of constraints. Various constraints can be applied, but in the case of this thesis, the most important one is that the total energy system has a limit on operational emissions. For the modelling of renewable energy sources, ESTD relies on twelve so-called *Typical Days* that allow it to model the entire year accurately enough. The program has three different parameter categories: the Demand (section 1.3.2), the Technologies (section 1.3.3) and the Resources (section 1.3.4). The optimisations working as well as the links between the three parameter categories are summed up in section 1.3.5. Finally, the data used for the present work is exposed in section 1.3.6, where Table 1.2 shows the predicted Belgian demand for 2035. Similar tables for technologies and resources can be found in Appendix E.

In the context of the research for a Belgian low-carbon energy mix, it is necessary to be able to identify and quantify the necessary technologies to implement them. To do so, the authors decided to use an open-source tool to model and optimise the energy mix of a country, i.e. ESTD. EnergyScope Typical Days (ESTD) is an open-source one-cell model for the regional whole-energy system like a country (it is multi-sector and multi-carrier). In this context, the country is Belgium. The energy system includes electricity, heat, transport and non-energy demand (NED). Taking into account several parameters for different demands, resources and technologies, ESTD then calculates what the energy mix should be in order to minimise the total yearly costs, taking into account a constraint on the maximum yearly operational emissions. The equivalent CO_2 emissions (i.e. constraint) are sometimes referred to as *global warming potential (GWP)*. The model has been developed through a collaboration of *UCLouvain* (Belgium) and *EPFL* (Switzerland) in 2011. It is written in an algebraic language which can be compiled with an open-source solver (GLPK) but also a commercial one (AMPL). The cost optimisation is linear, which has the disadvantage of being restrictive in terms of functionality and results accuracy but has the advantage of being easy to use and fast to compile. It is important to emphasise the fact that the construction emissions for different technologies are not taken into account in the emissions constraint. The constraint is only applied to the operational emissions. Therefore, it is also important to analyse the yearly emissions of the resulting energy system. Complete documentation about ESTD can be found in Limpens et al. (2019)[1].

In the case of this thesis, ESTD is used to analyse the relevance of including nuclear power into the Belgian energy mix to reduce emissions while minimising costs. ESTD gives the possibility to have a "single" optimum result for the energy system, which gives a good approximation of which path to choose from to achieve carbon neutrality. ESTD also gives the possibility to play with each input parameter separately, to add or remove technologies, etc. Its easy handling allows to play with different levers and to quickly exploit their effect on the energy system. It should be noted that ESTD is based on data where all costs are expressed in $€_{2015}$.

ESTD counts three categories of input parameters; the Demand, the Technologies and the Resources. During the optimisation process undergone by ESTD, they are linked in the way that the technologies require resources in order to transform them into energy or energy vectors. For example, if particular demand for electricity needs to be satisfied, the set of technologies will use the set of resources in order to transform them into electricity in the cheapest way possible while respecting the constraint in operational emissions. For this, several parameters are required to characterise the different technologies, resources and demands. The explanation of these parameters can be read in sections 1.3.2, 1.3.3 and 1.3.4.

1.3.1 The Typical Days Approach

Now that the general idea behind ESTD is clear, the working of the *Typical Days* should be explained.
To include the modelling of the power generation of intermittent RE sources as well as the consumption of each other resources, ESTD needs to calculate the hourly production of each technology over 8760 hours, i.e. one year. However, if the 365 days of a year were modelled, it would be very time-consuming to model. In order to give an idea, running ESTD on these 8760 time series would take more than 19 hours of computation. Therefore, to tackle this problem, the concept of *Typical Days* (TD) has been included. The idea behind this is to use a subset

of representative days, i.e. the TDs. In the previous work of Limpens et al. (2019) [1], the number of days required to represent a whole year has been estimated to be 12, each based on different conditions (especially weather conditions). The conditions are modelled each hour, so these 12 TD·24 hours = 288 time series approximations out of the 365 days·24 hours = 8760 real ones come from a trade-off between the computation time and an approximation error.

1.3.2 Demand Parameters

The parameters that are necessary to characterise a demand are listed below.

- **Baseload electricity** [GWh]: The electricity demand that is always required at any time of the day and any day of the year.
- **Variable electricity** [GWh]: The electricity demand that evolves throughout the day and week. During the night, the demand is low, during the day, the demand reaches a peak at two different times (see Figure 1.9).
- **High temperature heat** [GWh]: The industries require very hot temperatures for their various applications.
- **Space heating** [GWh]: Homes, offices and shops need to be heated.
- **Hot water** [GWh]: Homes, offices and shops need hot water (to take a shower for example).
- **Passenger mobility** [Mpkm][4]: People need to be able to move from one point to the other.
- **Freight mobility** [Mtonkm][5]: Goods need to be transported from the producers to the consumers.
- **Non-energy** [GWh]: Other products like packaging material or fertilisers require energy to be produced.

1.3.3 Technologies Parameters

The parameters that are necessary to characterise a technology are listed below.

- **Lifetime,** t_j [years] : the lifetime that can be expected from technology j.
- **Maximum capacity factor,** $C_{p,j}$ [-] : the maximum load factor that can be expected from technology j, (representing a percentage). Its value is between 0 and 1.
- **Specific investment costs,** $c_{inv,j}$ [€$_{2015}$/GW]: the investment cost of technology j for one GW of installed power. $c_{inv,j}$ and the so-called *overnight cost*[6] are the same. It represents the fictional cost of a facility as if it was built in one night, divided by the total power output of the facility.

[4] Million-person-kilometre

[5] Million-ton-kilometre

[6] "Overnight cost is the cost of the construction project if no interest was incurred during the construction, as if the project was completed "overnight". This concept is used for providing a simplistic cost comparison between power plant projects of technologies, through a ratio with the maximum power the plant can deliver." [21]

- **Specific maintenance costs,** $c_{maint,j}$[€$_{2015}$/GW] : the maintenance costs of technology j for one GW of installed power.
- **Construction global warming potential,** $gwp_{constr,j}$ [ktonCO$_2$e/GW]: the global warming potential of the construction of technology j for one GW of installed power. This corresponds to the CO$_2$e emissions linked to the construction of 1 [GW] capacity. This parameter is not taken into account when calculating the constraint on annual operation emissions.
- **Maximum allowed capacity,** $f_{max,j}$ [GW]: the maximum power output of technology j that ESTD is allowed to put in the energy system. In other words, it is an upper bound for technology j. This is useful for example if there is limited space for RE sources, and no more than a particular value of these technologies can be installed in the country.
- **Minimum allowed capacity,** $f_{min,j}$ [GW]: the minimum power output of technology j that ESTD is allowed to put in the energy system. It is a lower bound for technology j. For example if one wants to force a minimum geothermal capacity at 1 [GW]: $f_{min,GEOTHERMAL} = 1$ [GW]
- **Maximum & minimum percentage allowed capacity,** $f_{\%,max,j}$ **&** $f_{\%,min,j}$ [-]: ESTD subdivides technologies into different sectors. For instance, there is a sector "Electricity" which includes all electricity production technologies, a sector "Electricity Storage", which includes all electricity storage technologies, "Passenger Mobility" which includes transportation technologies that are used from passengers to get around, etc. $f_{\%,max,j}$ and $f_{\%,min,j}$ define what share of the sector can be taken by technology j as a maximum or minimum respectively. For example if $f_{\%,max,CCGT} = 0.2$, it means that maximum 20% of the electricity production can be done by CCGT.

It is important to mention that the units can vary depending on the sector of the technology. It makes no sense for example to speak about "*installed capacity*" in [GW] for a given quantity of transportation (car, bus, tram, ...). [GW] might not be the best unit for storage technologies either. Additional and complete information can be found in Limpens et al. (2019)[1].

1.3.4 Resource Parameters

The parameters that are necessary to characterise a resource are listed below.

- **Availability,** $avail_i$ [GWh/year]: the availability of resource i each year in terms of energy, i.e. the quantity that can be imported.
- **Operation global warming potential,** $gwp_{op,i}$ [ktonCO$_2$e/GWh]: the global warming potential of the resource i per GWh that it can deliver. These represent the CO$_2$e emissions that are linked to the combustion, but also to the extraction, transportation, preparation, refinement, etc. Pay attention that the global warming potential of a resource contains the direct emissions (see "Direct emissions" below) as represented in Figure 1.10.
- **Operational costs,** $c_{op,i}$ [€$_{2015}$/GWh]: the cost of resource i per GWh that it can deliver.
- **Direct emissions,** CO$_{2\text{op,i}}$ [kton$_{CO_2}$/GWh]: the CO$_2$ emissions that are directly linked to the combustion of fuel (or resource) i per GWh that it can deliver. The direct emissions are contained in the operational global warming potential as represented in Figure 1.10.

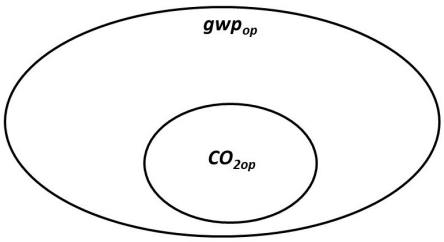

Figure 1.10: CO_{2op} is contained inside the value of gwp_{op}

1.3.5 The Minimisation Principle

As already mentioned, the model optimises the choice for technologies taking into account the input parameters and an additional constraint on emissions to minimise the total annual cost of the system (C_{tot}):

$$\min(C_{tot}) = \sum_{j \in \text{TECH}} \left(\tau_j C_{inv,j} + C_{maint,j}\right) + \sum_{i \in \text{RES}} C_{op,i}, \tag{1.1}$$

where

- τ is the annualising factor. It is detailed in Equation 1.5,
- τC_{inv} and C_{maint} account for the annualised investment and maintenance cost of a technology,
- C_{op} is the cost of operation of a resource

Equation 1.2, 1.3 and 1.4 define the investment, the maintenance and the operational cost respectively.

$$C_{inv,j} = c_{inv,j} F_j \qquad \forall j \in \text{TECH}, \tag{1.2}$$

$$C_{maint,j} = c_{maint,j} F_j \qquad \forall j \in \text{TECH}, \tag{1.3}$$

$$C_{op,i} = \sum_{t \in T | \{h,td\} \in T\_H\_TD(t)} c_{op,i} F_{t,i}(h,td)\, t_{op}(h,td) \qquad \forall i \in \text{RES}, \tag{1.4}$$

where

- $c_{inv,j}$ and $c_{maint,j}$ are the specific investment and maintenance cost of technology j as explained in section 1.3.3
- F_j is the installed capacity of technology j
- $c_{op,i}$ represents the operational cost of resource i
- t_{op} is the considered period
- F_t is the actual use of the resource in each time period
- "h" and "td" stand for the hours of a TD and TD respectively. Summing all the hours over all typical days in T_H_TD is equivalent to summing all the hours of a year together (i.e. 8760 hours), as explained in section 1.3.1

The annualising factor of technology τ_j of technology j and is obtained thanks to:

$$\tau_j = \frac{i_{rate}(i_{rate}+1)^{t_j}}{(i_{rate}+1)^{t_j}-1} \qquad \forall j \in \text{TECH}, \tag{1.5}$$

where

- t_j is the lifetime of technology j
- i_{rate} the interest rate

The constraint on operational global warming potential is expressed as follows:

$$GWP_{tot} = \sum_{i \in \text{RES}} GWP_{op,i} \leq gwp_{limit}, \tag{1.6}$$

$$GWP_{op,i} = \sum_{t \in T | \{h,td\} \in T\_H\_TD(t)} gwp_{op,i} F_{t,i}(h,td)\, t_{op}(h,td) \qquad \forall i \in \text{RES}, \tag{1.7}$$

where $gwp_{op,i}$ are the specific operational emissions of resource i as explained in 1.3.4. Once again, one can see that the construction emissions are not taken into account in the constraint shown in Equation 1.6.

1.3.6 Input Data

During his thesis [22], G. Limpens has developed an extension to ESTD namely "ESTD Pathways" that generates regular time intervals for which the energy model is optimised. The goal is to obtain a path that one can follow in order to make an energy transition. By contrast, "ESTD Snapshot" [7] only gives the optimum energy model of one particular moment without taking into account possibly already built facilities or parameters that may evolve in time. G. Limpens dedicated part of his time to gathering data to characterise the evolution of the model's input parameters. Data for every 5 year interval starting from 2015 to 2050 can be found in his work.
For this thesis, the authors chose to select data from 2035. Indeed, the target year is 2050, but it is not at this date that initiatives must be taken. To succeed in limiting our emissions to meet the Paris Agreements, it is crucial to start putting things in place as soon as possible. It makes sense to base the data on 2035, because that year is in the middle between now and the target year, 2050. The energy transition is not going to happen overnight, so today's data will be outdated in 10 [years] and 2050's data are not yet a reality, but also, they are quite uncertain. The 2035 data seem to be a good compromise in order to capture the whole set of years between today and 2050.
Table 1.2 shows the demand data that ESTD is relying on in the context of this thesis. They are predictions for the demand in 2035. Similar tables for resources and technologies can be found in Appendix E, Table E.2 and Table E.3. These data are the framework of the results obtained in the following sections (Chapters 2 and 4).

[7] "ESTD Snapshot" is referred to as "ESTD" in the rest of the thesis for more convenience.

DEMAND					
Category	**Subcategory**	**Households**	**Services**	**Industry**	**Transports**
Electricity [GWh]	baseload	14263	14083	33690	0
Electricity [GWh]	variable	7680	11065	11111	0
Heat [GWh]	high temperature	0	0	50436	0
Heat [GWh]	space heating	70242	34821	13118	0
Heat [GWh]	hot water	17955	7806	3399	0
Mobility [Mpkm]	passenger	0	0	0	194081
Mobility [Mpkm]	freight	0	0	0	98034
NED [GWh]	NED	0	0	53109	0

Table 1.2: Predictions for the 2035 Belgian demand from G. Limpens (2021) [22].

1.4 Uncertainty Analysis : Global and Local Parameter Variation

Briefly

A "deterministic" approach is an approach where each input parameter is deterministic, which means that the parameters have a single value that is assumed to be correct and exact. In reality, there is an inherent uncertainty linked to all parameters. An uncertainty analysis allows to quantifying what is the impact of the varying parameter on a metric of study, for example, the impact of a varying cost of natural gas (parameter) on the total cost of the energy system (metric of study). The uncertainty analysis can be local or global. In a local sensitivity analysis, one parameter is varying at a time and its direct impact on the metric of study is studied. This approach is interesting but it is only part of the picture as in reality all parameters are uncertain and may vary together. The study of all parameters varying at the same time is a GSA (GSA). It allows a more global picture of the variation of the metric of study. In this thesis, two methods are used for a GSA, the Monte Carlo method (MC) (see section 1.4.1) and the Polynomial Chaos Expansion (PCE) (see section 1.4.2). As explained below, the PCE method is favoured compared to the MC method because it is less time-consuming. Yet, a PCE is a surrogate model, so an error is made while approximating the real model. If the limits of a PCE approach are reached, an alternative method is required in order to have exploitable results. The alternative solution can be a MC method or any other method that is not covered in the framework of this thesis. Figure 1.11 shows a schematic of the difference between a local and global approach.

ESTD relies on numerous parameters that are exposed in section 1.3.6, but these are inherently uncertain as they evolve through time and space as well as depend on the sources they have been obtained from. This is why it is crucial to quantify the uncertainty of these parameters as well as their uncertainty propagation through the model. It is possible to analyse the effect of the variation of an input parameter on a metric of study of the result in two different ways, i.e. through a local or Global Sensitivity Analysis (GSA).
In the first of the two, only one input parameter varies at a time and the impact of this variation is observed on the metric of study. For example the impact of a varying cost of natural gas (parameter) on the total cost of the energy system (metric of study).
In the second, multiple parameters can vary at the same time and the impact is observed on the metric of study. For example the impact of the uncertainty linked to the cost of natural gas, its availability, the investment cost of different renewable energy sources and the emissions linked to the life cycle of battery electric vehicles (parameters) on the total cost of the energy system (metric of study).
Figure 1.11 shows a graphical representation of the difference between a local sensitivity analysis (a), where only parameter X varies, and a metric of study (b) where both parameters X and Y vary at the same time. Here, the x-axis and the y-axis both represent input parameters, so Figure 1.11 represents the input parameter space.

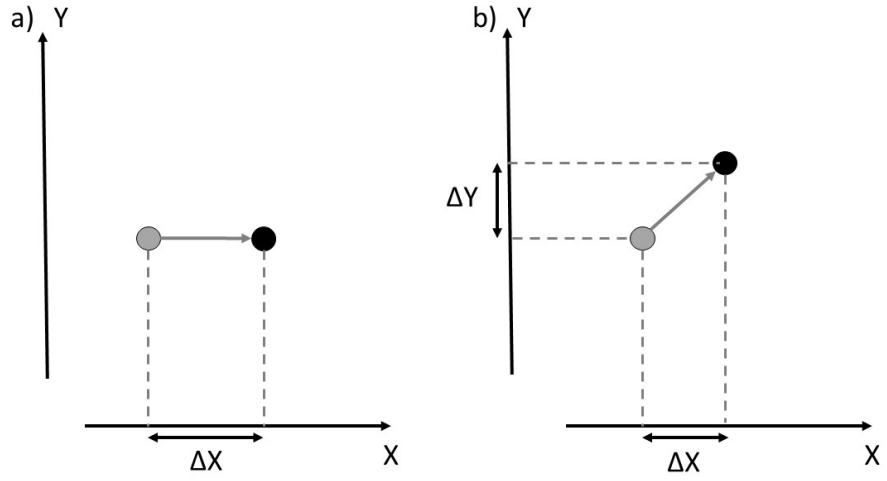

Figure 1.11: A graphical comparison between a local (a) and a global (b) sensitivity analysis. a) The only parameter that varies is X. (b) Both parameters X and Y are varying at the same time.

Both methods have their advantages.

- In the local variation, one sees exactly what is the direct impact of one parameter on the final result, but this impact might be different if other parameters vary with it.
- A global analysis allows to explore a wider range of the input-space and to get a more global view of the results, taking into account the uncertainty of each parameters at the same time. On the other hand, it is more difficult to deduce what is the impact of the variation of one particular parameter on the results.

While a local variation is easy to do, it does not reflect what is most likely to happen in reality. In a real case scenario, different parameters vary at the same time, but it is impossible to know how much each parameter will vary, which is why a global analysis is still not always accurate either.
Accordingly, after a deterministic[8] analysis, a local and a metric of study are useful to have a good understanding of the results and to put the deterministic results into context.
For the global uncertainty analysis, there are several possibilities. In the case of this work, two methods have been chosen in particular. On the one hand, the Monte Carlo (MC) method [23] and on the other hand the Polynomial Chaos Expansion (PCE) method [24].

1.4.1 GSA: Monte Carlo Method

The model on which the MC method is based is used repeatedly to generate a sufficient quantity of data to be able to determine statistical quantities such as the mean, the standard deviation and the distribution of the parameter studied. Easy to implement and understand, this method is very straightforward and "unstoppable" in the sense that it can be used in almost any problem. The disadvantage of this method is that it can take a long time to converge. Convergence means that there have been sufficient data generated for a statistical tendency to appear. Usually, the mean value is calculated at each new iteration and when the latter reaches a stable value, convergence has been reached. One can see that the aspect of convergence is vague and arbitrary, which is a disadvantage of this method.

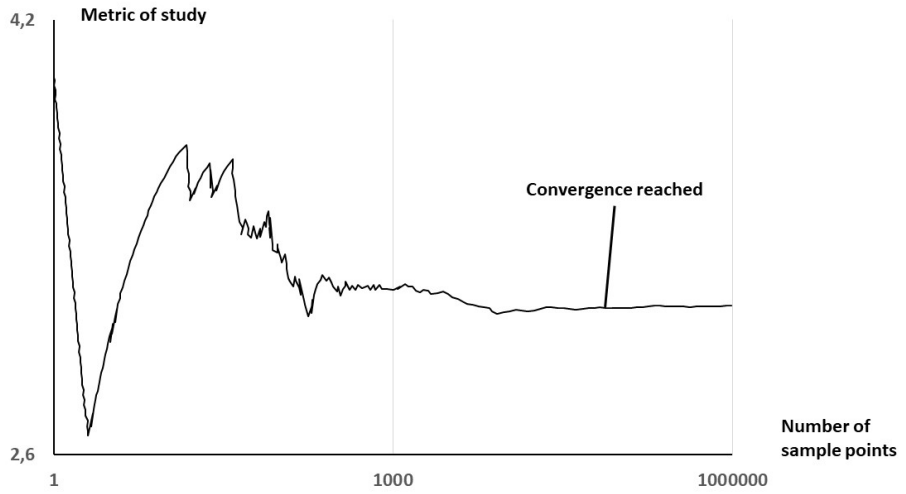

Figure 1.12: Evolution of the mean of a studied metric thanks to Monte Carlo method. The more samples generated, the less fluctuating the mean of the metric of study.

[8] A deterministic approach means that all parameters are considered to be certain. They are characterised as a single value number, in contrast to a stochastic approach that takes into account a certain randomness in the value of the input parameters. In the latter case, they are characterised by a distribution (uniform between two bounds for example)

To illustrate the simplicity of the method, Equation 1.8 provides a basic algorithm on how to use the MC method. $\mathscr{M}_i$ is the computational model with i sample quantities and $x^{(j)}$ is sample number j. The algorithm simply states that while the mean of the model with N sample has not converged, another sample is generated and a new mean is re-evaluated. The outcome of a MC method can be viewed in Figure 1.12. It represents the evolution of the metric of study as a function of the number of sample points. The more samples generated, the less fluctuating the metric of study.

$$\begin{aligned} &\texttt{while} \quad \text{mean}(\mathscr{M}_N) \ \texttt{ has not converged :} \\ &\qquad x^{(N+1)} = \texttt{model.run()}; \\ &\qquad \text{mean}(\mathscr{M}_N) = \text{mean}(\mathscr{M}_{N+1}); \end{aligned} \tag{1.8}$$

As already explained convergence is arbitrary and it can take a long time especially if the model takes a long time to run. In Figure 1.12, the number of sample points that have been generated goes up to 10^6, but the convergence criteria really depends on the precision that is required by the study. To tackle the disadvantages of the MC method, it is possible to have a different approach; the polynomial chaos expansion (PCE) method. It provides a computational efficiency alternative to the MC method.

1.4.2 GSA: Polynomial Chaos Expansion Method

MC method often takes some thousand to some ten thousands (or more) computations until convergence is reached. The aim of a PCE method is to drastically reduce this computational time. The principle is to approximate the real model $\mathscr{M}$ thanks to a PCE surrogate model $\mathscr{M}^{\text{PCE}}$, which is very fast to compute compared to the real model. A PCE surrogate model consists of a series of multivariate orthonormal polynomials $\boldsymbol{\Psi}_{\boldsymbol{\alpha}}$ with corresponding coefficients $\boldsymbol{u}_{\boldsymbol{\alpha}}$ [24]:

$$\mathscr{M}^{\text{PCE}}(\boldsymbol{X}) = \sum_{\alpha \in \mathscr{A}} \boldsymbol{u}_{\boldsymbol{\alpha}} \boldsymbol{\Psi}_{\boldsymbol{\alpha}}(\mathbf{X}) \approx \mathscr{M}(\boldsymbol{X}), \tag{1.9}$$

where $\boldsymbol{X}$ is a random vector with the independent input parameters and $\boldsymbol{\alpha}$ represents the multi-indices stored in the set $\mathscr{A}$. In order to limit the multivariate polynomial order in the expansion up to a certain degree, the size of $\mathscr{A}$ ($= |\mathscr{A}|$) is defined by a typical truncation scheme. Also $|\mathscr{A}|$ is equal to the number of coefficients in the PCE. The number of multi-indices in the set is equal to:

$$|\mathscr{A}^{M,p}| = \frac{(p+M)!}{p!M!}, \tag{1.10}$$

where $M = |X|$ is the number of input parameters, i.e. the stochastic dimension and p is the order of the polynomial. Therefore, the number of coefficients used for the PCE is also $|\mathscr{A}^{M,p}|$ and in order to find their values, least-square minimisation is applied [25]. In order to obtain enough data to rely on for the least-square minimisation of the coefficients, $2|\mathscr{A}^{M,p}|$ samples are generated from the real model. The input samples are denoted $\mathscr{X} = \{x^{(i)}, i = 1, ..., 2|\mathscr{A}^{M,p}|\}$. They are evaluated in the system model and then are stored in vector $\mathscr{Y}$.
The information gained through the sample generation allows to generate the following information matrix $\boldsymbol{A}$:

$$\boldsymbol{A} = \left\{ \boldsymbol{A}_{ij} = \boldsymbol{\Psi}_j \left(\boldsymbol{x}^{(i)} \right), i = 1, ..., 2|\mathscr{A}^{M,p}|, \quad j = 1, ..., |\mathscr{A}^{M,p}| \right\}. \tag{1.11}$$

The least-square minimisation returns:

$$\boldsymbol{u} = \left(\boldsymbol{A}^T \boldsymbol{A}\right)^{-1} \boldsymbol{A}^T \mathscr{Y}. \tag{1.12}$$

Once the PCE has been generated, the mean μ and the standard deviation σ of the metric of study are directly obtained:

$$\mu = u_0, \tag{1.13}$$

$$\sigma^2 = \sum_{i=1}^{\mathscr{A}^{M,p}} u_i^2. \tag{1.14}$$

Besides the mean and standard deviation, the PCE also allows to obtain the Sobol' indices. The so-called "total-order Sobol' indices" are a metric to measure the contribution of each input parameter to the variance of the metric of study, including the mutual interactions. The latter are obtained as follows:

$$S_i^{\mathrm{T,PC}} = \sum_{\boldsymbol{\alpha} \in \mathscr{A}_i^{\mathrm{T}}} u_{\boldsymbol{\alpha}}^2 / \sigma^2 \quad \mathscr{A}_i^{\mathrm{T}} = \left\{\boldsymbol{\alpha} \in \mathscr{A} \,:\, \alpha_i > 0\right\}. \tag{1.15}$$

where the index i indicates the Sobol' index of the i^{th} input parameter.

1.5 Methodology

Briefly

The two technologies that are studied in the context of this thesis are conventional nuclear power plants (Chapter 2) and SMRs (Chapter 4). In both cases, a deterministic approach is carried out, which turns out to have very similar results on the total energy system. They are compared to a case where none of these technologies are allowed. Because of the similarity of the results for both technologies, a local sensitivity analysis is only carried out for conventional reactors. Then, a GSA on the total system cost based on a PCE is done for both technologies. Finally, the installed capacity of SMRs is done via a MC method because the PCE did not work for this metric of study. Table 1.3 summarises all the steps taken.
Figure 1.13 illustrates the working of the MC and PCE method. When the MC method is used it runs ESTD many times before convergence of the metric of study while the PCE method uses ESTD to generate sufficient coefficients in order to create the approximating polynomial. The latter is very fast to run and is therefore used for a MC method (based on the approximating PCE, instead of the real model). The leave-one-out error (Equation 1.17 and Figure 1.15) allows to quantifying the error made by approximating the real model by a PCE. This indicates if the order of the polynomials chosen for the approximation is sufficient. If not, a higher order PCE needs to be generated, but this rapidly increases the computational time. The Sobol' indices allow it to identify the uncertain parameters that are little impacting the metric of study. These parameters can be considered deterministic if they are located below the threshold of "good practice" (Equation 1.18) in order to reduce the computational time for higher order runs.

Now that the tools have been introduced, the procedure for obtaining results can be explained. As the aim of this thesis is to study the relevance of nuclear energy in Belgium, it is necessary to get an idea of the overall energy system, which is where ESTD comes in very handy. First, the global operation mode is explained in section1.5.1 and the precise way how MC and the PCE are utilised is explained in section 1.5.2. It should be noted that all results (deterministic or from an uncertainty analysis) generated by ESTD were obtained using a constraint on operational emissions of 5000 [ktonCO$_2$e/year], which is 5% of the emissions from 2020[9]. This value has been arbitrarily chosen. It may seem ambitious but as a reminder, it only concerns the operational emissions so the emissions due to construction, transport, etc. are not taken into account in these 5000 [ktonCO$_2$e/year] and will come on top of them. Table 1.3 sums up all the steps that this work goes through.

1.5.1 Main Thread

In Chapter 2, the focus is made on conventional nuclear power. Starting with a deterministic approach where the energy system is analysed via 3 scenarios arbitrarily chosen; one where no nuclear power is allowed (modelling a phasing out of the technology), one where no upper quantity is imposed on nuclear power (to analyse how much ESTD is ready to rely on the technology) and one where a maximum of 6 [GW] of nuclear power is allowed (modelling the current nuclear capacity in Belgium). Results from a deterministic approach have limited

[9] based on the Belgian yearly CO_2 emissions from [16]

value, because there is no information on their reliability. This is why both a local and a global sensitivity analysis are carried out.

First, a local sensitivity analysis is shown with three separately varying parameters, the investment cost of nuclear power, operational costs of uranium and operational emissions linked to the uranium lifecycle.
After that, a multi-parameter local variation is made by varying the three latter parameters together. These approaches allow it to understand how the different parameters that are directly linked to the nuclear technology affect the total energy system, but the uncertainty of all the other parameters is not taken into account. This is why a metric of study is carried out that allows it to see what the impact is on the total cost and on the energy system. The metric of study on the total system cost is done thanks to the PCE method. The precise way how the method is used in the case of this thesis is explained below in section 1.5.2.

After a review of the SMR technology in Chapter 3, the latter technology is analysed similarly conventional nuclear power in Chapter 4. First, a deterministic approach is taken. Because of the similarity in results between SMRs and conventional reactors, no local variation is carried out in that chapter. A metric of study on total costs and the installed capacity of SMRs is shown. For the first, the PCE method is used, but for the second, the PCE did not work and the autos needed to rely on a MC method to extract results.
As a reminder, Table 1.3 gives an overview of all the analyses that are carried out.

	Summary of studies	
	Conventional Nuclear Chapter 2	**SMRs** Chapter 4
Deterministic	Analysis of the energy system with more or less nuclear power allowed	Analysis of the energy system with more or less SMRs allowed
Single parameter local sensitivity analysis	Analysis on the energy system with **separately** varying : 1) nuclear investment cost 2) uranium operational cost 3) uranium emissions	/
Muli-parameter local sensitivity analysis	Analysis on the energy system with **simultaneously** varying : 1) nuclear investment cost 2) uranium operational cost 3) uranium emissions	/
GSA with PCE	GSA on total system cost : 1) including nuclear power 2) excluding nuclear power	GSA on total system cost 1) including SMRs
GSA with MC	/	GSA on installed capacity of SMRs

Table 1.3: Table that summarises all the studies undergone in the context of this thesis

1.5.2 GSA in the Framework of ESTD

Figure 1.13 graphically represents how the PCE is made use of in the context of this thesis. MC (left) and PCE (right) methodologies are put side by side in order to compare the two approaches. The starting point is the intention of doing a GSA. In both cases, the computational model is ESTD.

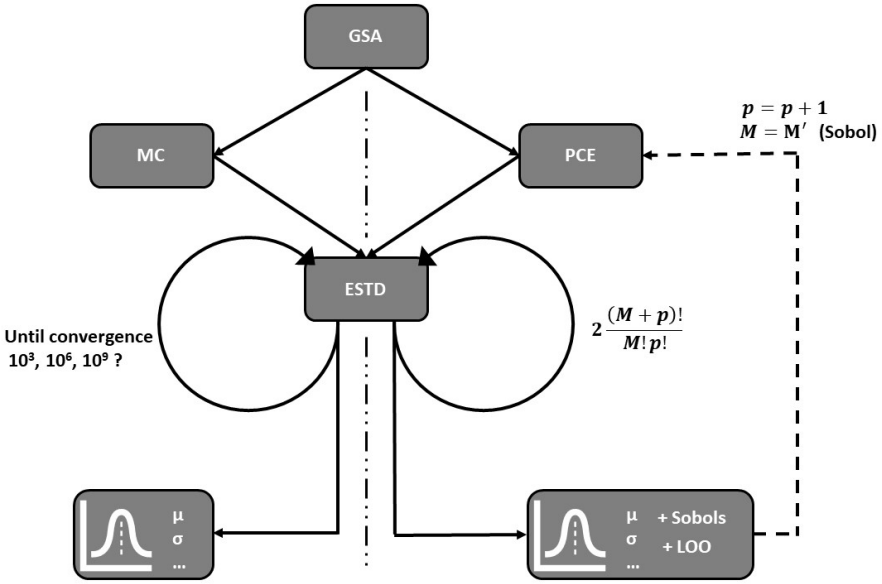

Figure 1.13: The Global sensitivity analysis (GSA) methodology using the PCE requires $2\frac{(M+p)!}{M!p!}$ runs of ESTD to find obtain an approximate Polynomial Chaos Expansion (PCE) of the real model (p being the order and M the number of uncertain parameters). This allows to obtain the leave-one-out (LOO) error and the Sobol' indices. For more precision, a higher order p can be selected. The Sobol' indices quantify the contribution of each uncertain parameter to the variance of the metric of study. In order to gain computational time, some little-influential parameters can be put as deterministic. On the other hand, MC ESTD would require many more iterations in order to obtain results.

Monte Carlo

If one were to choose to do a MC method, ESTD would be made use of in order to gather a lot of results. The model would need to run a lot of iterations as the criteria to stop would be that the mean values of the quantity of study reach convergence. Depending on the problem, the number of runs until convergence could reach very high values. When it is finally reached, the numerous results make it easy to gather the mean value, standard deviation and many other statistical quantities.

Polynomial Chaos Expansion

On the other hand, if the PCE method is chosen, the idea is to approximate the time-consuming and complex ESTD model thanks to a PCE surrogate model. Then, a MC method is run on the PCE that is much faster to run to gather results. However, for the approximation of the real ESTD model by a PCE, several runs need to be done beforehand. The number of

runs depends on the number of uncertain input parameters as well as on the order of the polynomials used to approximate the model. As explained in section 1.4.2, the number of runs is two times the number of coefficients used for the PCE :

$$N_{runs} = 2|\mathscr{A}^{M,p}| = 2\frac{(M+p)!}{M!p!}, \tag{1.16}$$

M corresponding to the number of uncertain input parameters and p to the order of the PCE. Once this number of runs is achieved, the MC method on the approximate PCE model is nearly instantaneous. This allows to obtain all statistical data, but one should not forget that by approximating the real model, an error has been made. A graphical representation of a PCE approximation is shown in Figure 1.14. The black line represents the real model $\mathscr{M}$ and the grey line is the PCE approximation $\mathscr{M}^{PCE}$. It is obvious that they are not the same, which is why the leave-one-out error can be calculated.

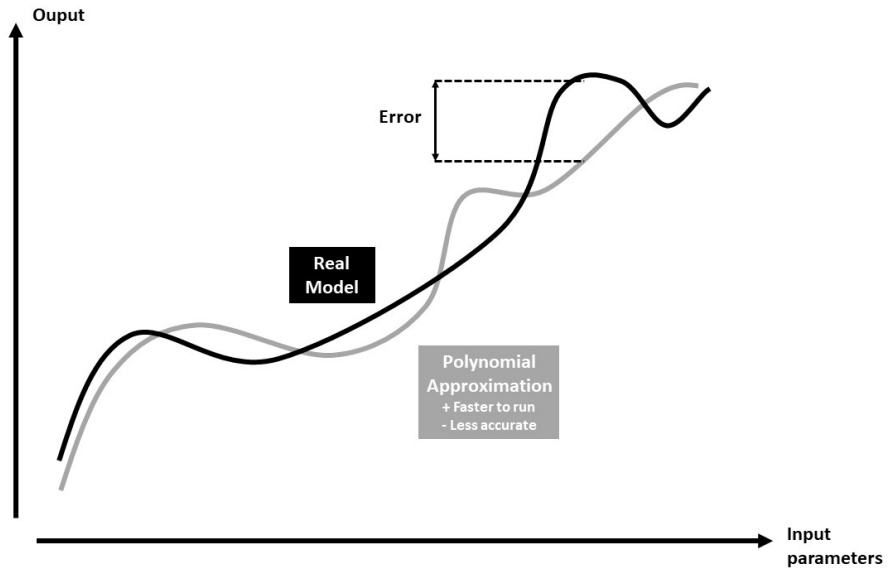

Figure 1.14: A Polynomial Chaos Expansion (PCE) approximates the real model. The PCE is faster to run, which comes in handy for statistical runs, but is less accurate. The error needs to be quantified in order to know whether the results are plausible or not.

The leave-one-out (LOO) error is used to quantify the error between the real model and the PCE. For the LOO error, an alternative PCE is constructed based on $N_{runs} - 1$ samples, so by excluding one sample point : $\mathscr{M}^{PCE/i}(.)$. The difference between the real model $\mathscr{M}$ and the PCE $\mathscr{M}^{PCE/i}(.)$ is calculated. Doing this alternatively excluding each sample point once and adding all errors together gives the LOO error [24]. An acceptable LOO error must be lower than 5%. This is a compromise between computation time and accuracy. ESTD is not the most accurate modelling tool for an energy system. Therefore, in this case, it has been arbitrarily estimated that below 5% the gain in accuracy is not considered relevant compared to the computation time.

Figure 1.15 shows a graphical representation of the calculation of the LOO error. In the latter figure, three sample points are represented, but each time one of the three is represented in grey, meaning that it is not taken into account to construct the PCE $\mathscr{M}^{PCE/i}(.)$, also in grey.

The black line represents the real model and the difference between the two is represented thanks to dotted lines. This difference is added together for each of the three sample points that are neglected once to form the LOO error. The mathematical formula for the calculation of the LOO error can be read in Equation 1.17:

$$LOO = \frac{1}{N_{runs}} \sum_{i=1}^{N_{runs}} \left(\mathcal{M}(x^{(i)}) - \mathcal{M}^{PCE/i}(x^{(i)}) \right)^2. \tag{1.17}$$

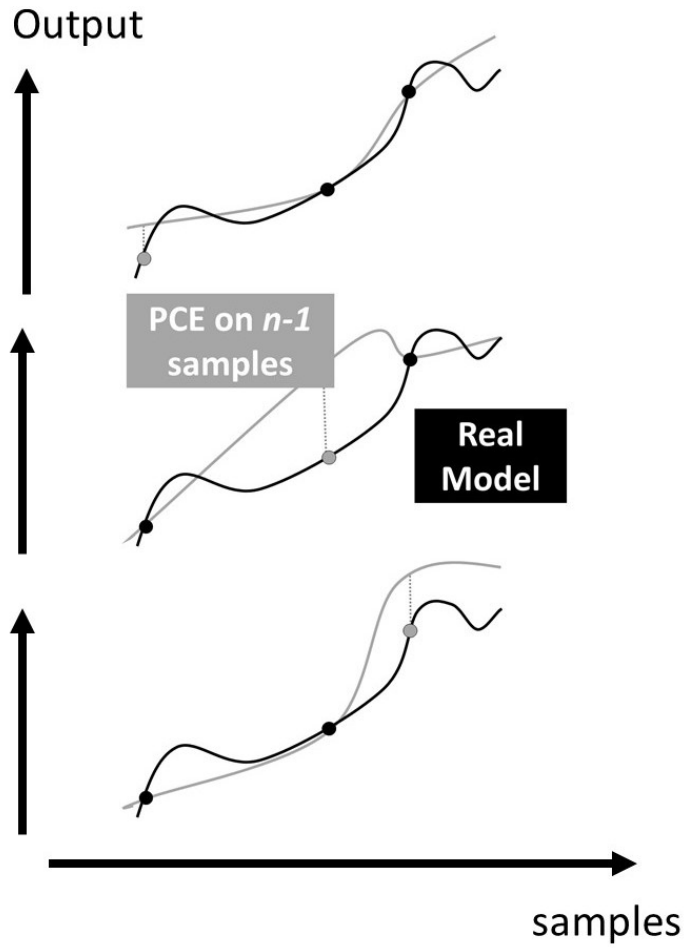

Figure 1.15: The leave-one-out (LOO) error quantifies the sum of each difference between the value of the real model at sample i ($\mathcal{M}(x^{(i)})$ and the PCE based in $N-1$ samples at sample i ($\mathcal{M}^{PCE/i}(x^{(i)})$. The full equation can be seen in Equation 1.17.

In addition to the LOO error, the PCE allows us to obtain Sobol' indices. As explained in section 1.4.2, these metrics quantify the importance of the input parameters on the variance of the quantity of interest. If for example, the GSA is about quantifying the variation of the total cost of the energy system, the Sobol' indices allow it to get an idea of which parameters have the biggest influence on the variation of the total cost and how much they affect it. The Sobol' indices are calculated as shown in equation 1.15. They are useful because they allow it to reduce the number of uncertain parameters. Parameters that are only little impacting the metric of study can be considered to be deterministic, which saves computational time.

All in all, the way PCE is used in this thesis is the following. To begin with, a first order PCE is run on 40 parameters considered uncertain. These parameters have been selected following the study of X.Rixhon et al. [2] and are listed in Appendix E in Table E.4. After $2\frac{(M+p)!}{M!p!}$ runs, the first order PCE yields Sobol' indices and the LOO. If the LOO is too high (which is usually the case), a second order PCE should be run. In order to save computational time, the Sobol' indices allow it to reduce the number of uncertain parameters. The selection of which parameters should be kept is made according to the following rule of good practice, just as it is done in [2]:

$$\boldsymbol{X}' = \{\boldsymbol{X} \geq Threshold : Threshold = \frac{1}{M}\}; \tag{1.18}$$

where M is the initial number of uncertain parameters. A new $p+1$ PCE can be calculated based on the new set of M' parameters and a higher order $p = p+1$. This procedure is repeated until the LOO error is acceptable. To fix ideas, a comparison between a MC method and a PCE method in terms of computational time is proposed in Appendix D.

1.5.3 Important Hypotheses

For the next sections, some important hypotheses need to be made. These are listed in this section. The justification of each hypothesis is made in the chapter where they are introduced:

- The operational emissions limit set to ESTD for each case study is 5000 [ktonCO_2e/year].
- The SMRs considered in chapter 4 are PWR only. Consequently, a lot of data is similar to conventional reactors and the cost domain in their GSA is based only on PWR predictions.
- The flexibility of a SMR is modelled such that the uranium consumption is in baseload mode while the electricity production is allowed to vary from 20% to 100% of its capacity. This models a bypass valve just like the *NuScale* reactors.
- A LOO is considered acceptable if it is less than 5%.

Chapter 2

An ESTD Case Study: Conventional Nuclear Power in Belgium

As mentioned in section 1.2, the deployment of renewable energy (RE) sources and the need to meet the Paris Agreement requires a change in the whole energy system. Flexible and affordable solutions need to be found to complement the RE sources in their electricity production and alternatives need to be implemented to cut Belgium's dependence on oil and gas. Nuclear power has been a big part of Belgium's electricity production since the 1980s (see Table 1.1), but Belgium plans to shut down 5 of its 7 reactors by 2025 reducing nuclear electricity share from 6 [GW] to 2 [GW], filling the gap with new combined cycle gas turbines (CCGTs)[5].

In this chapter, the nuclear power in Belgium is studied. First a deterministic approach with three different scenarios (section 2.1). Secondly, the *Reference Case* for nuclear power is defined (section 2.2). After that, a local variation is carried out, starting with a single-parameter variation and followed by a multi-parameters variation (section 2.3). Afterwards, a GSA is done on the total cost of the energy system with and without nuclear power (section 2.4.
As a reminder, the calculations have been obtained based on several important assumptions that are listed in section 1.5.3.
For this chapter, so-called Sankey diagrams (that are introduced in the course of the chapter) are used to analyse the different energy flows. For more reading convenience, these diagrams can be found in Appendix J as they take up much space.

2.1 Deterministic Approach

Briefly

Three scenarios are defined. One with no nuclear power allowed, one with the same amount of nuclear power allowed as in 2022 in Belgium (i.e. 6 [GW]) and one where no upper limit is put for nuclear power. Figures 2.1 to 2.3 show the results obtained from a cost optimisation in ESTD. The Sankey diagrams in Appendix J also allow a transparent sight of the energy system of each scenario. According to ESTD and the input data given in section 1.3.6, the cheapest and less emitting energy system is one where the electricity system includes a lot of nuclear. It seems to allow the country to be less dependent on other countries (be it on electricity imports or synthetic fuel imports). Belgium will never install 42 [GW] of nuclear power, as suggested by ESTD in scenario "Infinite nuclear allowed". Nevertheless, it seems to play a role in the decarbonation and energy independence of the Belgian energy system.

Currently (2022), Belgium has a total nuclear capacity of 5.94 [GW] (see Table 1.1) and only two reactors should be extended further than 2025 until at least 2035 (i.e. Doel 4 and Thiange 3)[26]. This leaves the country with a total of 2 [GW] of nuclear capacity from 2025 on. Based on this, three scenarios have been defined:

- **No nuclear allowed**: The first scenario corresponds to a scenario where political deciders announce a complete phasing out of nuclear power. A maximum of 0 [GW] is imposed on ESTD.
- **Infinite nuclear allowed**: The second scenario corresponds to a scenario where ESTD has no maximum limit for nuclear power.
- **6 GW nuclear allowed**: The third scenario is a scenario where the current capacity is kept by extending the whole fleet or by maintaining the current capacity by opening new facilities. A maximum of 5.94 [GW] is imposed on ESTD.

The difference between these three scenarios in ESTD lies in the value of $f_{max,NUCLEAR}$. The rest of the parameters remain the same, as described in section 1.3.6. Table 2.1 sums up the allowed nuclear capacity for the three cases.

	$f_{max,NUCLEAR}$ **[GW]**
No nuclear allowed	0
Infinite nuclear allowed	∞
6 [GW] nuclear allowed	6

Table 2.1: Maximum allowed capacity for different deterministic scenarios.

The results obtained by ESTD for the energy system can be observed in Figures 2.1, 2.2 and 2.3. A Sankey diagram has been drawn for each scenario. They are exposed in Appendix J. The Sankey diagrams allow it to track the energy flow of the different resources. A more detailed explanation of how to read them is also provided in Appendix J.

Results

Figure 2.1 shows the ESTD result from the installed electricity capacity for the three different scenarios. In the scenario where no nuclear is allowed, maximum capacity for photovoltaic (PV) panels is reached as well as for offshore and onshore wind turbines (WT). The remaining non-renewable part is covered by ammonia CCGT. Ammonia is considered a synthetic fuel as it can be produced[27]. Ammonia CCGT needs to be responsible for the load following of electricity demand as renewable energy (RE) sources are not suited for this task because of their intermittency.

The scenario where 6 [GW] of nuclear are allowed is pretty similar to the scenario with no nuclear allowed in terms of electricity production. The difference lies mainly in the fact that 6 [GW] of nuclear power allows more electricity production while slightly reducing the dependence on ammonia. The RE sources remain the same. On the other hand, if ESTD is allowed to put as much nuclear as it wants, it predicts that the cheapest option would be to install nothing but 42.3 [GW] of nuclear power and 10 [GW] of onshore WTs. Another important observation is that less total capacity output (around 40% less) is required in that case. Due to the small load factor of RE sources, more of them need to be installed to produce the same amount of energy.

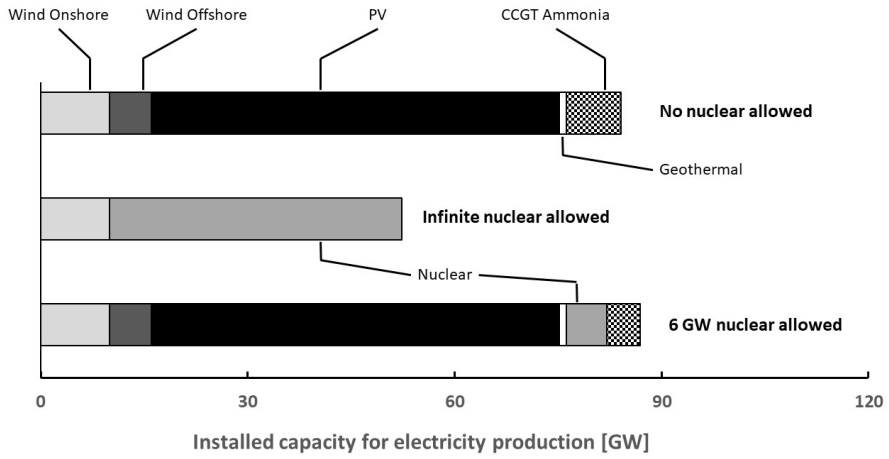

Figure 2.1: Nuclear seems to be favoured whenever it is allowed to be installed.

As the construction emissions are not taken into account when considering the GWP limit, the three scenarios have different total emissions. Figure 2.2 shows the yearly emissions of each scenario. One can see that in the case of an infinite amount of nuclear power allowed, the total emissions are noticeably lower than those of the other two solutions. This is due to the less emitting electricity sector in the case of a high nuclear capacity. In fact, according to ESTD data, the construction emissions for PV are nearly 3 times those of nuclear power (for the same power capacity). In addition to that, when relying on intermittent RE sources, more capacity needs to be installed for the same energy production (because of the lower capacity factor). So according to ESTD and the input parameters (see section 1.3.6), nuclear power seems to be able to save a considerable amount of yearly emissions.

Turning to Figure 2.3, which shows the cost of the total energy[1] system by sector one can see that the system relying on a lot of nuclear is noticeably cheaper than the alternative solutions. The system's total cost for scenario "infinite nuclear" is 43 billion €, compared to 51 billion € with 6 [GW] of nuclear capacity and 56 billion € per year when no nuclear is allowed. Indeed, nuclear power has a huge investment cost compared to other solutions, but its high load factor plays in its favour and it has a longer lifetime (60 [years] compared to 25 [years] for PV panels or 30 [years] for WT). Furthermore, it requires cheaper resources and infrastructures linked to the rest of the electricity system. The fewer resources (mostly imported synthetic fuels) required for a system with a lot of nuclear power compensate for its more expensive investment cost, as can be observed in Figure 2.3.

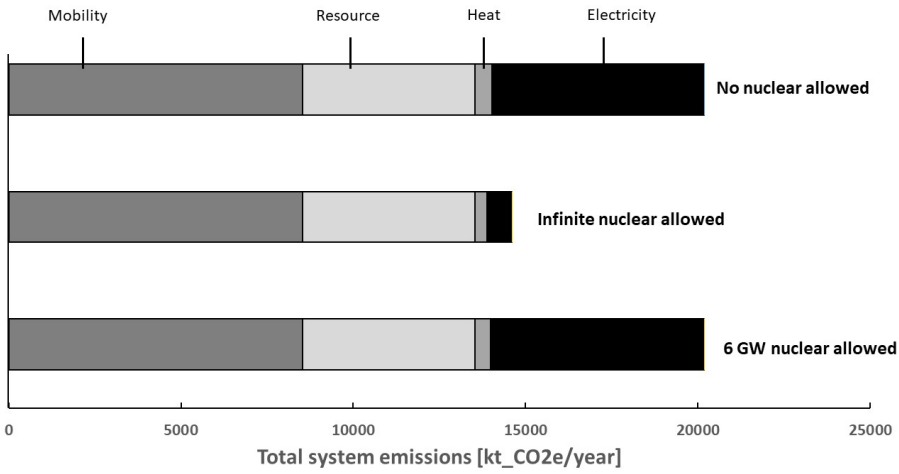

Figure 2.2: Fewer CO_2 emissions are expected for the case of a big nuclear capacity. Nuclear seems to save a non negligible amount of emissions each year.

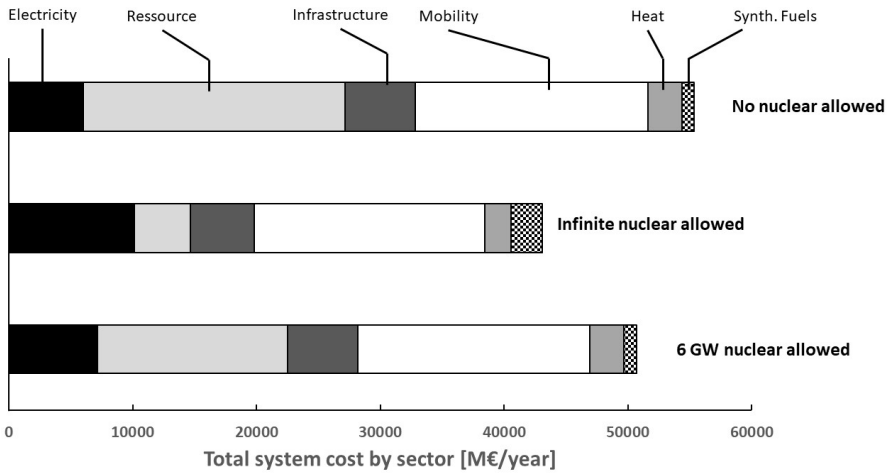

Figure 2.3: The cheaper resource share of the total costs of the energy system compensate for the more expensive electricity system.

[1]The **electricity** system is just a part of the **energy** system.

In the same figure, the share of synthetic fuel costs in a system with a lot of nuclear is higher than in the other two sectors, which can be surprising, because no ammonia CCGT is installed in that case. In the case of infinite nuclear allowed, the energy system predicts that Belgium should invest in electrolysers to produce all its hydrogen needs by itself and a big part of this hydrogen is used to produce other synthetic fuels. In the other two scenarios, a lot of synthetic fuels are imported; hydrogen, synthetic natural gas (SNG), renewable ammonia, methanol and bio-Diesel[2].

The synthetic fuels that are imported are considered as resources to feed the different sectors where they are being used. For example, the ammonia that is imported for the CCGT ammonia enters the operation cost of CCGT ammonia, so in the "electricity" sector and not in the "synthetic fuel" sector. The synthetic fuel sector however takes into account all infrastructures that are required to produce them. In the infinite nuclear scenario, a lot of electricity is being used to produce hydrogen via electrolysers, which adds to the costs of synthetic fuels. The difference between the scenario without nuclear and 6 [GW] allowed, is mainly in the quantity of synthetic fuel that is imported, so it would seem that the installation of nuclear power would enable Belgium to reduce its energy dependence on synthetic fuels.

While it is highly unlikely to have an as big share of nuclear power as in the infinite nuclear scenario, it still is interesting to see that nuclear seems to be favoured by ESTD over a lot of other technologies when it comes to minimise costs. It also allows it to realise that it plays in favour of a less emitting energy system, even compared to RE sources. This introductory study introduces the definition of the *Reference Case* for the following sections.

2.2 The "*Reference Case*"

Briefly

A *Reference Case* is defined to be able to compare different results to this *Reference Case*. The installed capacity of nuclear power is not limited. ESTD suggests to installing 42 [GW] of nuclear power.

The *Reference Case* takes the basic data implemented in ESTD as explained in section 1.3.6 without any restriction on nuclear power, in other words, $f_{max,NUCLEAR} = \infty$. It is the same scenario as "infinite nuclear" in section 2.1 and represents what ESTD estimates is the most suitable scenario for Belgium without any limit except for the operational GWP constraint.

This scenario will serve as a reference and starting point for a local sensitivity analysis of the amount of nuclear power installed in Belgium under various assumptions; what is the prediction if the investment cost of nuclear power is more than expected ? What if uranium gets more expensive ? Keeping the *Reference Case* in mind where ESTD suggests to installing 42 [GW] of nuclear power, this analysis will allow it to see how the system might vary in different, more realistic, or even pessimistic, scenarios. The Sankey diagram of the *Reference Case* is shown in Figure J.3, Appendix J.

[2]It should nevertheless be noted that no importation limit is put on these resources so ESTD considers that infinite quantities of synthetic fuels can be imported. Further studies need to be made to quantify how plausible it is to import such high quantities of synthetic fuels

2.3 Local Variation of Nuclear Parameters

Briefly

A single-parameter local sensitivity analysis is done (section 2.3.1) on three parameters directly linked to nuclear power. Based on the *Reference Case* (section 2.2), $c_{inv,NUCLEAR}$, $c_{op,NUCLEAR}$ and $gwp_{op,NUCLEAR}$ vary in the sense that should disfavour the installation of nuclear power in Belgium. A justification for the chosen variation intervals is included. Figures 2.4, 2.5 and 2.6 show how the electricity system evolves when varying these metrics. It can be observed that the nuclear capacity decreases but in the ranges that have been chosen, nuclear power never completely disappears from the energy system recommended by ESTD. In order to take a step back before doing a global sensitivity analysis, the three parameters are varying together in a multi-parameter local sensitivity analysis 2.3.2. For this analysis, 3 scenarios have been defined: Worst, Medium and the already known *Reference Case*. How they are defined is summarised in Table 2.4. Figure 2.7 shows the result of this multi-parameter study. Even in the case where the three parameters are 3 times worse than their deterministic value, 11 [GW] of nuclear capacity is recommended by ESTD. Which is nearly double the current Belgian nuclear fleet.
The conclusions that can be drawn from the local sensitivity analysis is that nuclear power seems to be a solution favoured by ESTD even in case its parameters worsen. It takes a lot for the energy system not to include nuclear power. A system with less and less nuclear power increasingly relies on synthetic fuels, which are themselves linked to a non-negligible uncertainty both in terms of cost and supply security for Belgium.

Now that the deterministic approach has been done by studying the effect of more or less nuclear power in the system, one can question the input data and study how the system will be affected if nuclear power is more expensive or more CO_2 emitting than what the deterministic input parameters may suggest. In other words, a local parameter variation is performed on three input parameters i.e. the investment cost of nuclear technology, the cost of nuclear fuel (uranium) and the CO_2e emissions that are linked to the life cycle of uranium. These three parameters undoubtedly have an impact on the nuclear capacity installed in the energy system as can be observed in the following sections. After the single parameter local variation, where each of the three parameters varies one at a time, the authors included a multi-parameter local variation during which 3 different scenarios are proposed; the three parameters vary at the same time, which could represent more realistic scenarios.

2.3.1 Single-Parameter Variation

Before justifying the variation of each parameter and showing any results, Table 2.2 provides a reminder of the deterministic values of each of the three parameters:

Parameter Units	$c_{inv,nucl}$ [€/GW]	$c_{op,uranium}$ [€/GWh]	$gwp_{op,uranium}$ [ktonCO2e/GWh]
Deterministic value	4845.75	0.004	0.0039

Table 2.2: Reminder of deterministic values of the investment cost of nuclear power, the operational costs of uranium and the global warming potential of uranium.

Nuclear investment cost

First, the investment cost of a nuclear facility is something that can vary a lot. It is difficult to predict the real final cost of a nuclear facility. The well-known Flamanville 3 reactor construction in France has been delayed many times and the initial budget of 3.4 billion € has been revised upwards with the latest estimate in 2020 being a construction cost of 19.1 billion €. The power output of this reactor will reach 1650 [MW], which gives an estimated investment cost of 11 600 [€/MW], compared to the initial 2 000 [€/MW].

The cost of the plant will therefore have cost 5.5 times the initially announced cost, provided that no further upward revision is made before it goes online in 2023[28]. Therefore, the authors considered that uncertainty on the investment cost of nuclear power (deterministic value at 4 850 [€/MW]) should be taken into account and therefore, the investment cost should be able to vary inside the following interval: [5 000 ; 25 000] in [€/MW] in the local sensitivity analysis.

Figure 2.4 shows the different electricity mixes calculated by ESTD for different investment costs of nuclear power. The *Reference Case* is the energy system for an investment cost of 5 000 [€/MW], where 42 [GW] of nuclear power and 10 [GW] of onshore WTs are installed. For a nuclear power cost that is twice as high, the maximum capacity of geothermal energy is reached and the total electricity production goes down.

Instead of producing synthetic fuels itself, it becomes cheaper for Belgium to import them and therefore the global electricity demand reduces. For even higher investment costs, RE sources play an increasingly important role but even for an investment cost that is 5 times higher than the *Reference Case*, 10 [GW] of nuclear power is estimated by ESTD, which is more than the current capacity in Belgium. Considering that even in the case of the much-discussed Flamanville plant the investment costs were 11 600 [M€/MW], reaching an investment cost of 25 000 [M€/MW].

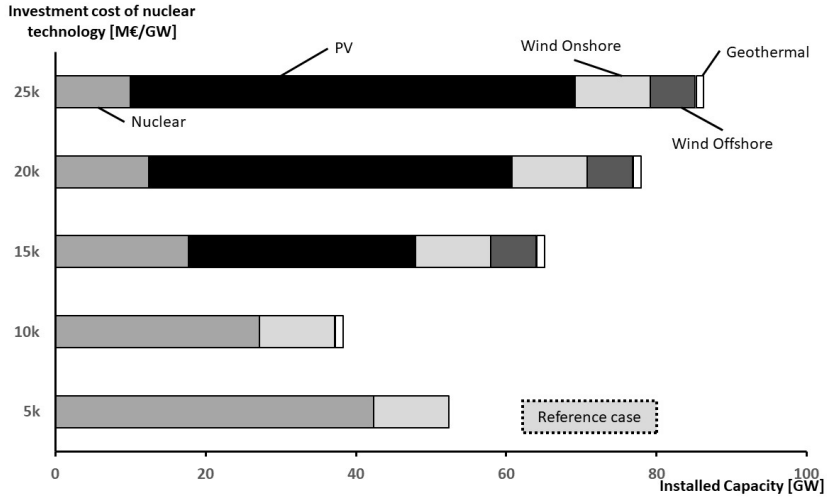

Figure 2.4: Nuclear capacity reduces as the investment cost of the technology goes up, but even for 25 000 [M€/GW], ESTD predicts that 10 [GW] of nuclear power is part of the cheapest solution towards a reduction of carbon emissions

Operational cost of uranium

The investment cost of nuclear power is not the only important cost factor that should be considered. The impact of the cost of uranium (i.e. the fuel) should be studied too. The latest estimations from the World Nuclear Association (WNA) sugget that the cost of uranium lies at 4 600 [€/GWh] [29]. The deterministic value taken in ESTD is at 4 000 [€/GWh]. Figure 2.5 shows the results of ESTD if the operational costs of uranium are increased until a factor of 10 compared to the *Reference Case*.

Similar to the increasing investment cost, first the electricity demand goes down because Belgium starts importing resources instead of using its electricity to produce them. Further increasing the cost of uranium, the model starts to recommend installing some CCGT ammonia to replace part of nuclear power, but even when the cost is 10 times higher than the *Reference Case*, ESTD does not rule out nuclear power completely.

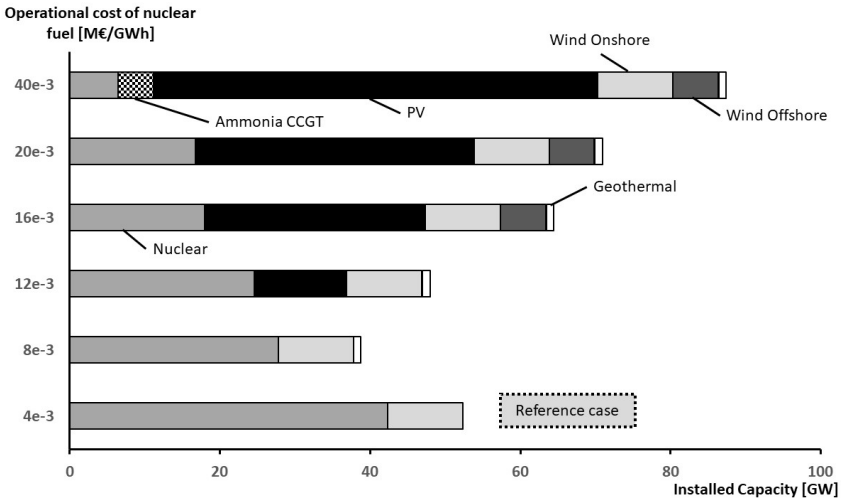

Figure 2.5: As uranium gets more and more expensive, the nuclear capacity in the electricity mix goes down. For a cost that is ten times the deterministic cost of uranium, the recommended nuclear capacity is around 10 [GW], so ESTD did not rule it out completely.

Global warming potential of uranium

Finally, Figure 2.6 shows the nuclear power capacity that is recommended by ESTD for increasing operational emissions due to the life cycle of its fuel, uranium. As the emissions go up, the nuclear capacity decreases and gets replaced by RE sources and then by ammonia CCGT. The *Reference Case* is based on a global warming potential of 4 [gCO_2e/kWh] and the local variation brings that value up to 20 [gCO_2e/kWh]. This scope is motivated by the study of Sovacool et al. (2008).

Sovacool et al. bring together several studies that quantify emissions from nuclear power electricity generation. In these studies, there is information on emissions related to fuel, construction, decommissioning, etc. The discrepancies between the different results are big because of the different assumptions made by the different studies and this is why it is sometimes difficult to compare them. In the context of the local variation in operational emissions due to uranium, it is necessary to focus on the emissions related to the fuel only.

Sovacool et al. (2008) refer to them as "frontend" emissions. For these figures, the differences are also quite large. As explained by the same study, this may be due to:

- different scopes,
- different hypotheses on uranium ore quality (10% to 0.013% U_3O_8) and mining type (open-pit or underground),
- different enrichment technologies (gaseous diffusion or centrifuge enrichment),
- different approaches (top-down or bottomup) or
- different purposes (study of historical emissions or predictions of future emissions).

More emissions are associated with a uranium ore that is poorer in U_3O_8 (due to its lower energy return on investment), open-pit mining (due to methane and radon emissions) and gaseous diffusion enrichment (as it is around 60 times more energy consuming than centrifuge enrichment)[30].

Sovacool et al. (2008) estimated (at the time) that modern technologies were going to be less emitting because GEN III(+) (see Appendix B) reactors would be more efficient and consume less uranium than previous generation reactors. With the energy mix being less and less greenhouse gas (GhG) emitting, each part of the lifecycle should be less and less GhG emitting too. Table 2.3 gathers all the studies analysed by Sovacool et al. (2008) and shows their respective prediction on frontend emissions. As a reminder, they all differ in their hypotheses.

The interval of study chosen by the authors (4 to 20 [gCO_2e/kWh]) represents the lower part of the predictions made by the set of studies, however, with the predictions of more modern technologies and hypothetically less emitting energy systems motivate that the emissions will probably go towards a less emitting uranium life cycle.

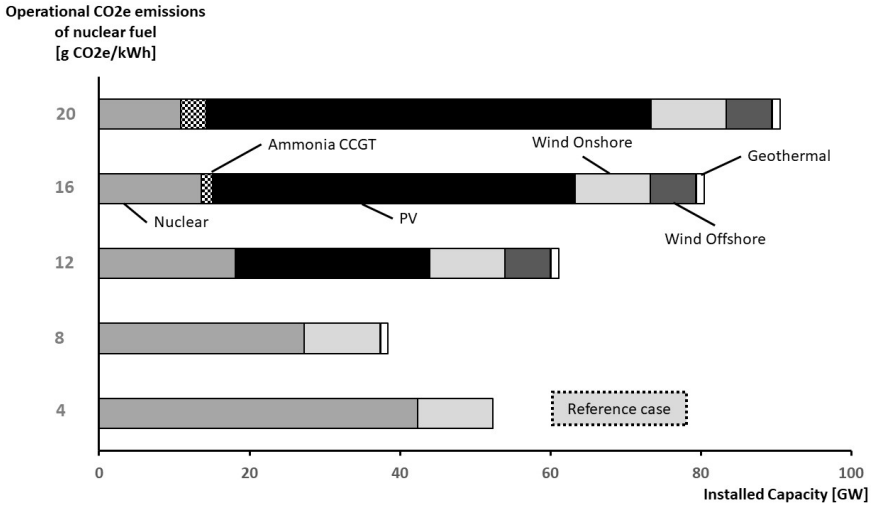

Figure 2.6: As the GhG emissions linked to the lifecycle of uranium goes up, the capacity installed for nuclear power goes down because the energy system still needs to respect the yearly maximum operational emissions of 5000 [kton CO_2e/year].

Name	Year	Location	Frontend estimates [g CO2e/kWh]
ExternE	1998	UK	-
Vorspools et al.	2000	World	-
Andseta et al.	1998	CA	0.68
IEA	2002	SE, JP	1.19-8.52
Dones et al.	2005	CH	3.5-10.2
Dones et al.	2003	CH, FR, GE	6-12
White and Kulcinski	2000	US	9.5
Fthenakis and Kim	2007	US, EU, JP	12-21.7
Hondo	2005	JP	17
Fritsche and Lim	2006	GE	20
Storm van Leeuwen et al.	2007	World	16.26-28.27
Rashad and Hammad	2000	EGY	23.5
ISA	2006	AU	4.5-54
ISA	2006	AU	4.5-58.5
Storm van Leeuwen et al.	2005	World	36
Storm van Leeuwen	2006	World	39
Dones et al.	2004	CN	7.4-77.4
Barnaby and Kemp	2007	UK	56
Tokimatsu et al.	2006	JP	5.9-118

Table 2.3: Frontend emissions from different scientific reviews [30]

2.3.2 Multi-parameter Variation : Different Scenarios

The idea in this section is to vary the investment cost of a NPP, the operational costs of uranium and its operational emissions simultaneously. The so-called "medium case" and "worst case" are cases that go in the direction that should disfavor the implementation of nuclear power plants. In fact, during these scenarios, the three parameters mentioned above are multiplied by 2 and 3 respectively. Table 2.4 sums up the three different cases that have been studied. The multiplication factors 2 and 3 were chosen arbitrarily, but they have been chosen so that they remain inside the ranges imposed in the single-parameter variation, only less "extreme".

	***Reference Case* (REF)**	**Medium case**	**Worst case**
c_inv,nuclear [M€/GW]	4845.73	2 x REF	3 x REF
gwp_op,uranium [ktonCO$_2$_eq./GWh]	0.0039	2 x REF	3 x REF
c_op,uranium [M€/GWh]	0.004	2 x REF	3 x REF

Table 2.4: Table regrouping the 3 scenarios with their parameters. The medium and worst cases have their values for the investment cost of nuclear power, the global warming potential of uranium and the operational costs of uranium multiplied by 2 and 3 respectively.

Figure 2.7 represents the installed capacity for each scenario, the *Reference Case*, "medium" and "worst" cases. It can be seen that the nuclear capacity decreases as the value of the three parameters increases. On the contrary, the PV capacity increases significantly. This increase can be explained by the fact that to compensate for the loss of nuclear capacity, a much bigger PV capacity has to be implemented because of its inherent intermittency.

The Sankey diagrams for the Medium and Worst scenarios are respectively located in Appendix J. As described in the deterministic approach (section 2.1), when nuclear is installed in large quantities (i.e. when it is the cheaper solution), part of the electricity production is used for hydrogen production in order to transform it into synthetic fuels. This hydrogen can also directly be used for people or freight transportation. In the *Reference Case*, no synthetic fuels and electricity imports are made. Everything is produced locally because electricity production is cheap and abundant.

In the Medium Case, part of the electricity production is provided by solar energy to compensate for the nuclear capacity that has decreased as shown in Figure 2.7. This decrease in nuclear capacity implies that the major difference between the Medium Case and the *Reference Case* really lies in the quantity of renewable fuel that is produced locally or imported. In the Medium Case, Belgium still produces hydrogen, but in reduced quantity compared to the *Reference Case*. However, still in the Medium Case, all the ammonia and methanol consumed by the country comes from abroad.

In the Worst Case, the solar capacity increases drastically. The electrical capacity is no longer sufficient to produce hydrogen. Therefore the latter is imported in limited quantities and used directly for the freight sector. Methanol and ammonia are also imported in order to meet the non-energy demand (NED). In short, no nuclear power means a lot of dependency on other resources coming from abroad. The more nuclear power is installed, the more independent Belgium gets in terms of energy supply.

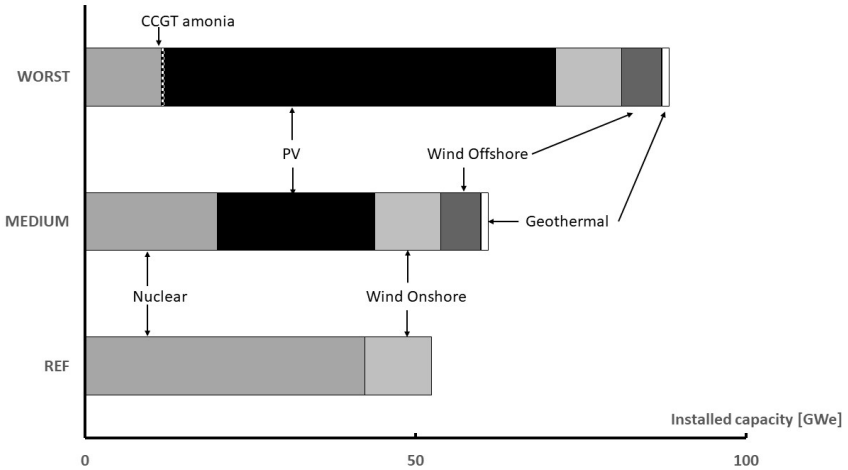

Figure 2.7: Electricity production, for the *Reference Case* (REF), the Medium Case (MEDIUM) and the Worst Case (WORST) (defined Table 2.4). When the cost of nuclear power (investment and operational) and the emissions linked to its fuel go up, the installed capacity for nuclear power goes down while the RE part goes up. In the Worst Case (i.e. when the three parameters have been multiplied by 3 compared to their reference value), ESTD predicts to install 11 [GW] of nuclear power.

2.4 Global Sensitivity Analysis

Briefly

A global sensitivity analysis is carried out on the system's total cost for two different situations. One where there is no restriction on nuclear power and one where nuclear power cannot be installed at all. Figure 2.12 shows the superposition of the resulting distributions for the two analyses, with and without nuclear power allowed.
Both distributions result from a second order PCE. Table 2.8 shows the statistical metrics resulting from these analyses. It is clear that an energy system with nuclear power is cheaper and the total cost distribution is less spread out than one where nuclear power is not allowed. As already mentioned a few times, without nuclear power, Belgium relies a lot on the importation of synthetic fuels. In such a case, a strong dependency is built on foreign partners.

2.4.1 Input parameters

Now that we have a global view of which technologies are favoured by ESTD and how the system evolves when varying technologies that are directly linked to nuclear power, it is useful to take a step back and analyse the place of nuclear power in a globally more uncertain energy system. For this, a global sensitivity analysis (GSA) is proposed.

A GSA provides a more comprehensive picture of the results taking into account the uncertainties on different input parameters. The uncertain input parameters can be found in Table E.4. Most of the parameters have been taken over from Rixhon et al. (2021)[2], but in the context of this study, some changes were made to the input parameters.

The goal is to study the importance of nuclear power in Belgium so the maximum nuclear capacity $f_{max,nucl}$ has been put to an infinite deterministic value as no upper limit is desired. Furthermore, the investment cost of nuclear power $c_{inv,nuclear}$, the lifetime of nuclear power plants $t_{nuclear}$, the operational emissions of uranium $gwp_{op,uranium}$ and the operational costs of uranium $c_{op,uranium}$ have been put as uncertain.

- $\boldsymbol{c_{inv,nuclear}}$: The IEA estimates in their 2020 report "*Projected Costs of Generating Electricity*"[31] that the overnight costs (or investment cost) for a nuclear power plant (NPP) ranged from around 2000 [M€/GW] in South Korea to around 6500 [M€/GW] in Slovakia. Taking into account exceptional events such as the construction of Flamanville 3, where the investment cost rose from an initial 2.1 to a final expected cost of 11.6 billion € per gigawatt [28], the authors have decided to take a safe margin and allow the nuclear investment cost to vary between 2.0 billion € and 15.0 billion € per installed gigawatt.
- $\boldsymbol{t_{nuclear}}$: The current nuclear power plants in Belgium are meant to be shut down after around 40 to 50 [years] of operation. According to the WNA's "*Plans for New Nuclear Reactors" (2022)*[32], most reactors worldwide had a design lifetime of 25 to 40 [years], but recent technical assessments have estimated that many could operate longer. In 2016, the Nuclear Regulatory Commission[3] granted life extensions for approximately 85

[3] "The Nuclear Regulatory Commission (NRC) is an independent agency of the United States government tasked with protecting public health and safety related to nuclear energy."[33]

reactors to between 40 and 60 [years]. Therefore the lifetime has been left uncertain between 40 and 60 [years] of operation.

- $c_{op,uranium}$: In 2021, the WNA estimated the cost of uranium to 0.0046 [M€/GWh]. In order to provide some margin, the upper limit for operational costs has been fixed at around 10 times this number. This is why the uncertainty in uranium operating costs has been set at a range that goes from 0.003 to 0.040 [M€/GWh].
- $gwp_{op,uranium}$: As discussed in section 2.3.1 the global warming potential that is linked to the lifecycle of uranium is dependent on many things (scope of the study, enrichment method, ...). Based on Sovacool et al.(2008)[30] and considering the fact that modern societies should evolve towards a less emitting lifestyle, the authors decided to fix the range of values to [0.001; 0.020] [ktonCO$_2$/GWh].

While most parameters have their deterministic value more or less centered inside their stochastic interval, $c_{inv,nucl}$, $gwp_{op,uranium}$, $c_{op,uranium}$ and t_{nucl} are different. Their deterministic values have been considered to be approximately the starting point of a "pessimistic" analysis.

Table 2.5 summarises the choice of the added input parameters to the stochastic input space It is obvious that for these four parameters the deterministic value lays in at the edge of their respective uncertainty interval. The procedure of a global sensitivity analysis has been explained in section 1.5.

A global sensitivity analysis of the total cost of the system has been made for two different cases. First, a case where no limit is put on nuclear capacity and then a case where nuclear power can not be installed.

	Uncertainty interval	**Deterministic value**	**Units**
$c_{inv,nucl}$	[2000; 15000]	4850	[M€/GW]
t_{nucl}	[40; 60]	60	[years]
$c_{op,uranium}$	[0.003; 0.040]	0.004	[M€/GWh]
$gwp_{op,uranium}$	[0.001; 0.020]	0.004	[ktonCO$_2$/GWh]

Table 2.5: Uncertain input parameters that have been added for the purpose of this thesis. The remaining parameters have been taken up from [2]. The complete set of uncertain parameters for the global sensitivity analysis (GSA) can be found in Appendix E, Table E.4. c_inv_nucl represents the investment cost of nuclear power, t_nucl the lifetime of a nuclear facility, c_op_uranium the operational cost of uranium and gwp_op_uranium the emissions that are linked to the lifecycle of uranium.

2.4.2 Results

Including Nuclear Power

Figure 2.8 and Table 2.6 show the outcome of the GSA on the total system cost for a case where there is no limit on installed nuclear capacity. For the first order polynomial chaos expansion (PCE) 40 stochastic parameters (Table E.4) are implemented. A leave-one-out (LOO) error of 26.2% is obtained, which is too high compared to the threshold of 5%. This is why a second order is run afterwards with a reduced set of stochastic parameters. Figure 2.9 shows the different Sobol' indices for the first order PCE. 7 out of the 40 have been conserved.

As a reminder, the threshold is obtained from a rule of good practice as explained in section 1.5 at $1/M$ where M is the number of uncertain parameters (40 in this case). The mean value has not drastically changed between the first and second order PCE, but the standard deviation is slightly lower for the second order (Table 2.6), which indicates that the total cost is more likely to be located around the mean, 51 653 [M€/year]. By application of the central limit theorem (CLT) [34], the resulting distribution can be approximated by a normal distribution (see Appendix F). Therefore, the following relation holds:

$$\boldsymbol{P}(\mu - 2\sigma \leq Total\ cost \leq \mu + 2\sigma) = 95\% \tag{2.1}$$
$$\boldsymbol{P}(41291 \leq Total\ cost \leq 63059) = 95\%$$

In other words, there is 95% chance that the total cost is located in the interval [41 291; 63 059] [M€/year].

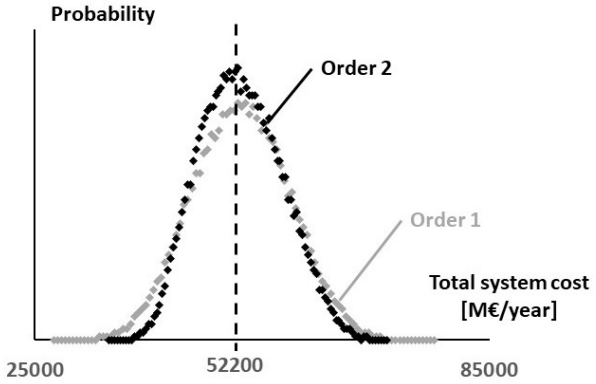

Figure 2.8: Distribution of the total system cost results of an order 1 and 2 PCE including nuclear power

	Order 1	**Order 2**
LOO	26.2%	1.9%
mean	52186	52175
std. dev.	6360	5442

Table 2.6: Statistical results of order 1 and 2 PCE on total cost including nuclear power. Mean and standard deviation are in [M€/year].

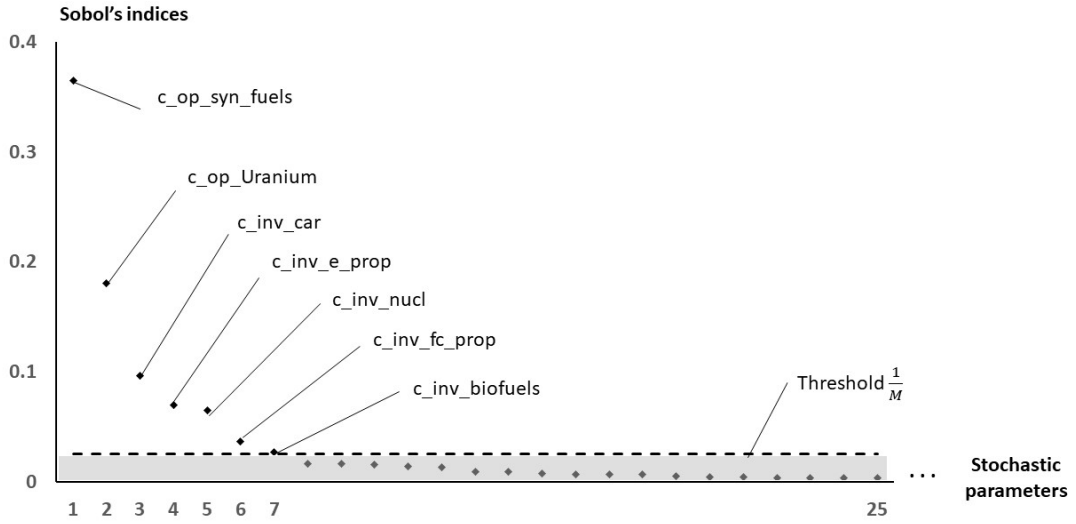

Figure 2.9: Sobol' indices for the first order PCE on the total system cost including nuclear power. Only the parameters above the threshold are kept when improving from a first order PCE to a second order.

Following the definitions of the Sobol' indices (Equation 1.15), the higher their value, the more influential they are on the studied metric. Figure 2.9 shows the 20 highest Sobol' indices. The 7 most impacting parameters are those that have been kept for the second order PCE.

1. c_{op,syn_fuels} : operational cost of synthetic fuels
2. $c_{op,uranium}$: operational cost of uranium
3. $c_{inv,car}$: investment cost of cars
4. c_{inv,e_prop} : investment cost of electric vehicle propulsion system
5. $c_{inv,nucl}$: investment cost of a nuclear power plant
6. c_{inv,fc_fuels} : investment cost of fuel cell propulsion system
7. $gwp_{inv,biofuels}$: investment cost of biofuels producing facilities

Two of these seven are linked to nuclear power. Three are linked to the cost of cars and the two last ones are respectively the cost of synthetic fuels imports and the cost of producing biofuels locally in Belgium. As already discussed in section 2.1, and as can be observed in the Sankey diagrams (Appendix J), ESTD switches between systems either relying on synthetic fuel imports or local synthetic fuel production.

Nuclear power helps to provide sufficient electricity to produce the synthetic fuels in Belgium but of course, the choice of producing or importing depends on the cost of either solution. Therefore, the cost of nuclear power and synthetic fuels have a big impact on the total system cost. In addition, transport accounts for a large share of the energy consumed.

The best solutions to decarbonise this sector are to electrify it either with batteries or with fuel cells by using synthetic fuels. It is clear that if society does not reduce its travelling, the cost of the vehicles and the technologies involved will play an important role in the total cost of the system.

Excluding Nuclear Power

In a second phase, a GSA is done on an energy system with no nuclear power allowed. Again, the PCE is calculated on the total cost of the system starting with a first order PCE based on a set of 40 parameters (Table E.4). Figure 2.10 shows the distribution of the outcome while the statistical metrics are presented in Table 2.7.

The LOO error of the first order at a value of 10.3% is still a bit too high so a second order is run and the final LOO error on the second order is below 0.60% which is very good. The average total system cost is around 57 billion € with a standard deviation of around 7.30 billion €. The second order distribution is not quite resembling a normal distribution, but if we were to assume that it can be approximated by a normal distribution, there would be a 95% chance to be located between 42.4 and 71.5 billion €.

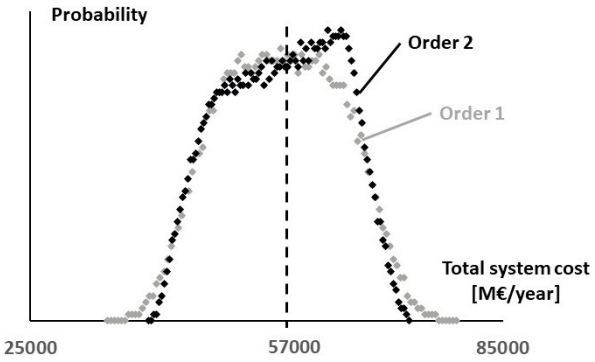

Figure 2.10: Distribution of the total system cost results of an order 1 and 2 PCE excluding nuclear power.

	Order 1	**Order 2**
LOO	10.35%	0.58%
mean	56784	56966
std. Dev.	7652	7285

Table 2.7: Statistical results of order 1 and 2 PCE on total cost excluding nuclear power. Mean and standard deviation are in [M€/year].

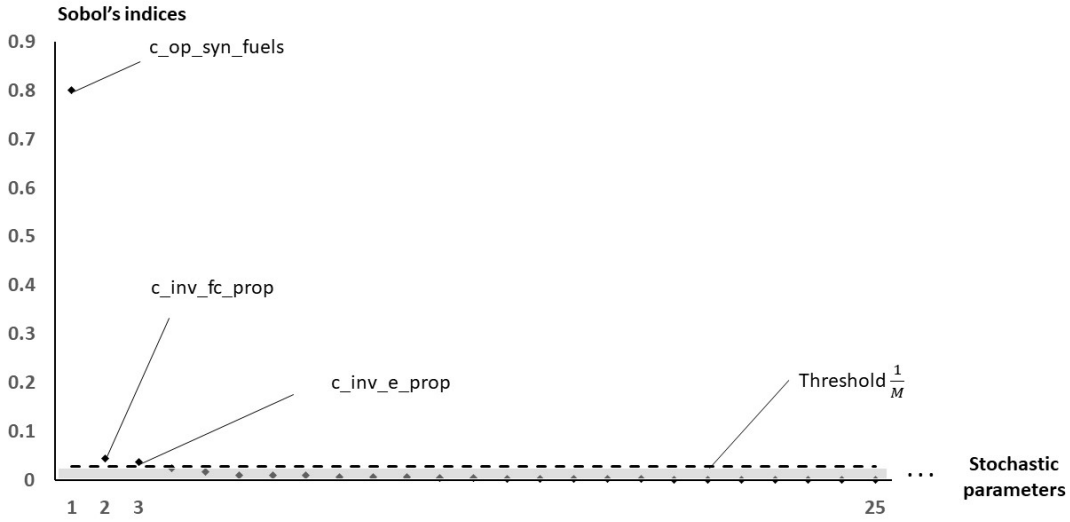

Figure 2.11: Sobol' indices for the first order PCE on the total system cost excluding nuclear power. Only the parameters above the threshold are kept when improving from a first order PCE to a second order.

Turning again to the Sobol' indices, there is one that is particularly impacting, but 3 are located above the $1/M$ threshold:

1. c_{op,syn_fuels} : operational cost of synthetic fuels
2. c_{inv,fc_fuels} : investment cost of fuel cell propulsion system
3. c_{inv,e_prop} : investment cost of electric vehicle propulsion system

In a scenario without nuclear power, the cost of synthetic fuels has an even bigger influence on the total system cost. If no nuclear is allowed, there is no other choice but to rely a lot on imported synthetic fuels for a carbon-free energy system. The disparity that is linked to their costs has a huge influence on the Belgian energy system, as Rixhon et al. [2] confirm;

Comparison of both Cases

In the deterministic approach and local sensitivity analysis, results proved that it is more expensive to consider an energy system without nuclear power. The global sensitivity analysis seems to confirm this claim. Table 2.8 sums up the different statistical metrics of both GSA with and without nuclear power. Excluding nuclear power from a carbon-free energy system results in an energy system with a higher mean value and a higher disparity. Furthermore and as already mentioned, a system with no nuclear power relies more on synthetic fuels that need to be imported, which increases Belgium's dependency on other countries around the world and could jeopardise its security of supply.

	mean	**std. dev.**	**95% certainty interval***	**Units**
Including nuclear power	52 175	5 442	[41 291; 63 059]	[M€/year]
Excluding nuclear power	56 966	7 285	[42 396; 71 536]	[M€/year]

Table 2.8: Statistical metrics comparing a GSA on the total system cost including and excluding nuclear power. On average, relying on a system including nuclear power is cheaper. The 95% certainty interval is less dispersed and lower than in a case excluding nuclear power.
* The 95% interval is obtained making the assumption that the resulting distributions can be approximated by a normal distribution by application of the CLT (see Appendix F[34]

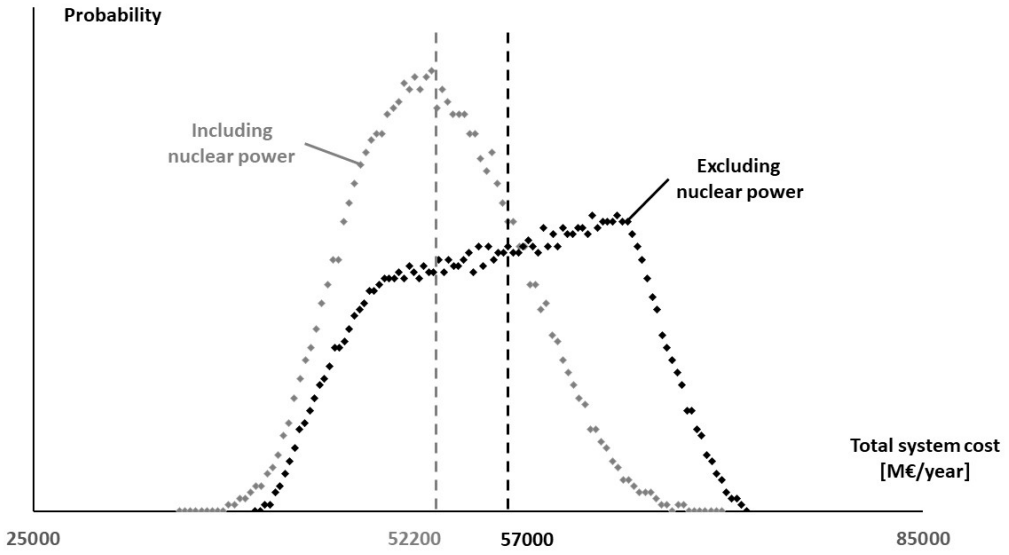

Figure 2.12: PDF of total system cases both including and excluding nuclear power. The solution including nuclear power is cheaper and less dispersed.

Chapter 3

SMR Technology : an Overview

After a quantitative analysis of conventional nuclear power, it is already clear that nuclear power in its present form has many economic and ecological advantages. However, it also has its shortcomings. The scale of the plans for the construction of new power plants scares investors, not to mention the lack of public acceptance. In response, a promising new technology is emerging: SMRs. These small-scale reactors are the talk of the town and Belgium has already announced an investment of €100 million in their research [35].

First, a global definition of SMRs is given (section 3.1) then, their differences with current nuclear facilities are explained in section 3.2. The current situation on the advance of different designs can be found in section 3.3 and finally, a whole section is dedicated to studying the flexibility of SMRs3.4.

3.1 Defining SMR Technology

Briefly

SMRs are smaller nuclear reactors (from 10 to 300 [MW]) with a standardised design and the possibility to gather multiple modules in order to increase the global power output of a facility. On top of that, they are predicted to be mass-produced and therefore rely on standardised designs.

Following the NEA report *Small Modular Reactors: Challenges and Opportunities*[36], a small modular reactor (SMR) is a nuclear reactor that mainly differs from conventional reactors by its size and so its power output. Small modular reactors are reactors that are meant to stay between 10 and 300 [MW]. One can also refer to micro modular reactors (MMRs) if the power output of a reactor is even smaller than 10 [MW]. Several technical features have been put upfront to potentially reduce construction costs as well as construction schedules. There are currently around 70 SMR concepts under development, each having a different technology

readiness level (TRL[1]) and licensing readiness level (LRL[2]). Around 50 % of these designs are light water reactors (LWR). In other words, they are very similar to the latest conventional GEN III[3] reactors. It is a well-known technology and therefore these designs are among the most advanced SMR designs. The remaining 50 % are GEN IV reactors having various coolants like liquid metal, gaseous species or molten salts[36].
Technically, SMRs are very close to the current form of nuclear power plants (NPPs), especially those relying on light water for cooling. As cited in *Tractebel*'s report *The rise of nuclear technology 2.0 Tracrtebel's vision on Small Modular Reactors* [39]: "SMRs are not a single product; they are a business model that brings sensible answers to the crucial questions of the 21^{st} century energy context, becoming an enabler of the zero-carbon transition". In other words, SMRs are not meant to be a completely new technology on their own, but rather a different form of already known nuclear power production that should tackle some of the issues nuclear power is facing at the moment, which is discussed in section 3.2.
Figure 3.1 graphically represents the classification of SMRs. On the top right can be found the LWRs. The lower branch contains a lot of different GEN IV technologies that will emerge after 2030 according to [39].

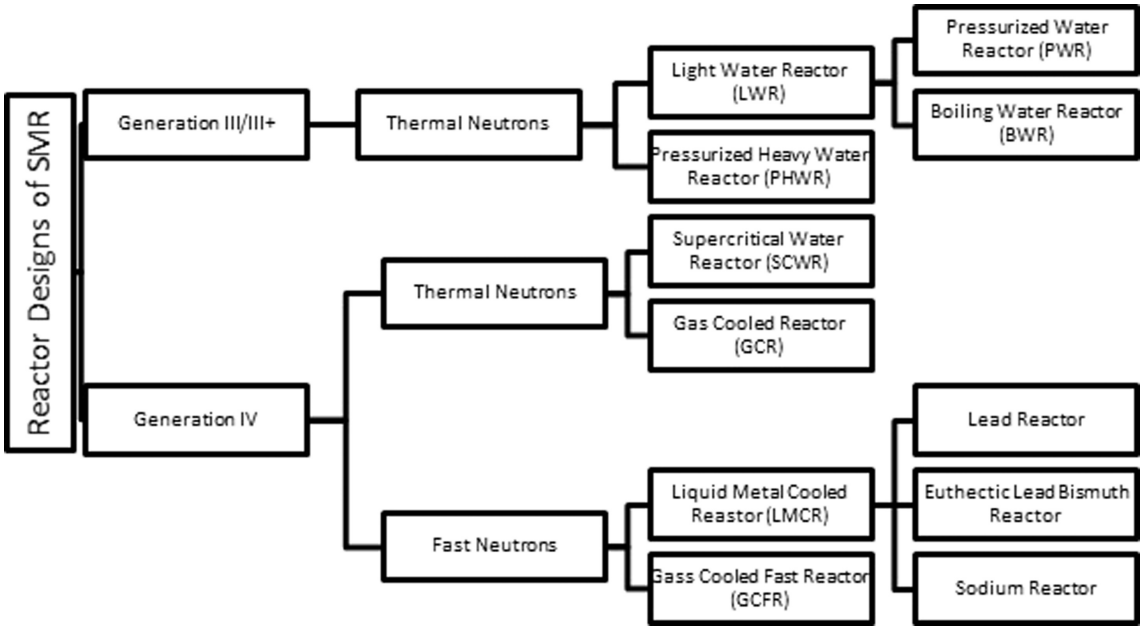

Figure 3.1: Different technologies possible for SMRs [40]

[1] "Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest."[37]

[2] "License potential, also referred to as "licensability" is an assessment of the likelihood that you will see revenue from your innovation. Just as technology transfer is the intersection of science, business and law - a licensable innovation occurs when the potential for commercialisation, protection and market need intersect. It is a determination of whether an innovation fulfills a need and is appealing enough for industry to invest in product development. Another way to look at it is that in order to determine if the innovation is licensable one has to determine the commercial potential, intellectual property position and market opportunity - this includes the stage of development of the innovation."[38]

[3] The different nuclear power plant generations are explained in Appendix B

Because of their reduced size, SMRs can count on reduced construction time. Modularity is key as it makes the switch from an economy of scale toward mass production. As stated in Abdulla et al. (2013)[41], the idea is to make the nuclear industry look more like the aircraft industry where smaller designs can be mass-produced in a factory with high levels of quality controls and can then be delivered by train, by road or by ship to the construction site.

SMRs can group multiple modules into one bigger facility. In figure 3.2, one can see a schematic representation of a micro-grip including photovoltaic (PV) panels, wind turbines (WT), batteries and 3 SMR modules packed together for additional power. This figure comes from Michaelson et al. (2021) [42] that review the compatibility of SMR modules inside a micro-grid with renewable sources. It is important to mention that the different modules of one facility do not necessarily need to be built at the same time. Additional modules can be added after a few years for example allowing them to progressively scale up to the demand [42].

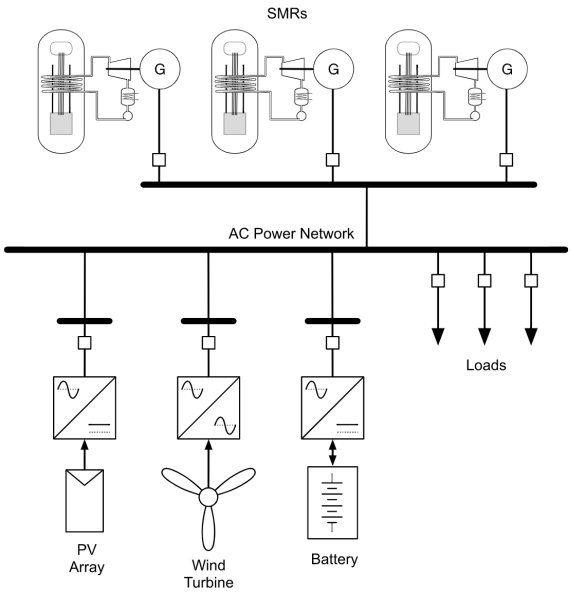

Figure 3.2: 3 SMR modules are grouped into one facility to add supplementary power to the micro-grid [42]

3.2 SMRs put into perspective : their Advantages

Briefly

It is yet unclear if SMRs will be cheaper than conventional NPPs, but their smaller size, standardised and modular designs should offer enhanced flexibility and a smaller financial risk per reactor than big conventional ones. The idea is to switch from an economy of scale to mass production of smaller reactors. As more reactors would be built the designs should evolve and improve faster. All in all, this should make the construction of SMRs more predictable and therefore more attractive to political deciders.

The construction of a conventional NPP requires a lot of capital investment and this drives the investors and the political choices towards other solutions. The goal of SMRs is to reduce the huge investment that is required to build a NPP. Building smaller reactors means a reduced absolute cost which also reduces the financial risk undergone by investors [43]. Additional to this, there are multiple arguments that justify the choice of SMRs.

Smaller size

Indeed, the SMRs will not be able to benefit from an economy of scale. This is why the production philosophy must be changed. It is necessary to shift towards mass production with standardised and modular designs. Furthermore, due to their reduced size (and therefore capacity), more reactors should be produced. This would lead to faster technological progress[36]. This makes it difficult to know whether SMRs will indeed have a lower LCOE than conventional NPP. Abdulla et al. (2013)[41] is a study that gathers 16 experts "who are involved in, or have access to, engineering-economic assessments of SMR projects" and asks them to predict the overnight costs of SMR facilities. The experts had very different opinions, but the conclusion of most of these experts is that SMRs will probably not be cheaper than conventional NPPs, but that they will not necessarily be much more expensive either.
Figure 3.3 shows the expert's predictions on the overnight cost[41]: Sixteen experts who were assigned the letters A to P gave their estimates of the overnight cost for different scenarios. Scenario 1 corresponds to a conventional LWR reactor with 1 [GW] capacity. Scenario 2 corresponds to a single 45 [MW] reactor. Scenario 3 and scenario 4 are scenarios in which respectively 5 and 24 SMR reactors of 45 [MW] are installed. Finally, scenario 5 corresponds to the cost of a single SMR reactor of 225 [MW].
Having the possibility to build smaller reactors allows it to use them to power remote areas in off-grid applications. Currently, these communities rely mostly on Diesel generators, but this solution is highly carbon-emitting and frequently needs to be refueled. SMRs, on the other hand, have a very long fuel cycle and are more or less carbon-neutral [42].
Because of their small size, some SMR designs can rely on natural phenomena to cool down the core of the reactor. No mechanical component would be used and in case of emergency, cooling would be insured. The American company *NuScale* for example has designed a reactor relying on natural convection cooling. Figure 3.4 shows the reactor and its features 3.4.

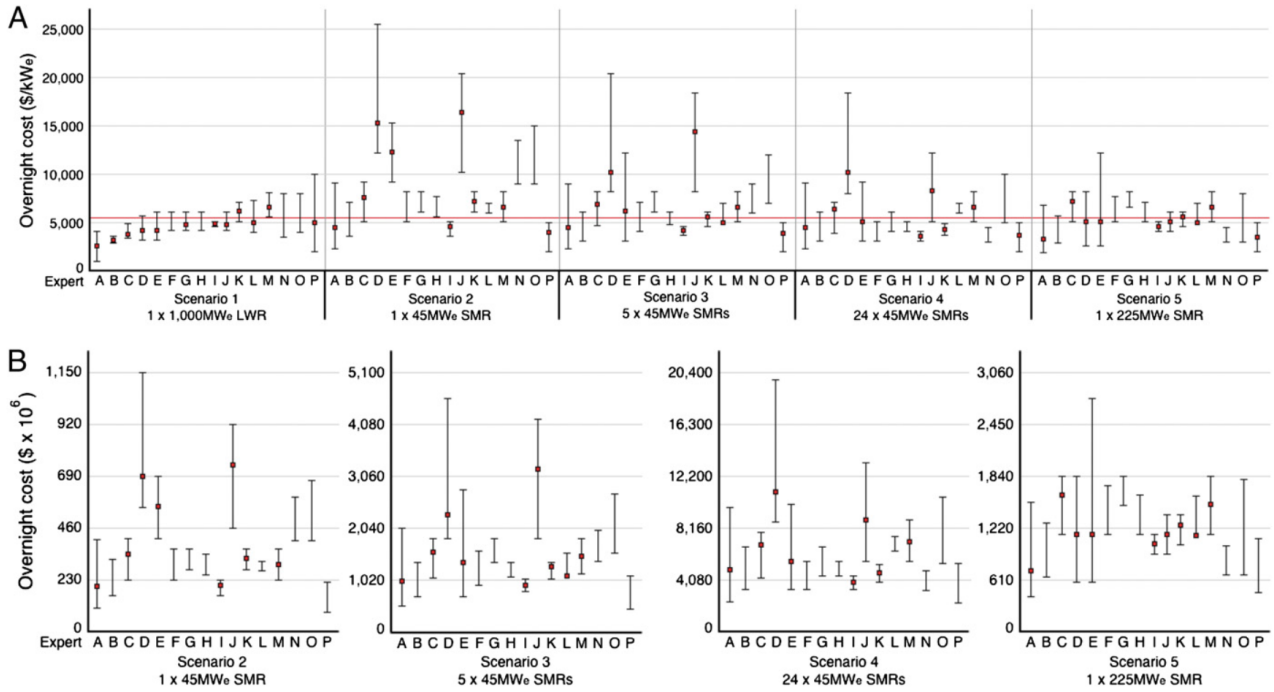

Figure 3.3: "Estimates of overnight cost elicited from sixteen nuclear power experts for each of five nuclear reactor deployment scenarios. (A) Each expert (A through P) provided estimates of the overnight cost per kilowatt of reactor capacity for each scenario. The details of the scenarios are noted on the horizontal axis. The solid line represents the Energy Information Administration's 2011 estimate of the overnight cost of dual-unit large LWR plant [44]. (B) For the four SMR-plant configurations, each of the estimates in (A) is multiplied by plant capacity to arrive at project cost." [41]

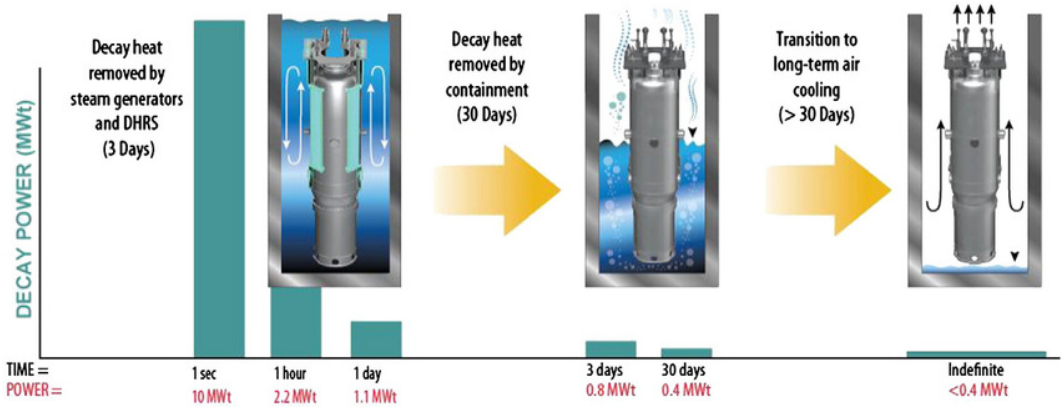

Figure 3.4: The *NuScale* reactor design relies on natural convection for its core-cooling, as can be seen on the very left.
In case there is a prolonged station black out, the *NuScale* reactor design follows the procedure as depicted in order to reach a long-term and safe cooling[45]

Standardisation

The smaller size allows for standardised manufacturing techniques and enhanced quality control leading to lower construction risks, faster improvement and new manufacturing techniques [36].
As each part is mass-produced and does not need to be specifically designed for one single NPP, it allows for a more predictable NPP construction. Reducing the uncertainty coming from the production leads to a gain in time and money and makes nuclear technology more attractive to potential clients or investors [36].

Modularity

Even though SMRs will be mass-produced and will all be similar, there is the possibility to group multiple reactors (i.e. modules) into a multi-module plant. This feature would provide a "scalable and flexible approach to deploying nuclear power", according to Ingersoll et al. (2015)[46]. It is expected that these multi-module plants will be "more adaptable to integration with inherently variable generating sources such as wind" [46].

It is important to mention that at the moment of writing, SMRs are still at an early stage. Very few first-of-a-kind (FOAK) real size SMRs has been constructed yet and it is difficult to know whether the features explained here above will indeed be observed in practice or not. It is therefore important to keep a critical mind about the SMR technology.

3.3 Different Reactor Types

Briefly

According to [47], around the world, more than 70 SMR concepts are under various stages of development, which is 40% higher compared to 2018. They can be classified into 5 categories :

- Single-unit LWR-SMRs
- Multi-module LWR-SMRs
- Mobile/transportable SMRs
- Generation IV SMRs
- Micro modular reactors (MMRs)

Even though the term "SMR" is used worldwide, different designs still can vary a lot from one another, especially in their degree of modularity. Table 3.1 shows the most advanced example for each subcategory while Table G.1 in Appendix G shows a more representative sample of them. Detailed documentation can be found in the 2020 report published by the IAEA [47].

There are a lot of possibilities to classify and differentiate SMRs among them. They may rely on different technologies (see Figure 3.1), they may be designed for different types of use and they may have different TRLs or LRLs. Still, one can group all the SMR designs in these five categories [4], as has been done in *Small Modular Reactors: Challenges and Opportunities* by the NEA[36]:

[4] It is possible that a SMR design falls into multiple of these categories

1. **Single-unit LWR-SMRs** : Relying on the well-established LWR technology, these reactors are meant to function on their own in order to replace smaller fossil-fuel units or to be deployed as distributed-generation.
2. **Multi-module LWR-SMRs** : Also relying on the well-established LWR technology, these reactors can group multiple modules to form a bigger facility. These can be used for mid-size baseload capacity or in a distributed framework depending on the total capacity of the multi-module SMR.
3. **Mobile/transportable SMRs** : Currently, these reactors are meant to rely on LWR technology. They are meant to be easily transportable from one place to another. Floating reactors for example are included in this category.
4. **Generation IV (Gen IV) SMRs** : These reactors do not rely on LWR technologies and include many features that have been investigated by the Generation IV International Forum (GIF) in past years.
5. **Micro modular reactors (MMRs)** : These reactors have a power output that is lower than 10 [MW]. Their smaller size should allow them to also be easily transportable and most of the time, these reactors will not rely on LWR technologies and therefore also fall under the category of Gen IV reactors.

The technology that has the highest TRL and LRL are LWR-based SMRs. They are the ones that are most likely to come out first for commercial use. Some concepts are already under construction, like the *CAREM* reactor in Argentina and the ACP-100 in China for example. A PWR SMR is in operation in Russia. According to the NEA's report *Small Modular Reactors: Challenges and Opportunities* [36] : "This first-of-a-kind (FOAK) floating nuclear power plant "Akademik Lomonosov", with two KLT-40S reactors, was connected to the grid on 19 December 2019 in Pevek, Chukotka Peninsula(Rosatom, 2019). It started full commercial operation on 22 May 2020, generating electricity for households and local industries in Russia's east Arctic region (Rosatom, 2019).". Other designs should start to emerge by the end of the 2020s. Pressurised heavy-water reactors are also pretty advanced and similar conclusions can be drawn for them [36].

Gen IV technologies rely on different coolants such as liquid metals or gaseous species. These are at an earlier stage than PWR technologies even though several units are under construction or already under operation[36]. In China, for example, the HTR-PM high-temperature gas-cooled reactor should have started electricity production at the end of 2021[47]. These reactors may provide other fields of use than only electricity production as some of them operate at higher temperatures (i.e. $500 - 900°C$) [36].
The Internal Atomic Energy Agency (IAEA) has published its report on the worldwide advances of SMR technology advancements in [47]. A lot of more detailed information can be found about many SMR designs in this work.

Design	Net output per module [MW]	number of modules	Type	Designer	Country	Status
Single unit LWR-SMRs						
ACP100	125	1	PWR	CNNC	China	Contruction began in 2019
Multi-module LWR-SMRs						
NuScale	50	12	PWR	*NuScale* Powertrain	US	Certified design. US NRC and the CNSC as part of the licensing process
Mobile SMRs						
KLT-40S	52	2	Floating PWR	OKBM Afrikantov	Russia	Connected to the grid in December 2019
GEN IV SMRs						
HTR-PM	210	2	HTGR	China huaneg/ CNEC/ Tsinghua Univ.	China	Under construction
MMRs						
Aurora	2	1	LMFR	Oklo	US	License application submitted in the US NRC

Table 3.1: Most advanced reactor type from each category. A bigger sample of advanced designs can be found in Table G.1 in Appendix G. It has been adapted from the NEA report *Small Modular Reactors : Challenges and Opportunities*[36].
*It should have started electricity production since December 2021[47]

3.4 Flexibility of a SMR

Briefly

In order to complete the intermittent and space dispersion of RE sources, SMRs are should have a certain load-following capability. The *NuScale* reactors are rather flexible and capable of meeting a varying load demand. They meet the URD requirements listed in Table 3.2. There are 5 different ways that SMRs can adapt their electrical power output to the demand:

1. Rod control to regulate nuclear fission.
2. Feed-water flow regulation.
3. A bypass valve or a co-generation facility that allows it to skip the turbine.
4. Taking one or more modules offline for extended periods where the demand is lower.
5. Manoeuvring of independent modules.

The different nature of the possible ways to tune the output electrical power makes them complementary as they all have a different response time.
In conclusion, SMRs could play a role in helping RE sources meet the varying load demand, but while increased flexibility is claimed by the SMR constructors, the effectiveness of the different features still needs to be demonstrated.

The current tendency in Belgium is the massive deployment of RE sources (see section 1.2.2) to reach carbon neutrality. However, their intermittency and space disparity requires either the support of additional storage facilities or dispatchable load-following electricity production means. This is why it is important that the SMRs develop a sufficient load-following capability to be able to work together with RE sources.
Figure 3.5 shows the layout of a nuclear reactor-based power generation unit, more precisely the one of a *NuScale* SMR. In this case, the SMR is a 45 [MW] reactor. The reactor produces thermal energy to generate steam, which then produces electrical energy thanks to the turbine. Not all thermal energy is converted into electrical energy of course. A significant amount of thermal power (around $60-70\%$) is lost at the condenser.

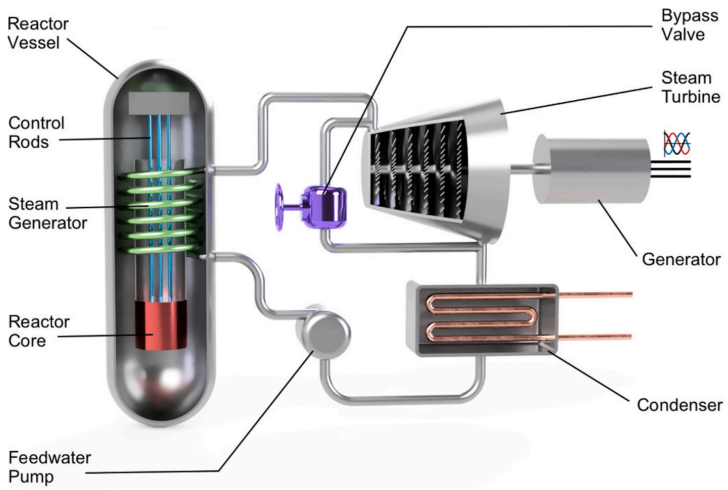

Figure 3.5: Schematic *NuScale* reactor with bypass valve.

There are several possibilities to adjust the electrical output power of a nuclear reactor.

1. Rod control can directly modify the thermal power that is generated by the reactor through the rate of fission happening inside the core. The fission chain reaction is complex and can limit the manoeuvrability of the reactor as it includes inevitable transient behaviours when subjected to large power changes [42]

2. Regulating the feed-water flow has a more indirect effect by adjusting the rate of heat removal from the core, which then affects the core reactivity [42].

3. A bypass valve allows a part of the steam to skip the turbine. As a consequence, a part of the steam does not participate in electricity production. This option increases significantly the thermal losses at the condenser and can harm on some mechanical parts in addition to reducing the efficiency of Uranium-electricity conversion [42]. The SMR reactor would need to include this feature in its design, which is the case of the *NuScale* 45 [MW] reactor. The bypass valve can be observed in Figure 3.5.
   In the same idea, co-generation allows it to switch from electricity demand to the generation of different products. The *NuScale*-based study [45] suggests a co-generation plant sharing electricity production with a water desalination plant. This might not be of greatest interest in Belgium, but the electricity production can be coupled to different fields too, like heat generation or hydrogen production. Both co-generation and the bypass valve allow the tune of electricity production while keeping the core power rather constant. In the case of a co-generation plant, non-electricity production is valued to produce something else. This is not the case for the bypass valve, where the heat that skips the turbine is just pure loss.

4. The nuclear facility can take one or more modules offline for extended periods when the grid demand is low or when RE sources' production is sufficient [46].
   This can also be useful when a module needs to be re-fueled. The remaining modules can continue electricity production during that time [46]. This solution only works for SMR designs that allow the possibility to merge multiple modules.

5. The manoeuvring of independent modules is possible such that the facility can compensate for intermediate periods of hourly changes in RE generation or demand. From an atomic point of view, freshly re-fueled modules are more reactive. Having different fuel stages for each module gives greater freedom to adapt to the demand [46]. This solution only works for SMR designs that allow the possibility to merge multiple modules.

Different solutions listed above have different response times, which makes them complementary.

In the United States, the Electric Power Research Institute maintains the User Requirements Document (URD) that states the standardised plant designs, including specifications for load-following characteristics. The URD requirements can be read in Table 3.2.
Requirement 3.4.1.1 states that the SMR should be able to lower its power from 100% down to 20% and then back up again to 100% in 24h time and that the maximum ramp rate it should be able to achieve is 40% per hour.
Requirement 3.4.3 asks for a quick step change of 20% in 10 minutes.
Requirements, 3.4.2.1 and 3.4.4.1, refer to the grid characteristics. There are markets, called "Frequency Markets", that try to reach the equilibrium on the grid between the demand (consumption) and the offer (production) of energy. At 50 Hz, they are perfectly equal, if the

frequency is greater than 50 Hz, it means that the production is greater than the consumption and inversely. The requirements stipulate that SMRs should be able to participate in this real-time load following.
According to Ingersoll et al. (2015) [46], the most recent requirements for SMRs listed in Table 3.2 are indeed met by the *NuScale* reactors.

URD Requirement	**Rev.13 Description**
3.4.1.1	24h load cycle : 100% → 20% → 100%
3.4.1.1	Ramp rate of 40% per hour
3.4.2.1	Capable of automatic frequency response
3.4.3	Step change of 20% in 10min
3.4.4.1	Frequency variation

Table 3.2: The Electric Power Research Institute maintains the User Requirements Document (URD) that states the standardised plant designs, including specifications for load-following characteristics. SMRs should be able to meet these URD requirements in order to be licensed.

Figure 3.6 illustrates two different ways to pilot the *NuScale* reactor when it is linked to a 71 km^2 wide wind farm yielding a maximum generation capacity of 57.6 [MW]. This is the work of Ingersoll et al. (2015)[46]. On the left, the nuclear reactor operates at full power while the load-following is done only by the bypass valve. One can see that the losses linked to this solution are huge. On the right, the reactor does not operate at full power all the time. The latter solution requires a precise prediction of the weather forecasts to predict the wind production in advance and to plan the power output of the reactor.

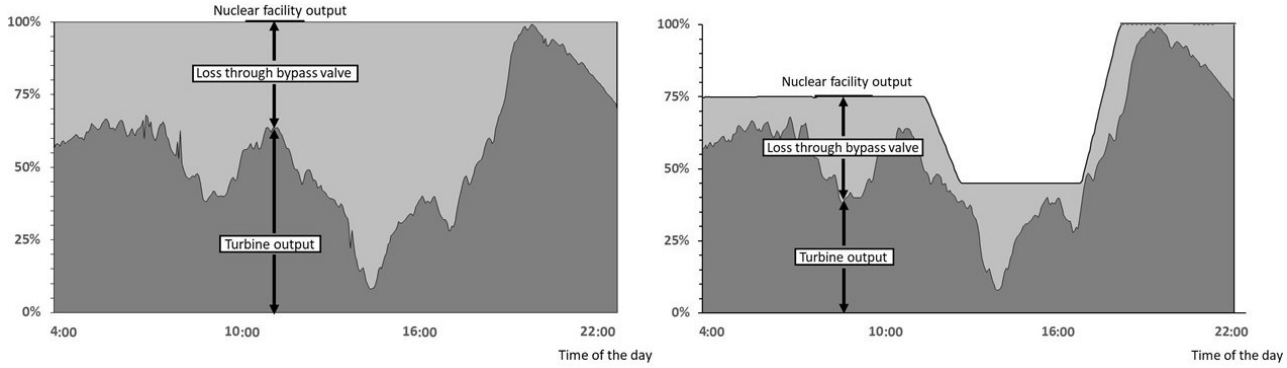

Figure 3.6: Load following of the multi-module *NuScale* facility thanks to the bypass valve only (left) or thanks to the bypass valve and reactor step changes (right). Figure adapted from Ingersoll et al. (2015)[46]. The left graph shows the important losses that are linked to this solution. The losses on the right are reduced, but that solution requires an accurate weather forecast to adapt the power of the nuclear reaction.

Finally, some special considerations should be taken into account:

- Because of the frequent thermal cycling of the fuel, the latter should be properly designed and optimised.
- More regular maintenance operations are required resulting in lower module availability as certain mechanical parts will degrade faster due to regular thermal and operational cycling which decreases the capacity factor of the technology.

- Some boron adjustments are needed for extended periods of low power operations. This plays on the reactivity control of the facility.
- The more frequent power variations require more operation workload and overall higher staffing requirements.
- An enhanced use of the turbine bypass increases the heat waste of the plant and adds complexity to the design requirements of the cooling tower.

All in all, load following thanks to PWR SMR facilities is possible. It is claimed that they are more flexible than conventional NPPs, yet still limited in their manoeuvrability. According to [39], GEN IV SMRs will have even better manoeuvrability. As a reminder, the claims are based on predictions because too few nuclear reactors are under operation at the moment.

Chapter 4

An ESTD Case Study: SMRs in Belgium

Now that the SMR technology has been explained, a quantitative study based on it is proposed. For this purpose, it was first necessary to implement a new technology in EnergyScope Typical Days (ESTD) and to characterise it. As the most advanced SMR technologies are PWRs, the rest of the thesis will focus on these in particular. It is easier to find data and the predictions might be the most accurate as it is a technology that is already mastered since the 1970s. So the SMRs implemented in ESTD are based on the *NuScale* reactors, which are PWRs.
Indeed, technically, there is little to differentiate SMRs from conventional nuclear reactors, especially with the hypothesis that the studied SMRs are s only. In short, it is a smaller reactor that produces less power and the difference lies mainly in the investment costs and flexibility (or at least it is claimed so), as explained in the previous chapter. Scientific research has provided the data in Table E.5 on investment costs. Indeed, it can be observed that there is some disparity in this parameter. SMR still being at the research stage, costs are difficult to predict. Flexibility has been taken into account in the implementation of a new technology into ESTD. It is explained in section 4.1. Deterministic and stochastic results are then provided in sections 4.2 and 4.3.

In this chapter, first the implementation of the SMRs in ESTD is explained (section 4.1). Following this, a deterministic approach is done on the three main parameters of the SMR technology (section 4.2). Finally, two GSAs are carried out in section 4.3 The first is on the total cost using the Polynomial Chaos Expansion (PCE) method and the second one is on the installed capacity of SMRs relying on a Monte Carlo (MC) method.
As a reminder, the calculations have been obtained based on several important assumptions that are listed in section 1.5.3.
For this chapter, so called Sankey diagrams (that are introduced in the course of the chapter) are used to analyse the different energy flows. For more reading convenience, these diagrams can be found in Appendix J as they take up much space.

4.1 Implementation of SMR Technology in ESTD

Briefly

SMRs are modelled in ESTD to resemble the functioning of the *NuScale* reactors that claim to be very flexible. To achieve their high flexibility, they include a bypass valve that enables to skip the steam turbine. However, by doing so, part of the energy is lost. Therefore, in ESTD the implementation of a SMR is done by modelling a baseload consumption of **Uranium** and varying electricity production. The part of the **Uranium** energy that is not converted into **ELECTRICITY** is lost. In order to model the SMRs, the following variables have been added to ESTD.

- **SMR HEAT** represents the heat inside the nuclear reactor,
- **SMR CORE** models the conversion between uranium and **SMR HEAT**,
- **SMR ELEC** models the conversion between **SMR HEAT** and **ELECTRICITY**,
- **SMR BYPASS** models the **SMR HEAT** that gets lost as **Curtailment**.

Figure 4.1 schematically represents them, their links and how they work. Equations 4.1 to 4.4 expose the mathematical link between each variable.

In this section, the implementation of SMR technology in ESTD is explained. The flexibility of a SMR has been described in section 3.4, but in the context of this paper, SMRs have been modelled to work like a module proposed by the American company *NuScale*, i.e. with the presence of a bypass valve that allows the reactor to be very flexible [48]. For this, the SMR technology is modelled using a set of one Resource and three Technology variables which are explained here below. Furthermore, Figure 4.1 provides a graphical representation of the links between these variables.

- **Resource**

  1. **SMR HEAT** : represents a temporary resource created by technology **SMR CORE** (explained below). It is the result of a transformation from the energy contained in **Uranium**. Physically this resource represents the heat inside the core of the nuclear reactor.

- **Technology**

  1. **SMR CORE** : represents the power of the conversion created in the core of the nuclear reactor. It is responsible for the conversion of **Uranium** into **SMR HEAT**. The conversion **Uranium** - **SMR HEAT** is implemented to have an efficiency of 100%. This technology is assumed to work in "base load" mode, which means the power output coming from **SMR CORE** is constant. Consequently, the consumption of **Uranium** is constant.

  2. **SMR ELEC** : represents the electricity production of a SMR. It converts the **SMR HEAT** produced by **SMR CORE** into electricity thanks to a steam turbine. Like any other steam turbine, the efficiency of its conversion is not 100%. **SMR ELEC** has been implemented such that the conversion has a technological efficiency of $\eta_{tech,SMR\ ELEC}$ = 38%. This number comes from the already ESTD implemented technology "NUCLEAR" where the conversion between resource **Uranium** and **ELECTRICITY** has an efficiency of 38%. Thanks to the bypass valve, the electricity production is free to change from 20% to 100% of its maximum electric capacity

production. How much this production actually is can vary in time and is defined by the load status η_{load} (bounded between 20% and 100%). The load status depends on the grid demand. The lower value of 20% has been chosen arbitrarily based on the fact that in Table 3.2, the load cycle should be able to do 100% down to 20% and then back up to 100% in 24h. As no other value was mentioned anywhere, this percentage has been taken for the minimum value that SMRs can reach in "normal" conditions.

3. **SMR BYPASS** : represents the part of the **SMR HEAT** that skips the turbine (i.e. 1-η_{load}). This is helpful for the load following characteristics of the SMR. This quantity is a loss because the heat flowing through the bypass is not valued, but it could be valued for hydrogen production, district heating or water desalination [48], as explained in section 3.4. This loss is considered as **Curtailment**. The technical conversion from **SMR HEAT** to **Curtailment** is 100% efficient (i.e. $\eta_{tech,SMR\ BYPASS}$ = 100%).

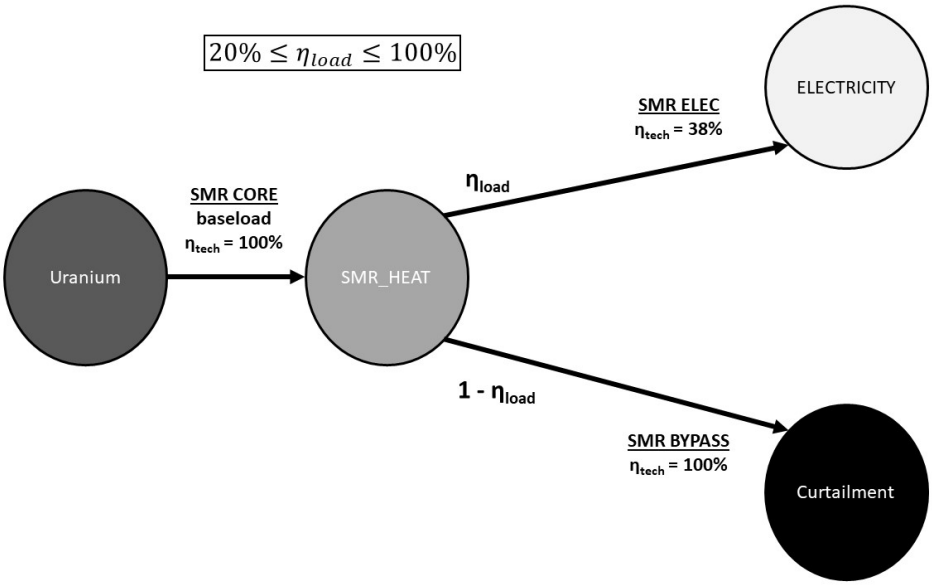

Figure 4.1: Graphical representation of the links between the new SMRs variables. The circles represent the resources (or type of energy) and the arrows represent the technologies used to convert one type of energy into another. The conversion between uranium and **SMR HEAT** has a conversion efficiency of 100%, but the conversion between **SMR HEAT** and **ELECTRICITY** depends on the demand. The technological efficiency is 38% but the load status η_{load} can vary from 20% to 100%. The total conversion efficiency is the product of technological efficiency and load status. Therefore the minimum possible efficiency between **SMR HEAT** and **SMR ELEC** is 7.6 % (= 20% of 38%). The part of **SMR HEAT** that does not flow into the steam turbine to produce electricity (**SMR BYPASS**) flows through the bypass valve and creates "**Curtailment**" or in other words, loss.

Figure 4.1 and the set of Equations 4.1, 4.2, 4.3 and 4.4 allow a better understanding of how the different variables have been defined and interact with one another. The total efficiencies $\eta_{tot,SMR\ ELEC}$ and $\eta_{tot,SMR\ BYPASS}$ are the products between the load status η_{load} and the respective technological efficiency of **SMR ELEC** and **SMR BYPASS**.

$$20\% \leq \eta_{load} \leq 100\% \tag{4.1}$$

$$\begin{aligned} \eta_{tech,SMR\ ELEC} &= 38\% \\ \eta_{tot,SMR\ ELEC} &= \eta_{load} \cdot \eta_{tech,SMR\ ELEC} \\ \Rightarrow 7.6\% \leq \eta_{tot,SMR\ ELEC} &\leq 38\% \end{aligned} \tag{4.2}$$

$$\begin{aligned} \eta_{tech,SMR\ BYPASS} &= 100\% \\ \eta_{tot,SMR\ BYPASS} &= (1-\eta_{load}) \cdot \eta_{tech,SMR\ BYPASS} \\ \Rightarrow 0\% \leq \eta_{tot,SMR\ BYPASS} &\leq 80\% \end{aligned} \tag{4.3}$$

$$\textbf{ELECTRICITY} = \eta_{tot,SMR\ ELEC} \cdot \textbf{SMR HEAT}$$

$$\textbf{Curtailment} = \eta_{tot,SMR\ BYPASS} \cdot \textbf{SMR HEAT}$$

$$\textbf{SMR HEAT} = \frac{1}{\eta_{tech,SMR\ ELEC}} \textbf{ELECTRICITY} + \frac{1}{\eta_{tech,SMR\ BYPASS}} \textbf{Curtailment} \tag{4.4}$$

According to *NuScale* Company, a *NuScale* reactor is very flexible thanks to its bypass valve and other feature (see section 3.4). Based on this, in the context of this thesis, the ramp up and down of the SMR technology is modelled similarly to a combined cycle gas turbine (CCGT). The difference is that SMRs are not allowed to go below 20% of their potential electricity production and that their resource is constantly consumed over time. The freedom to operate freely between 20% and 100% capacity allows for a certain amount of flexibility in the SMRs without overlooking the fact that some energy is lost by diverting part of the steam through the bypass.
Table 4.1 shows the numbers assigned to each parameter contributing to the definition of the SMR technology. The values of SMRs and conventional nuclear are equal. As a first approach, the authors decided that the deterministic values should be the same because they are both s and the cost indicators for both technologies are quite uncertain. Furthermore, looking back at the results of the study of Abdulla et al. (2013)[41] in Figure 3.3, this assumption is not senseless. Several experts predict the costs of SMRs (scenarios 2-5) to be situated around the same price as conventional nuclear (scenario 1).
SMR CORE and **SMR BYPASS** are free of cost because they should not constitute an over-cost for the installation of **SMR ELEC**. The same counts for **SMR HEAT**; it has zero availability because the only way to produce it is via **SMR CORE** using uranium.

TECHNOLOGIES					
	c_inv [M€/GW]	**c_maint [M€/GW]**	**gwp_constr [ktonCO$_2$e/GW]**	**lifetime [years]**	**c_p,max** -
NUCLEAR	4845.73	102.93	707.88	60	0.85
SMR ELEC	4845.73	102.93	707.88	60	0.85
SMR CORE	0	0	0	60	1
SMR BYPASS	0	0	0	60	1
RESOURCES					
	avail [GWh/y]	**gwp_op [ktonCO$_2$e/GWh]**	**c_op [M€/GWh]**	**CO2_op [ktonCO$_2$e/GWh]**	X X
SMR HEAT	0	0	0	0	X

Table 4.1: Summary of data used for the modelling of SMRs in ESTD. SMRs are working in the same way as conventional nuclear power plants, so there are a lot of similarities. As a first approach, the deterministic data is considered equal for "NUCLEAR" and "SMR". The complementary technologies (**SMR CORE** and **SMR BYPASS**) and resource (**SMR HEAT**) have a zero cost because they should not constitute an over-cost to the system that desires to install **SMR ELEC**, which cannot function without them. The availability of **SMR HEAT** is zero to force the consumption of **Uranium** to create **ELECTRICITY** via **SMR ELEC**.

4.2 Deterministic Approach

Briefly

Figure 4.3 shows an example of the load following happening on the 12 Typical Days and Table 4.1 displays the values of the deterministic input parameters of the SMR variables. A deterministic approach is taken to quickly analyse the place of SMRs in the energy system. Results turn out to be very similar to what is obtained in Chapter 2 for the deterministic approach of nuclear power: the SMR capacity is pushed to its maximum allowed capacity. If no SMR is allowed, RE sources and synthetic fuels drive the energy system as can be seen in Figure 4.2.

In order to be able to compare the results with conventional nuclear technology, a study similar to the one conducted in section 2.1 is made. It is important to note that the "NUCLEAR" technology from ESTD is not permitted. Three scenarios very similar to those from section 2.1 are defined :

- **No SMR allowed**: No SMR is allowed in the system (and no conventional nuclear either) This is the same scenario as "No nuclear allowed" (in section 2.1).
- **Infinite SMR allowed**: No upper limit is put for the capacity of SMR.
- **6 [GW] SMR allowed**: The same power is allowed for SMRs as nuclear capacity is installed nowadays in Belgium : 6 [GW].

Figure 4.2 shows the resulting electricity mix in these three scenarios. As with nuclear power, ESTD installs as many SMRs as it is allowed to do. When the SMR technology is not allowed, it is replaced by photovoltaic (PV) and CCGT ammonia. These results are very similar to the ones in section 2.1.

Because of the similarity of the results with the ones in chapter 2, other deterministic results are only shown in Appendix H. Not showing them here avoids redundant graphs and results.

However, in order to demonstrate the working of SMRs as explained in section 4.1, Figure 4.3 is shown. It is the hourly data of the scenario allowing 6 [GW] of SMR power based on 12 typical days. These 12 days are required to model and represent a whole year as explained in section 1.3.1.
In Figure 4.3, one can see that **SMR HEAT** is operating as baseload at 16.2 [GW] while the electricity production of SMRs is most of the time constant too, but 38% lower because of the technical efficiency, so at 6 [GW]. During days where renewable energy (RE) sources produce a lot, the SMR electric production drops as the bypass valve is used. The RE sources are made of onshore and offshore wind turbines (WT) and PV panels as can be seen in Figure 4.2.

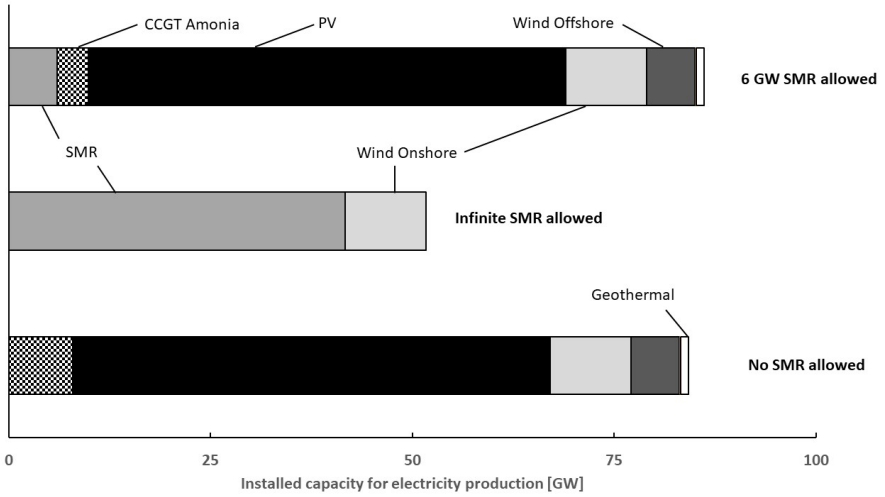

Figure 4.2: Three scenarios with SMR technology. ESTD installs as much SMR as it can. For the infinite SMR scenario, 42 [GW] are installed. When SMR is not allowed (or not a lot), it is replaced by a lot of PV. The difference between no SMR and only 6 [GW] of SMR lies in the fact that ammonia CCGT gets replaced by SMRs when they are allowed.

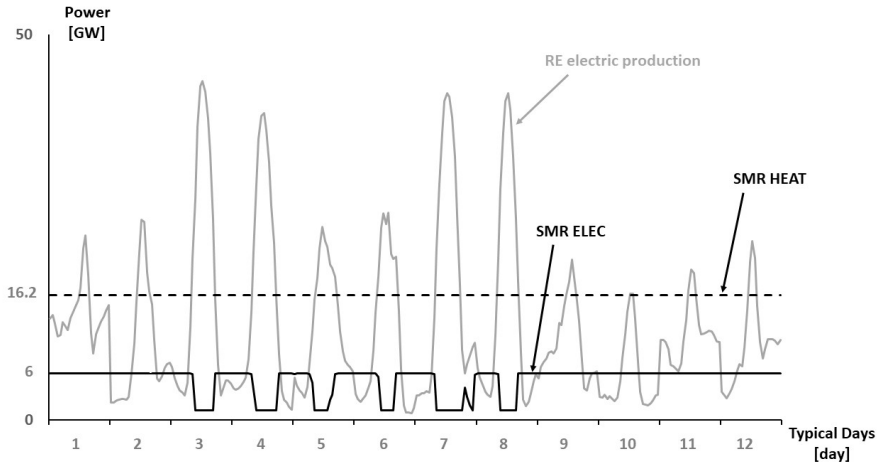

Figure 4.3: Hourly data of 12 typical days in a system including SMRs and renewable energy sources. SMR HEAT operates as baseload at 16.2 [GW]. SMR ELEC is often at full capacity (i.e. 38% of SMR HEAT), but when renewable energy sources produce a lot it falls at 1.2 [GW] (= 20% of 6 [GW]) power capacity. The RE sources are made of wind turbines (on and off shore) and PV panels.

4.3 Global Sensitivity Analysis

Briefly

Firstly, as a result of scientific research, uncertainty ranges could be determined for the 4 parameters of the SMR technology. Only two of them have been changed compared to the case with nuclear energy. They are listed below with their range :

- $c_{inv,SMR} \in [2200; 11200]$ [M€/GW]
- $t_{SMR} \in [40; 80]$ [years]

The uncertainty on the two parameters specific to uranium are unchanged from the case with conventional NPPs, see Table 2.5. With these uncertainty intervals, two global analyses are carried out.

- The first one on the total system cost using a PCE, which allows to compare the results to section 2.4. Table 4.2 shows the stochastic space of the input parameter linked to SMRs with the remaining parameters taken over from Rixhon et al. (2021)[2]. The results are pretty similar to the ones obtained in section 2.4 for nuclear power.
- The second analysis is on the installed capacity of SMRs. The PCE method did not work, because the resulting distribution yields negative values, which has no physical meaning (see Figure 4.6). Therefore a MC method has been carried out generating 1060 samples. The approximate resulting distribution is shown thanks to the histogram in Figure 4.7. Around 12% of the 1060 samples generated yielded a value at 0 SMR capacity. Figure 4.8 (a) shows that these samples have a low synthetic fuel cost and high SMR and uranium cost as well as higher GWP linked to the lifecycle of uranium. On the other hand, samples that predict more than 30 [GW] of SMR capacity have in common that the synthetic fuels are expensive, SMRs and uranium cheap with low operational emissions as can be seen in Figure 4.8 (a).

As explained in the previous section, a more detailed deterministic approach and a local sensitivity analysis with SMRs would be redundant, because of the similarity between a solution with SMRs and conventional NPPs so the authors decided to focus immediately on the global sensitivity analysis (GSA).

In this section, a GSA is carried out on the total system cost and then on the installed quantity of SMRs. For the GSA on total cost, the same polynomial chaos expansion (PCE) method (see section 1.4.2) is used as in chapter 2 with ESTD as a working model. On the other hand, the GSA on the installed capacity of SMRs is carried out differently. A Monte Carlo (MC) method (see section 1.4.1) is used because the PCE method did not yield satisfactory results. Before exposing any results, the input data for the stochastic dimensions are specified.

4.3.1 Input parameters

Before showing any results, the input data needs to be motivated. As in section 2.4, the initial stochastic input data is the data provided and motivated in Rixhon et al. (2021)[2]. In the latter work, $f_{max,NULEAR}$ is an uncertain parameter, but in the case of this thesis, it should not be so it is removed from the stochastic space. On the other hand, 4 other parameters are added just like in section 2.4. The uncertainties taken for parameters linked to uranium are the same as in section 2.4 because the fuel of conventional NPPs and SMRs is the same as the hypothesis of using only pressurised water reactors (s) has been made.
A summary of the added stochastic data can be found in Table 4.2 and as a reminder, the rest of the data can be found in Table E.4.

	Uncertainty interval	**Deterministic value**	**Units**
$c_{inv,SMR}$	[2200; 11200]	4850	[M€/GW]
t_{SMR}	[40; 80]	60	[years]
$c_{op,uranium}$	[0.003; 0.040]	0.004	[M€/GWh]
$gwp_{op,uranium}$	[0.001; 0.020]	0.004	[ktonCO$_2$e/GWh]

Table 4.2: Uncertain input parameters that have been added for the study on the installed capacity of SMRs. The remaining parameters have been taken up from Rixhon et al.[2]. The complete set of uncertain parameters for the global sensitivity analyses (GSA) can be found in Appendix E, Table E.4. $c_{inv,SMR}$ represents the investment cost of nuclear power, t_{SMR} the lifetime of a nuclear facility, $c_{op,uranium}$ the operational cost of uranium and $gwp_{op,uranium}$ the emissions that are linked to the lifecycle of uranium. The ranges taken for the operational cost and the global warming potential of uranium are the same for conventional nuclear and SMRs as the hypothesis of PWR SMRs has been taken. These ranges are justified in section 2.4.1

- $c_{inv,SMR}$: To estimate the cost of SMRs, scientific research has been carried out and Table E.5 summarises the findings. In some sources, intervals were mentioned, in which case, the lower bound is in column "low" and the upper bound is in column "high". When only one deterministic value is mentioned in a source, that value is in column "single". The values were found in different currencies and different years. For their conversion in €$_{2015}$, the same approach was taken by G. Limpens in his thesis [22]. He converts different currencies from different years using the CEPCI (Chemical Engineering's Plant Cost Index) conversion method. Based on the values in Table E.5, the stochastic space for the investment cost of SMRs has been selected such that the lowest cost found in any reference has been taken over for the lower bound and the highest value for the upper bound. Therefore the interval takes values between 2.2 and 11.2 billion € per gigawatt. Comparing these ranges to Figure 3.3, the experts from Abdulla et al. (2013) [41] predict similar figures.
- t_{SMR} : Most designs predict a lifetime of 60 [years]. Some also mentioned 40 and others 70-80 [years] [47]. This parameter does not only depend on technological designs, but also political decisions. Based on this, the stochastic space for the lifetime of SMRs has been fixed to [40; 80] [years].
- $c_{op,uranium}$: The same uncertainty is considered for this parameter as in section 2.4, i.e. 0.003 to 0.040 [M€/GWh].

- $gwp_{op,uranium}$: The same uncertainty is considered for this parameter as in section 2.4, i.e. [0.001; 0.020] [ktonCO$_2$e/GWh].

4.3.2 Results

Metric of Study : Total System Cost

Similarly to the procedure followed for the analysis on the total cost of the energy system using conventional NPPs in section 2.4, a first order PCE is run, then a second order to improve the error between the approximate PCE and the real model. Figure 4.4 shows the resulting distribution of the first and second order. Table 4.3 displays the different statistical metrics. The final leave-one-out (LOO) error is at 2.8%, which is acceptable. The mean cost of the system is at 51.6 [billion€/year] with a standard deviation of 5.3 billion €. These values are a bit lower than the results obtained for nuclear power in section 2.4. Again, the Central Limit Theorem (CLT) (see Appendix F)[34] can be applied and the resulting distribution can be considered normal. The 95% interval for the total system cost is the following: [40 981; 62 181] [M€/year]. Consequently, it is also cheaper and less dispersed than a system without any nuclear.

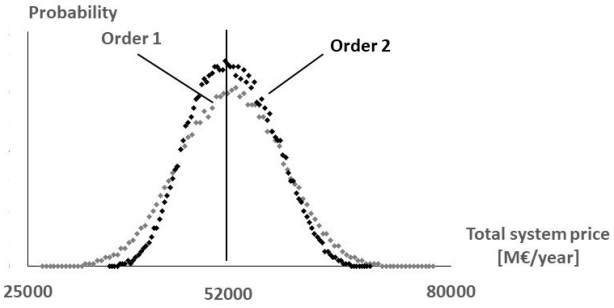

Figure 4.4: A graphical representation of the total system cost results of an order 1 and 2 PCE for SMR technology. The 2^{nd} order is more accurate than the 1^{st} one.

	Order 1	**Order 2**
LOO	30.8%	2.8%
mean	51423	51581
std. dev.	6492	5300

Table 4.3: Statistical results of order 1 and 2 PCE on total cost including SMRs. The mean value is very close but the standard deviation reduces slightly from order 1 to order 2.

	mean	**std. dev.**	**95% confidence interval***	**Units**
Conventional Nuclear	52 175	5 442	[41 291; 63 059]	[M€/year]
SMR Nuclear	51 581	5 300	[40 981; 62 181]	[M€/year]
No Nuclear power	56 966	7 285	[42 396; 71 536]	[M€/year]

Table 4.4: Summary of statistical results on total system costs. The cheapest and less dispersed solution is the SMR technology.
* The 95% interval is obtained assuming that the resulting distribution can be approximated by a normal distribution.

Table 4.4 sums up the results of the three analyses for the total system cost.
It must be said though that the uncertainty interval of the SMR technology is in favour of installing the latter technology (see Table 4.2). First the upper bound of the investment cost is a bit lower for SMRs than for conventional NPPs (11 200 vs 15 000 [M€/GW]). Then, SMRs' interval for the lifetime contains higher values than conventional NPPs ([40;80] vs [40;60] [years]). In general, a longer lifetime is favouring a technology. It is possible that the slightly

different results between the scenario with SMRs or conventional NPPs comes from this difference. Nevertheless, scientific research seems to show that the most economical solution is most of the time nuclear energy, either in the form of SMR or conventional nuclear power plants.

Figure 4.5 shows resulting the Sobol' indices. Unsurprisingly, the parameter with the most impactful Sobol index is the one indicating the price of synthetic fuels. In fact, the Sobol indices are very similar for the case where conventional nuclear is analysed.

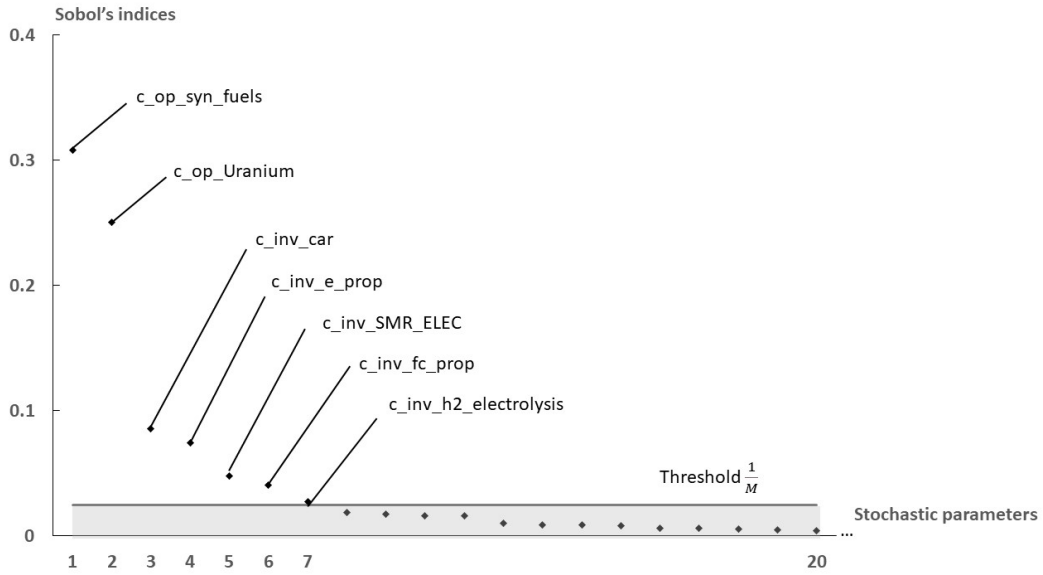

Figure 4.5: Sobol' indices of the first order PCE on the total cost including SMRs. All the parameters above the threshold limit are kept for the second order.

Metric of Study : Installed Capacity

After a study on the total cost of the system, it is interesting to analyse what quantity of SMRs is installed according to ESTD taking into account the uncertainty of the input parameters and what are the parameters that influence this quantity the most. For this study, the authors first tried to do a PCE method, but this did not yield satisfactory results. Therefore, a MC method has been applied from which some conclusions can be drawn.

Figure 4.6 and Table 4.5 show the results of the PCE analysis on installed SMR capacity. In Figure 4.6 we see that the resulting distribution goes to the negative side of the installed capacity. Installing a negative SMR capacity does not make physical sense and ESTD never displays negative capacities. For these reasons, we can deduce that the issue comes from the PCE approximation. Indeed, the PCE approximates the model in a restricted area around where the majority of the results are located. However, in the case of the installed capacity of SMRs, the results are quite close to zero with a significant number of them falling to zero. The result set changes from continuous (above zero) to discrete (at zero) and the PCE is not able to model such a phenomenon, since it consists of a set of continuous polynomials. The continuous polynomials try to approximate non-existing negative values and the resulting distribution is based on the PCE with these negative value approximations.
Consequently, the LOO error is still very high at the second order and even at the third order,

the error is not acceptable. A fourth order PCE would not improve the LOO as the PCE still tries to approximate non-existing values in the negative domain. This shows that the use of a PCE method is not possible while carrying out the study of the installed capacity of SMRs.

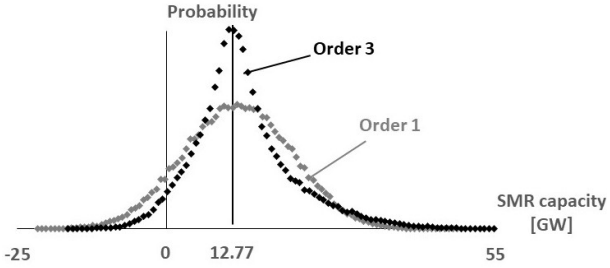

Figure 4.6: A graphical representation of the installed capacity of SMR results of an order 1 and 3 PCE. The distribution includes some values in the negative space, which has no physical sense.

	Order 1	**Order 2**	**Order3**
LOO	50.5%	18.3%	14.5%
mean	11.9	12.94	12.77
std. dev.	8.93	8.58	8.32

Table 4.5: Statistical results of order 1 and 2 PCE on SMR capacity. The LOO is too high to consider these results.

The alternative for a PCE method is the MC method (see section 1.4.1). As a reminder, the principle of a MC method is to generate enough samples in order to calculate statistical parameters and draw conclusions from them. In the case of this study, the authors decided to generate around 1000 samples (1060 exactly) and analyse the results based on them. It is difficult to say if 1000 samples are enough or not. This number is enough to get an idea of what the distribution of installed capacity looks like but is maybe a bit too few for precise statistical predictions.

Alternative methods using maybe other surrogate models instead of polynomial chaos expansion could resolve the discontinuity problem but this is out of the scope of this thesis. A thousand runs of a model taking approximately 90 seconds per iteration takes 90 000 seconds or 25 hours. Figure 4.7 shows the histogram resulting from these 1000 runs. Each bar constitutes the number of iterations where the installed capacity for SMRs is contained in a 1 [GW] interval. Accordingly, on the very left, the interval containing the most iterations is the interval from 0 to 1 [GW] of installed capacity for SMRs (0 [GW] included). The intervals containing the most iterations apart from the first one are intervals [10; 11] and [11; 12]. As shown in Table 4.6 the mean value is at 12.4 [GW] of installed capacity with a standard deviation of 8.4 [GW]. 127 runs that have exactly 0 capacity for SMRs. Based on these, the probability to install 0 SMR capacity is given by:

$$\boldsymbol{P}(F_{SMR} = 0) \approx \frac{\#(F_{SMR} = 0)}{N_{samples}} = \frac{127}{1060} = 12.0\%, \tag{4.5}$$

In other words, there is 100% - 12% = 88% chance that ESTD installs a non-zero capacity of SMRs. In the case a non-zero SMR capacity is recommended by ESTD, the most probable quantities lie between 10 and 12 [GW] with a total probability of 17.5%.

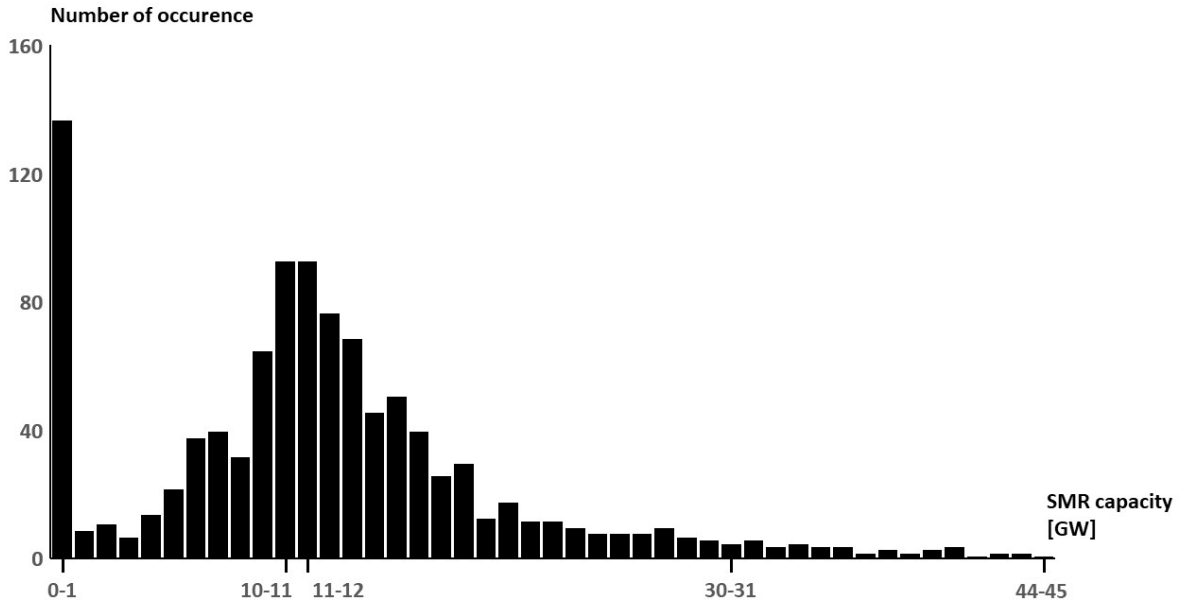

Figure 4.7: Histogram resulting from MC method on installed capacity of SMR. Zero capacity represents 127 of the total 1060 samples. The most probable quantity of SMRs that is recommended by ESTD is between 10 and 11 or 11 and 12 [GW] with a total probability of 8.75% each or a probability of 17.5% to be between 10 and 12 [GW].

	MC method on SMR capacity	**Units**
mean	12.4	[GW]
std. dev.	8.4	[GW]
$\boldsymbol{P(F_{SMR} = 0)}$	12.0%	-
$\boldsymbol{P(F_{SMR} \neq 0)}$	88.0%	-
$\boldsymbol{P(10 \leq F_{SMR} \leq 12)}$	17.5%	-

Table 4.6: Table containing statistical data resulting from MC method on installed capacity of SMR

Having no access to Sobol' indices in a MC method, another way is used to study the influence of different input parameters on the installation of SMR technology. Figure 4.8 (a) and 4.8 (b) show the interquartile range (IQR) of the input parameters for all the cases where 0 respectively ≥30 [GW] SMR capacity is installed. An IQR (i.e. each box) represents the value between the 25% and the 75% quartile. The y-axis of Figure 4.8 quantifies a percentage. This percentage represents the position of the value that the parameter takes within its uncertainty interval. In other words, a value of 0% means that the value is on the lower bound of the uncertainty interval while a value of 100% indicates that the value is on the upper bound of the interval.

This choice makes it possible to represent all the parameters together in the same graph because all parameters have a different order of magnitude and different units. Representing each parameter in absolute values would make this graph unreadable. These graphs allow to deduce where the values are located in their stochastic design space from the position of one box.

For example, let's focus on Figure 4.8 (a) which represents the situation of all zero SMR capacity iterations. The box representing the operational cost of synthetic fuels is very low compared to most other boxes. This may suggest that from the 1000 runs, the ones that have zero SMR capacity tend to have low costs of synthetic fuels. In other words, the value of synthetic fuels seems to have an important role to play in the installation of SMR capacity. Boxes of the investment cost of SMRs, operational costs and emissions of uranium seem to stand out as well. These parameters are located a bit higher than others, which may suggest that they also have a bigger influence on the installed capacity of SMRs.
High costs for SMRs and low costs for synthetic fuels seem to disfavour the installation of SMRs. Figure 4.8 (b) shows the parameter IQRs for all iterations that estimate higher SMR capacity than 30 [GW] (i.e. the right part of Figure 4.7). The parameters that stand out are the same as for the zero SMR capacity. One can see that ***c_op_syn_fuels*** is sensibly higher than other parameters while ***c_inv_SMR_ELEC***, ***c_op_uranium*** and ***gwp_op_uranium*** are lower. The results show that high synthetic fuels costs, low investment costs of SMRs and low operational costs and emissions of uranium favour the installation of a lot of SMR capacity.

In conclusion, it is clear that the most impacting parameters on the installation of SMRs are the operational cost of synthetic fuels, the investment cost of SMRs, the operational cost and emissions of uranium. In previous studies (i.e. deterministic, local variation or global sensitivity analysis on total cost) the most impacting parameters were the same parameters. As already mentioned, ESTD switches from an energy system relying a lot on nuclear power or synthetic fuels importations depending on these parameters. They are the determining factor on how much nuclear (under either form) should be installed.

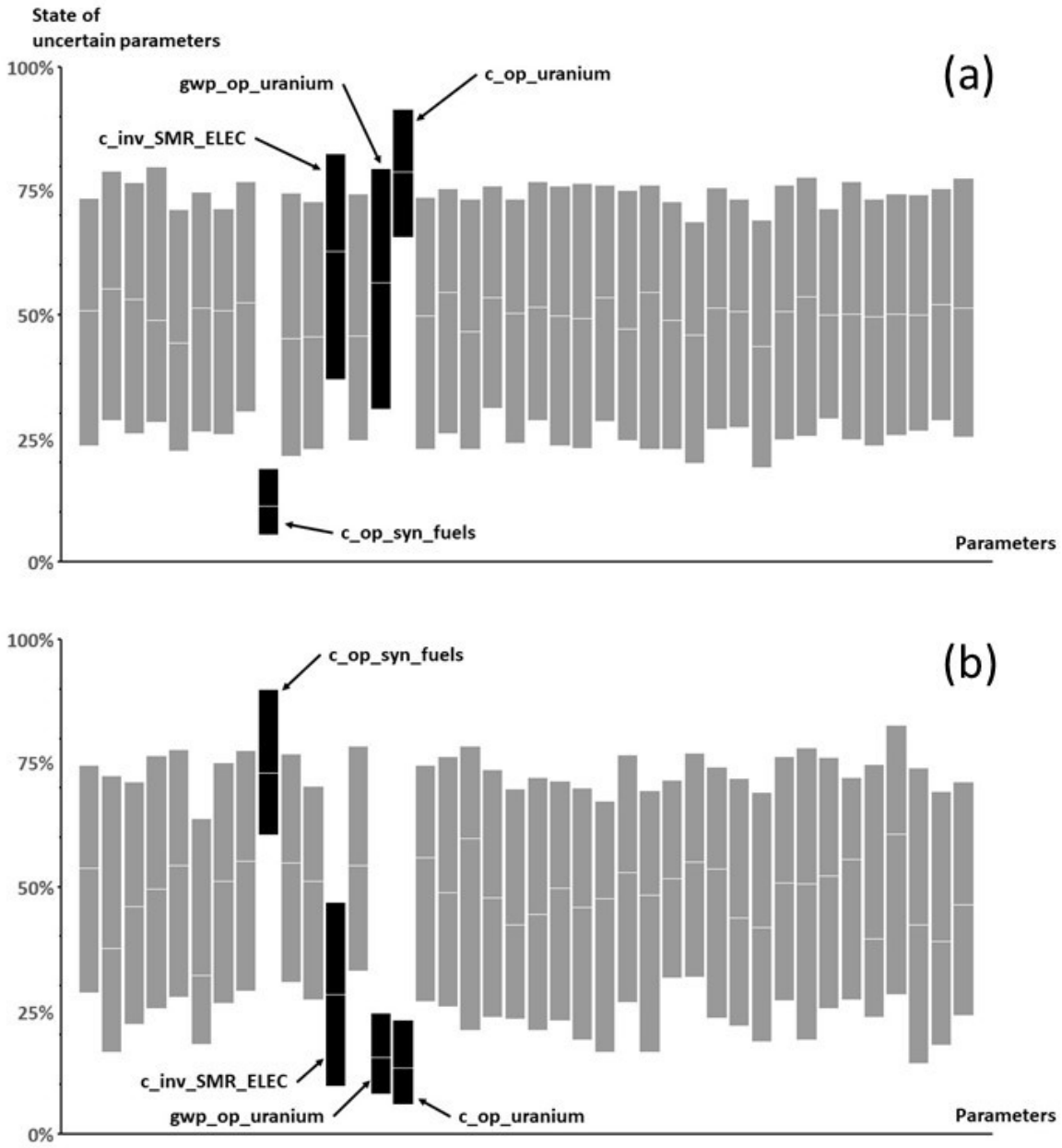

Figure 4.8: IQR of input parameters for zero (a) and ≥ 30 (b) SMR capacity. On the y-axis is the percentage of the stochastic interval. A value at 0% means that the value is on the lower bound of the uncertainty interval while a value at 100% translates that it is at the upper bound. A 50% value means that the value of the parameter is exactly in the middle of the uncertainty interval. The different boxes represent the IQRs of different parameters (40 in total from Rixhon et al.[2] and see Table E.4 in Appendix E).
(a) : For the 0 [GW] of installed SMRs, the operational cost of synthetic fuels are low, but the operational cost and emissions of uranium and the investment cost of SMRs is high.
(b) : For the ≥30 [GW] of installed SMRs, the operational cost of synthetic fuels is high, but the operational cost and emissions of uranium and the investment cost of SMRs are low.

Chapter 5

Discussion

In the context of this thesis, an in depth analysis on the Belgian energy system including conventional nuclear power plants (NPP), small modular reactors (SMR) or none of them has been built up. The energy system optimisation tool EnergyScope Typical Days (ESTD) has been used and sensitivity analyses were carried out via a Polynomial Chaos Expansion (PCE) and a Monte Carlo (MC) method. Total system costs and installation capacity have been analysed and the most impacting parameters have been highlighted. Nevertheless, a few hypotheses and arbitrary choices have put boundaries to the work. These need to be questioned and discussed. Also, the results obtained throughout the previous chapters give margin for discussion. The central question of the thesis on the relevance of nuclear power in Belgium is once again and above all addressed in this final chapter.

The areas of improvement (section 5.1) and a more global discussion on the relevance of nuclear power are presented hereafter.

5.1 Areas for Improvement

Briefly

The methodology that has been followed contained different hypotheses and the authors needed to make different choices to converge on a conclusion. On top of that, some limitations came from the lack of data, time, precision in the modelling tools, etc. These limitations put boundaries on the present work. This section is supposed to highlight the limiting factors, discuss their relevance and what other possibilities there might be, possibly for future analyses on the subject.

CO_2 emissions

The operational emissions limit is fixed at 5000 [ktonCO_2e/year] ($\approx$ 5% of Belgium's emissions in 2019) for any cases studied. This number represents approximately the emissions of a country like Luxembourg according to the *IEA Data browser*[16]. In 2050, each European country is supposed to have zero CO_2 emissions in order to respect the Paris Agreement[49] (see Appendix A), but zero operational emissions are technically not possible to implement in ESTD. Furthermore, it may even seem ambitious, but as a reminder, ESTD is only constrained

on operational emissions, which means that construction or assembly emissions of each technology for any sector are not taken into account. It would be interesting to do a sensibility analysis on total emissions by including uncertain input parameters on emissions of different technologies.

Stochastic input data

The stochastic input data for the GSA has been taken over from Rixhon et al.(2021)[2]. Except for the few parameters that have been added to characterise nuclear power and SMRs, no in depth research has been made to further investigate the uncertainty of other parameters. Following this procedure, some parameters that could have a significant influence on the installation of NPPs (conventional or SMR) may have been overseen. On top of that, it could be that some uncertainty intervals are not up to date, but the study they are based on has been published one year earlier than the publishing of this thesis.

A lot of uncertainties regarding SMRs

SMRs are a technology that is still very young. Currently, some test reactors are being constructed around the world and a lot of research is still performed on the subject, but very few (practically none) SMRs for electricity production are finished yet. While a lot of technical data can be found about the more than 70 potential SMR designs[47], very few highlight figures on costs or emissions, which is what is required in ESTD. This leads to the fact that a lot of numbers found in scientific research are predictions and not experimental values, but there is no certitude that these predictions are accurate.

The most mature technology is pressurised water reactors (PWRs), which is why this thesis has only included predictions regarding these. They are the reactors for which predictions might be the most accurate as they are the closest to be released and they rely on a technology that has been around since the previous century. Nevertheless, future designs based on different kinds of fuel and coolants can also be considered for powering the future. There are promising GEN IV[1] reactors; High-temperature gas-cooled SMRs, Fast neutron spectrum SMRs and Molten Salt SMRs. The Chinese HTR-PM high-temperature gas-cooled reactor for example was scheduled to reach commercial electricity production in 2021[47].

Modelling of the SMR technology in ESTD

The modelling of the SMR technology in ESTD has its limits. Indeed, the biggest difference between SMRs and conventional NPPs is that they are smaller and it is predicted that they have the potential to be more flexible. Therefore, a lot of parameters have been taken over from the conventional "NUCLEAR" technology already present in ESTD. On top of that, some flexibility has been enabled by allowing the SMR to dump some of the steam through the bypass, as the US company *NuScale* does in their design. No limit on the core ramp up or down has been implemented, because this would have a negative impact on the computational time of ESTD.

In the end, a study has been made on two extreme situations: conventional nuclear power that operates at full baseload (so without any flexibility) and on SMRs having nearly full flexibility on the electricity production (keeping in mind that the uranium is consumed in

[1]The different nuclear power plant generations are explained in Appendix B

baseload mode). More precise modelling of the technology taking into account the ramp up and down of the nuclear core would be something worth studying in order to complement the intermittent and dispersed renewable energy (RE) sources to meet the energy demand. This has been done by Michaelson et al. (2021)[42] and Ingersoll et al.(2015)[46] based on the US-designed *NuScale* reactor. Their results are promising, but yet again are only predictions. Real experiences would need to be done.

The limits of a quantification approach

ESTD does a cost optimisation and takes into account CO_2 emissions but does not tackle other issues like the public acceptance, proliferation risks, nuclear waste, etc. Indeed when the discussion is put on the table if nuclear power should or should not be part of the electricity system of a country, a lot of things have to be considered. Despite its advantages, nuclear power also has its disadvantages[50] which cannot be forgotten. There are examples where there has been nuclear accidents. Most of the time these accidents included few (or no) human deaths[51]. But disasters like Fukushima or Chernobyl cannot be ignored. In the first many people have been forced to leave their homes due to too high radiation following the accident and in the second, many people died (immediately or after some time) or suffered from diverse health issues without mentioning the fact that many families had to leave their homes as well[52].

For these reasons, it is important to take a step back from all advantages that nuclear power counts. The issue of nuclear waste cannot be forgotten either. The more nuclear power is used, the more waste is produced. This radioactive waste needs to be stored safely for a few hundreds of thousands of years. There exist projects that will tackle this issue like the MYRRHA reactor[15], but these projects are not to be seen before at least 2030. The MYRRHA reactor should be functional in 2036 for example[15]. In the meantime, a sustainable solution is required for the safe storage of nuclear waste.

Combination of conventional nuclear power and SMRs

In the context of this study, technologies "NUCLEAR" and "SMR" in ESTD have been studied separately. They have not been allowed to be installed at the same time and "compete" against each other. The authors estimated that the two technologies had been implemented too similarly in terms of how they work for the results to be pertinent.

- The input parameters of both technologies have the same deterministic values.
- In ESTD, SMRs are just conventional nuclear reactors that have the ability to load follow the electricity demand.
- Most of the time, the SMR operates in baseload anyway.
- the other advantages of SMRs, like their modularity, their higher attractiveness in investment because of their smaller size, etc. are not modelled in ESTD.

Indeed it is difficult to have a quantification approach on the comparison between conventional nuclear power plants and SMRs because on paper they are very similar. As cited in *Tractebel*'s report *The rise of nuclear technology 2.0 Tractebel's vision on Small Modular Reactors*: "SMRs are not a single product; they are a business model[...]."[39]. This shows that current generation SMRs have few aspects that separate them from conventional NPPs apart from their attractiveness in terms of investment cost.

SMRs have potential for a cogeneration production

In this work, SMRs are not implemented in cogeneration mode. The bypass valve that allows the load following does not value the excess steam and is therefore a loss. Howeve,r there is potential to value this heat loss. One possibility would be to use the loss for district heating networks as the heat demand in Belgium is non-negligible, especially in winter. Another possibility would be to value the excess energy in water desalination however this might not be the most useful application in Belgium. This is what has been studied by Ingersoll et al.(2014)[45]. Although the application is not district heating, it gives an insight into what possibilities there are for cogeneration using SMRs.

Too much nuclear power may not be the best idea

Even though ESTD recommends to install until 42 [GW] of nuclear power (under either form), this is neither realistic nor a good idea. Figure 2.1 in Section 2.1 shows the cheapest solution according to ESTD for different maximum capacities allowed for nuclear power. In case nuclear power has no upper limit, 42 [GW] are suggested by ESTD, which is a lot. Figure 2.1 also highlights the fact that in such a scenario, Belgium would be very dependent on nuclear power and consequently on uranium.

First, there are probably not enough sites with sufficient access to water in Belgium to make this possible. Indeed, with its high population density, it seems complicated to find a suitable location for a nuclear power plant. Secondly, having an electricity mix such dependent on one single resource might not be the best solution either. If there is a problem in the supply of a resource because of any logistic or political reason, no power at all will be assured to the country that is too dependent on that one resource. It seems not difficult to stock up supplies of uranium according to the INN[53], but in general it is probably a better idea to diversify the energy mix to be less dependent on one single resource.

Thirdly, if one is not careful and nuclear power is used too intensely everywhere around the world, this will lead to an anticipated depletion of uranium resources. Even though, at the current rate, it is predicted that there are still sufficient uranium reserves for at least 80 [years][54], other more sustainable solutions are required. Newer nuclear reactors (SMRs or conventional) are predicted to enable to considerably reduce the consumption of uranium and multiply the depletion date by at least a factor 1000, but these are technologically not ready yet[54].

5.2 The Results back into Context

Briefly

A step back from the result is taken. ESTD recommends a lot of nuclear power, on average 10-12 [GW]. Figure 5.1 shows the energy mix when 11 [GW] of SMRs are allowed. REs occupy the majority of the Belgian energy mix. To reach this predominantly RE system in 2050 (about 75 [GW] in total), Belgium would have to install 2.2 [GW] of RE per year (PV, onshore WT and offshore WT altogether). As shown in Table 5.1, during 2019, only 1.8 [GW] of RE sources have been installed, which is still not enough. Moreover, realistically, carbon neutrality should be reached before 2050, which requires an even higher annual RE installation as shown in Table 5.1. Furthermore, to decrease the Belgian emissions from 100 [MtonCO_2e] in 2019 to 0 in 2050, different paths are possible. Some of these different possible paths are provided in Figure 5.2. The closer the path gets to path (a), the fewer total emissions are rejected.

Having presented the fact that nuclear energy seems to be favourable to an energy system in terms of costs, emissions, flexibility and energy independence, it is necessary to take a step back and refocus on the central problem, namely CO_2 emissions. In order to reach the Paris Agreement (section A)[49] and stay below the +2°C mark as well as reach carbon neutrality by 2050, Belgium must, like every other country, find alternatives to fossil fuels. According to ESTD, the key technologies and features for reducing emissions are:

- The extensive use of synthetic fuels and battery electric vehicles in the mobility sector.
- An electricity production fleet relying on RE sources, nuclear power and synthetic fuels.
- An industry and heating system based on synthetic and biofuels

Depending on the value of the input parameters, ESTD often selects a set of technologies that is very radical. In other words, if nuclear power is cheap, ESTD will predict an energy system that relies heavily on nuclear power and will install a lot of it, as is the case in the deterministic case where the capacity of nuclear power is allowed to be unlimited (see Figure 2.1). The best solution is probably to include all technologies together.

As proven in section 4.3 via the MC GSA, taking the uncertainties into account, around 10-12 [GW] of nuclear power are suggested by ESTD. This number is actually pretty realistic. Currently Belgium is relying on around 6 [GW] of nuclear power (see Table 1.1) and in order to replace the fossil fuels, the country will undoubtedly rely increasingly on electricity (for the mobility or heating for example).

Relying on 10-12 [GW] of nuclear power would enable to drastically reduce the use of natural gas (NG) for electricity production as well as deliver a surplus of electricity to cover the growing demand. On top of that, the deployment of RE needs to continue their growing tendency as shown in Figure 1.8. An energy system containing 11 [GW] of nuclear power on top of the RE sources for electricity production is sufficient to meet the Belgian electricity needs as can be shown by Figure 5.1 displaying results of an ESTD run with 11 [GW] of SMRs.

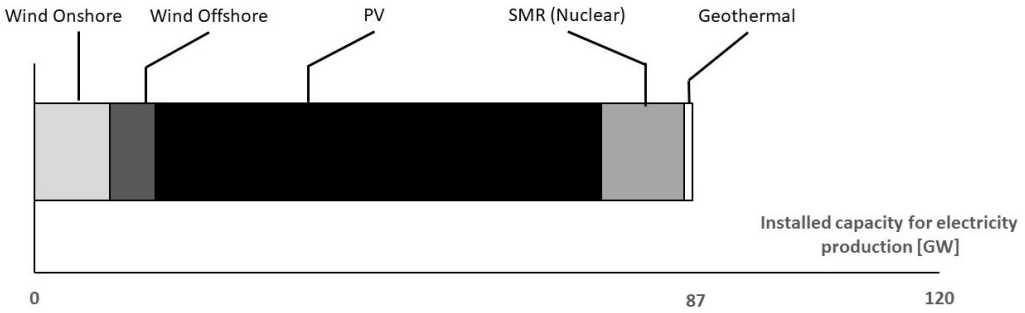

Figure 5.1: Belgian electricity mix for 12 [GW] SMRs allowed. Full renewable potential and 11 [GW] of nuclear power is sufficient to meet the Belgian electricity demand.

The Sankey diagram of this situation is displayed in Figure J.8. It can be seen that the system highly relies on electricity for heating, for mobility and for the regular electricity demand. On top of that, a non negligible part of synthetic fuels are imported. Most of them are used for the non-energy-demand (NED). For the freight, imported hydrogen and bio fuels are used. This case scenario represents a diversified energy system as described before. The total yearly emissions linked to this solution are 20 [MtonCO_2e/year]. This number represents about a fifth of Belgium's yearly emissions in 2019, according to the *IEA Data browser*[16]. As all countries switch towards a more carbon-free energy system, these 20 [MtonCO_2e/year] will probably decrease. The emissions linked to construction and building of different technologies often come from the fact that the extraction of their raw materials relies on high emitting technologies. These technologies should be replaced with non-emitting alternatives as time goes on.

So the goal is to reach carbon neutrality in 2050. In 2019, Belgium's emissions were around 100 [MtonCO_2e]. It means that during the remaining 30 years before 2050, Belgium should reduce its emissions by 3.33 [MtonCO_2e] each year[2]. If this is the case, the zero-emissions is reached linearly as shown by scenario (b) in Figure 5.2. The latter figure represents different possible paths from 2019 to 2050 for the reduction of emissions. Scenario (a) shows a situation where it is easy to cut emissions right now, but as time goes on, the remaining ones become more difficult to eliminate. Scenario (b) is the previously mentioned linear trajectory, i.e. reducing the emissions by 3.33 [MtonCO_2e] each year. Scenario (c) will be discussed later. Scenario (d) is a scenario where the initial emissions are difficult to eliminate, but it gets easier and the majority of emissions drop 10 years before the deadline.

Even if the endpoint is the same, i.e. zero emissions, the outcome of each scenario is not at all the same. For instance, in scenario (d), higher emissions are emitted for a longer period whereas, in scenario (a), they immediately drop and in the end, less CO_2 has been released into the atmosphere in scenario (a) than in scenario (d). The total greenhouse gases released between 2019 and 2050 are quantified by the area under the curve of each trajectory, so on top of reaching 0 emissions by 2050, one wants to minimise the area of the trajectory to minimise the total impact.

In reality, one can imagine a case where the transition is both difficult to initiate and difficult to complete. This would be a scenario mixing the beginning of the trajectory of (d) with the end of the trajectory (a). Indeed, it takes some time for the decisions taken to be put in place

[2]This reduction corresponds at the half of the reduction in CO_2 emissions of Belgium during COVID 19.

and it seems intuitive that it is not easy to cut all CO_2 emissions. Especially the last few will be difficult to eliminate. Some industries have no choice but to emit CO_2 because their product is based on a chemical process with CO_2 as an output. It is possible though to design carbon capture to compensate for these unavoidable emissions.

In a scenario where Belgium decides to initiate the construction of new reactors to reach a power level similar to the one proposed above, i.e. 10-12 [GW], the construction would take some time and before that, the reactor does not bring any emission reduction. However, according to the ESTD data, it takes about 100 days of operation of a combined cycle gas turbine (CCGT) to emit a similar amount of greenhouse gases as building a nuclear reactor to replace it. In other words, 100 days after the opening of a nuclear power plant, its construction emissions are amortised compared to CCGT. This small calculation can be seen in Appendix I.

Consequently, the reduction in emission is very suddenly observed when a reactor starts operating. Scenario (c) of Figure 5.2 represents a possible trajectory that Belgium could take if it decided to include nuclear reactors (SMR or conventional) in its energy mix. It is an illustrative example based on reflection. This curve has not been obtained based on any modelling. It has been assumed that the first "new" reactor coming online would be finished by 2030. The trajectory shows that every time a reactor is started, it brings significant emission reduction at once.

A scenario without any new nuclear reactors would need a significant installation rate of RE sources, but even then, there is not sufficient space in Belgium to fully rely on these sources. Synthetic fuels would be required to fill the gap. These would need to be imported and there is no certainty that these are indeed carbon-free. A little calculation has be done in order to see at which linear rate these RE sources must be constructed to reach the RE capacity suggested by ESTD when 11 [GW] of SMRs are allowed. This can be seen in Figure 5.1. This calculation takes only into account PV, onshore WT and offshore WT, which represent the main part of the RE electricity production according to ESTD. The current Belgian RE capacity of 10 [GW] has been taken into account, and needs to reach around 75 [GW] at the targeted year, 2040, 2045 or 2050. The rates are grouped here bellow in Table 5.1.
However, currently, no new nuclear power plants are planed. On the contrary, Belgium will

Belgian installed capacity [GW_RE/year]			**Linear rate needed [GW_RE/year] to reach RE capacity expected by ESTD by**		
2017	**2018**	**2019**	**2040**	**2045**	**2050**
0.859	1.838	1.232	3.2	2.6	2.2

Table 5.1: On the left, the current rate of Belgium to install RE capacity from 2017 until 2019, obtained from the website Our World in Data[55]. On the right the linear rate needed in order to reach 75 [GW] of RE at the targeted year. One can see that the current Belgian rate is not enough to reach this goal, even in 2050. Here only the installed capacity of PV, onshore WT and offshore WT are taken into account. Indeed, according to ESTD, they provide the main parts of the electricity when 11 [GW] of nuclear are allowed.

start to shut down its reactors at the end of the year (see Table 1.1). By the end of 2025, only 2 of the current 6 [GW] will be kept for electricity production. Belgium has planned new CCGTs

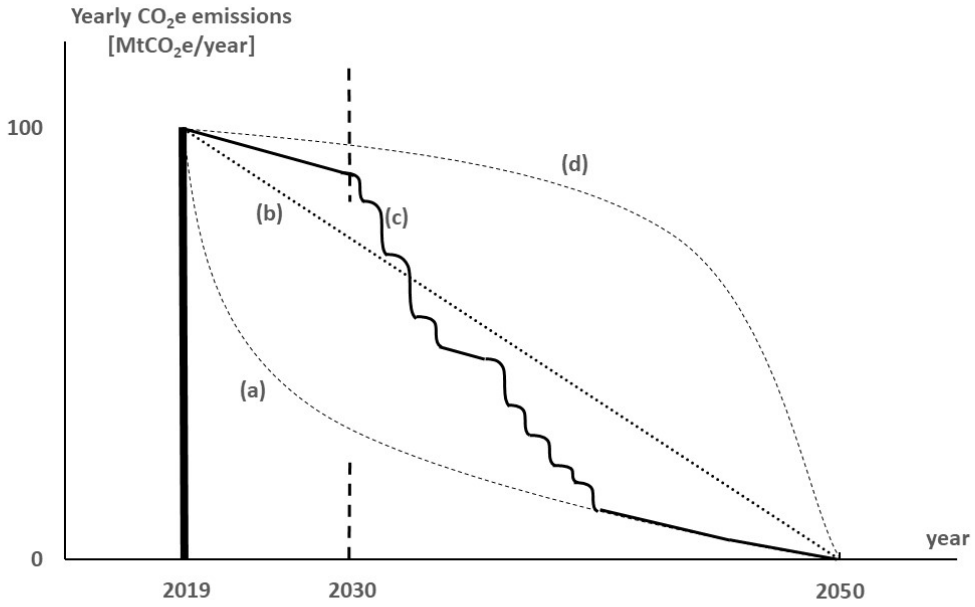

Figure 5.2: Different possible paths to choose from in order to reach carbon neutrality. (a): minimal efforts today can result in an immediate emission decrease, but the closer neutrality is reached, the more difficult it gets to decarbonise. (b): the rate is constant towards neutrality. The later we start, the bigger the rate will need to be. (c): Some elements like nuclear reactors (conventional or SMR) enable abrupt decarbonation decrease It allows to help the decarbonation as soon as the first reactor is connected to the grid. (d): the beginning of the decarbonation is difficult, but each next step is easier than the previous one. This leads to a rapid decrease in emissions 10 years before the deadline.
The area under each curve represents the total CO_2 emissions. While each path leads to carbon neutrality, not all of them are equivalent in terms of environmental consequences. A minimum area under the curve is desired to minimise the global temperature rise.

to replace the missing 4 [GW] in order to buy time for the deployment of more RE sources[5]. In the meantime, this decision will increase the emissions linked to electricity production which does not go in the right direction for the carbon-free energy system. Nevertheless, in May 2022, the Belgian government allocated 100 million € to its Nuclear Research Centre, the SCK-CEN [3], to conduct research into SMRs, according to the World Nuclear News[35].

[3] StudieCentrum voor KernENergie

Conclusion

With time running out and many efforts still to be made before we have fully decarbonised our energy system, the main objective of this thesis was to study the relevance of nuclear reactors within our Belgian energy system to complement other technologies in the decarbonisation of our country. The study was based on minimising the total cost of the energy system, while imposing an emission limit of 5000 kilotonnes of CO_2 per year, i.e. 5% of Belgian emissions in 2019. For this purpose, the tool developed by a consortium of UCLouvain and EPFL, EnergyScope Typical Days (ESTD) was used.

In order to achieve its objective, the study went through several steps which are developed in this thesis. Starting with a background explaining the Belgian situation and the tools used and their implementation 1, a study on nuclear power as we know it today was conducted 2. Then, scientific research on Small Modular Reactors (SMRs) 3 was carried out to explore the future paths and these could be modelled and studied in a more global context 4. Finally, a question mark was placed on the validity of the assumptions made during the study and a discussion on realistic and sensible future trajectories was carried out 5.

In the course of the deterministic analyses, ESTD forecasts an energy system that is almost exclusively nuclear-based. It installs 10 [GW] of onshore wind and 42 [GW] of nuclear power generation at a total cost of 43.2 billion Euros per year. The rest of the system relies on electricity, as mobility is highly electrified and other applications such as heating and non-energy demand (NED) are based on the production of synthetic fuels produced in Belgium on a nuclear basis. In comparison, a system where no nuclear is allowed relies heavily on the installation of renewables and the import of synthetic fuels, at a total cost of 55.6 billion Euros per year.
However, a global sensitivity study on the total cost of the system shows that the difference between these two scenarios narrows. If the system is required not to include nuclear in its electricity mix, the 95% confidence interval is between 42.4 and 71.5 billion Euros, whereas if nuclear is allowed to be included, the latter is bounded by 41.3 and 63.0 billion Euros.

Alongside the conventional nuclear power developed in the 1970s, new projects are emerging, including SMRs. This new technology, which is still not very widespread, would have some major advantages over conventional nuclear power, particularly in terms of load following, investment cost and safety. Given the early stage of these projects, there are many uncertainties about this new technology. SMRs have been modelled in ESTD with higher flexibility than conventional reactors and with their uncertainties, to study what impacts this new technology has on the energy mix. In the context of the study on the total cost of the energy system,

ESTD recommends an average of 12 [GW] of SMRs. However, it was noted that in the study on installed SMR capacity, there is a 12% chance of not having any SMR installed, which is not negligible. Despite this, it should be noted that in the other 88%, SMRs are installed in different quantities. Among these quantities, the most likely installed capacity is between 10 and 12 [GW] with a total probability of 17.5%. Regarding the uncertainty on the total system cost, there is very little difference between a solution including SMRs and a solution with conventional nuclear power.

In conclusion, it can be seen that Belgium, like Europe, is moving towards a nuclear phase-out. Nevertheless, the country will have to replace these 6 [GW] of nuclear power with another source of energy and Belgium plans to install combined cycle gas turbines (CCGT) accordingly. However, the country's energy mix is already predominantly based on fossil fuels. Especially gas and oil for mobility, heating and NEDs. Moreover, these energies are already responsible for the majority of the country's CO_2 emissions. To keep the global temperature increase below 1.5 [°C] compared to pre-industrial times, the use of these fossil fuels must be reduced. Keeping nuclear power seems to be a good solution, as it has been pointed out that an energy mix composed of nuclear power is firstly less expensive. Moreover, nuclear power is a decarbonised energy, so its use has a less direct impact on the climate. In any case, it is necessary to electrify a large number of sectors while importing the missing amount of synthetic fuels. Even if Belgium still refuses geological burial to treat its nuclear waste, there are alternative solutions, notably nuclear transmutation, which is being studied in the Belgian MYRRHA project. In the fight against climate change, it is important to consider any avenue that can contribute to the solution. According to the results obtained, nuclear power is one of them, along with renewable energies, the use of synthetic fuels and all the downstream technologies.

Appendix A

Paris Agreement

Briefly

Human activity is intrinsically linked to climate change. Indeed, it is the first source of greenhouse gas emissions. The Paris Agreement allows each country to have a series of measures to maintain this activity while minimizing the impact on the environment. These measures are no strict, these are just rules of good practice.

Climate change is one of the major issues of the 21st century. Europe has set itself the goal of becoming carbon neutral by 2050. However, in order to reach this goal, a series of specific measures are needed. This is the purpose of the Paris Agreement: to have a series of environmental measures to respect between member countries. Based on[49], "The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016. Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century." In order to work, the Paris Agreement requires economic and social transformation. It works on a 5-year cycle of increasingly ambitious climate action. By 2020, countries submit their plans for climate action which is known as nationally determined contributions (NDCs). Despite this, research groups looked at the effect of combining the different country NDCs. They concluded that even if each country met its own NDC, it would not be possible to limit global warming to 1.5 degrees (compared to pre-industrial level)[19].

Appendix B

Different generations of nuclear power plants

Briefly

Different generations of nuclear reactors have been developed over time. Ranging from the first to the third generation. The current reactors in Belgium belong to generation II. GEN III+ and GEN IV are more in the planning stage. Some countries are working on the next generation, GEN IV. Six reactor projects have been selected by the Generation International Forum (GIF). They are summarised here:

- Gas-Cooled Fast Reactors
- Lead-Cooled Fast Reactors
- Molten Salts Fast Reactors
- Sodium-Cooled Fast Reactors
- Supercritical Water Cooled Reactors
- Very High Temperature Gas Reactors

Table B.1 gives more information about these 6 projects.

Nuclear reactors are not new, the first reactors built to produce power were built in the 1950s. At that time, since they were the first reactors, they were called the first generation, GEN I. However, GEN I reactors were not yet developed on an industrial scale. They were used as experimental reactors, so they did not generate enough power to be commercialised.

The industrialisation of nuclear reactors developed strongly in the 1970s, with reactors capable of delivering higher power. These reactors formed the second generation, GENII. The current Belgian reactors are all of this generation.

In the early 2000s, the GENII technology was improved to create the third generation of reactors. Since 2010, new concepts are emerging to make nuclear technology more economically attractive. This is GEN III+.

Currently, the most common reactors are (GEN)II reactors. Some countries are working on the development of the next generation of reactors, GEN IV, and they form the Generation International Forum (GIF). The purpose of GIF is to share research & development rather than build reactors.

In 2002, after two years of deliberation GIF announced the selection of six reactor technologies. They were selected because of their safety, cost-effectiveness, resistance and high security against terrorist attacks. These 6 technologies are further developed internationally, with expenditure of about $6 billions over 15 years. Approximately 80% of the cost is being met by the USA, Japan and France[56].

Table B.1 shows these 6 projects of GEN IV nuclear reactors. More information can be found on the website of the WNA[56].

	Neutron spectrum (fast or thermal)	Coolant	Temperature [C°]	Pressure high = 70-150 [bar]	Fuel	Fuel cycle	Size [MW]	Use
Gas-Cooled Fast Reactors (GCFR)	fast	helium	850	high	$U-238^{+}$	closed, on site	1200	electricity & hydrogen
Lead-Cooled Fast Reactors (LCFR)	fast	lead or Pb-Bi	480-570	low	$U-238^{+}$	closed, regional	20-180 300-1200 600-1000	electricity & hydrogen
Molten Salt Fast Reactors (MSFR)	fast	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Sodium-Cooled Fast Reactors (SCFR)	fast	sodium	500-550	low	U – 238 and MOX	closed	50-150 600-1500	electricity
Supercritical Water Cooled Reactors (SWCR)	thermal or fast	water	510-625	low	UO_2	open (thermal) closed (fast)	300-700 1000-1500	electricity
Very High Temperature Gas Reactors (VHTGR)	fast	helium	900-1000	low	UO_2 prism or pebbles	open	250-300	electricity & hydrogen

Table B.1: 6 projects of nuclear reactors of GEN IV according to the WNA[56]

.

Appendix C

Notion of LCOE and VALCOE

Briefly

All in all the LCOE is an indicator that quantifies the price of generated electricity and allows comparison between different production means. Figure C.1 and Equation C.1 help its understanding, while Figures C.3 and C.2 give some examples for the most addressed electricity production technologies in Belgium. While LCOE is very useful, it is not the only metric that should be taken into account when comparing different technologies. A technology might have a very low LCOE, but a very high carbon footprint (as it is the case for coal for example[31]), which only strengthens the argument that LCOE is just a tool and not a purpose on its own. The VALCOE (value-adjusted levilised cost of energy) is an improvement of the LCOE because it takes into account further notions.

To compare different energy sources, a lot of different parameters need to be taken into account. The selection of the energy source is mostly driven by the costs, but not only. Different indicator have been created to compare different energy sources, one of them being the levelised cost of electricity (LCOE). The VALCOE (value-adjusted levelised cost of energy) is an improvement of the LCOE because it takes into account further notions.

C.1 The notion of LCOE

It has been developed to compare which electricity source is the cheapest over its entire lifetime. As easy as it may sound, the LCOE is relying on multiple predictions and is therefore sometimes difficult to quantify. Nevertheless it is an easy way to compare different electricity production means among them.
The LCOE quantifies the cost of produced electricity via one production mean. Figure C.1 gives a visual representation of how the LCOE is calculated; It contains the annualised costs of the facility construction, the operation and maintenance costs per year as well as the price of the required fuel (if there is any) for one year of operation. Adding these three elements together and dividing the result by the electricity produced during one year gives a value in [€/MWh]. The varying value of currency is also taken into account thanks to the discount rate. The discount rate includes the fact that 1.0 € might be worth 0.95 € next year. In that case : $r = \frac{1.0 - 0.95}{1.0} = 5.0\ \%$.

The LCOE is given by the following relation:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{C.1}$$

where

- I_t are the annual investment expenditures in [year] t
- M_t are the operational and maintenance expenditures in [year] t
- F_t are the fuel expenditures in [year] t
- E_t is the electricity generation in [year] t
- r is the discount rate
- n is the lifetime of the facility

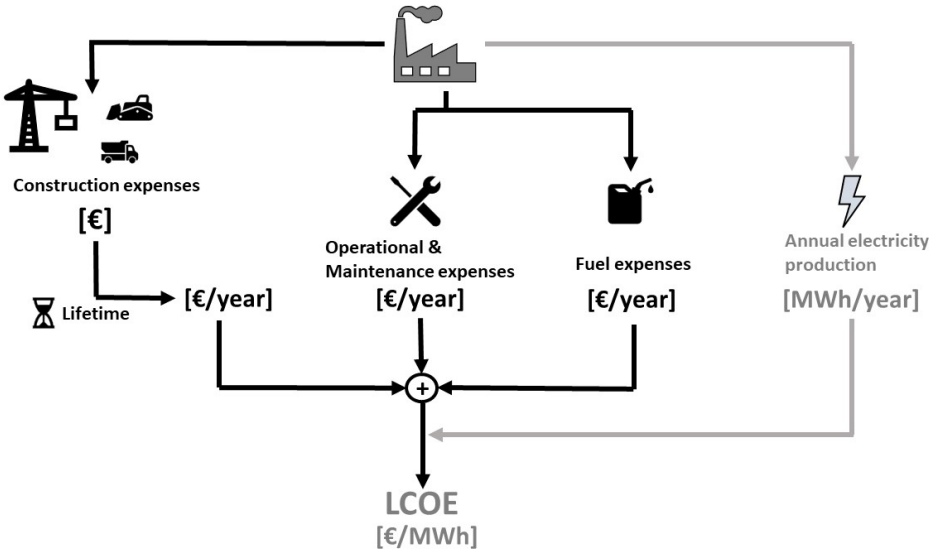

Figure C.1: A graphical representation of the LCOE

In order to give some examples, Figure C.2 shows the median values for a discount rate of 7%. Indeed, the LCOE is a metric that is difficult to quantify and predict as it includes a lot of parameters that are not always easy to foresee. Therefore, interquartile ranges (IQRs) are also represented, which gives an idea on how "sure" one can be about the predictions of the LCOE.
In order to illustrate the impact that the discount rate can have on the LCOE, Figure C.3, obtained from numbers in[31], shows different median LCOEs for different discount rates (3, 5 and 7 %) and for different technologies. One can see that some technologies are affected much by the discount rate, like nuclear for example, while CCGT is not affected that much.
From these two figures, one can see that nuclear power seems to be very sensitive to the discount rate, but long-term operation (LTO) nuclear[1] power is very little sensitive to it. On

[1] "LTO nuclear can be defined as operation, [...], that goes beyond a previously established time frame corresponding to initial design assumptions (typically referred to as "origin design lifetime" and usually 30-40 [years] depending on the design)."[57]

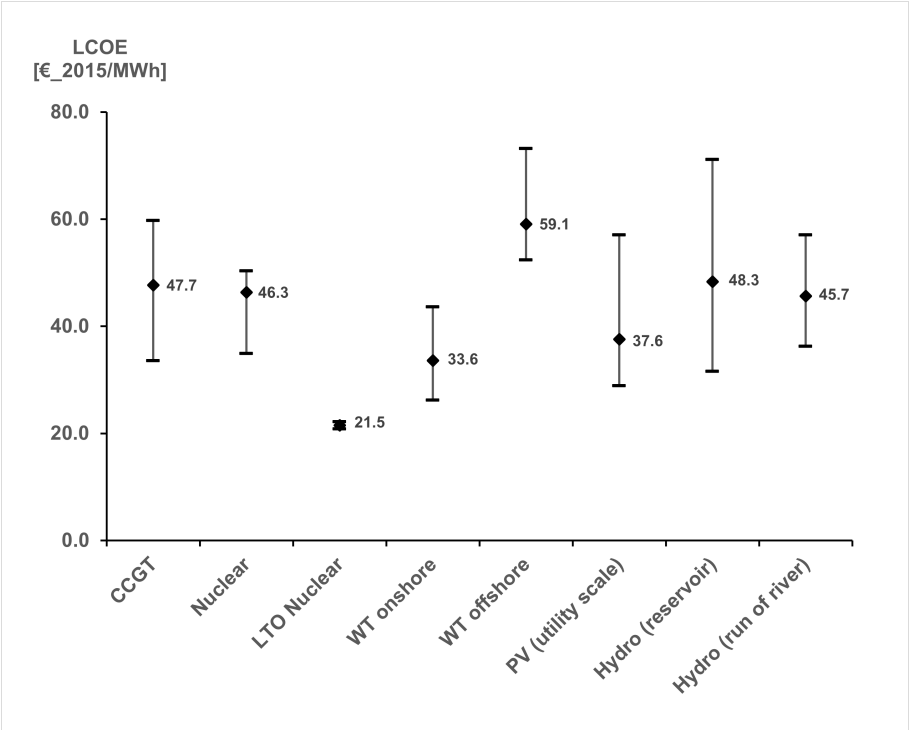

Figure C.2: Median LCOE values for 7% discount rate and for different technologies. The IQRs are also represented.Figure adapted from[31]. The data has been converted to 2015 €.

the other hand for a given discount rate, nuclear power has the smallest difference between the lower quartile and upper quartile compared to other represented technologies with a difference of 15.4[€/MWh] and even 1.3[€/MWh] for LTO nuclear

Onshore WT are close with a difference between the upper and lower quartile of 17.5[€/MWh] while CCGT is more uncertain with a difference of 26.2[€/MWh].
It is worth mentioning that for graphical clarity an quality, not all technologies that are quantified in [31] are showed in Figures C.3 and C.2. Technologies like coal or concentrated solar for example are not of interest for the Belgian energy system and have been left out.
In general, lower LCOEs are favoured over higher ones as it minimises the produced energy, but not always. There are other parameters to take into account when selecting a technology like its ecological impact, its flexibility[2] or its associated risk (human, financial, ...), which is why LCOE on its own should not be enough to decide which technology should be installed or not.
While "it [the LCOE] compresses all the direct technology costs into a single metric, [...] it lacks of value or indirect costs to the system and it is particularly poor for comparing technologies that operate differently"[58]. This is why different entities have tried to find alternative or complementary indicators. The International Energy Agency (IEA) for example introduced an indicator called value-adjusted levelised cost of electricity (VALCOE) in their 2018 *World Energy Model Documentation.* The latter indicator is briefly explained in appendix **??**. Additional information about it can be found in[58]. Other examples are the *System LCOE* or the *levelised avoided cost of energy (LACE)*. They are described in[59].

[2]Here, flexibility will refer to the ability to adapt the electricity production to a varying demand load.

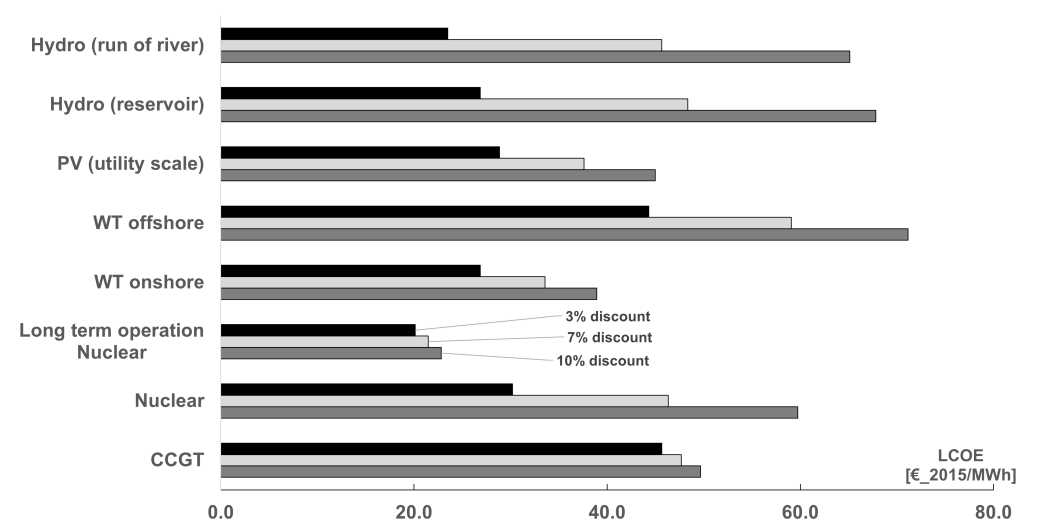

Figure C.3: Median LCOE values for different technologies depending on the discount rate. Figure adapted from [31]. The data has been converted to 2015 €.

C.2 VALCOE

Electricity produced by the means of renewable sources has a very low LCOE. Indeed, when the sun shines, nothing is cheaper than producing electricity thanks to photovoltaic (PV) panels. The same is true for wind turbines (WT) when the wind blows. But the key word here is "when".
Under the condition that the wind blows, it may be cheap to produce wind energy, but we might not need it. In the contrary, if we need electricity, but the wind does not blow there is not enough power supply. These aspects are not taken into account by the LCOE. While the energy produced by the means of variable renewable sources might be very cheap, the latter has a low value, because no flexibility is added to its production means.
In other words, having a cheap AND pilotable electricity source might be more valuable than an only "cheap" source. In the end we need both, a cheap and valuable energy production. This is why the value-adjusted levelised cost of energy (VALCOE) has been developed by the international energy agency (IEA). The VALCOE is a metric that is intended to complement the LCOE[59] by taking into account other parameters than purely costs.

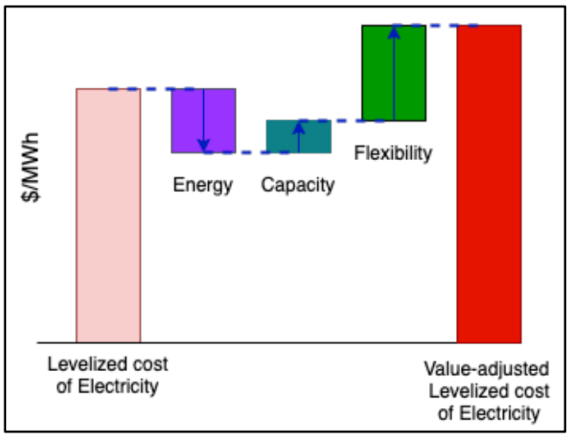

Figure C.4: A graphical comparison of LCOE and VALCOE [59]

Illustrated in figure C.4, the VALCOE builds up on the LCOE adding three elements of value: energy, capacity and flexibility. These three elements are used to adjust the value of the LCOE by comparing each of the three elements and for each technology to the system mean. As shown in the figure C.4, this difference can be either positive or negative. Equation C.2 clarifies how the VALCOE is calculated:

$$\text{VALCOE}_x = \text{LCOE}_x + (\bar{E} - E_x) + (\bar{C} - C_x) + (\bar{F} - F_x) \tag{C.2}$$

where

- the subscript x represents a given technology
- $\bar{E}$, $\bar{C}$ and $\bar{F}$ represent respectively the mean system value of the three elements energy, capacity and flexibility
- E_x, C_x and F_x represent the single value of the three elements energy, capacity and flexibility for technology x.

Appendix D

Comparison of computation time between PCE and MC method

Briefly

In this appendix, a calculation is done for the computation time between the Polynomial Chaos Expansion (PCE) and the Monte Carlo (MC) method in order to fix ideas. Some hypothesis are done for this calculation. As already mention, MC needs a longer computation time.

For the global sensitivity analysis, two methods are used in this thesis, the Polynomial Chaos Expansion (PCE) and the Monte Carlo (MC) method. MC is a versatile method which works on any problem, which is its main advantage. So the MC method finds the exact distribution of the problem. On the other hand, PCE is a surrogate model, i.e. an approximation model so an error is made between this approximation and the real model. However, this loss in accuracy is compensate by a computation time lower than the one required for the MC method. A quick example is proposed down bellow to show the difference of computation time between these two methods. The hypothesis taken for this calculation are regrouped here bellow:

- The MC method requires $N_{runs,MC} = 10^4$ iterations.
- The PCE requires a run until order $p_3 = 3$ to have an acceptable LOO error.
- The number of initial uncertain parameters is fixed to $M = 40$
- After a first order PCE run and in view of the Sobol's indices, only $M' = 8$ of them are kept for future runs.
- The computational time for the ESTD model is $t_{ESTD} = 90$ s, which is more or less a realistic time taken by the model.

Monte Carlo

$$\begin{aligned} T &= N_{runs,MC} \cdot t_{ESTD} = 10000 \cdot 90 = 900000 \text{ s} \\ &= 250 \text{ h} \\ &\approx 10.5 \text{ days}, \end{aligned} \tag{D.1}$$

PCE

$$
\begin{aligned}
T_1 &= 2\frac{(M+p_1)!}{M!\,p_1!}\cdot t_{ESTD} = 2\frac{(40+1)!}{40!\,1!}\cdot 90 = 7380 \text{ s} \\
T_2 &= 2\frac{(M'+p_2)!}{M'!\,p_2!}\cdot t_{ESTD} = 2\frac{(8+2)!}{8!\,2!}\cdot 90 = 8100 \text{ s} \\
T_3 &= 2\frac{(M'+p_3)!}{M'!\,p_3!}\cdot t_{ESTD} = 2\frac{(8+3)!}{8!\,3!}\cdot 90 = 29700 \text{ s} \\
T &= T_1 + T_2 + T3 = 7380 + 8100 + 29700 = 45180 \text{ s} \\
&= 12.6 \text{ h} \\
&\approx 0.5 \text{ days}
\end{aligned}
\tag{D.2}
$$

where T is the total time required. It is clear that a PCE approach allows to gain a considerable amount of time. Something that should be pointed out is that we do not actually know how many iterations are required for a MC method. It could be 10^3 iterations, in which case the computational time would be 25 h, so about one day or it could be 10^5 iterations in which case it would be 105 days (around 3 months). It becomes obvious that this is not acceptable in the context of this work, even more so that the number of runs could be even higher. Nevertheless, it should be noted that the PCE method also suffers from the curse of dimensionality. If a higher order run is required, the computational time increases considerably too.

Appendix E

Input data

Briefly

In order to work, ESTD needs inputs. Belgium has been modelled and the data needed for its modelling have been found by G.Limpens[1]. This data are grouped in 3 main groups listed here bellow.

- **The Demand**: Indeed, ESTD needs to know how much electricity, heat etc. have to be produced. This amount is fixed by the Demand.
- **The Resources**: In order to satisfy this demand, resources are needed.
- **The Technologies**: The primary energy provided by the Resources has to be transform in another kind of energy which is usable. This is the role of the Technologies. for example it is impossible to consume directly uranium, it should be transform into heat and/or electricity.

Then, for the global sensitivity analysis, **stochastic parameters** need to be defined. The deterministic values come from G. Limpens[1] while the stochastic data has been taken over from Rixhon et al. (2021)[2].
Finally, in the context of this thesis, some data on the technology of the SMRs should be determined. The last section of this appendix provides the investment cost of PWR SMRs that have been found from literary researches.

E.1 Demand

DEMAND					
Category	**Subcategory**	**Households**	**Services**	**Industry**	**Transportation**
Electricity [GWh]	baseload	14263	14083	33690	0
Electricity [GWh]	variable	7680	11065	11111	0
Heat [GWh]	high temperature	0	0	50436	0
Heat [GWh]	space heating	70242	34821	13118	0
Heat [GWh]	hot water	17955	7806	3399	0
Mobility [Mpkm]	passenger	0	0	0	194081
Mobility [Mpkm]	freight	0	0	0	98034
NED [GWh]	NED	0	0	53109	0

Table E.1: Data from the Belgian demand predicted for 2035 from[22].

E.2 Resources

RESOURCES					
Subcategory	**Name**	**avail**	gwp_{op}	c_{op}	CO_2op
Units:		GW/year	[ktonCO$_2$e/GWh]	[M€/GWh]	[ktonCO$_2$/GWh]
Fossil Fuel	Gasoline	∞	0.3448	0.0824	0.25
		...			
Biofuel	Bioethanol	∞	0	0.111	0.25
		...			
Biomass	Wood	23400	0.0118	0.033	0.39
		...			
Other non-renewable	Uranium	∞	0.0039	0.004	0
Other non-renewable	Electricity	27567.3	0.206	0.084	0
		...			

Table E.2: Resources data predicted for 2035 from[22].

E.3 Technologies

TECHNOLOGIES								
Subategory	**Name**	c_{inv}	c_{maint}	gwp_{constr}	$lifetime$	$C_{p,max}$	f_{min}	f_{max}
Units:		[M€/GW]		[ktonCO$_2$e/GW]	[years]	[-]	[GW]	
Electricity	Nuclear	4845.75	102.93	707.88	60	0.85	0	∞
				...				
Electricity	CCGT	771.99	19.55	183.79	25	0.96	0	∞
				...				
Heat high T°	Boiler wood (industry)	115.18	2.3	28.87	17	0.9	0	∞
				...				
Heat low T°	Heat pump (DHN)	344.76	11.69	174.79	25	0.95	0	∞
				...				
Units:		[M€/(Mkmpass/h)]		[ktonCO$_2$e/(Mkmpass/h)]	[years]	[-]	[Mkmpass/h]	
Passenger public	Bus diesel	611.11	30.56	0	15	0.3	0	∞
				...				
Units:		[M€/(Mton/h)]		[ktonCO$_2$e/(Mton/h)]	[years]	[-]	[Mton/h]	
Freight	Train	104.42	2.09	0	40	0.34	0	∞
				...				
Units:		[M€/GWh)]		[ktonCO$_2$e/GWh]	[years]	[-]	[GWh]	
Electricity storage	Pumped hydro storage	58.8	0	8.33	50	1^a	5	6.5
				...				

Table E.3: Some of the Technologies data predicted for 2035 from[22].
The signification of the different input parameters are explained in 1.3.3
(a) : The capacity factor of this technology is dictated by the weather conditions, and so by the typical days (TD) as explained in 1.3.

E.4 Stochastic Parameters

Parameter	Centered	Deviation	Units
avail_elec	27567.30	8849.10	[GWh]
avail_waste	17800.00	5713.80	[GWh]
avail_coal	33355.00	10706.96	[GWh]
avail_biomass	1.00	0.32	[-]
c_op_electricity	0.10	0.06	[M€/GWh]
c_op_coal	0.02	0.01	[M€/GWh]
c_op_biomass	1.21	0.69	[-]
c_op_biofuels	1.21	0.69	[-]
c_op_syn_fuels	1.21	0.69	[-]
c_op_hydrocarbons	1.21	0.69	[-]
gwp_op_ELECTRICITY	0.21	0.06	[ktonCO$_2$/GWh]
c_inv_nucl	6700.00	4500.00	[GW_e]
lifetime_nucl	60.00	20.00	[years]
gwp_op_Uranium	0.0105	0.0095	[ktonCO$_2$/GWh]
c_op_Uranium	0.0215	0.0185	[M€/GWh]
c_inv_pv	870.00	344.52	[M€/GW_e]
c_inv_wind_onshore	1046.76	231.40	[M€/GW_e]
c_inv_wind_offshore	5007.34	1106.94	[M€/GW_e]
c_inv_dhn_hp_elec	344.76	74.47	[M€/GW_th]
c_inv_dec_hp_elec	492.00	106.27	[M€/GW_th]
c_inv_h2_electrolysis	696.00	275.62	[M€/GW_h2]
f_max_pv	59.20	14.27	[GW_e]
f_max_windon	10.00	2.41	[GW_e]
f_max_windoff	6.00	1.45	[GW_e]
f_max_geoelec	1.00	1.00	[GW_e]
f_max_geodhn	1.00	1.00	[GW_th]
elec_extra	0.98	0.08	[-]
ht_extra	0.98	0.08	[-]
sh_extra	0.98	0.08	[-]
freight_extra	0.98	0.08	[-]
passenger_extra	0.98	0.08	[-]
ned_extra	0.98	0.08	[-]
c_inv_bus	1.02	0.23	[-]
c_inv_car	1.02	0.23	[-]
c_inv_truck	1.02	0.23	[-]
c_inv_ic_prop	1.02	0.23	[-]
c_inv_e_prop	1.00	0.40	[-]
c_inv_fc_prop	1.00	0.40	[-]
cpt_pv	1.00	0.11	[-]
cpt_winds	1.00	0.11	[-]

Table E.4: List of stochastic parameters. The parameters are defined thanks to a uniform distribution between a lower bound and an upper bound. Adding the deviation to the centered value defines the upper bound while subtracting the deviation defines the lower bound.

E.5 Researches on investment cost of PWR SMRs

Name or company	Source	currency before conversion	Power output	investment cost			Comment
				low	single	high	
RollsRoys	IAEA : ARIS report (2020)[47]	Pounds	443		1754		-
Happy200	IAEA : ARIS report (2020)[47]	Yuon	66		488		only thermal power is available. An efficiency of 33% has been assumed
IMR	IAEA : ARIS report (2020)[47]	Euros	350		4846		same as today
Wenstinghouse	Abdulla et al. (2013)[41]	Dollar	225	2190		4860	
NuScale	Abdulla et al. (2013)[41]	Dollar	45	2'740		11200	a single 45 Mwe *NuScale* reactor
NuScale	Abdulla et al. (2013)[41]	Dollar	125	2660		9850	Combination of 5 45 Mwe *NuScale* reactors
NuScale	Abdulla et al. (2013)[41]	Dollar	1080	2500		7000	Combination of 24 45 Mwe *NuScale* reactors
-	Tractebel report (2020)[39]	Euros	-	3010		5020	-

Table E.5: Summary of research on investment costs of SMRs in $€_{2015}$. Some numbers were found as an interval. In that case, the lower bound is indicated in column "low" and the upper bound in column "high". Sometimes the numbers were a single value, in which case, the number is in column "single". The different sources originated from different reactors and researches, which is why they were initially in different currencies. A conversion following the method used in G. Limpens has been used for the conversion.

Appendix F

Central limit theorem for ESTD Results

Briefly

The Central Limit Theorem (CLT) is a well known statistic theorem. This theorem allows to approximate an unknown distribution with a Gaussian distribution if enough samples are randomly generated. CLT is especially used with the results of the PCE to easily compute a 95% confidence interval.

The central limit theorem (CLT) states that if you have enough samples randomly generated from a population with replacement, then the distribution of the sample means will approximately be following a normal distribution. Usually, the number of samples required must be greater or equal to 30. If the population is normal, the theorem holds for any number of sample generated, greater or lower than 30[34].

In the context of this thesis, the mean and the standard deviation can be directly obtained thanks to PCE coefficients while the distribution of the studied metric can be computed thanks to the many PCE runs. Given the large number of samples, this distribution can be approximated as normal, using the CLT. Thanks to this approximation, a 95% confidence interval (CI) can be easily generated. Indeed, for a normal distribution the 95% CI is given by:

$$\boldsymbol{P}(\mu - 2\sigma \leq Studied\ metric \leq \mu + 2\sigma) = 95\%$$

Where

- μ is the mean, easily computed thanks by the PCE1.13.
- σ is the standard deviation, easily computed thanks by the PCE1.14.

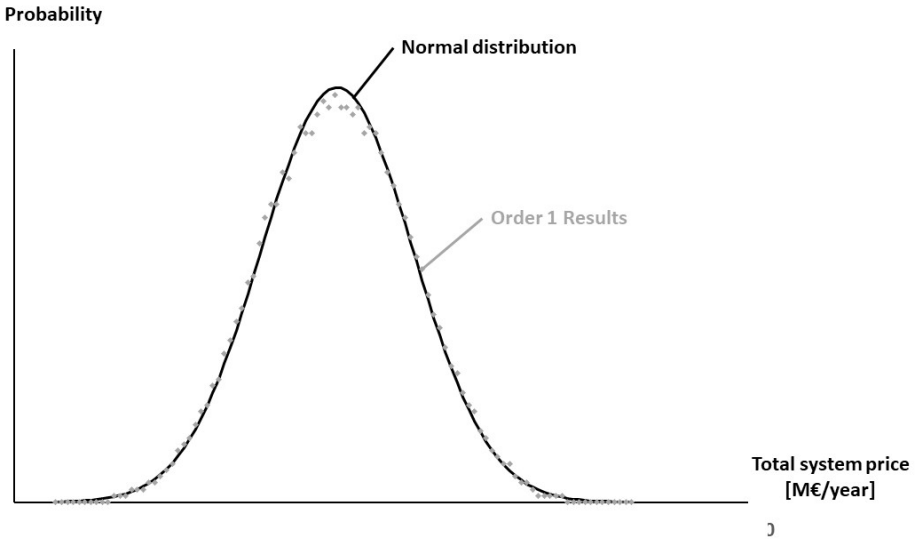

Figure F.1: The normal distribution fits the result of the first order PCE

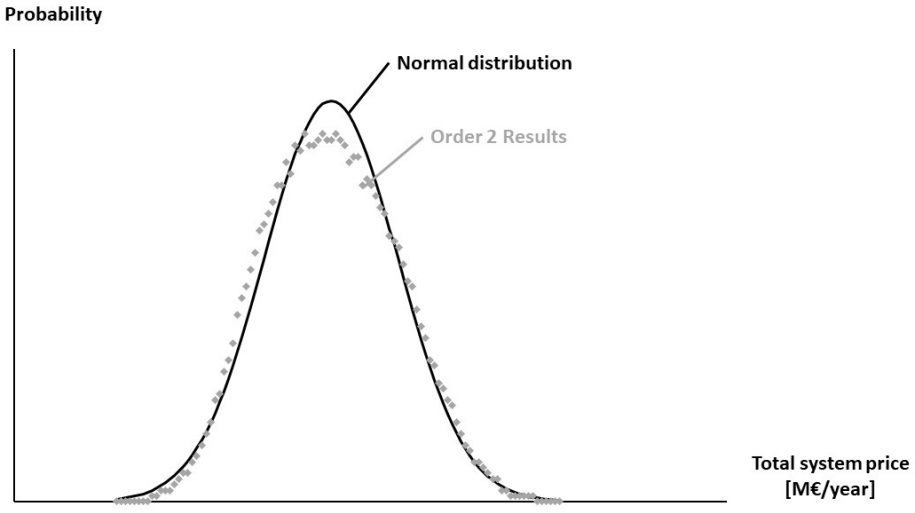

Figure F.2: The normal distribution fits the result of the second order PCE

Appendix G

Reactor Types

Briefly

This appendix regroups the sample of SMRs in development around the world. Most of them are PWRs, which is the kind of reactor used in this thesis.

Small Modular Reactors (SMRs) are a fairly new technology. Despite the fact that most of them are Pressurised Water Reactors (PWRs), a technology well known since the 1970s, many of them remain in the project stage. It can be seen in Table G.1 that most of them are American projects. Almost no project is envisaged at the European level.

Design	Net output per module [MW]	Number of modules (if applicable)	Type	Designer	Country	Status
Single unit LWR-SMRs						
CAREM	30	1	PWR	CNEA	Argentina	Under construction
SMART	100	1	PWR	KAERI	Korea	Certified design
ACP100	125	1	PWR	CNNC	China	Construction began in 2019
SMR-160	160	1	PWR	Holtec International	United States	Conceptual design
BWRX-300	300	1	BWR	GE HITACHI	United States - Japan	First topical reports submitted to the US NRC and to the CNSC as part of the licensing process
CANDU SMR	300	1	PHWR	SNC-Lavalin	Canada	Conceptual design
UK SMR	450	1	PWR	Rolls Roys	United Kingdom	Conceptual design
Multi-module LWR-SMRs						
NuScale	50	12	PWR	*NuScale* Power	United States	Certified design. US NRC and to the CNSC as part of the licensing process
RITM-200	50	2	PWR	OKBM Afrikantov	Russia	Land-based nuclear power plant - conceptual design
Nuward	170	2-4	PWR	CAE/ EDF/ Naval Group/ TechnicAtome	France	Conceptual design
Mobile SMRs						
ACPR50S	60	1	Floating PWR	CGN	China	Under construction
KLT-40S	35	2	Floating PWR	OKBM Afrikantov	Russie	Commercial operation
GenIV SMRs						
Xe-100	80	1 to 4	HTGR	X-energy LLC	United States	Conceptual design
ARC-100	100	1	LMFR	Advanced Reactor Concepts LLC	Canada	Conceptual design
KP-FHR	140	1	MSR	Kairos Power	United States	Pre-conceptual design
IMSR	190	1	MSR	Terrestrial Energy	Canada	Basic design
HTR-PM	210	2	HTGR	China Huaneng/ CNEC/ Tsinghua University	China	Under construction
EM2	265	1	GMFR	General Atomics	United States	Conceptual design
Stable Salt Ractor	300	1	MSR	Moltex Energy	United Kingdom	Pre-conceptual design
Natrium	345	1	SFR	Terrapower/GE Hitachi	United States	Conceptual design
Wensting-house Lead Fast Reactor	450	1	LMFR	Westinghouse	United States	Conceptual design
MMRs						
eVinci	0.2-5	1	Heat pipe reactor	Westinghouse	United States	Basic design
Aurora	2	1	LMFR	Oklo	United States	License application submitted to the US NRC
U-Battery	4	1	HTGR	Urenco and partners	United Kingdom	Basic design
MMR	5- 10	1	HTGR	USNC	United States	Basic design

Table G.1: Different reactor types by categories indicating their TRL[36]

Appendix H

Results of the deterministic approach with SMRs

Briefly

The conclusions for the deterministic approach are identical to those for nuclear 2.1:
When SMRs are authorised:

- SMRs' installed capacity is always at its maximal allowed capacity,
- The energy system is more and more self-sufficient. Less and less imports are made,
- The cost of the electricity sector is higher, but the total cost of the energy system is lower,
- CO_2 emissions are lower.

Conventional nuclear power plants and SMRs are almost the same technology. Indeed, both are PWRs, so their parameters are pretty close. Therefore, the conclusion on the results of their deterministic approach is the same. To avoid redundancy in the results of the deterministic approaches, the results for the SMRs have been put in this appendix.

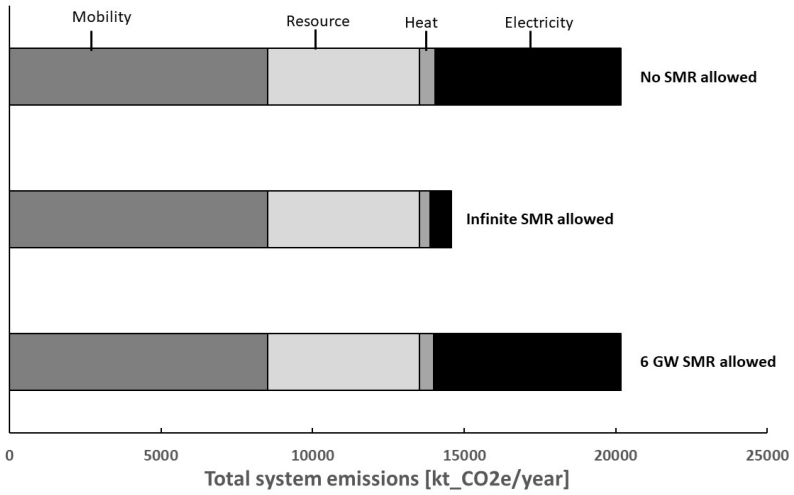

Figure H.1: As expected, there is less emissions when SMRs are allowed. Furthermore, they seems to save a non negligible amount of emissions each year 2.2.

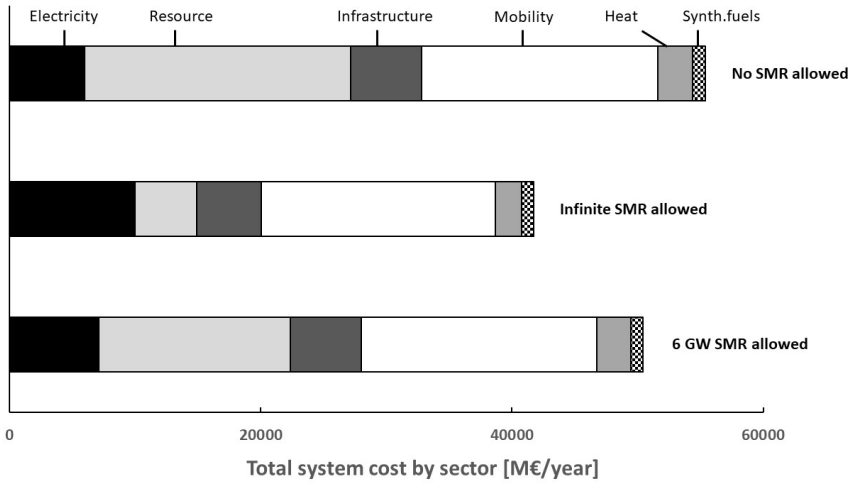

Figure H.2: The total cost of the system is lower when SMRs are allowed. Indeed, the energy mix is by less technologies, SMRs produce the majority of the electricity. So as expected, the Resource sector is less expensive because the entire system rely on less different kind of Resources2.3. E.g. when infinite SMR is allowed, the energy system is mainly composed by SMRs and Wind Turbine (WT). So the Resources used are mainly wind and uranium.

Appendix I

Comparison of emissions between a CCGT and a NPP

Briefly

The objective is to give a better idea, a better quantification of what is the emissions produced by the construction of a conventional NPP. The comparison is done between a new NPP which must be build and an existing CCGT. The CCGT produces power since the beginning. After 100 days of production, the NPP has produced the same amount of CO_2e than the CCGT. In other words, construct a new NPP is the same as running a CCGT at practically full load during 100 days.

In order to give a better quantification of the emissions of a NPP, a comparison is done between a CCGT. The following hypothesis are taken :

- The NPP needs to be built, the produced power is 1 [GW],
- The CCGT is already built, the produced power is 1 [GW]
- The following values are used, see Table I.1. There are directly coming from[1] :

	CCGT	**NPP**
Construction's emissions [ktonCO$_2$e/GW]	/	707.88
Fuel's emissions [ktonCO$_2$e/GWh]	0.2666	/
Capacity factor [-]	0.96	0.85

Table I.1: Values used for the calculation. They were taken from[1]

.

By solving this system, the response is obtained directly:

$$\mathrm{CO_2}e_{NPP} = GWP_{constr,NPP} \cdot \frac{1}{C_{p,NPP}}$$
$$\mathrm{CO_2}e_{CCGT} = GWP_{op,CCGT} \cdot \frac{1}{C_{p,CCGT}} \cdot t$$
$$\mathrm{CO_2}e_{NPP} = \mathrm{CO_2}e_{CCGT}$$
$$t \approx 100 \text{ days}$$

Appendix J

Sankey

Briefly

A Sankey diagram allows to track the energy flow of the different resources. They make it possible to see the various transformations undergone within the energy system and are useful to get a better global understanding. The boxes on the left represent the resources that are being used and those on the right represent the demands. The boxes in between represent all the intermediate transformations in order to convert the resources to energy and meet the different demands. The coloured bands represent the different energy flows that are connecting the different elements within the system.

A Sankey diagram is a representation of the energy flow of the different resources. In this thesis, Sankey diagrams allow to understand the energy system in its entirety and the connections between each fields. The vertical grey bars on the left of the diagram represent the resources, those on the right represent the final consumption, i.e. the demand. The grey vertical bars in the middle represent all the intermediate transformations. It is interesting to see where the energy flow coming from the uranium is going and what is put in place in the event that nuclear power is not authorised. Indeed it can be noted that :

- **Nuclear power/SMR allowed**: Uranium is used extensively to produce electricity, which is then used for electric transport, for the heating network via the operation of heat pumps and for the electric network directly. It should be noted that when nuclear power is not limited and is therefore installed in large quantities, uranium is also used to produce hydrogen via the electrolysis of water. In the end, more and more nuclear power is allowed, less and less imports are made, so the energy system is more and more self-sufficient. This case is represented by Sankey J.3 and J.7. It seems like there is a slight problem in these diagrams though. The "Elec. demand" does not appear on the graph. The authors suppose that there have been a problem in the generation of the graph. However, one can imagine that the electricity demand in these cases is similar is in other scenarios.
- **Nuclear power/SMR not allowed**: Conversely, when uranium is not licensed, the amount of imported resources increases drastically. This case is represented by Sankey J.1.

Intermediate quantities of nuclear power and SMRs show intermediate results with an decreasing dependence on synthetic fuels as the nuclear capacity increases.
A short summary of the Sankey diagrams found below is proposed:

- *Reference Case* or no nuclear power allowed J.1
- 6 [GW] conventional nuclear allowed J.2
- Infinite conventional nuclear allowed J.3
- "Medium" case scenario where $c_{inv,nucl}$, $c_{op,uranium}$ and $gwp_{op,uranium}$ parameters are doubled compare to the *Reference Case* J.4
- "Worst" case scenario where $c_{inv,nucl}$, $c_{op,uranium}$ and $gwp_{op,uranium}$ parameters are tripled compare to the *Reference Case* J.4
- 6 [GW] SMR capacity allowed J.6
- Infinite SMR capacity allowed J.7
- 11 [GW] of SMR capacity J.8

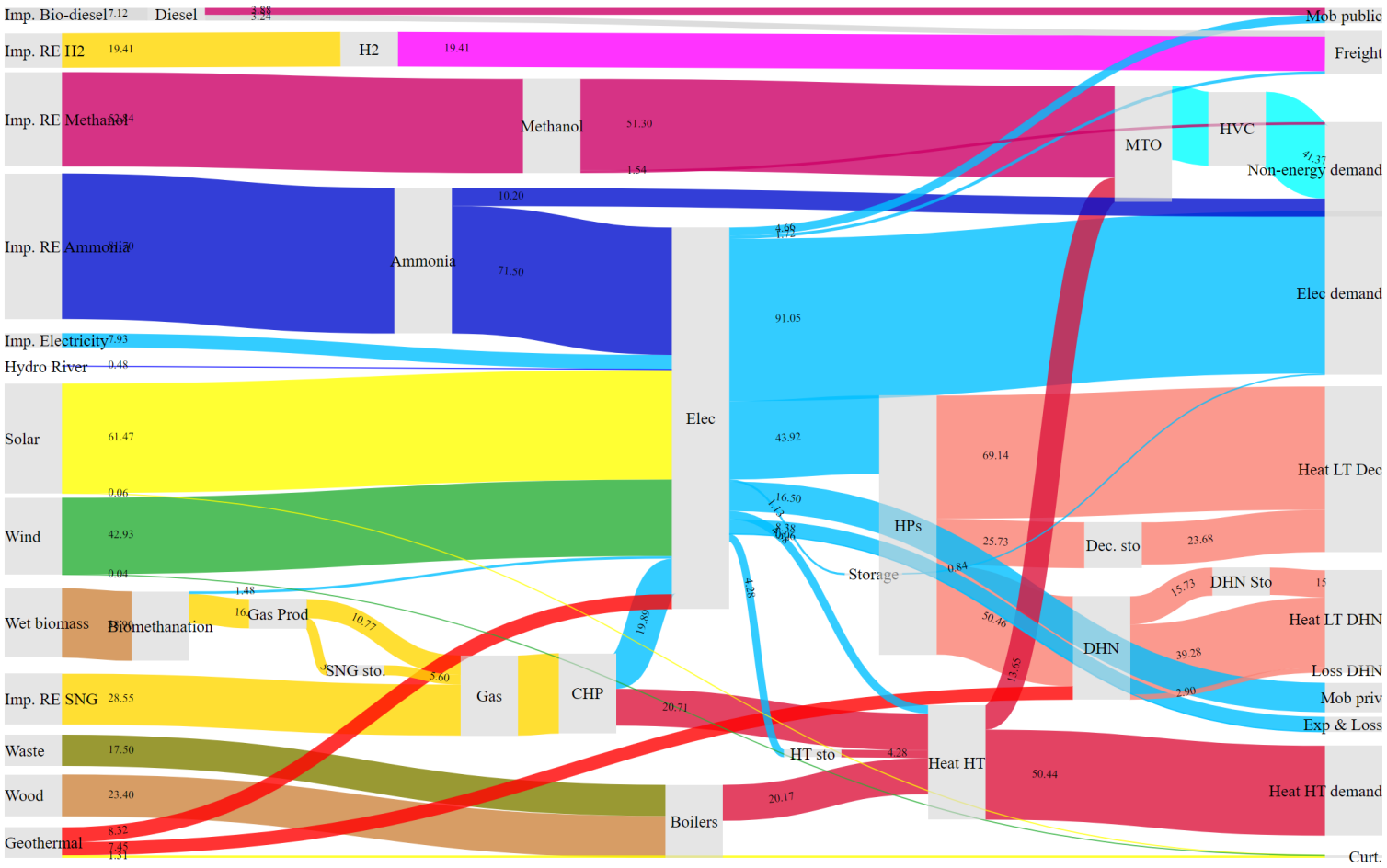

Figure J.1: Sankey diagram when 0 [GW] nuclear are installed
Representation of the scenario where no nuclear power is allowed in the Belgian energy system.
Also represents the *Reference Case*.
When no nuclear power is allowed, the energy system is quite complex with a lot of synthetic fuels imports.

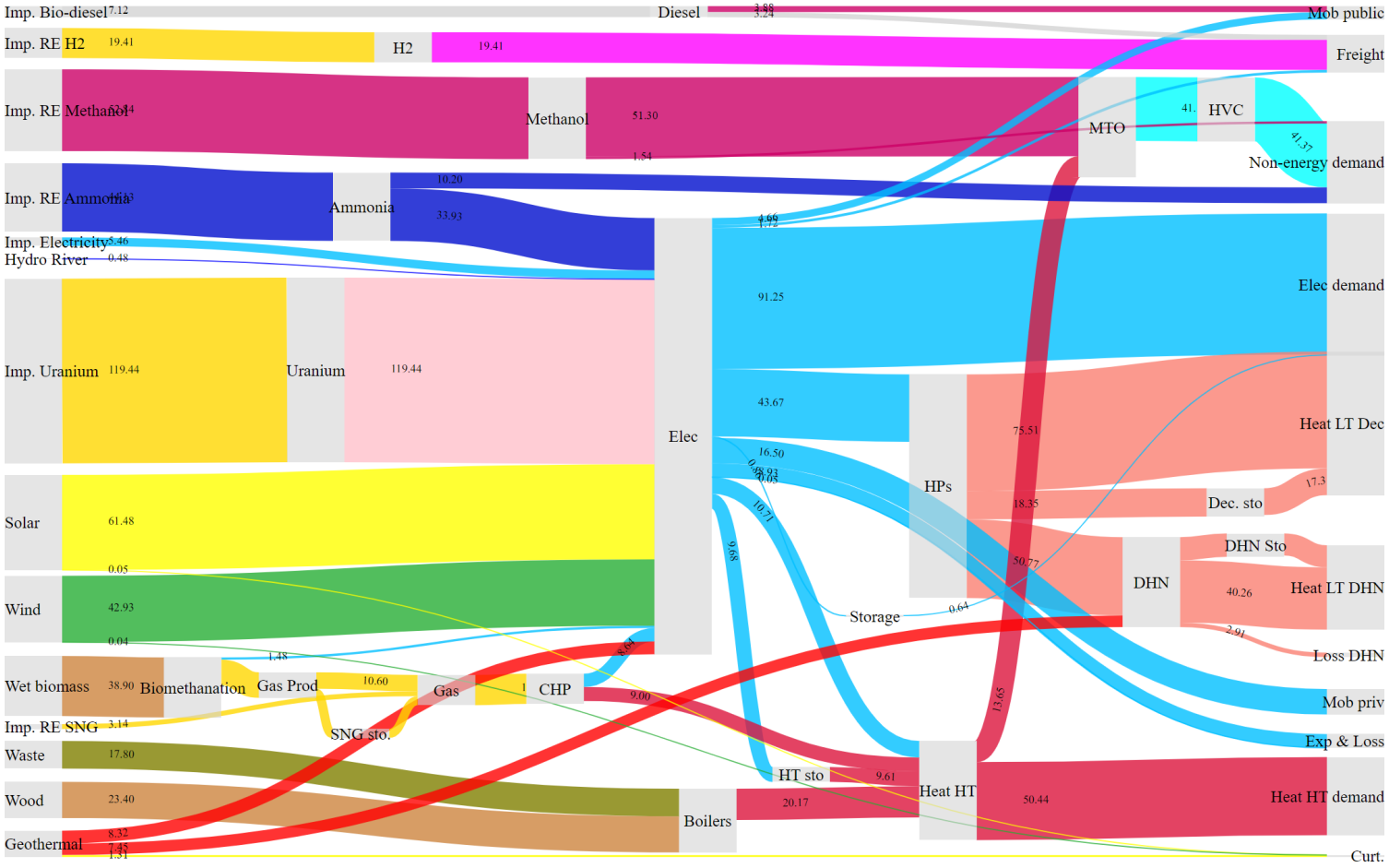

Figure J.2: Sankey diagram when 6 [GW] nuclear are installed.
Representation of the scenario where 6 [GW] of nuclear power are allowed in the Belgian energy system.
The energy system relies on a non-negligible quantity of synthetic fuels. Nuclear power allows to reduce this dependence on synthetic fuels compared to a case without nuclear power.

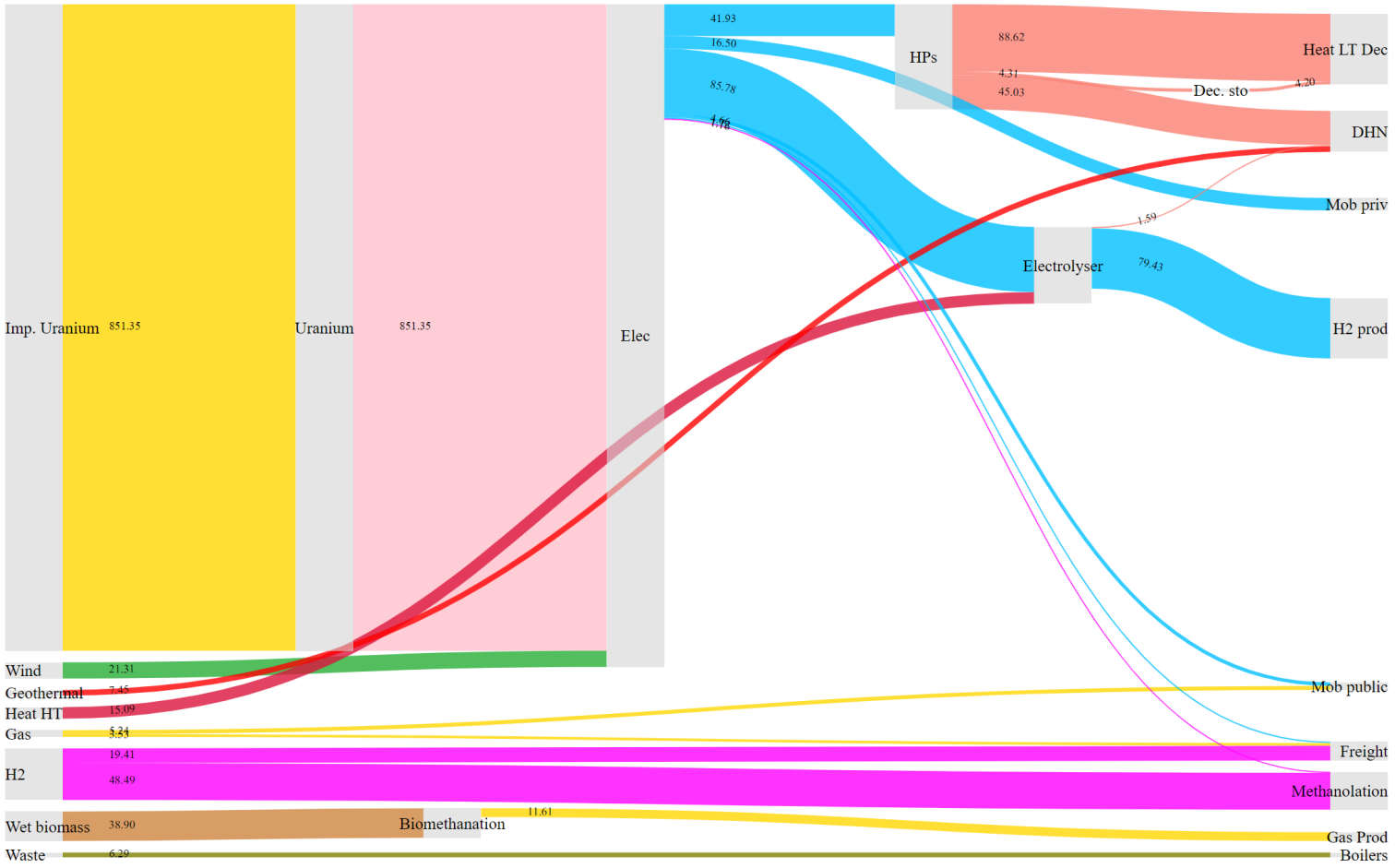

Figure J.3: Sankey diagram when 42 [GW] nuclear are installed. Representation of the scenario where infinite nuclear power is allowed in the Belgian energy system.
The energy system is simple relying a lot on nuclear power for different sectors. There seems to be an issue with the modelling of the Sankey as no "Elec. demand" is displayed.

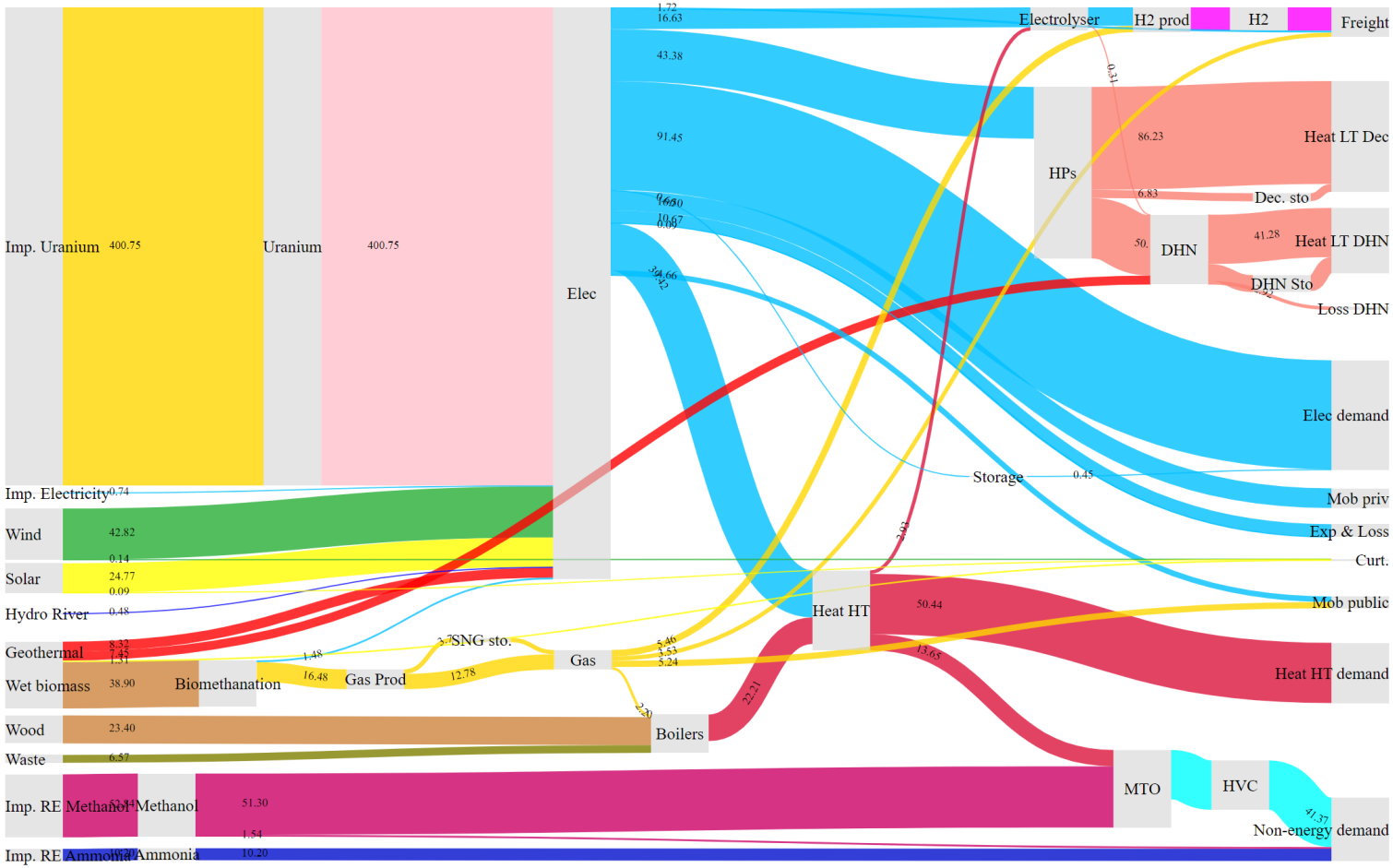

Figure J.4: Representation of the "Medium Case" where the values of $c_{inv,nucl}$, $c_{op,uranium}$ and $gwp_{op,uranium}$ parameters are doubled compare to the *Reference Case*.
As the price and emissions of nuclear power go up, the system relies less on it. In contrast, it relies more on synthetic fuels

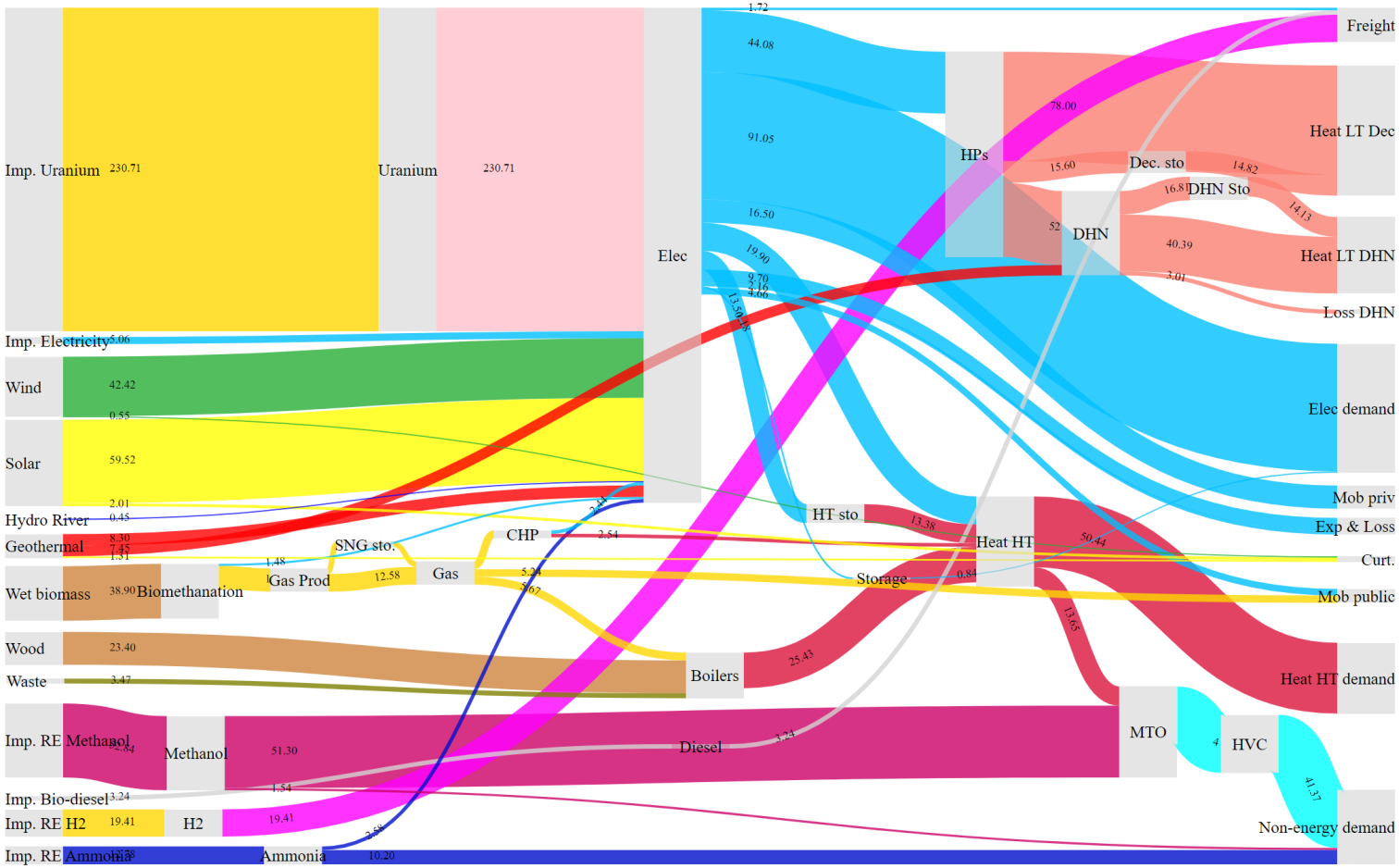

Figure J.5: Representation of the worst case where the values of $c_{inv,nucl}$, $c_{op,uranium}$ and $gwp_{op,uranium}$ parameters are doubled compare to the *Reference Case*.
In case the latter three parameters are multiplied by 3, nuclear power becomes even more expensive and emitting. Nuclear power is still part of the energy system, but in fewer quantities. The system relies a lot on synthetic fuels.

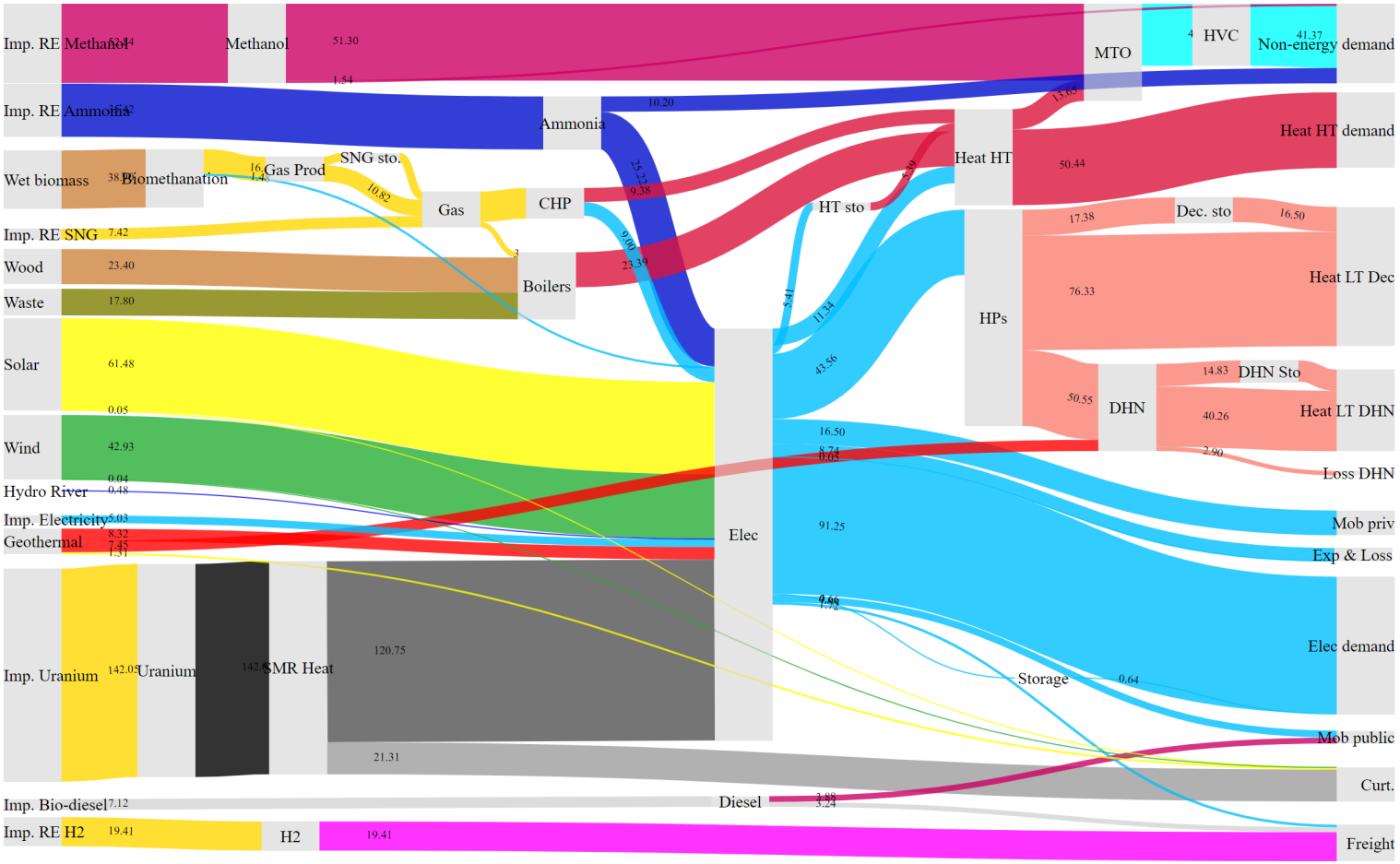

Figure J.6: Representation of the energy system for 6 [GW] of SMRs installed.
In order to have a decarbonised energy system, Belgium needs to rely a lot on synthetic fuels.

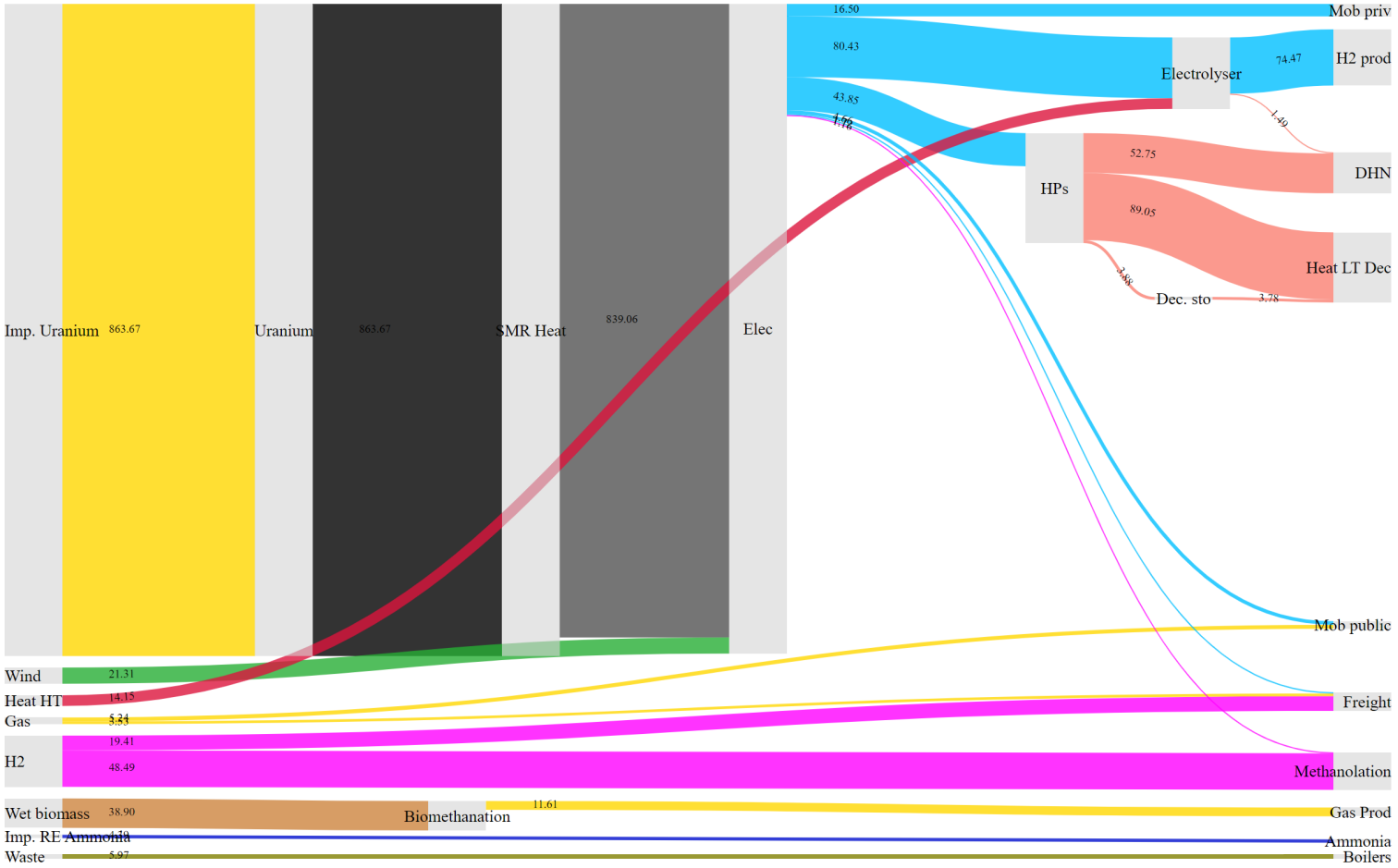

Figure J.7: Representation of the energy system for 42 [GW] of SMRs installed.
The energy system is simple relying a lot on nuclear power for different sectors. There seems to be an issue with the modelling of the Sankey as no "Elec. demand" is displayed.

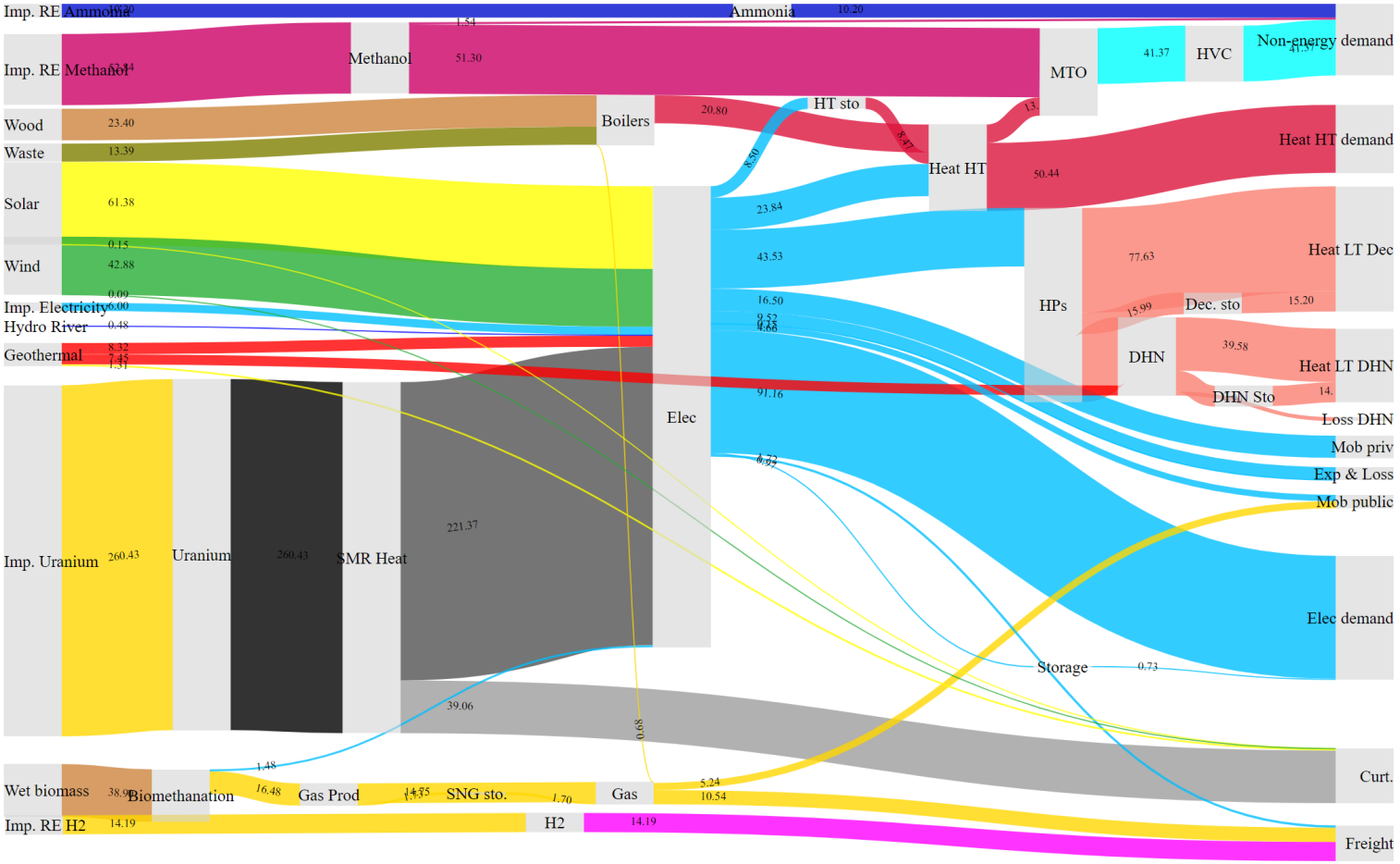

Figure J.8: Representation of the energy system for 11 [GW] of SMRs installed.
Following a global sensitivity analysis on SMR installed capacity, the results showed that the most probable scenarios are the ones with a SMR capacity between 10 and 12 [GW], with a mean of 12.4 [GW]. The underlying energy system is the one displayed in this figure.

Bibliography

[1] G. Limpens, S. Moret, H. Jeanmart, and F. Maréchal, "Energyscope td: A novel open-source model for regional energy systems," *Applied Energy*, vol. 255, (March) 2019.

[2] X. Rixhon, G. Limpens, D. Coppitters, H. Jeanmart, and F. Contino, "The role of electrofuels under uncertainties for the belgian energy transition," *Energies*, vol. 14, 7 2021.

[3] CarbonBrief, "*The trouble with Europe's ageing nuclear power plants.*" URL: https://www.carbonbrief.org/the-trouble-with-europes-ageing-nuclear-power-plants/. (visited on 05/20/2022).

[4] Eurostat, "*Nuclear energy statistics.*" URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Nuclear_energy_statistics. (visited on 06/05/2022).

[5] EnerData, "*Engie plans to add 3 GW of CCGT plants in Belgium to replace its nuclear fleet.*" URL: https://www.enerdata.net/publications/daily-energy-news/engie-plans-add-3-gw-ccgt-plants-belgium-replace-its-nuclear-fleet.html. (visited on 04/30/2022).

[6] Wikipedia, "*Belgique.*" URL: https://fr.wikipedia.org/wiki/Belgique. (visited on 04/11/2022).

[7] J. van Zalk and P. Behrens, "The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the u.s.," *Energy Policy*, vol. 123, pp. 83–91, 12 2018.

[8] N. Lallemant, "Des déchets nucléaires en province de luxembourg ? : "stop à la mascarade de consultation publique !"," *DH les sports +*, 2020.

[9] LaLibre, "La région wallonne rejette l'enfouissement géologique des déchets nucléaires," *La Libre ECO*, 2020.

[10] WNA, "*Nuclear Power in Belgium.*" URL: https://world-nuclear.org/information-library/country-profiles/countries-a-f/belgium.aspx. (visited on 04/11/2022).

[11] WNA, "*Nuclear Power Reactors.*" URL: https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx. (visited on 04/20/2022).

[12] LeSoir, "*Nucléaire : Accord pour la prolongation de deux réacteurs.*" URL: https://www.lesoir.be/431012/article/2022-03-18/

nucleaire-accord-pour-la-prolongation-de-deux-reacteurs. (visited on 05/24/2022).

[13] EuropeanCommission, "*Assessment of the final national energy and climate plan of Belgium.*" URL: https://energy.ec.europa.eu/system/files/2021-01/staff_working_document_assessment_necp_belgium_en_0.pdf. (visited on 04/21/2022).

[14] ONDRAF, "*Rapport stratégique sur les incidences environnementales (SEA) relatif à une destination finale pour les déchets de haute activité et/ou de longue durée de vie en Belgique,*" tech. rep., 2020.

[15] Myrrha, "*Nuclear waste treatment by MYRRHA.*" URL: https://myrrha.be/myrrha-applications/nuclear-waste-treatment-myrrha. (visited on 05/28/2022).

[16] IEA, "*Belgium.*" URL: https://www.iea.org/countries/belgium. (visited on 05/11/2022).

[17] Interenerstat, "*Non-Energy Use.*" URL: http://www.interenerstat.org/definitions/results.asp?id=168&Type=Flows. (visited on 04/30/2022).

[18] Flanders, "*How Flanders' chemical industry sets off a chain reaction of success.*" URL: https://www.flandersinvestmentandtrade.com/invest/en/sectors/chemicals. (visited on 04/30/2022).

[19] IPCC, "*SPECIAL REPORT: GLOBAL WARMING OF 1.5°. Mitigation pathways compatible with 1.5°C in the context of sustainable development.*" URL: https://www.ipcc.ch/sr15/chapter/chapter-2/. (visited on 05/20/2022).

[20] ElectricityMap, "*Belgium.*" URL: https://app.electricitymap.org/zone/BE. (visited on 05/16/2022).

[21] Wikipedia, "*Overnight Cost.*" URL: https://en.wikipedia.org/wiki/Overnight_cost. (visited on 04/18/2022).

[22] G. Limpens, *Generating energy transition pathways: application to Belgium.* PhD thesis, Ecole Polytechnique de Louvain, 2021. DOI: 10.13140/RG.2.2.25755.18724.

[23] Wikipedia, "*Monte Carlo method.*" URL: https://en.wikipedia.org/wiki/Monte_Carlo_method. (visited on 05/10/2022).

[24] B. Sudret, "*Polynomial chaos expansions and stochastic finite element methods. Kok-Kwang Phoon, Jianye Ching. Risk and Reliability in Geotechnical Engineering, CRC Press,*" 2015. 9781482227215. ffhal-01449883f.

[25] D. Coppitters, W. D. Paepe, and F. Contino, "Robust design optimization and stochastic performance analysis of a grid-connected photovoltaic system with battery storage and hydrogen storage," *Energy*, vol. 213, 12 2020.

[26] WorldNuclearNews, "*Extended operation of two Belgian reactors approved.*" URL: https://www.world-nuclear-news.org/Articles/Extended-operation-of-two-Belgian-reactors-approve. (visited on 05/01/2022).

[27] P. Berwal, S. Kumar, and B. Khandelwal, "A comprehensive review on synthesis, chemical kinetics, and practical application of ammonia as future fuel for combustion," *Journal of the Energy Institute*, vol. 99, pp. 273–298, 12 2021.

[28] Wikipedia, "*Centrale nucléaire de Flamanville*." URL: https://fr.wikipedia.org/wiki/Centrale_nucléaire_de_Flamanville. (visited on 05/18/2022).

[29] WordlNuclearAssociation, "*Economics of Nuclear Power*." URL: https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx. (visited on 05/18/2022).

[30] B. K. Sovacool, "Valuing the greenhouse gas emissions from nuclear power: A critical survey," *Energy Policy*, vol. 36, pp. 2950–2963, 2008.

[31] IEA and NEA, "*Projected Costs of Generating Electricity*," tech. rep., 2020.

[32] WordlNuclearAssociation, "*Plans for New Reactors Worlwide*." URL: https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx. (visited on 05/20/2022).

[33] Wikipedia, "*Nuclear Regulatory Commission*." URL: https://en.wikipedia.org/wiki/Nuclear_Regulatory_Commission. (visited on 05/20/2022).

[34] Sphweb, "*Central limit theorem*." URL: https://sphweb.bumc.bu.edu/otlt/mph-modules/bs/bs704_probability/BS704_Probability12.html#:~:text=The%20central%20limit%20theorem%20states,will%20be%20approximately%20normally%20distributed. (visited on 05/21/2022).

[35] WNN, "Belgium government allocates funding for smr research," *World Nuclear News*, 2022.

[36] NEA, "*Small Modular Reactors: Challenges and Opportunities*," tech. rep., 2021.

[37] NASA, "*Technology Readiness Level*." URL: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level. (visited on 03/30/2022).

[38] APIOix, "*Licensing Readiness Level*." URL: https://apioix.com/assessing-licenseability#:~:text=License. (visited on 03/30/2022).

[39] P. Monette, C. Piette, and A. Touré, "*The rise of nuclear technology 2.0 Tractebel's vision on Small Modular Reactors*," 2020.

[40] M. Rowinski, T. White, and J. Zhao, "Small and medium sized reactors (smr): A review of technology," vol. 44, pp. 643–656, 2015. ISSN: 13640321. DOI: 10.1016/j.rser.2015.01.006.

[41] A. Abdulla, I. L. Azevedo, and M. G. Morgan, "Expert assessments of the cost of light water small modular reactors," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 110, pp. 9686–9691, 6 2013.

[42] "Review of integration of small modular reactors in renewable energy microgrids," *Renewable and Sustainable Energy Reviews*, vol. 152, 12 2021.

[43] "Small modular reactors: A comprehensive overview of their economics and strategic aspects," *Progress in Nuclear Energy*, vol. 73, pp. 75–85, 5 2014.

[44] EIA, "*Updated Capital Cost Estimates for Electricity Generation Plants*," 2010. In: *report prepared by the U.S. Energy Information Administration (EIA), the statistical and analytical agency within the U.S. Department of Energy*.

[45] D. T. Ingersoll, Z. J. Houghton, R. Bromm, and C. Desportes, "Nuscale small modular reactor for co-generation of electricity and water," *Desalination*, vol. 340, pp. 84–93, 5 2014.

[46] D. T. Ingersoll, C. Colbert, Z. Houghton, R. Snuggerud, J. W. Gaston, and M. Empey, "*Can Nuclear Power and Renewables be Friends?*,."

[47] IAEA, "*Advances in Small Modular Reactor technology developments 2020 Edition A Supplement to: IAEA Advanced Reactors Information System (ARIS)*," tech. rep., 2020.

[48] NuScale, "*Flexibility and adaptability for a wide range of electrical and thermal applications*." URL: `https://www.nuscalepower.com/benefits/diverse-applications`. (visited on 05/27/2022).

[49] UNFCCC, "*The Paris Agreement*." URL: `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement`. (visited on 04/25/2022).

[50] S. Power and Gas, "*The Pros and Cons of Nuclear Energy: Is it safe ?*." URL: `https://springpowerandgas.us/the-pros-cons-of-nuclear-energy-is-it-safe/`. (visited on 05/30/2022).

[51] OCDE, "Évaluation des risques d'accidents nucléaires comparés à ceux d'autres filières énergétiques."

[52] BBC, "*The true toll of the Chernobyl disaster*." URL: `https://www.bbc.com/future/article/20190725-will-we-ever-know-chernobyls-true-death-toll`. (visited on 05/30/2022).

[53] INN, "Uranium stockpiling: The rise of nationalism or an energy security effort?," *Investing News Network*, 2022.

[54] ScientificAmerican, "*How long will the world's uranium supply last*." URL: `https://www.scientificamerican.com/article/how-long-will-global-uranium-deposits-last/`. (visited on 05/30/2022).

[55] OurWorldinData, "*Belgium*." URL: `https://ourworldindata.org/country/belgium`. (visited on 06/04/2022).

[56] WNA, "*Generation IV Nuclear Reactors*." URL: `https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx`. (visited on 06/04/2022).

[57] NEA, "*Long-Term Operation of Nuclear Power Plants and Decarbonisation Strategies*," tech. rep., 2021.

[58] IEA, "*World Energy Model Documentation*," tech. rep., 2021.

[59] G. Doluweera, "*Using System Levelized Cost, Levelized Avoided Cost and Value-Adjusted Levelized Cost to Evaluate Electricity Generation Technologies*," 2020.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**