



**UCLouvain**

Institute of Mechanics,  
Materials and Civil Engineering

# Robust optimisation of the pathway towards a sustainable whole-energy system

## A hierarchical multi-objective reinforcement-learning based approach

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Doctoral dissertation presented by

**Xavier RIXHON**

in partial fulfillment of the requirements for  
the degree of Doctor in Engineering Sciences

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### **Thesis committee**

Pr. Francesco CONTINO (supervisor, UCLouvain)

Pr. Hervé JEANMART (supervisor, UCLouvain)

Dr. Stefano MORET (ETH Zurich)

Pr. Sylvain QUOILIN (ULiège)

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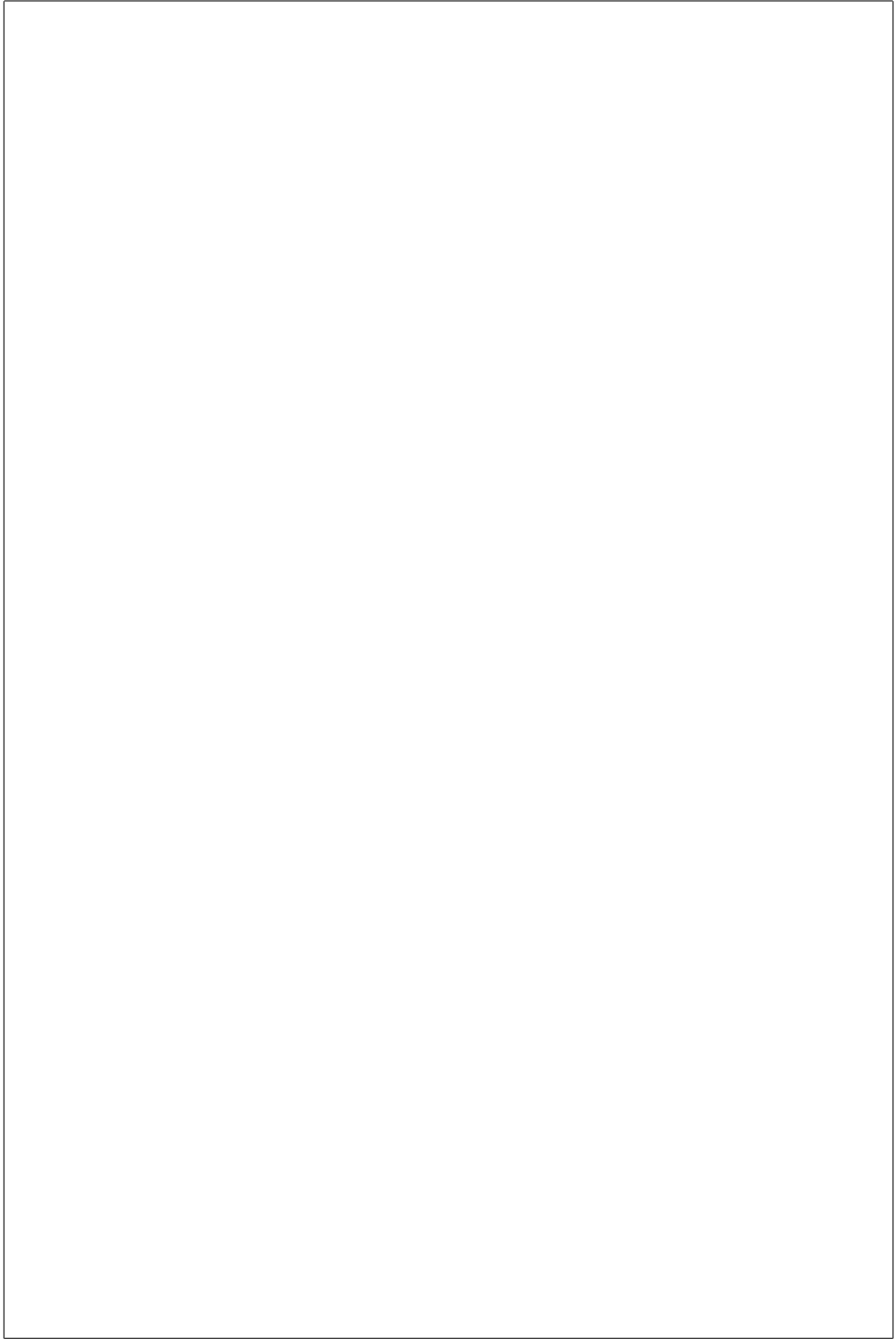
## Abstract

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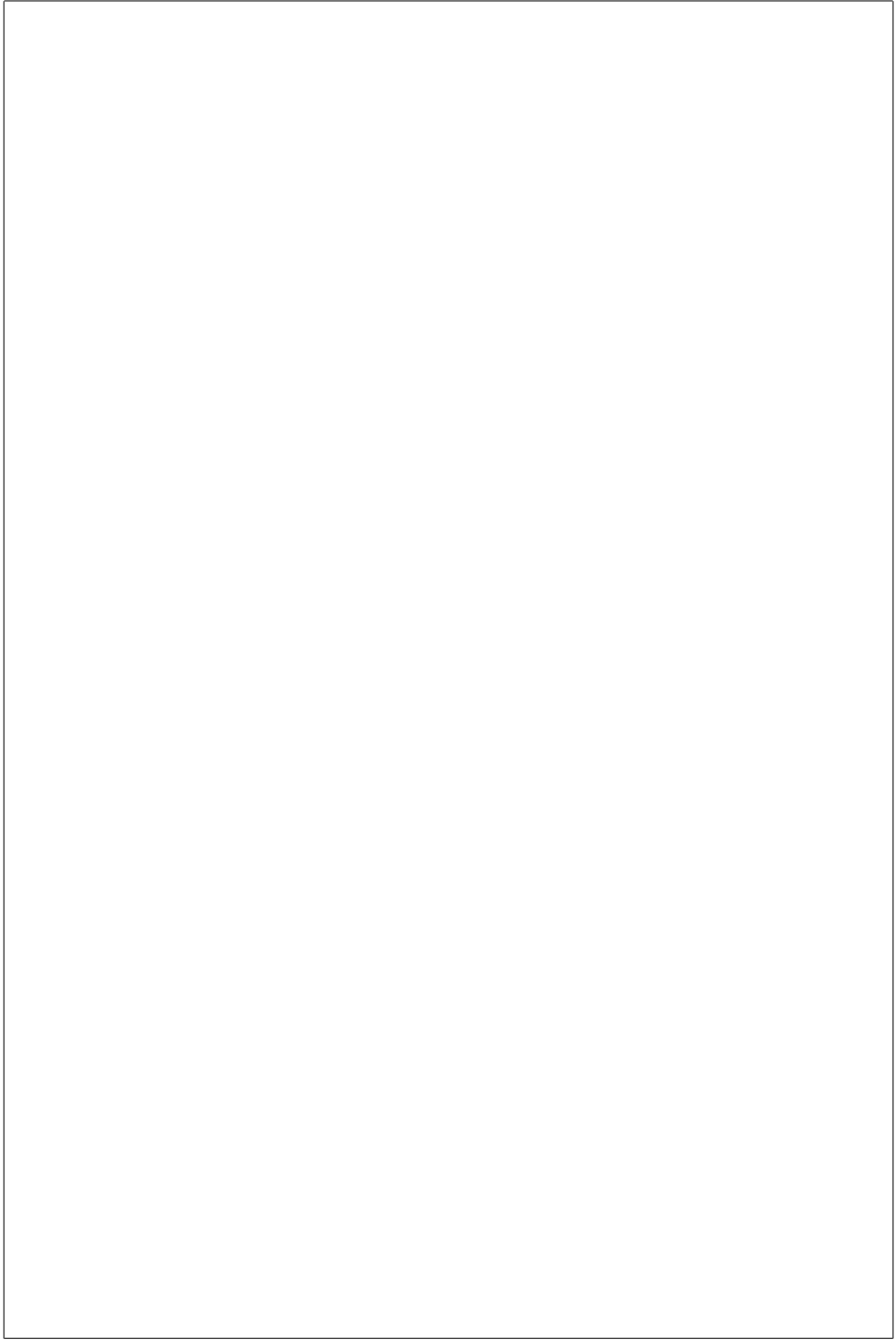
*“Pour ce qui est de l’avenir, il ne s’agit pas de le prévoir,  
mais de le rendre possible”*

– Antoine de Saint Exupéry, Citadelle, 1948

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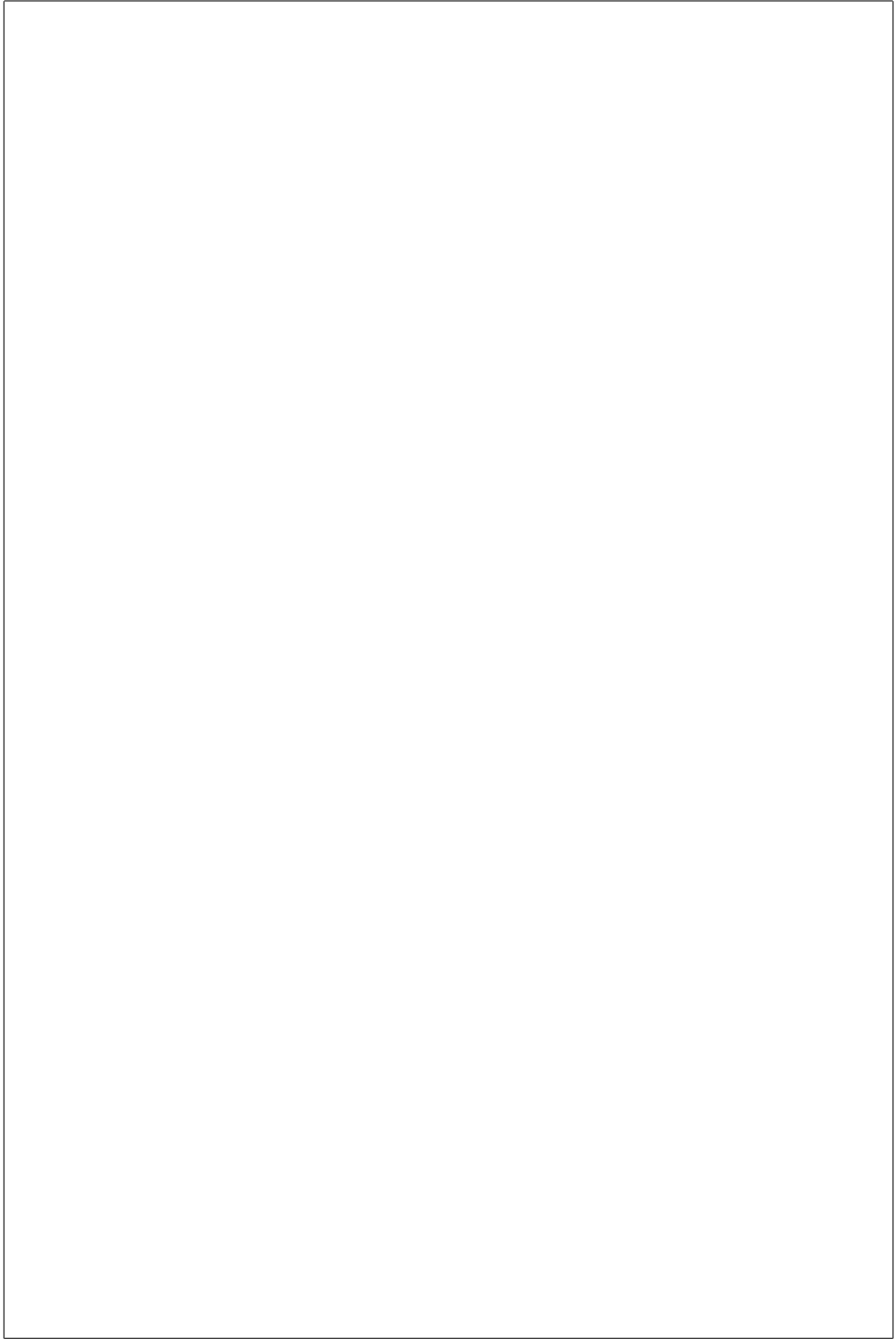
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# Remerciements

Thank you, thank you, far too kind

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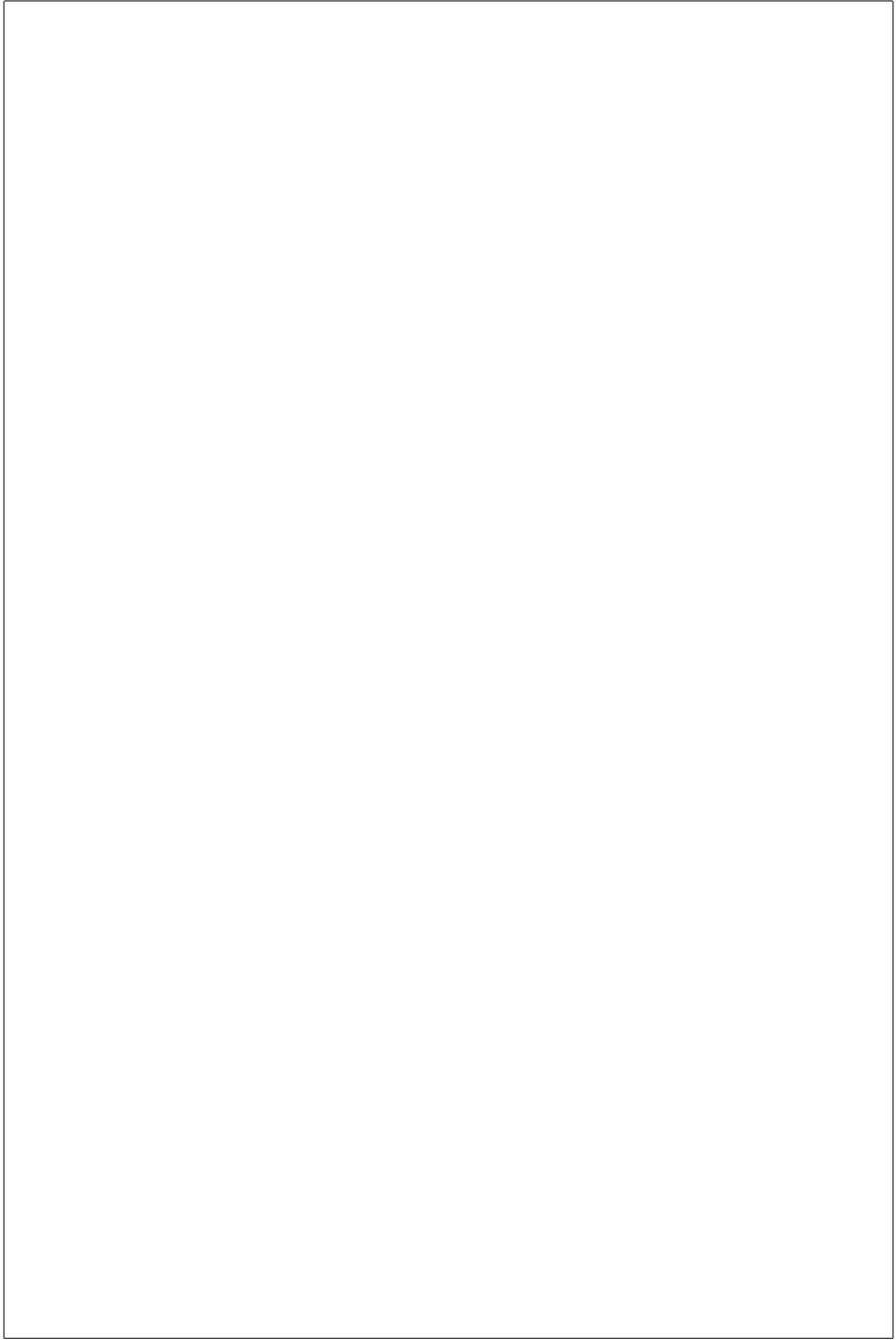
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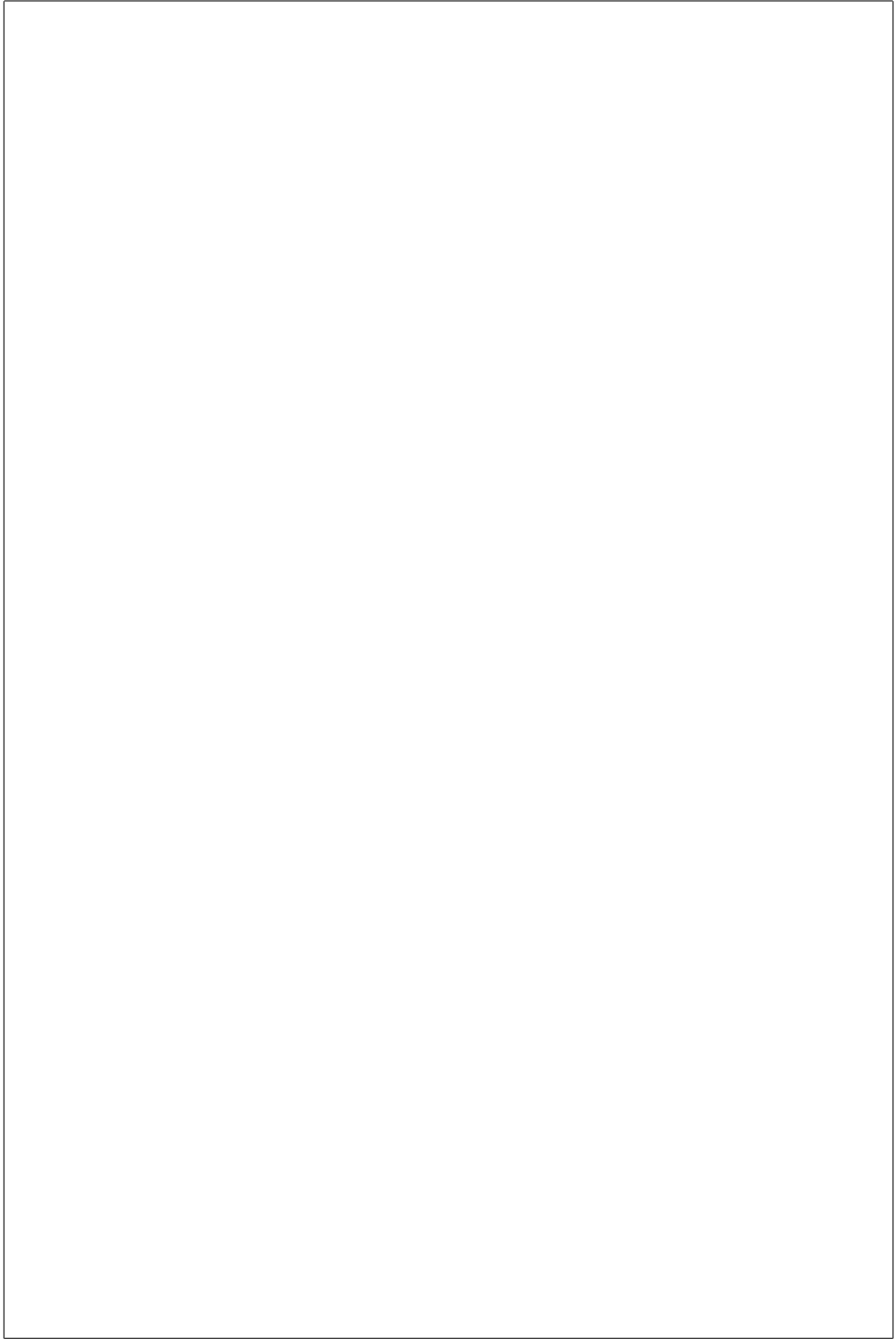
# Symbols

## Acronyms

<b>BEV</b>	battery electric vehicle
<b>CCGT</b>	combined cycle gas turbine
<b>DHN</b>	district heating network
<b>EUD</b>	end-use demand
<b>FC</b>	fuel cell
<b>GWP</b>	global warming potential
<b>HP</b>	heat pump
<b>HVC</b>	high value chemicals
<b>LCOE</b>	levelised cost of energy
<b>NED</b>	non-energy demand
<b>PCE</b>	Polynomial Chaos Expansion
<b>PV</b>	photovoltaic
<b>SDGs</b>	Sustainable Development Goals
<b>SMR</b>	small modular reactor
<b>UQ</b>	Uncertainty Quantification

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## Chapter 1

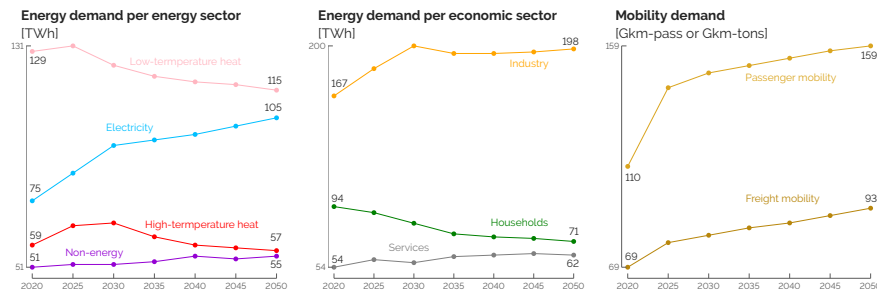
# Case study: the Belgian energy system

As detailed by Limpens et al. [1], the analysis carried out in this work can be applied to any regional whole-energy system. As a densely-populated and highly-industrialised country with limited local renewable potentials (mainly solar and wind), the transition of Belgium from a fossil-dominated system in 2020 (Appendix A) to carbon-neutrality in 2050 makes it an intricate case study. Moreover, this case study and the subsequent analyses can be transferred - to some extent - to other industrialised countries highly dependent on fossil fuels with limited local renewable potentials (e.g. the Netherlands or Germany) [2]. This section presents the different demands to satisfy as well as the resources available and the conversion technologies to supply those. The focus here is given to the renewable molecules to import from abroad as well as the techno-economic details of small modular reactor (SMR). For a comprehensive understanding and detailed descriptions of the technologies, please refer to the documentation [3]. Finally, the CO<sub>2</sub>-budget over the 2020-2050 transition is presented.

### 1.1 Demands

End-use demands, exogenously imposed as inputs to the model, are characterised by yearly quantities to satisfy and are also distributed over the different hours of each representative years of the transition, in order to account for their daily or seasonal variability. In this work, the yearly end-use demands (EUD) for all sectors are calculated from the rather slightly increasing forecast proposed by the European Commission for Belgium (Appendix 2 in report [4]). Although, given a significant and unsubstantiated discrepancy in the non-energy use forecasts compared to their previous report (i.e. +80% over the 2020-2030 time window), the evolution trend of the non-energy de-

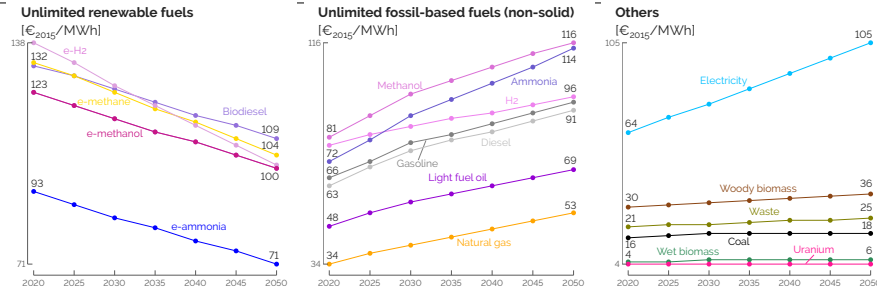
mand (NED) of the current work has been inferred from the previous edition, published in 2016, [5]. Looking at Figure 1.1, between 2020 and 2050, one observes a noteworthy increase of the electricity (+40%), passenger (+45%) and freight mobility (+35%) demands. The rise of the non-energy demand is more limited, i.e. +6%, whereas the heating demands is forecast to decrease: -11% and -3% respectively for the low and high-temperature heat demands. Regarding the center graph of Figure 1.1, it is the aggregation of the same data as in the left graph but per category, rather than per sector, with the non-energy demand being associated with the industry. This illustrates how industrialised is Belgium, compared to households and services, and, consequently, highly energy-intensive. The right graph of Figure 1.1 gives the passenger and the freight mobility. The sharp increase from 2020 to 2025 is due the COVID-crisis that has significantly reduced these demands in 2020. As far as the hourly discretisation of these demands is concerned, time series are based on historical values of 2015 for parts of electricity and low-temperature heating demands [6]. A daily time series is used for the passenger mobility and applied similarly to every typical days. Finally, for the other demands, the yearly demand is distributed uniformly over the different hours of the year.



**Figure 1.1.** EnergyScope splits the whole-energy system end-use demands (EUD) into two sets: (non)-energy and transport-related. This figure presents the nominal values of each of these demands. In the center graph, the non-energy demand has been fully associated with the industrial demand. As detailed by Rixhon et al. [7], the non-energy demand is expressed in tons of physical products (i.e. high value chemicals (HVC), ammonia and methanol) and then translated into their respective energy equivalent, in TWh. Graphs have been adapted from [1].

## 1.2 Resources

To supply the aforementioned demands, EnergyScope Pathway implements a variety of resources defined by their cost of purchasing,  $c_{op}$ , their global warming potential,  $gwp_{op}$ , as well as their availability, as detailed by Limpens et al. [1]. Figure 1.2 depicts the evolution the respective costs of purchasing. Regarding “renewable electrofuels”, these are in line with the recent study of Genge et al. [8] who carried out an extensive review and “meta-analysis[9, 10] of 30 studies on the supply costs of chemical energy carriers”. Then, besides their cost, the resources are either limited or unlimited in terms of availability and either renewable or not. The limitation in terms of availability can be direct or indirect. On the one hand, woody (23.4 TWh) and wet biomass (38.9 TWh) are limited by their local potentials and the consumption of waste (17.8 TWh) and coal (33.4 TWh) is assumed not to exceed the current use. On the other hand, wind, solar, hydro and uranium are limited by the technical potentials respectively, of photovoltaic (PV) panels (59.2 GW), onshore (10 GW) and offshore (6 GW) wind turbines, run-of-the-river power plants (0.1 GW) and nuclear power plants (6 GW). As SMR are foreseen, if installed, to be around the same locations (i.e. Thiange and Doel) as the conventional nuclear power plants and using the same area in kW/ha, the same 6 GW are assumed to be the maximum capacity for SMR. This is even without considering the potential limit due to the local availability, in terms of volume and flow rate, of enough water that would be a more socially-accepted solution than cooling towers exhausting a dense plume. Imported electricity is limited in two ways: the potential of instantaneous capacity of interconnection with neighbouring countries (i.e. 11.9 GW by 2050 [11]) and a limitation to 30% of the yearly electricity end-use demand (i.e. 32.4 TWh by 2050). In the current work, the electrofuels (i.e. e-methane, e-hydrogen, e-methanol and e-ammonia) are assumed to be “sustainable” in the sense that they do not increase the concentration of  $CO_2$  in the atmosphere [12]. In practice, it means that their global warming potential (GWP) is assumed to be zero in the model. Regarding specifically these electrofuels, the Hydrogen Import Coalition [13] has carried out an extensive techno-economic analysis to estimate their respective cost of purchasing, after having identified some key locations from which importing these energy carriers (e.g. Chile, Australia or Morocco). As the amount to import from each of these locations is hard to forecast, the current work considers the average cost between the different locations. Besides these, every other resource has its specific GWP like coal ( $gwp_{op,coal} = 0.40 \text{ kt}_{CO_2,eq}/\text{GWh}$ ), natural gas ( $gwp_{op,NG} = 0.27 \text{ kt}_{CO_2,eq}/\text{GWh}$ ) or the fossil-based molecules equivalent to the electrofuels (e.g.  $gwp_{op,ammonia} = 0.46 \text{ kt}_{CO_2,eq}/\text{GWh}$  or  $gwp_{op,methanol} = 0.41 \text{ kt}_{CO_2,eq}/\text{GWh}$ ).



**Figure 1.2.** Cost of purchasing the different resources. Besides the free local renewables (i.e. sun, wind and hydro) limited by technical potentials, EnergyScope accounts for renewable energy carriers and their respective fossil counterparts (left and center graphs). These fuels can be imported from abroad without limitation on their availability. Other carriers are limited either by their local potentials (i.e. biomass and waste) or other considerations like the power grid interconnections or the capacity of nuclear power plants.

### 1.3 SMR and other conversion technologies

Finally, as the end-use demands are defined as energy (and non-energy with the NED) services rather than a certain quantity of oil or solar irradiance, technologies are implemented to convert these resources into the end-use demands. Besides their CAPEX, OPEX and lifetime defined in Section ??, production and conversion technologies (i.e. combined cycle gas turbine (CCGT), car or boiler) have a conversion efficiency whereas storage technologies (i.e. thermal storage, battery or molecule storage) exhibit their own charge/discharge losses. Eventually, there are also infrastructure technologies like the grid or the district heating network (DHN) that allow to account for the investment necessary, respectively, to integrate more intermittent renewables in the power sector and the expand the use of centralised heating systems.

A specific attention is to put on the implementation of small modular reactor (SMR) whereas the 6 GW of conventional nuclear are assumed to drop to 2 GW in 2025 and total phase-out by 2035. Similarly to the analysis of EnergyVille [14], a Belgian consortium for energy research, and in line with the Belgian Nuclear Research Centre (SCK-CEN) [15], SMR are implemented with the features listed in Table 1.1. Where most of the features are similar to conventional nuclear power plants, it differs from these on two main points: their potential year start, 2040, and their flexibility. Indeed, unlike the current nuclear power plants, constrained in the model to produce a constant power output at every hour of the year (i.e. baseload production as it is actually the case



in Belgium), SMRs, are flexible in the sense that their production can vary between 0 and their full capacity independently at any hour of each representative year. Here, the authors simplify SMRs as only producing electricity and assume that the after-heat is lost to the atmosphere anyway.

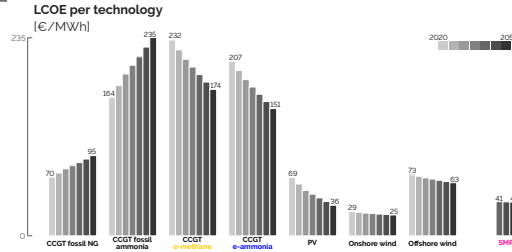
**Table 1.1.** Nominal features of the SMRs in EnergyScope. SMR exhibits the advantage to have a fully flexible production (i.e. between 0 to the full capacity) unlike conventional nuclear that is constrained to produce a constant baseload at every hour of the year. <sup>(a)</sup> This annual availability accounts for yearly maintenance where the reactors might not operate or, at least, not at their maximum capacity. <sup>(b)</sup> 2040 is the soonest year at which SMR could be available, optimistically assuming industrial prototypes being completed by 2035 and 5 additional years for their commercial installation.

Feature	Value	Unit	Similarity with conventional nuclear
CAPEX	4850	€/kW	✓
Annual OPEX	103	€/kW/year	✓
Lifetime	60	year	✓
Efficiency	40%	-	✓
Maximum capacity	6	GW	✓
Annual availability	85% <sup>(a)</sup>	-	✓
Operational year	2040 <sup>(b)</sup>	-	✗
Flexibility	Full	-	✗

For the sake of comparison, Figure 1.3 gives the levelised cost of energy (LCOE) of the principal technologies to produce electricity, based on the computation used by Limpens [16]. Compared to the other flexible generation units, SMR is significantly more cost-effective. In addition, we see that CCGT supplied by e-ammonia outcompetes its e-methane equivalent, unlike their respective fossil-based equivalent.

## 1.4 CO<sub>2</sub>-budget for the transition

In most of the studies carried out on the pathway optimisation of a whole-energy system, a CO<sub>2</sub>-trajectory is *a priori* set to reach carbon-neutrality by 2050. Nerini et al. [17] used the emission trajectory indicated by the UK's Committee on Climate Change in their analysis of the impact of limited foresight to achieve the target of 80% reduction of ?? by 2050 in the United Kingdom. In their assessment of the impacts of economy-wide emissions policies in the water-energy-land nexus, Licandeo et al. [18] analysed



**Figure 1.3.** Levelised cost of energy (LCOE) for the main technologies in the power sector. Where SMR is cheaper than the other flexible options, CCGT running on e-ammonia is, a priori, cheaper than its e-methane alternative.

different CO<sub>2</sub>-trajectories considering more or less severe water scarcity for the US. Poncelet et al. [19] with LUSYM (Leuven University SYstem Model) and EnergyVille [14] with TIMES-BE also set decreasing emission trajectories in their analysis of respectively the Belgian power sector and whole-energy system. Others only set the objective as the carbon-neutrality by 2050. For instance, Heuberger et al. [20] investigated the impact of different factors (e.g. limit of the foresight in the future, availability of “unicorn technologies” or committed versus market-driven decarbonisation strategies) to reach this ultimate objective in the UK system.

In this work, the effect of greenhouse gases is cumulative over time and a constraint is set on the overall emissions of the transition—a CO<sub>2</sub>-budget for the transition. This budget (1.2 Gt<sub>CO<sub>2</sub>,eq</sub>) corresponds to the proportion of Belgium’s emissions in the world emissions in 2020 (34.8 Gt<sub>CO<sub>2</sub>,eq</sub> [21]) applied to the global budget to have a 66% chance of limiting warming to 1.5°C of 420 Gt<sub>CO<sub>2</sub>,eq</sub> [22]. Therefore, in this work, a limit has been put on  $gwp_{lim,trans} = 1.2 \text{ Gt}_{CO_2,eq}$  in Eq. (??). This is another sign of the urgency to act to mitigate climate change as this 30-year budget represents only 10 years of the current emissions. Compared to a linear decrease from the current emissions, as done by Limpens et al. [1], this budget represents a 60% reduction of the cumulative emissions over the transition. Appendix B compares the emissions trajectory between the REF case and a case (without SMR) where the linear decrease is imposed between 2020 and carbon-neutrality in 2050.

**GRANDFATHERING dans la vision d’attribuer le budget CO<sub>2</sub> donné à la Belgique. Defining the share of the safe operating space from How to bring absolute sustainability into decision-making: An industry case study using a Planetary Boundary-based methodology. Sharing the safe operating space**

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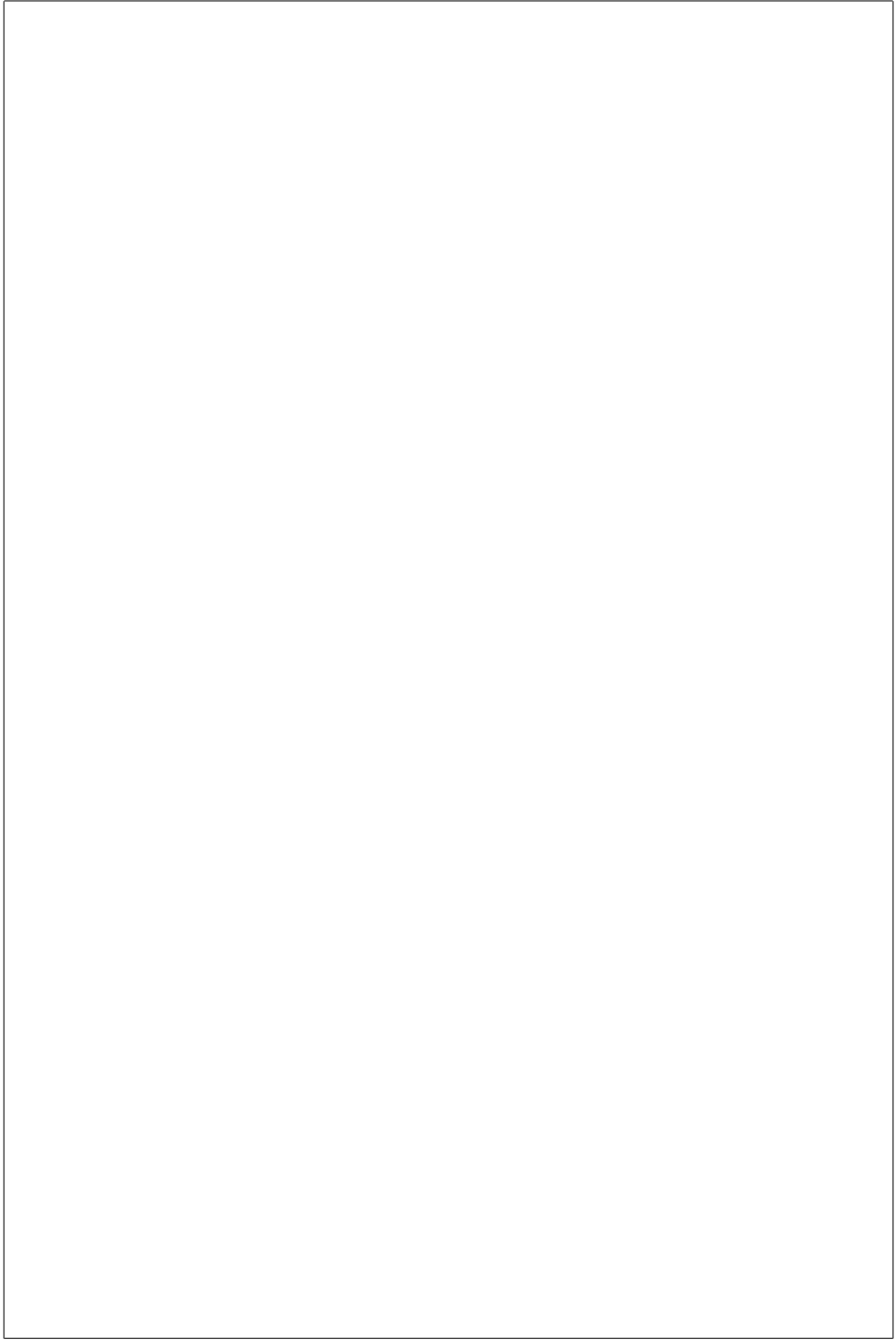
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## **Appendix A**

### **Belgian energy system in 2020**

The Belgian whole-energy system of 2020 was largely based (88.6% of the primary energy mix) on “conventional fuels”(i.e. oil and oil products (38.2%), natural gas (29.5%), uranium (16.3%) and solid fossil fuels (4.6%) while the rest mainly accounts for 26.7 TWh of lignocellulosic and wet biomass, 12.8 TWh of wind and 5.1 TWh of solar [23]. Given the data available in the literature (mostly for the power sector) and, when not available, following the assumptions made by Limpens et al. [6], Table A.1 gives the major technologies used in 2020 to supply the different demands of Figure 1.1.

**Table A.1.** Major technologies used to supply the 2020-demands of Figure 1.1 in terms of share of production and installed capacity. <sup>(a)</sup> The decentralised heating units provide 98% of the low-temperature heat demand. <sup>(b)</sup> The private mobility accounts for 80% of the passengers mobility.

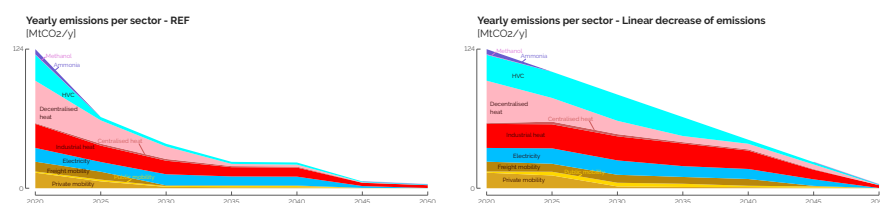
End-use demand	Major technologies	Share of supply	Installed capacity
Electricity	Nuclear	39%	5.9 GW
	CCGT	21%	3.9 GW
	Wind turbines	14%	5.0 GW
Heat High-Temp.	Gas boiler	36%	3.3 GW
	Coal boiler	30%	2.3 GW
	Oil boiler	20%	1.5 GW
Heat Low-Temp. (DEC) <sup>(a)</sup>	Oil boiler	48%	21.4 GW
	Gas boiler	40%	17.5 GW
	Wood boiler	10%	4.4 GW
Heat Low-Temp. (DHN)	Gas CHP	59%	0.3 GW
	Gas boiler	15%	0.3 GW
	Waste CHP	15%	0.1 GW
Private mobility <sup>(b)</sup>	Diesel car	49%	93.5 Mpass.-km/h
	Gasoline car	49%	94.7 Mpass.-km/h
	HEV	2%	5.9 Mpass.-km/h
Public mobility	Diesel bus	43%	3.6 Mpass.-km/h
	Train	43%	3.9 Mpass.-km/h
	CNG bus	5%	0.8 Mpass.-km/h
Freight mobility	Diesel truck	74%	62.7 Mt.-km/h
	Diesel boat	15%	10.8 Mt.-km/h
	Train	11%	2.5 Mt.-km/h
HVC	Naphtha/LPG cracking	100%	4.6 GW
Ammonia	Haber-Bosch	100%	1 GW
Methanol	Import	100%	-



## Appendix B

# CO<sub>2</sub>-budget versus linear decrease of emissions

Figure B.1 shows the yearly emissions attributed for each sector in the REF case (i.e. imposed CO<sub>2</sub>-budget) and a case where the CO<sub>2</sub>-trajectory is constrained instead. Interestingly, these two transition pathways end up in a similar carbon-neutral whole-energy system in 2050. The two main sectors that significantly reduce their emissions in the REF case are the production of high value chemicals (HVC) and the high-temperature heat. In the former, this is linked to the extended use of oil products through naphtha-cracking. The latter is produced by industrial coal boilers for longer, until 2040. Overall, ending up to the same level of emissions in 2050, the REF case represents a 60% reduction of the cumulative emissions compared to the linear decrease, for a 7.5% more expensive transition.



**Figure B.1.** Respecting the CO<sub>2</sub>-budget imposed in the REF case drastically cuts the emissions of the system, especially in the production of high value chemicals (HVC) and the high-temperature heating sector.