Optimal design of multi-energy systems with high shares of renewable energy sources

A linear-programming approach for integrating electricity, heating, and hydrogen in multi-energy systems

S. Feijen

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A linear-programming approach for integrating electricity, heating, and hydrogen in multi-energy systems

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Summary

In pursuance of reducing emission from greenhouse gasses (GHG), the energy system is undergoing a significant transition. The uptake of renewable energy sources (RES) has severely increased over the last years. However, the transition towards a carbon-neutral energy system also involves the integration of RES in the energy system as a whole. This brings about several challenges due to the stochastic characteristics of variable renewable energy sources (VRES).

A recent and promising approach which has received increasing attention from the scientific community and system operators is that of multi-energy systems (MES). A MES is defined as an energy system whereby different energy sectors interact with each other. It builds on the notion of considering the optimization (economic, environmental and/or technical) of the whole energy system instead of focussing on specific energy sectors. This approach offers several benefits compared to optimization of an energy system where sectors are treated as separated. In particular, the system's flexibility can be increased by the substitution of one energy carriers into another through various conversion technologies.

The transition towards a sustainable future energy system requires deliberate planning. Grid operators are facing substantial investment decisions in the coming years, such as choices on which energy generation technologies to invest in, their location and installed capacities, the required transmission infrastructure and how to ensure system flexibility. However, the planning of the energy system is a challenging and complex task: energy systems operate on large scales, are very capital intensive and have long lifetimes to consider. In addition to planning, the design of energy systems should include considerations on the operation: the meeting of supply and demand is increasingly challenging in energy system with high VRES uptake. Furthermore, the concept of MES results in increased integration of different energy sectors, bringing about complex interdependencies.

To aid decision-makers in the planning of future energy systems, energy investment models are often used to design the optimal configuration, from which valuable insights can be obtained. Similarly, a MES investment model allows to analyse the implications and potential benefits of increasing integration between different energy sectors in a systematic and integrated way. This provides a quantitative assessment on the capability of a MES in increasing system flexibility. However, a suitable model to optimally design a future MES in which electricity, heating, natural gas, and hydrogen sectors are integrated is currently not described in literature. Therefore, this research sheds light on the optimal design of highly renewable future energy systems, focusing on the increased integration between different energy sectors. The main research question of this thesis is as follows:

"What are the cost-optimal designs of a multi-energy system integrating electricity, heating, and hydrogen sectors, given different RES targets?"

To find the cost-optimal configuration of an energy system, an optimization model was developed. This thesis presents a MES investment model which is able to find the cost-optimal investment in a future energy system in which three types of demand (electricity, heating, and hydrogen) are met. The model is able to find the optimal generation, conversion, storage, and transmission investments and the optimal operation of the energy systems simultaneously, whilst adhering to balance and RES target constraints. The model is an extension of the current cost-optimal energy investment Greenfield Renewables Investment Model (GRIM). It allows the incorporating of spatial characteristics of VRES supply, leading to a more realistic representation of the real energy system. Furthermore, the model is able to account for limitations on maximum available land for onshore wind and solar photovoltaics (PV). It is able to capture a range of generation, conversion and storage technologies. The model can be used as a quantitative tool to systematically find the cost-optimal investment and operation lay-out of an energy system where multiple energy sector are integrated, and can therefore provide a basis for energy policy and related investment decisions.

A case study was conducted on the energy system of the Netherlands. GHG reduction ambitions are put into practice in the Netherlands by formulating a target amount of RES capacity to be integrated into the system. To support the transition, the Dutch government formulated the Regional Energy Strategy, in which the Netherlands is divided into thirty regions. The considered energy inputs are the generation from onshore wind, solar, natural gas, hydrogen, biomass and electricity import. These can be converted through four types of conversion technologies: EHP, electrolysers, combined cycle gas turbines (CCGT) and heat pumps. Finally, three storage technologies were included: batteries, thermal energy storage (TES) and hydrogen storage.

The model was used to run several scenarios, which differ on the RES target, level of sector integration and land-use restriction for solar and onshore. The outputs of the optimization model consist of the system costs, the energy mix and spatial distribution of generation and conversion technologies. A few interesting findings can be concluded from the results.

First, the results shows that a MES leads to a more cost-efficient optimum compared to an energy system where the energy sectors are not integration. The increased connections between electricity, heating and hydrogen sectors results in a decrease in generation, storage, and network capacity investment. It can be deducted that integration of energy sectors is a cost-efficient approach to provide system flexibility, is especially with higher VRES uptake: in a fully renewable scenario, sector integration can lead to a reduction in average energy costs of 25%. Cross-sector utilization is particularly beneficial for electricity usage in the hydrogen sector, and hydrogen usage in the electricity sector.

Second, in order to increase the energy system's flexibility needed with higher RES uptake, the results show that a combination of storage, network transmission and integration of different energy sectors is better than investing heavily in a single option. Combining different flexibility options shows to be a very effective approach to cope with the intermittent characters of VRES, significantly reducing total system costs as a result of the complementary advantages of combining different flexibility options. Especially apparent is the combination of electrolysers investment, VRES generation capacity, hydrogen storage and hydrogen transmission.

Third, in order to meet all three demands of electricity, heat and hydrogen in the Netherlands in a fully renewable energy system, installed capacities of generation technologies needs to be increased significantly compared to current levels. For every scenario, the cost-optimal investment portfolio consist of a mix of different energy sources.

Finally, the results highlight the importance of considering the spatial component of generation investment. Both limitations on land-use and spatial-temporal VRES supply profiles have very significant impact on the total costs. Failing to account for these can lead to increases in total system costs and different generation portfolios. For the Netherlands, imposing land-use constraints resulted in a decrease in market share from onshore and an increase in solar, since the maximum amount of available land for onshore wind is reached, when including three types of demands. Besides the spatial differences of generation investment, the study highlights the relevance of spatial distribution of conversion technologies, in particular electrolysers. High investments in the onshore region should be paired with high investment in electrolysis in that region.

The academic relevance of this thesis is found in the modelling approach developed. In addition, this thesis builds on existing energy planning literature by providing a case study of the future energy system of the Netherlands. Future research could analyse different objectives, include additional generation technologies, and more extensive analysis of institutional aspects.

Preface

This thesis marks the end of my time studying at the Delft University of Technology, during which I have learned many things. The Master's degree of Complex System Engineering and Management, with the specialization in energy, have allowed me to develop a unique set of multidisciplinary academic skills, to strengthening my analytical skill set and to expand curiosity even further.

The previous two years have been two of the most demanding, hard-working years, in particular the new challenges resulting from the Covid-19 pandemic. Albeit certainly challenging, the progressions made in conduction research, modelling and writing have been utterly rewarding, as well as the final work which I am very proud of to present.

This would not have been possible without the assistance of others. I would like to sincerely thank Petra Heijnen and Aad Correljé for their constructive and critical feedback. In addition, I would like to thank Ni Wang for the various meetings, teachings and constructive feedback he provided. This allowed me to get the most out of this thesis and continuously staying critical of my work, which indisputably raised the quality of my thesis.

Sven Feijen
Delft, September 2021

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List of abbreviations

CAES	Compressed Air Energy Storage
CapEx	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CO2	Carbon dioxide
CLC	Corine Land Cover
DP	Dynamic Programming
DSO	Distribution System Operator
DSM	Demand- side management
EH	Energy Hub
EHB	European Hydrogen Backbone
EHP	Electric Heat Pumps
ENTSO-E	European Network of Transmission System Operators for Electricity
ESI	Energy Systems Integration
ETM	Energy Transition Model
FOM	Fixed Operation & Maintenance
GEP	Generation Expansion Planning
GHG	Greenhouse Gasses
GDP	Gross Domestic Product
GRIM	Greenfield Renewables Investment Model
HHV	Higher Heating Value
HV	High-voltage
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kg	kilo gram
kV	kilo volt
kW	kilowatt
kWh	kilowatt-hour
LHV	Lower Heating Value
LP	Linear Programming
LV	Low-voltage
ME-GRIM	Multi Energy carrier Greenfield Renewables Investment Model
MES	Multi-energy System
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MV	Medium-voltage
MW	Megawatt
MWh	Megawatt-hour
P2G	Power to Gas
PCS	Power Conversion System
PES	Primary Energy Sources
PV	Photovoltaics
PSH	Pumped-storage hydropower
R&D	Research and Development
RES	Renewable Energy Sources
SEP	Storage Expansion Planning
SMES	Superconducting Magnetic Energy Storage
TEP	Transmission Expansion Planning
TES	Thermal Energy Storage
TFEC	Total Final Energy Consumption
TRL	Technology Readiness Level
TSO	Transmission System Operator
TWh	Terawatt-hour
UTES	Underground Thermal Energy Storage
UK	United Kingdom
VOM	Variable Operation & Maintenance
VRES	Variable Renewable Energy Sources

1
Introduction

In 2015, 196 parties signed the Paris Agreement, an international and legally binding treaty on climate change [140]. Agreements were made for a collective endeavour of "holding the increase in the global average temperature to well below 2 °C" [141, p.3]. To achieve this, countries aim to reach a climate neutral world by mid-century [140]. Despite these ambitions, total annual emissions of greenhouse gasses (GHG) have not reduced. In fact, apart from 2008 and 2020, global annual emissions of carbon dioxide (CO2) have increased for every year over the past decades [5]. The supply of energy still originates mostly from non-renewable energy sources: in 2018, coal, oil and natural gas accounted for 81.3% of global total energy supply, whereas less than 2% originated from solar photovoltaics (PV) and wind energy [6]. However, the most severe impacts of climate change can still be mitigated if sufficient effort is put toward the transformation of the energy system [34].

1.1. Towards a carbon-neutral energy system

In pursuance of reducing GHG emission, the energy system is undergoing a significant transition. Renewable energy sources (RES) present an abundant source of energy with a total production that can, theoretically, be enough to supply all electricity demand [36, 52]. In this context, the uptake of RES has severely increased over the last years. Globally, the total installed capacity of both wind and solar PV is forecasted to surpass the total capacity of natural gas and coal by 2023 or 2024 [71]. However, besides increasing the capacity of RES, the transition towards a carbon-neutral energy system also involves the integration of RES in the energy system as a whole. This brings about several challenges, in particular due to the stochastic characteristics of variable renewable energy sources (VRES).

1.1.1. Intermittent supply

Wind and solar PV generation are dependent on levels of wind speed and solar irradiation, which are stochastic in nature. Hence, it is not possible to perfectly predict the exact amount of energy generated, adding uncertainty to both planning and operation of the energy system [53, 146]. Moreover, VRES supply is usually spatially distributed and does not always correlate with the particular demand of that region [53]. The supply and demand of energy, however, have to be met at all times, from which two types of mismatch can occur. First, the supply of VRES can be insufficient to meet the demand due to the absence of wind or solar radiation: this can be either for short periods, but also for a week or longer (known as 'wind drought' or 'Dunkelflaute') [146]. Second, oversupply occurs when the supply exceeds the demand.

Whereas the spatial distribution and stochastic characteristics of VRES result in large variability in energy supply, the current energy system is designed to operate on a conventional top-down level, for instance through means such as the established infrastructure [117]. The mismatch of supply and demand can lead to outages, fluctuating electricity prices and severe challenges of balancing the electricity grid, and altogether hamper the large-scale uptake of VRES in the energy system [37, 117]. In some countries, some of these issues have already started to take shape. For instance, in Germany wind power generation is concentrated mostly in the North, whereas demand is higher in the more densely populated southern Ruhr areas. Due to insufficient transmission capacity, grid operators are forced to shut down wind farms in the North, which would otherwise be producing energy at a marginal costs close to zero. To compensate for this deficit in supply, conventional power plants in the South have to throttle their production. Besides environmental consequences, the costs of redispatching measures in Germany for 2015 were estimated to be over €400 million [8]. Another example is found in Australia, which experienced several blackouts in 2017. VRES oversupply can lead to extremely low (sometimes even negative) electricity wholesale prices [30, 146], which in turn negatively affect the investment environment [146]. In Australia, this led to gas plants being pushed out of the market by solar PV and wind, leaving the energy system without any option to provide system flexibility [128]. This implies the need to increase the system's flexibility in order to facilitate increasing shares of VRES.

1.1.2. Requirements of future energy system

In addition to intermittent supply, the design of future energy system faces other challenges, such as increase in costs. The requirements which a future energy system should adhere to, are often divided into three categories: the availability, affordability and acceptability [42, 146]. Where the availability refers to the reliability of the energy system, i.e. the security of supply, the affordability concerns the costs and end user prices. The acceptability involves two aspects: social and environmental acceptability. Social acceptability refers to issues such as equal access to energy services, whereas environmental acceptability is related to climate change, local air pollution and environmental harm from the production of energy.

Various options are currently being researched to increase the reliability, affordability and environmental acceptability of energy systems with high VRES uptake, such as storage technologies, flexible generation, demand-side management [28], and transmission infrastructure [53, 146]. A promising approach to address these issues, which has recently received increased attention in scientific literature as well as from energy planners, is that of multi-energy systems (MES).

1.2. Multi-energy systems

A MES is defined as a system whereby different energy sectors, such as electricity, heat, natural gas, and hydrogen "optimally interact with each other at various levels" [95, p.1][1]. From this definition, all energy systems can be perceived as a MES from physical perspective, since different energy vectors always interact with each other [95]. The term "multi-energy" refers mostly to the approach of considering the optimization (economic, environmental and/or technical) of the whole energy system, by extending the scope of analysis beyond a single energy sector [95]. Traditionally, different energy sectors have been de-coupled[95]. However, interactions between the various sectors are recently increasing: several technological developments have led to an increase in investigation, scientific discussion as well as real-world application of different sector coupling concepts [64, 84, 95, 138]. For instance, the coupling of electricity, gas and heat sectors is increasing through combined heat and power (CHP) plants, the coupling of electricity and heat is increasing through electric heat pumps (EHP), coupling of hydrogen and natural gas sectors is increasing through steam methane reforming (SMR) and coupling of the biomass and hydrogen sectors is increased through biomass gasfication. A particularly interesting development in light of increased VRES uptake is that of power-to-gas (P2G) applications, such as the production of hydrogen from electricity through electrolysis [50, 97].

1.2.1. Advantages of MES

As opposed to separate energy systems, MESs offer several technical, economic and environmental benefits. First, integrating different energy sectors could be an effective measure to increase the energy system's flexibility, as well as to increase the overall optimization [132]. The different conversions possibilities allow optimization of the system through substitution of different energy carriers. Different sources can be used to meet different types of demand. For instance, in times of high supply levels from wind or solar, a MES would allow to use this electricity to meet electrical or heating demand, or produce hydrogen through electrolysis, hence increasing the flexibility. This way, increasing the possibilities to substitute one energy carrier into another can promote the uptake of VRES [64, 93, 118]. Lund and Münster [93], for example, showed how the incorporation of CHP plants in the balancing system can increase in the share of wind power from 20 to 40% in Denmark.

Second, through increased conversion possibilities, a MES allows to exploit the specific benefits of different energy carriers. This is especially evident for hydrogen, with both system operator [138] and researchers [55, 55, 134, 156] recognizing hydrogen as a potentially important energy carrier in future energy systems.

[1] Synonyms include sector coupling, integrated energy systems, or energy system integration [90]

As energy carriers, electricity and hydrogen offer particular benefits as well as limitations: whereas electricity can be generated sustainably and at low marginal costs, the long-term storage of electricity is inefficient and expensive [94]. On the other hand, hydrogen has the favourable features of the suitability for long term storage and the ability to supply energy when needed. The gas infrastructure is already in place and offers operational flexibility through a well established gas pipeline infrastructure and large storage capacities [95], being the results of decades of investments and developments [22]. Retrofitting of current natural gas infrastructure to hydrogen infrastructure (discussed in more detail in section 5.2.2), could significantly reduce investment costs [148]. Due to the possibility of carbon-neutral hydrogen production through electrolysis, MESs could promote the effective utilization of hydrogen, in particular in a system with high levels of VRES uptake.

Third, whereas some energy services are relatively straightforward to decarbonize, through electrification (such as light-duty transportation, heating, cooling, and lighting), other energy sectors are more difficult to decarbonize [95]. For instance, long-distance freight transport, shipping, air travel and industrial processes such as steel and cement manufacturing, currently have no commonly agreed upon, detailed pathway to decarbonization [27]. These sectors are, nevertheless, responsible for high shares of global CO2 emissions: in 2019, the combined emission of these sectors amounted to about 16.8% of total global emission [5, 72, 74, 75]. Through increased coupling between the various sectors, RES could be integrated within the whole energy system, as opposed to only within specific sectors.

Fourth and finally, due to increased conversion efficiency, MES could increase the economic and environmental efficiency [42, 44, 63, 95, 127, 143]. Capuder and Mancarella [17], for instance, showed how integrated energy systems can lead to significant operational and investment cost savings, primary energy saving, and emission reduction when compared to a reference case of separate systems.

1.3. Problem statement and research question

Ensuring an effective transition towards a sustainable future energy system requires careful planning, with grid operators facing substantial investment decisions in the coming years. Decisions on which energy generation technologies to invest in, their location and installed capacities, the required transmission infrastructure and how to ensure system flexibility are among the most critical [138]. However, the planning of the energy system is a challenging and complex task: energy systems generally operate on a large, border-crossing scales, and consists of elements on different levels — from small, low power electric appliances to large power plants. Investment in energy infrastructure are very capital intensive and have long lifetimes to consider. Furthermore, increasing integration of different energy sectors brings about complex interdependencies. Lastly, in addition to planning, the design of energy systems should include considerations on the operation. Whereas the planning refers to the future of an energy system, the operation refers to the present, where mainly the meeting of supply and demand is challenging. In light of increased VRES uptake, the meeting of supply and demand will be an increasingly challenging endeavour for system operators.

To aid decision-makers in optimally designing future energy systems, energy investment models provide a powerful tool and are often used to obtain valuable insights [111]. A MES investment model would allow, inter alia, to analyse the implications and potential benefits of increasing integration between different energy sectors. In particular, simultaneously considering investment decisions and the operation of a future MES, could lead to a more realistic representation of reality. This would enable a quantitative assessment on the capability of a MES to provide increased system flexibility. However, although energy system modelling literature is extensive, current literature does not fully capture the implications of increasing sector coupling.

1.3.1. Main research question

Therefore, this thesis aims to shed light on the implications of integrating different energy sectors. This thesis investigates the cost-optimal design of a future, sustainable energy system, by assessing the investment and operation of three design elements: generation, transmission and storage. This is realized through the development of a multi-carrier optimization model of electricity, heat, natural gas and hydrogen energy carriers. In order to demonstrate the correct workings of the model, a study on the Dutch energy system is conducted. The main research question of this thesis is as follows:

"What are the cost-optimal designs of multi-energy systems integrating electricity, heating, and hydrogen sectors, given different RES targets?"

The results obtained from this research can increase academic understanding of energy system planning and the implications of increased interactions between various energy sectors, especially in light of providing increased system flexibility with higher (V)RES penetration. Additionally, a modelling approach can be particularly valuable in aiding decision makers on the design of future energy systems (such as system operators) and provide a systematic and comprehensive study of the benefits offered by MES.

1.3.2. Description of the case study: the Dutch energy system

This section briefly describes the case study of this thesis, the Dutch energy system. Of all 30 members countries associated to the International Energy Agency (IEA), the Netherlands ranks as the third-lowest in terms of energy generation from RES, well below the IEA median of 12.1% [73]. However, energy generation from wind and solar photovoltaic (PV) increased by 50% between 2008 and 2018 and is expected to increase further in the coming decades [73]. The goals of the Dutch government, as stated in the Dutch Climate Agreement of 2019, include a reduction of 55% in emissions compared to 1990, with wind and solar energy providing more than 70 percent of electricity needs by 2030 [112]. These ambitions are put into practice in the Netherlands by formulating a target amount of RES capacity to be integrated into the system. To support the transition, the regional energy strategy was formulated [3]. In this strategy the Netherlands is divided in thirty regions, as shown in fig. 1.1. The regions are commissioned to investigate how electricity can be generated renewably and how the meeting of heat demand can be realized.

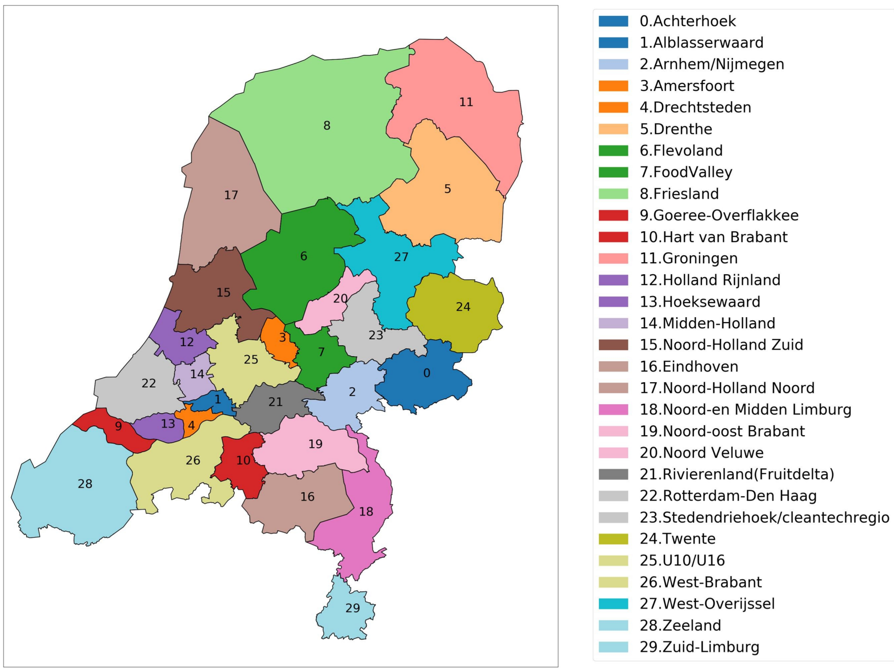


Figure 1.1: The 30 regional energy strategy regions in the Netherlands. Reprinted from [151]

In the Dutch energy systems, the transmission system operator (TSO) (TenneT) is responsible for the balancing of the energy supply and demand in the transmission network and management of the electricity transmission network. Gas network operator Gasunie is responsible for the management of the gaseous transmission network. To assess which changes are needed in the Dutch energy systems and infrastructure for 2050, a joint study was conducted by TenneT and Gasunie [107]. The most critical challenges which need to be addressed when designing the future Dutch energy system are the choice of energy generation locations, the expansion of transmission infrastructure and the ensuring large-scale flexibility. For all of these issues, TenneT and Gasunie envisions a critical role for sector integration, indicating that "the coupling of the complementary energy infrastructures for electricity and gas (i.e. hydrogen and methane) is essential to integrate large-scale RES in the energy system" [138, p.3].

1.4. Thesis outline

This thesis is structured as follows. First, a summary of relevant literature on energy system planning is given in the second chapter. Several definitions and concepts related to the design of energy system are introduced. Furthermore, a literature review was conducted in order to assess the state-of-the-art in MES optimization modelling. Second, the research approach and methodology is described in the third chapter. Thereafter, in the fourth chapter, the model is described conceptually. The fifth chapter describes the model formalization, which covers the translation from the abstract model of the fourth chapter into the workable, final model. This chapter also describes the experimental design and the constructed scenarios used to obtain insights from the model. The sixth chapter presents and discusses the results following from the model runs, as well as the validation of the model. The results of the model run are discussed in more detail by reflecting on both the qualitative and quantitative findings. The seventh and final chapter provides the conclusion by answering the research question and provides the recommendations following from this thesis.

2

Current state of MES modelling

In order to define a suitable modelling approach to answer the research question, first the literature on energy system investment modelling is consulted. This chapter is structured as follows. The first section briefly summarizes the broad field of literature on energy system modelling. Thereafter, the literature on MES optimization models is described. This is done in two stages: first, several literature reviews on MES models were consulted. This resulted in a comprehensive understanding of the available modelling approaches, their intended uses as well as advantages and limitations. The implications of various modelling aspects is described, resulting in what would be the ideal set of modelling aspects to answers the research question. Finally, the state-of-the-art in MES optimization models was described by analysing 15 models in depth based on these modelling aspects. It followed that none of the models found in literature cover the ideal set of aspects. From this, the specific modelling approach is defined. The following chapter describes the research approach in more detail.

2.1. Energy system modelling

Energy models are bound to abstract to a certain degree from reality, and are always a simplified representation of the real energy system [59]: the well known quote by Box & Draper states that "essentially, all models are wrong, but some are useful.' [13]. Nevertheless, specific energy problems, including the research question of this thesis, would be impossible to answer without reducing the scope and making approximations. Energy models can be powerful tools in supporting decision-makers. As a result, the modelling of energy system has developed to a very well-established field of research, with different users relying on energy models for a wide variety of applications, such as policymakers, researchers or large energy companies [59]. To provide guidance in this enormous field of literature, several authors have conducted extensive literature reviews. An overview of the literature studies which were consulted is shown in table 2.1: both general energy system review and MES specific literature reviews are included.

Table 2.1: Literature review studies on energy system modelling and MES modelling that were consulted, including the focus, the number of articles covered per review and the key challenges listed

Reference	Focus	Articles covered
Oree et al. [116]	GEP optimization with RES integration	-
Koltsaklis and Dagoumas [83]	Review of GEP	26
Pfenninger et al. [121]	Challenges of energy systems modelling	130
Dagoumas and Koltsaklis [25]	Review of models for RES integration in GEP	-
Hall and Buckley [54]	Categorization of energy system models in the UK	163
Mancarella [95]	MES concepts and modelling	172
Beuzekom et al. [12]	MES for urban sustainable development	78
Mancarella et al. [96]	Integrated MES modelling	132
Kriechbaum et al. [84]	Grid-based MES modelling	-
Mohammadi et al. [102]	Energy hub modelling approach	153

Energy modelling approaches can be categorized in top-down or bottom-up models [59]. Top-down approaches aim to provide a more economically and holistic perspective on an energy problem, often considering the energy system in a simplified and aggregated manner. Bottom-up models, on the other hand, incorporate more technological detail, allowing for comprehensive outlooks on future energy supply and demand and the role of different technologies [84]. The higher technological detail of bottom-up models requires more extensive data incorporation in the model, which are often paired with assumptions [59]. Since the problem formulation of this thesis requires a certain degree of technological detail - namely, the modelling of the cost-optimal energy system investment, which entails the complex interaction between different energy sectors - a first scoping step can be made towards bottom-up models.

Table 2.2: General categorisation of energy systems modelling approaches [59].

Top down	Bottom-up
Input-output models	Simulation models
Econometric models	Optimization models
Computable general equilibrium models	Partial equilibrium models
System dynamics models	Multi-agent model

As shown in table 2.2, bottom-up models can be subsequently divided into four types: simulation models, optimization models, partial equilibrium models and multi-agent models [59], with each having their advantages and limitations . [25]. Based on these, the second scoping step can be made towards optimization models. The theoretical basis of an optimization problem is to find the optimal solution of a given objective (either minimization or maximization), with certain decision variables under different constraints. Optimization models are considered robust, since they allow incorporating high details of techno-economic characteristics, making them suitable to analyse possible transitions of an energy system [123]. Although it leads to a single solution, and this "perfect foresight" characteristic could theoretically be perceived as a disadvantage, it is useful in the sense that is allows to formulate one or more ideal benchmark scenario(s) [25]. Therefore, these are very commonly applied in energy system expansion planning (especially GEP)[25], where they are used by, for example, system operators and national regulators to evaluate the adequacy of suggested policies [123]. Hence, for the remainder of this thesis the scope is limited to optimization models.

2.2. Relevant modelling aspects to consider

Several authors have provided schemas to categorize the wide variety of models. Five literature review studies were consulted to determine which modelling aspects are relevant to be considered in this thesis. First, Hall and Buckley [54] reviewed 110 publications on energy system modelling in the UK and propose a schema to classify models based on the model purpose and structure, technological detail and mathematical approach. Second, Kriechbaum et al. [84] reviewed grid-based MES models, which they categorized in five general and four specific grid-based MES modelling aspects. Third, Beuzekom et al. [12] reviewed 72 tools on MES planning and optimization for urban development. They categorized models in three modelling approaches, eight general and technical characteristics and eight energy characteristics. Fourth, Guelpa et al. [51] reviewed the state-of-the-art in MES infrastructure literature. They categorized different models based on technologies, operational strategies and energy networks (electricity, gas, or heat) considered. Finally, Mohammadi et al. [102] reviewed literature on the energy hub, a concept often found in MES literature (the concept will be introduced and discussion in more detail in section X). From these studies, 10 modelling aspects were used to categorize the literature on MES optimization models. Table 2.3 lists the 10 modelling aspects as well as their available levels.

Modelling scope: First, the modelling scope can be planning or operation. Whereas "planning" refers to the future design of energy systems, the “operation” refers to the current situation. The operation of an energy system can be a challenging endeavour, since the supply of energy has to be met with the demand at all times. Besides variations resulting from several technical, institutional and economic factors, the balancing of supply and demand will become increasingly difficult with higher shares of VRES [116].

Assessment criteria Optimization models are commonly used for cost-optimization problems. However, they are increasingly applied for the optimization towards other objectives, such as minimization of environmental, reliability, or multiple objectives [84].

Expansion planning elements Energy system planning involves the design of future energy systems through three components. First, *Generation Expansion Planning*(GEP) consists of finding the optimal long-term plan for the construction of new generation capacity, such as the optimal type of energy technology, the

Table 2.3: Modelling aspects used to categorize literature on MES optimization models

Aspect	Levels			
Modelling scope	Planning	Operation		
Assessment criteria	Economic	Environmental	Technical	Other
Expansion planning elements	GEP	NEP	SEP	
Mathematical formulation	LP	MILP	MINLP	
Spatial coverage	Local	District	Country	
Spatial resolution	Buildings	Districts, cities	Regions	
Time horizon	Short	Medium	Long	
Time step size	Minutely	Hourly	Monthly	Yearly
Level of detail	Black-box	Grey-box	White-box	

capacity, location and time of construction [83, 116, 133]. GEP is a well researched field in energy literature [51], and is generally a complex task due to the wide range of relevant aspects that need to be considered, such as financial, economic, environmental, regulatory, technical, operational, social considerations, as well as potential interdependencies with other sectors [51]. This is especially true when integrating RES, since the stochastic and intermittent nature bring about investment risks, and risks related to the development of global carbon and fuel markets [25, 83]. Second, *Network Expansion Planning* (NEP) refers to the process of determining the optimal network specifications, such as transmission cables and piplines [133]. Numerous factors influence the decision, often leading to an enormous number of alternatives to consider in NEP [133]. Third, *Storage Expansion Planning* (SEP) focusses on the planning of Energy Storage Systems (ESS), such as the optimal combination, type, selection and size [159]. Available ESS technologies, such as batteries, pumped hydro storage or hydrogen storage, differ greatly in terms of their investment costs, capacity, lifetime and others characteristics [94]. Similar to GEP and NEP, several factors, such as technical features, economical cost and local wind power characteristics, can influence the ESS selection.

Mathematical formulation The mathematical formulation relates to which mathematical modelling technique is used to obtain the optimal solution. In linear programming (LP), all relationships are fully linearized, which are generally easier to use, however could lead to deviations when describing non-linear phenomena [11]. In mixed integer linear programming (MILP), decision variables are discrete and non-convex. This allows to formulate in greater detail, such technical properties and relations, for example allowing to model on/off mode individuals units [115]. Mix integer non-linear programming (MINLP) also allows for non-linear objective functions and constraints [124]. However, although this does result in the most close approximations of real world systems, it adds a significant layer of complexity.

Spatial resolution and coverage The spatial coverage refers to the geographical boundaries of the energy model. The spatial coverage can range from very local, such as an individual building [4, 39], to medium scale such as districts [40] and large scale model such as countries [122] or even multiple countries [29]. Whereas spatial coverage refers to the total area covered by the model, the spatial resolution refers to the granularity of the locations in the model. The highest degree of spatial resolution is on the level of individual buildings, whereas the lowest level concerns countries.

Time horizon and time step size The temporal horizon refers to the total time span covered by the model. This can range from short periods, such as a single day, up to longer ones, spanning multiple years or decades. The temporal resolution refers to the size of the time-steps in the model.

Level of detail Energy transmission via networks can be modelled in three different levels of detail: black-box, grey-box and white-box [46]. Black-box refers to data input-output models without representation of the underlying physical principles [125]. In general, black-box models are more straightforward and easier models. Black box models feature energy flows transmission without incorporating losses [84]. *White box* (or glass box) offer higher degrees of detail and consider physical principles to calculate load flows and conversion efficiencies [125]. In white box models, network flow losses are incorporated as a function of the corresponding flow (based on conservation laws) leading to more accurate but also induce non-linearity [84]. Consequently, this affects computational time. A third category, between black and white box models, are *Grey box* models, which use simplified physical representations [88].

2.2.1. Trade-offs in computational time

The selection of modelling aspects almost inevitably leads to a trade-off between computation time on the one hand, and the degree of realistic representation of the problem in question on the other hand [84, 116]. The trade-offs are related to the six of the model technicalities listed in table 2.3: the mathematical formulation, the spatial coverage and resolution, the time horizon and time step size, and finally the level of detail. Hereafter, the implications of each of these is discussed.

The first trade-off is related to the mathematical formulation. The identification of the global optimum among the local optima in non-linear problems requires much greater computational effort [147]. Consequently, MILP and MINLP are often only applied on smaller scale energy systems: most energy optimization models for planning are LP models [21].

Second, since energy supply and demand are often in different locations [84], another important aspect to consider in MES optimization modelling is the spatial resolution and coverage. In general, larger models with higher spatial resolutions leads to higher computational times. Most publication on MES modelling focus on a small or medium spatial scale (suburbs, districts, cities or small regions), with higher spatial resolution; these often apply either MILP or MINLP. Publications on country scale level present a much smaller share in MES optimization literature [16, 84]. Due to the trade-off on computational time, these studies (such as [60, 92, 119, 135]) almost exclusively use LP and lower spatial resolution.

Reducing the spatial resolution results in simplification on the spatial distribution of demand, the stochastic supply profiles of VRES [84] and details of network transmission expansion planning [151]. Such simplifications on land-use characteristics in energy system planning can lead to different outcomes in terms of the generation mix, the spatial distribution of generation technologies and the total costs of the system. The implications of spatial simplifications should be considered carefully. For instance, Hörsch and Brown [65] analysed the effects of the spatial resolution in an optimization problem including GEP and NEP. They compared two extremes of spatial resolution: a single node in a region, compared to many nodes in the same region. They found that the cost-optimal network configuration is about 20% less expensive than the single node variant, and can lead to exposure of transmission bottlenecks and inaccurate using of land area for RES capacity. Similarly, Li [87] analysed heating future scenarios in the UK using a spatially explicit model and concluded that different spatial resolutions lead to different optima. In addition, compared to traditional energy sources, wind turbines and solar panels are characterized by more intensive land-use. Also, social resistance poses a problem in the development of VRES, due to aesthetic reasons or noise pollution [151]. Therefore, in order to enable a realistic investigation of the future energy system with high VRES uptake, spatio-temporal details should be considered. This can be realized through land-use limitations and the location-specific production profiles.

Third, the time horizon and time step size is critical [20, 56, 157]. Depending on the research question, the temporal resolution can range from micro seconds, to hourly, or months in some cases [16]. A smaller time steps leads to more realistic results: for example, Hawkes and Leach [56] show a difference of 50% in energy capacity needed for of a micro CHP power plant between 5 min and 1 hour time resolution for the energy capacity a micro combined heat and power plant. Modelling using a unsuitable resolution can lead to over- or underestimation of RES shares [20]. Larger time steps, often found in GEP optimization models, are not able to fully capture the operation details [116].

Finally, the level of detail can be important to consider in MES, since different energy sectors and therefore also different network are connected (such as electricity, gas and district heat). The formulation of power flow equations that describe the physical laws (such as the relation between electric voltage and current, and gaseous pressure) can be complicated to model [84], especially since the physical relations are specific for each energy carrier, making it difficult to interconnect different energy carriers [46]. Hörsch et al. [66] compared solving methods for a linear optimal power flow problem, in a system with a high share of VRES and found that PTDF can greatly increase model solving time. Therefore, in general, white box approaches are found less often in MES optimization literature, especially on larger scales. Higher level of details, combined with higher degree of spatial and temporal resolution, require significantly more computational time. None of the models found in the literature operate on white-box level of detail whilst simultaneously covering country or district spatial coverage.

2.2.2. Other considerations

Second, numerous authors mentioned the need of simultaneous optimization of both operation and investment in MESs [25, 82–84, 116]. Optimization models should account for variability and uncertainty presented by VRES; combining investment decisions and operation leads to more realistic representations of the real energy system and could provide valuable insights. Whereas optimization models, in particular on GEP, traditionally primarily focused simply on ensuring adequate generation capacity [116], most recent models consider both operation and planning. However, as also argued by Beuzekom et al. [12], the issue still appears to be under addressed in MES literature, with no models combining planning and operation into a practically feasible model. The synthesis of planning and operational in MES optimization models is often technically challenging because it requires combining small time steps (ideally hourly) with high technical details and sufficient spatial resolution. This would allow to provide a holistic perspective on the value of different operational flexibility measures, ideally when considering both GEP, NEP and SEP.

2.2.3. Selection criteria

The previous section discussed the implications of the modelling aspects. From this, the set of levels for the modelling aspects most fit to answer the research questions can be formulated. The cost-optimal design of a future, country-scale multi-energy system should be investigated by considering the three design components of GEP, NEP and SEP. In order to capture increased VRES uptake and increased integration of different electricity, heating, natural gas, and hydrogen sectors, the investment and operation should be simultaneous captured, on at least an hourly timescale over a year, ideally considering region-specific temporal VRES supply profiles. The ideal configuration is as follows:

Ideal set of modelling aspects to answers the research question

- **Modelling scope:** should capture both operational and planning of the energy system, in order to account for the stochastic characteristics of VRES in a highly renewable energy system.
- **Assessment criteria:** should at least allow for cost-optimal minimization.
- **Expansion planning elements:** Ideally, all three expansion planning elements (GEP, NEP and SEP) should be included in order to provide a holistic analysis on the provision of system flexibility.
- **Spatial coverage and resolution:** The spatial coverage should be country level, and the spatial resolution should be at least regions to account for the spatio VRES supply profiles. Although MILP or MINLP approach could lead to an even more realistic representation, a LP approach is sufficient.
- **Time step size and time horizon:** Since the focus of this thesis is on RES integration, with emphasize on the benefits of integrating different energy sectors in terms of provide system flexibility, the time step size should be at least hourly, in order to account for VRES fluctuations. In addition, in order to account for weekly and seasonal differences, an annual horizon is preferred.
- **Level of detail:** To account for interdependencies between different energy sectors in a MES, the level of detail should be grey-box.

2.3. State-of-the-art in MES optimization models

After determining the selection criteria, the state-of-the-art of MES optimization models is reviewed. A systematic literature review was followed, as defined by van Wee & Banister as "a comprehensive overview of (or a selection of) the literature in a specific area, bringing together the material in a clearly structured way, and adding value through coming to some interesting conclusions"[144, p.297]. By reviewing the literature on MES optimization modelling, often used practices and approaches are identified, which allows to formulate a more precise modelling approach by addressing the knowledge gap. Two databases were used to gather literature: Scopus and Web of Science. The search terms that were used can be found in Appendix A, including the number of results per database and search term. For these search terms, the time range was set to 1990 to present and articles written in other languages than English were excluded. In addition to these search terms, a snowballing technique was used. The initial findings included studies covering a wide field of modelling aspects, addressing a range of research subjects: ranging anywhere from large, macro-economic models with multiple energy sectors to bottom-up, local models. The literature review is thereafter limited by including only those which fit the aim of the research, resulting in 15 models being investigate in more detail, as shown in table 2.4.

Table 2.4: MES optimization models found in literature

Ref.	Model name	Modelling scope	Assessment criteria	Expansion planning elements	Mathematical approach	Spatial coverage	Spatial resolution	Time horizon	Time step size	Level of detail	Additional notes
[92]	EnergyPLAN	planning	Economic	GEP, SEP	Unspecified	Country (Denmark)	Region	year	hourly	Unspecified	Developed and expanded since 1999
[16]	HyFlow	operation & planning	Technical (reliability)	GEP, NEP, SEP	Unspecified	Region	Households, regions	flexible	Flexible	high detail	Highly detailed network characteristics
[145]	GHOTEM	operation	Technical (reliability)	none	Unspecified	Region (Veneto, Italy)	Buildings	Unspecified	Unspecified	Unspecified	
[135]	urbs	operation & planning	Economic	GEP, SEP	LP	Country	Region	Year	hourly	Unspecified	Demand response
[119]	Calliope	operation & planning	Economic	GEP, SEP	LP, MILP	Country (UK)	Region	Year	hourly	Unspecified	Ramp rates, focus on spatial temporal explicitness, transparency (open-source).
[60]	oemof	operation & planning	Economic	GEP, NEP, SEP	LP	Country	Region	Year	hourly	Unspecified	Ramp rates for storage, open source, adaptable
[82]	I-ELGAS	operation	Economic	NEP	LP	Country (NL)	Region	year	hourly	grey-box	No investment cost
[44]	-	operation & planning	Economic, environmental	SEP	MILP	Region (Zurch, Swiss)	-	year	hourly	grey-box	Focus on storage
[39]	-	operation & planning	Economic, energy, environmental	GEP, SEP		Local / buildings	-	year	hourly	grey-box	
[64]	-	operation & planning	Economic	GEP, SEP		District (Tongzhou, Beijing)	-	year	hourly	grey-box	
[89]	-	operation	Economic, technical, environmental	none	Unspecified	District (Campus, University of Manchester)	small	day	hourly	grey-box	Operational costs
[98]	-	operation	Economic	none	MILP	District	-	day	hourly	white-box	
[7]	-	operation	Unspecified	none	MINLP	Unspecified	-	day	hourly		
[151]	GRIM	operation & planning	Economic	GEP, NEP, SEP	LP	Country (NL)	Regions	year	hourly	grey-box	Detailed spatio-temporal VRES supply details
[18]	IPHO	operation & planning	Economic	GEP, SEP	MILP	Region / country (Jing-Jin-Tang , China)	-	year	hourly		No network, limited investment costs

2.3.1. Selection of modelling formalism

Based on the selection criteria formulated in section 2.2.2, the most suitable model can be determined from table 2.4. First, since this thesis emphasizes investigating how MES can increase system flexibility, the model should be able to capture all three expansion planning elements (GEP, NEP and SEP). From this, the number of models is limited to three: HyFlow (Hybrid Load Flow-Modelling Framework) [16], oemof (Open Energy Modelling Framework) [60] and GRIM (Greenfield Renewables Investment Model) [151]. Second, the focus of this thesis is on a MES of country; therefore, only models with a spatial coverage of country are suitable and the scope is limited to oemof and GRIM. Third, simplifications on land-use characteristics should be avoided, since these can lead to unrealistic outcomes in terms of the generation mix, the spatial distribution of generation technologies and the total costs of the system. Finding the cost-optimal design without taking into account the location-specific characteristics leads to inaccurate results. Therefore, VRES should be modelled with high spatio-temporal resolution. The spatio-temporal characteristics of VRES can be captured in two components: the spatio-temporal supply profiles of regions, and the land-use constraint per region. Of two models, GRIM is able to capture both in a systemic way, and hence allow for a more accurate inclusion of spatio-temporal details of VRES supply. Unique from the approach of GRIM is that, in contrast to other models, does not assume unlimited land available for VRES technologies. The method found in GRIM quantifies the geographical distribution of the land-use of VRES, allowing for a more realistically modelling approach to assess the implications of land-use constraints on, for instance, the total costs. Moreover, this approach enables to spatio distribution of GEP, NEP and SEP more accurately.

However, GRIM currently only handles electricity energy assets, and hence is not a MES model. Extending GRIM towards a MES model would lead to a more realistic representation of reality as compared to currently developed MES models. In turn, allowing to analyse the benefits of increasing integration between different energy sectors from a quantitative, holistic assessment on the capability of the system increased system flexibility. Such an energy investment models provide a powerful tool to aid decision-makers, since it would describe the optimal planning of future energy systems with integration of (V)RES through a high spatial and temporal resolution and consider multiple expansion planning elements.

This chapter provided a discussion of the literature on energy system investment modelling in general, from which the scope was limited to an optimization model. Thereafter, several literature reviews on MES modelling were consulted to create an overview of modelling aspects to consider and their implications. The ideal set of modelling aspects to answers the research question was formulated, and finally, the state-of-the-art in MES optimization models is described by analysing 15 models in depth. It followed that none of the models found in literature cover the ideal set of aspects. The next chapter will describe the research approach in order to construct the optimization model and answer the research questions.

3

Research approach and methodology

This chapter describes the research approach and methodology in order to answer the research question. The objective of this chapter is to provide understanding on how the research is conducted, the approaches used, the structure followed, and how the main research question can be answered. This chapter is structured as follows. First, the sub research questions are formulated and the general structure of the thesis is given. The content per chapter and how the different chapters relate to one another is shown in the research flow diagram. Second, the modelling approach is discussed in more detail.

3.1. Sub research questions

The objective of this research is to determine the optimal design of a MES and obtain insights in the implications of increasing integration between different energy sectors. In order to answer the research question, a modelling approach is followed. A modelling approach is generally used to address issues related to a lack of understanding in the functioning of a (socio-technical) system [62]. Models can be very powerful and useful when investigating complex situations [111], and are commonly used to study energy systems. Numerous energy models exist, each with their own associated advantages and limitations. Therefore, the current literature on energy system modelling was consulted to assess the state-of-the-art in MES models. The outcomes of this literature review allow determining which modelling formalisms and types are suitable to answer the main research question, and which modelling aspects should be considered. The first sub-question is as follows:

Sub question 1: *Which modelling aspects need to be considered when designing an optimal MES, and how are these reflected in literature?*

The first sub research question is covered in chapter 2. It is established that the model should be an extension to GRIM. Furthermore, this chapter describes the implications of the various modelling aspects, leading to a comprehensive understanding of the benefits, limitations and intended uses. From this, the ideal model configuration is formulated and the modelling approach of this thesis is established. GRIM captures only electricity assets, and therefore the second research question is centred on the construction of the multi-energy carrier model:

Sub question 2: *How can the GRIM be extended towards a multi-energy carrier model, in terms of the mathematical relationships?*

To construct the model, the following steps are taken: First, a description of the current, non-integrated energy system is given to define the system boundaries. Then, the theoretical framework to describe the energy flows within a MES is presented. From these, the overall structure and the workings of the model can be described, which can then be translated into mathematical relationships. The second sub research question is covered in chapter 4. Once the model is described in terms of the mathematical relationships, it could theoretically produce outcomes. However, in order to obtain valuable insights from the model, first the data input and values for parameters have to be defined, and the model should be verified. Besides these, the experimental design has to be determined, i.e., the scenarios used to run the model. This is covered in the third sub research question:

Sub question 3: *How can the conceptual model be translated to a workable model?*

The third sub research question is covered in chapter 5. After the construction of a workable model which is able to produce valuable outcomes, the model can be used to obtain insights based on a case study. The case study in this thesis centred around the geographical scope of the Netherlands. By running the model based on a set of constructed scenarios, the implications of increased integration between different energy sectors can be analysed. This is done by comparing a baseline scenario without integration, with a scenario with integration. The fourth rub research question covers this:

Sub question 4: *What are the implications of increased integration between different energy sectors on the energy costs, generation mix, and spatial distribution?*

The fourth sub-research questions is covered in chapter 6. This chapter will also describe the validation of the model. The analysis consists of analysing how the optimal solution changes for different inputs, namely different levels of RES targets, local RES targets, land-use restrictions and level of sector integrations.

The content per chapter and how the different chapters relate to one another is shown in the research flow diagram (fig. 3.1). The modelling approach is described in more detail in the next section.

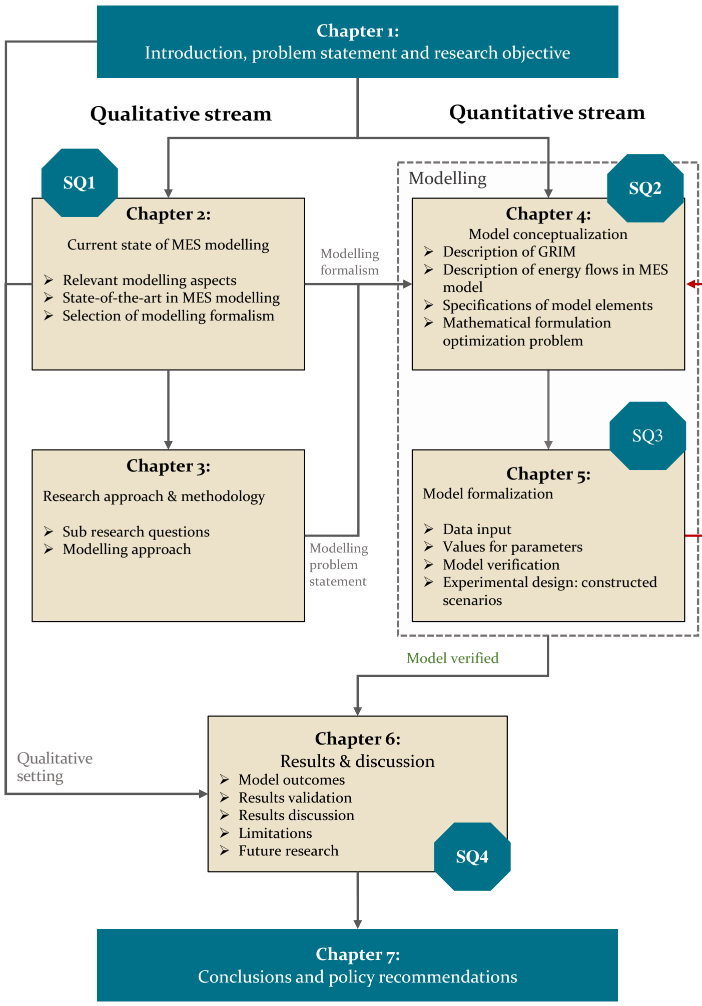


Figure 3.1: Research flow diagram

3.2. Modelling approach

The goal of a modelling approach is to "answer specific questions", and not to "provide general descriptions of systems" [111, p.5]. Therefore, prior to construction of the model, the modelling problem statement is formulated. First, the overarching rationale to construct the model is captured in the policy question. The fundamental goal of an energy system is to "deliver energy that either directly or indirectly provides goods and services to meet people's needs and aspirations" [45]. In addition, in section 1.1.2, the three requirements of an energy system are defined: the affordability, availability and acceptability. From this, the policy goal for this thesis is to determine the (cost-)optimal design of a (multi-)energy system with increasing shares of supply from RES.

However, determining the optimal design of a MES is a complex assignment, due to several characteristics: First, energy system operate on very large scales and consists of components on various levels: ranging from small, low power electric appliances to large power plants [133]. Secondly, energy infrastructures are often very capital intensive, with investment costs usually in the range of hundreds of millions of euros [101]. Also, long lifetimes need to be considered, ergo investment decisions need to be made under uncertainty [101]. Thirdly, since energy systems can be described as socio-technical systems, in addition to the technical components also institutional and economical considerations need to be taken into account [101, 155]. Finally, a MES results in increased integration of between energy sectors, which brings about complex interdependencies [42]. A model can aid in addressing this policy issue by providing a quantitative tool to systematically find the optimal investments. To define more accurately what the model should capture, the modelling problem statement is as follows:

"What is the impact of sector integration, land-use restrictions and different RES uptake scenarios on i) the total system costs; ii) the optimal investment in different generation, conversion and storage technologies and iii) the capacities of network transmission flows?"

The research approach and methodology to answer the research question are described in this chapter. The following chapter will describe the conceptual model.

4

Model conceptualization

This chapter describes the conceptual model which was developed in order to answer the research questions of this thesis. The model conceptualization entails the "collection of statements, assumptions, relationships and data that describe the reality of interest. A schematic description of how the conceptual model is constructed is shown in fig. 4.2, which also indicates the structure of this chapter. First, it was determined that the model should be an extension on the GRIM. Therefore, prior to describing the model of this thesis, the GRIM is explained in more detail in the first section. Second, the system boundaries of the extended model are determined before describing the relationships in the conceptual model: this is done by providing a technical description of the current separated, non-MES energy stem. The third section describes the framework which is used to describe the various flows of energy within a MES, the energy hub. The fourth section describes which energy inputs, outputs and technologies are included. Once these are defined, the mathematical relationships of the conceptual model can be described, which is the covered in the fifth section.

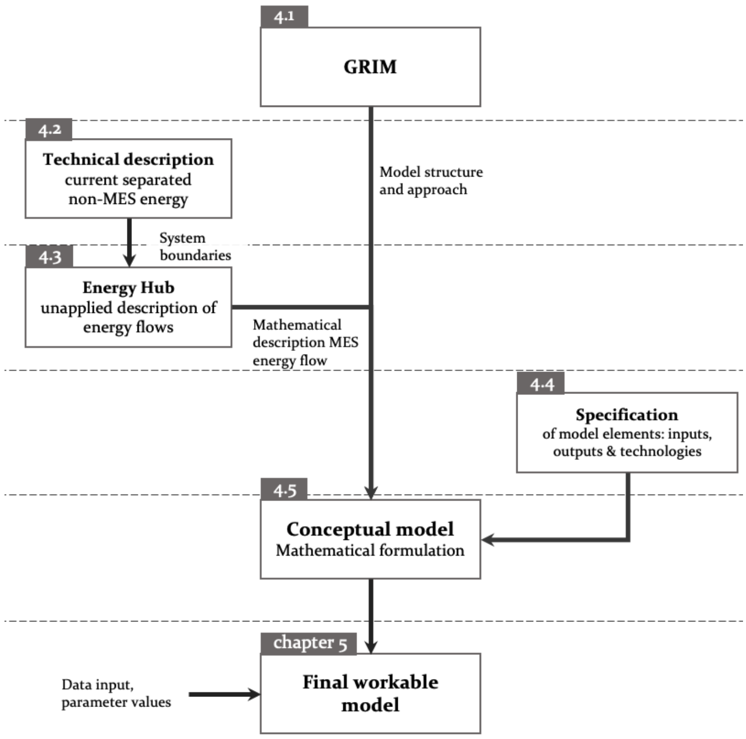


Figure 4.1: Schematic of how the conceptual model is constructed

4.1. Description of GRIM

Wang et al. [151] developed a spatially explicit planning approach for modelling power systems with higher shares of RES. With this approach, three domains are connected: land cover assessment, VRES potential and energy system planning: see fig. 4.2. GRIM is a (cost-) optimization model, which is able to incorporate the location-specific land-use of VRES and the location-specific VRES production profiles when optimizing the investment and operation of an energy system with high shares of RES. As discussed in chapter 3, considering the spatial-temporal details of VRES is increasingly important. Whereas land cover aspects have largely been ignored in literature, GRIM accounts for these in two ways: the location-specific VRES supply profiles, and the VRES potential per region based on the available land, leading to a more realistic outcome.

The planning approach consists of four components: the modelling of polygons and locations of nodes, the land cover assessment to obtain VRES potential estimations per region, the location-specific VRES data and finally the optimization. The approach is generic, meaning it allows to systematically find all of these components. However, the land cover assessment is not the main focus of this thesis and will be explained from the point of view of the case study. However, this can also be applied to other geographical boundaries of interest. For more details on the generic approach for, in particular the land cover assessment, see Wang et al. [151].

Polygons and locations of nodes: The model used a data set of coordinates that present geographical boundaries of regions to be modelled. In this thesis, this consist of the thirty regional energy strategy regions, as shown in 1.1. These regions can be represented as polygons. The centroids of the regions are the locations of the nodes in the optimization model: see top of part of fig. 4.2.

Land cover assessment and VRES potential estimation: After the regions are defined, the land inside each region is assessed to obtain values for the available area for VRES instalment. The land cover assessment allows to include, partially include, or exclude land. Land is classified in categories based on Corine land cover database [1]. The generic approach to obtain VRES potential estimations is described in Wang et al. [151]. The land cover assessment for the Netherlands is detailed in 5.2.2

Location-specific VRES data: In contrast to conventional energy sources, wind and solar are not always readily available. In other words, the supply of VRES follows an intermittent character. In addition, these vary between different locations. In order to represent the intermittent characters of VRES, the model accounts for the location-specifics of the VRES hourly profiles for a year. The data is normalized such that the values lie in the range of 0 to 1. The location-specific VRES profiles for the Netherlands are detailed in 5.2.2. An example of the hourly capacities of onshore and wind over a full year is shown in the bottom part of fig. 4.2.

Finally, the optimization allows to find the cost-optimal configuration of the energy system in terms of the investment in generation technologies, transmission and storage technologies and the operation of the energy system. The optimization problem is described in more detail in section 4.5.3. The model is written in the programming language Python [1]. After describing the modelling approach of GRIM, the following sections will describe how the model is extended towards a MES model, following the structure shown in fig. 4.2.

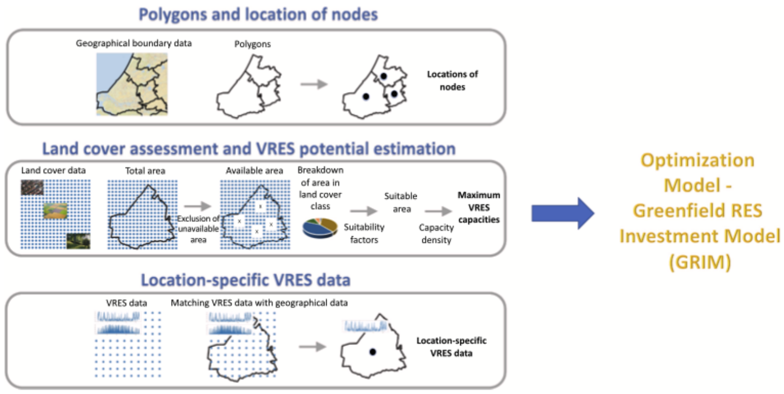


Figure 4.2: Schematic of the spatial planning approach. Reprinted from [151]

[1] Packages used include numpy, pandas, pyomo and others. The optimization solver used is Gurobi [2], although others can be used as well.

4.2. Technical description of non-integrated energy systems

A comprehensive understanding of the current energy system is necessary in order to define the system boundaries of the model and to place the results in context (chapter 6). The energy system can be defined as a "system that comprises all components related to the production, delivery, and use of energy" [77]. Fig. 4.3 provide a schematic on how the current energy system can be described [45].

The energy systems consist of sequences of several steps. Fig. 4.3 shows a schematic of the energy system, where the steps are indicated on the left side of the figure. The flows of energy carriers through the stages shown are illustrative examples and are not fixed. The starting point is the *extraction and treatment* of energy supply. This entails the raw materials as they occur in nature, such gas wells. Secondly, these are converted to *primary energy resources*, which are defined as the energy embodied in natural resources, i.e., energy carriers that have not been subject to any engineering conversion process, such as the refinement of crude oil, uranium or solar radiation [45]. Third, primary energy sources are harnessed and converted into *secondary energy carriers*, for example electricity or hydrogen. Secondary energy carriers are generally more easily transportable than primary energy sources. In the fourth step, these secondary energy carriers are distributed, through for example the electricity grid or gas pipelines. In the fifth step, they are distributed and used in end-use applications for the provision of energy forms, such as heat, cold or kinetic energy. Finally, these are required to deliver energy services, such as cooking, thermal comfort or mobility [45]. Not all steps are considered in this thesis: the scope is limited to the *energy sector*, as indicated with the dotted red area in fig. 4.3. The energy sector "comprises all energy extraction, conversion, storage, transmission, and distribution processes that deliver final energy to the end-use sectors" [77, p.516].

The description of the energy system in terms of a linear process (fig. 4.3) allow to establish the terminology needed to describe the different stages of energy flows and to define the system boundaries. In the next section, a concept to describe the energy flows in a non-linear MES, the energy hub, will be introduced.

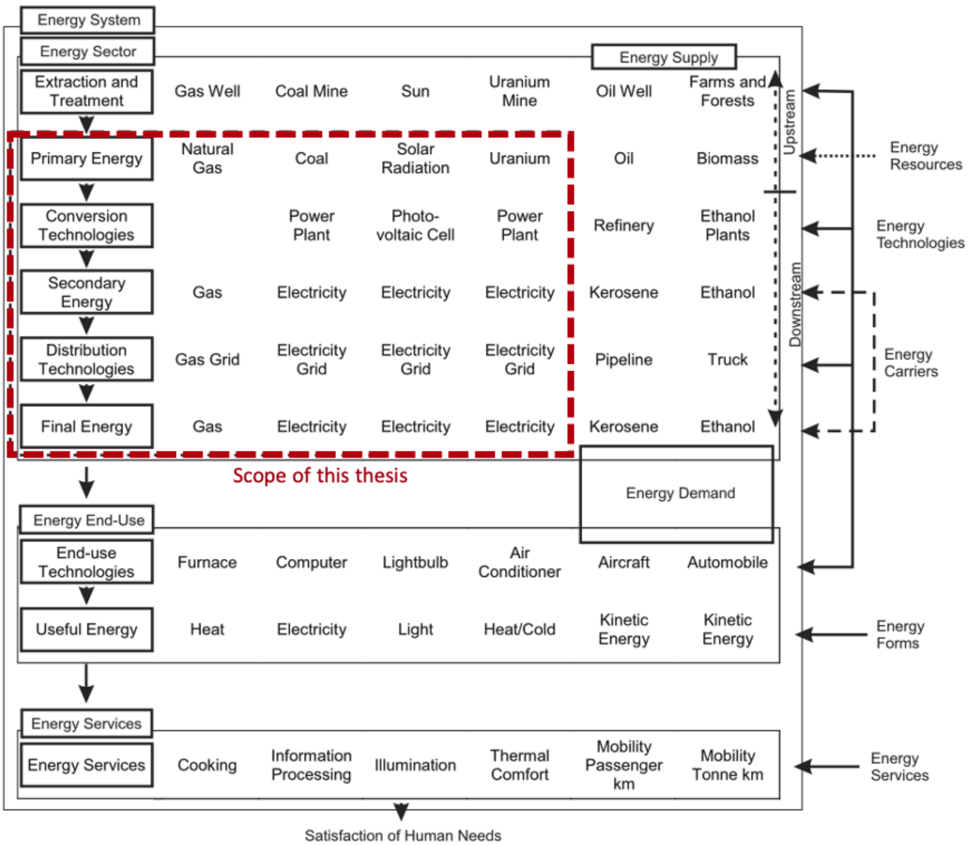


Figure 4.3: Schematic of the energy system and energy sector. Flows of energy carriers through the stages are illustrative examples and are not fixed. The red area indicated the system boundaries for this thesis. Adapted from [45, 84]

4.3. Energy hub

The inclusion of energy storage, network transmission and the numerous options of converting one energy carrier into another make it increasingly difficult to describe the energy system as a simple linear process. An approach often used in MES modelling literature is that of an energy hub, first developed by Geidl and Andersson [47]. An energy hub is a framework for describing the generic interface between different energy inputs and outputs of multiple energy carriers. It allows to describe the different energy flows and optimization a single hub in terms of (mathematical) relationships, in terms of four components: the input flows, conversions, storage and finally the output of final energy demand. The basic model of an energy hub is shown in fig. 4.4: the centre of the figure shows the hub, wherein conversion and storage occur. P represent the inputs and L the outputs; α, β, and ξ represent different energy carriers.

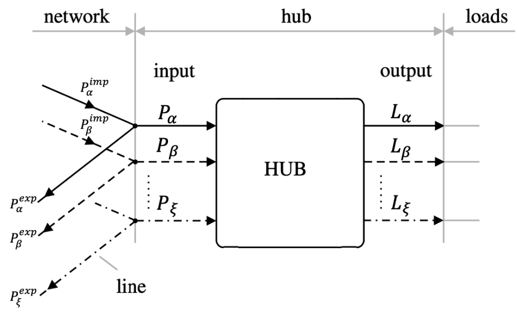


Figure 4.4: Basic model of an energy hub. The centre shows the energy hub: P represent the inputs and L the outputs; α, β, and ξ represent different energy carriers. The flows over lines are indicated with P^{imp} and P^{exp}. Adapted from [47]

Single energy hub optimization A single hub can be optimized through two processes: conversion to other energy carriers or the storage of energy. By fixing the outputs, other three components (the inputs, conversion and storage) can be changed so that the demand is optimally met. Various energy flows can be considered as inputs, conversion, storage or outputs, these are defined more specifically as follows. First, the *inputs* of the energy hub of a given region consist of two types of energy flows: energy generation (secondary energy carriers, see section 2.2.1) and importing transmission flows from other regions. Second, internally in the hub energy *conversions* can occur, referring to the process of changing one type of energy carrier into to another type. Third, energy *storage* refers to the process of reserving energy in a medium; then, the stored energy can be converted back into energy when needed [94]. Fourth, the *outputs* consist of two types: the *energy demands*, i.e. the energy flows used for end-use applications (such as heating or electrical load) and the *exporting transmission flows* to other regions.

Connecting multiple energy hubs Multiple energy hubs can be connected. These are connected in a network, by considering the energy transmission between regions as either input (import) or output (export): see fig. 4.5. The flows over lines are indicated with P^{imp} and P^{exp}.

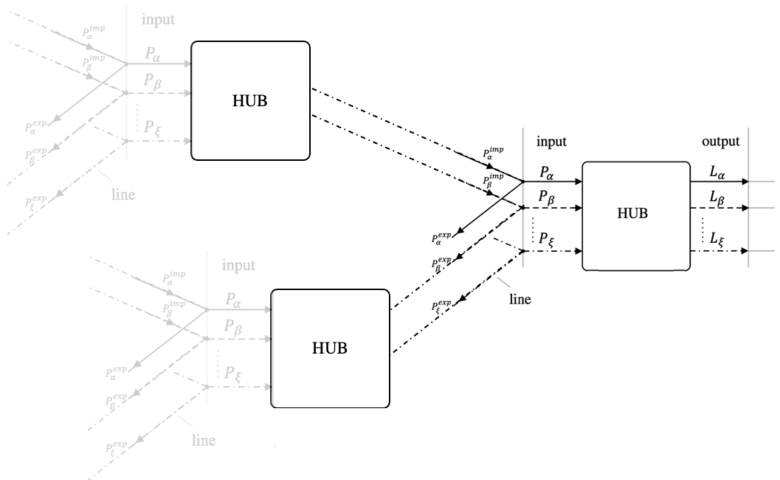


Figure 4.5: Description of connecting multiple energy hubs in a network. model of an energy hub. The flows over lines are indicated with P^{imp} and P^{exp}. Adapted from [47]

4.4. Specification of model elements

The previous section described the generic approach to model the different energy flows in a MES. This section specifies the boundaries of the energy system considered, that is, which elements are included and which are left out. First, the selection of the different energy inputs, energy outputs, conversion technologies and storage technologies is described. Then, in the following section, the specific description of the conceptual model is given.

4.4.1. Energy inputs

Several energy inputs can be considered. The IEA categorizes different energy sources into coal, oil, natural gas, nuclear, hydro, biofuels and waste, geothermal, solar, wind, tidal/wave/ocean, and other sources [6]. However, including all of these would lead to an overly complicated model, and therefore most MES models reduce this number significantly. The number of energy hub inputs is reduced to eight; hereafter, the rationale is given for the exclusion of several inputs.

Excluded energy sources As a starting point, the physical situation of a country determines the possibilities of the energy systems to a large extent; they are a set of relatively 'hard' constraints [23]. Therefore, hydropower, nuclear, geothermal, marine, solar heating, concentrating solar power and district heating are not considered because of the relative small contribution in the area of interest, the Netherlands. Second, coal and oil are not considered. Although these currently represent a large share in global total energy supply (26.9% for coal and 31.6% for oil in 2018, [6]), the GHG emissions of these are amongst the highest of all energy sources. The lifecycle GHG emission of coal ranges from 675 to 1689 gram carbon dioxide equivalent (CO2eq) per kilowatt-hour (kWh) [15]. The lifecycle GHG emission of oil ranges from 510 to 1170 gram CO2eq/kWh [15]. Since a future energy system is considered with the goal of meeting RES targets, these energy sources are not considered.

Included energy sources After excluding several energy sources, eight energy inputs are included in the model. The first two energy sources included are electricity from onshore wind and electricity from solar PV, since these are among the most promising sources to provide long-term renewable energy supply [35]. Offshore wind technology is promising due to higher wind speeds and more wind hours [35], but also has higher investment costs [79]. Offshore technology is less mature than onshore and, for the purposes of this model, resembles more or less similar characteristics as onshore (with the exception of land-use: for more discussion see limitations). Therefore, offshore is not included to reduce the model's size.

Third, biomass is included, since it presents a flexible and easily storable RES [35]. Biomass presents an alternative to conventional sources, and is mostly used for heating in the Netherlands [24]. Biomass refers to all organic material originating from plants, trees and crops [35] and consists of a wide range of sources [129]. In general, biomass comes either directly from land or from waste [136].

Fourth, natural gas is incorporated into the model. Of all fossil fuels (oil, coal, and natural gas), gas has the lowest lifecycle GHG emission, ranging between 410 and 650 CO2eq/kWh [15]. Although eventually the energy system should be carbon-neutral, natural gas is included to allow for analysing the implications of increasing RES targets. The Dutch climate agreement states that by 2050, all buildings in the Netherlands will be disconnected from natural gas and aims to replace this with other gaseous energy carriers, such as hydrogen [112].

Therefore, the fifth energy source included is hydrogen. Hydrogen does not occur naturally and has to be produced [110]. Several processes exist to produce hydrogen. Although some of these methods show (long-term) potential for sustainable hydrogen production, these are mostly in infant stages and require further research to improve production rates [33, 61, 110]. Depending on the production method, hydrogen can be sustainable or lead to emission of GHG. A colour prefix is often used to describe different types of hydrogen [109]. Green hydrogen refers to the production method of electrolysis using electricity from RES, such as solar or onshore, leading to no GHG emission. Grey hydrogen, on the other hand, refers to hydrogen production from fossil fuels such as natural gas through SMR, which leads to emission of GHG. Hydrogen produced through SMR using natural gas, where GHGs are captured through carbon capture and storage (CCS), is referred to as blue hydrogen. Two sources of hydrogen are included in the model: import from neighbouring countries, which is assumed to be blue hydrogen (see section 5.1.3 and production of hydrogen through the conversion of electricity through electrolysis (green hydrogen)

Sixth, foreign electricity import is included, since the Netherlands is generally a net importer of electricity. In 2018, the total amount of net electricity import was 8.0 TWh in the Netherlands (26.8 TWh import and 18.8 TWh export) [73]. Compared to a domestic generation of 114.5 TWh, about 6.5% was met by electricity import.

Transmission inputs The final two energy inputs of an energy hub are related to transmission within the network of the country itself. Two types of networks are considered in this thesis: electricity and hydrogen. Network modelling details are covered in section 4.6.2.

First, the electricity grid is modelled. The electricity grid is limited to the high-voltage (HV) network; although the Dutch electricity network also consists of the medium-voltage (MV) network and the low-voltage (LV) network [142], these are not considered since the model covers a geographical scale of a country.

Second, the transmission of hydrogen transmission is included, whereas the transmission of natural gas is not. Although a hydrogen transmission network has currently not emerged, compared to a very well established natural gas network, the emphasis of this thesis on a renewable energy system for 2050, in which natural gas eventually will be phased-out. Hydrogen present a gaseous alternative to natural gas, with system operators (including Gasunie) investigating the potential emergence of a hydrogen transmission network [148]. Such a hydrogen network could emerge through the installation of new hydrogen pipelines, but especially through retrofitting of existing natural gas pipelines through coating [148]. Moreover, the inclusion of multiple transmission networks vastly increases the number of decision variables and thus the computational time, and therefore it is assumed that one type of gaseous transmission will suffice.

A final energy carrier that can be transferred through a network is heat. However, heat transfer is mostly economically efficient in locally, densely populated urban areas, but less so on larger scales [103]. Since the considered spatial scale in this thesis is a country, with a resolution of 30 regions, heat transfer is not included in the model.

4.4.2. Energy outputs

Similar to the energy inputs, several types of outputs are found in literature. Most MES studies considered electricity and heating demand [102]. A few types of energy outputs are not considered in this thesis. First, due to the marginal share in final demand in the case study, the Netherlands, cooling demand is not included: in 2017, total demand for residential cooling in the Netherlands amounted to 0.083 TWh, compared to a total residential space heating demand of 70.416 TWh in the same year [73]. Second, although several studies include other final outputs such as water, compressed air or CO2, these are considered irrelevant for the scope of this thesis, namely the cost-optimal energy investment. In total, five energy outputs are considered: the final energy demands for electricity, heating and hydrogen, and the electricity and hydrogen export through transmission to other regions.

The energy transmission export to other regions is modelled endogenously. In contrast, the energy outputs for the three types of final demand are modelled exogenously, that is, these are given input values. Several conversions are calculated endogenously for the model. Therefore, the final demand of a particular type should not include the demand for these conversion technologies as well. For example, the amount of energy required for the energy hub could be considered both electrical demand or heating demand. Hence, the final energy demands of each type of demand are defined as follows:

- *Electricity demand* for agriculture, lighting and other appliances in buildings, CO2 capture, power sector own use, households cooking, industry, transport and other final electricity demands.
- *Heating demand* for heating of households, buildings and others.
- *Hydrogen demand* for industrial, fertilizer production (feedstock) and transport hydrogen demand

4.4.3. Conversion technologies

Within a MES, different energy outputs can be met by different energy inputs. In order for the energy conversion to take place, energy conversion technologies are required. Although similar to generation technologies — formally both types of technologies convert one energy carrier into another — conversion technologies convert secondary into other secondary energy carriers, whereas generation technologies convert primary energy into secondary energy (e.g. solar PV). Four conversion technologies are included in the model: electrolyser, EHP, CCGT and boilers or heat pumps (see fig. 4.6. First, electrolysers integrate electricity and hydrogen sectors. Electrolysis entails the splitting of water using electrical power to produce hydrogen in an electrolyser. Several technologies for electrolysis are available, such as alkaline [26], polymer electrolyte membrane and solid-oxide electrolysers [19, 149, 150]. Although currently less than 0.1% of global hydrogen is produced through water electrolysis, this is expected to increase in future due to declining costs of renewable electricity [69]. Second, EHPs use electricity to move heat from a cool space to a warm space [113]. HencEHPs couples electricity and heating sectors. Thirdly, gas turbines allow the generation of electricity from different fuels. Gas turbines can have different energy carriers as input, depending on the type of combustor and manufacturer of the turbine [14]. Currently, several gas turbine manufacturers are developing gas turbines capable of burning 100% hydrogen gas [126]. Gas turbines couple the electricity sector with the natural gas, hydrogen and biomass sectors. Although a distinction between open cycle gas turbines and CCGT can be made, the model is limited to the CCGT [139]. Finally, heat pumps or boilers allow the generation of heat from different energy carriers as input and couple the heating sector with the natural gas, hydrogen and biomass sectors.

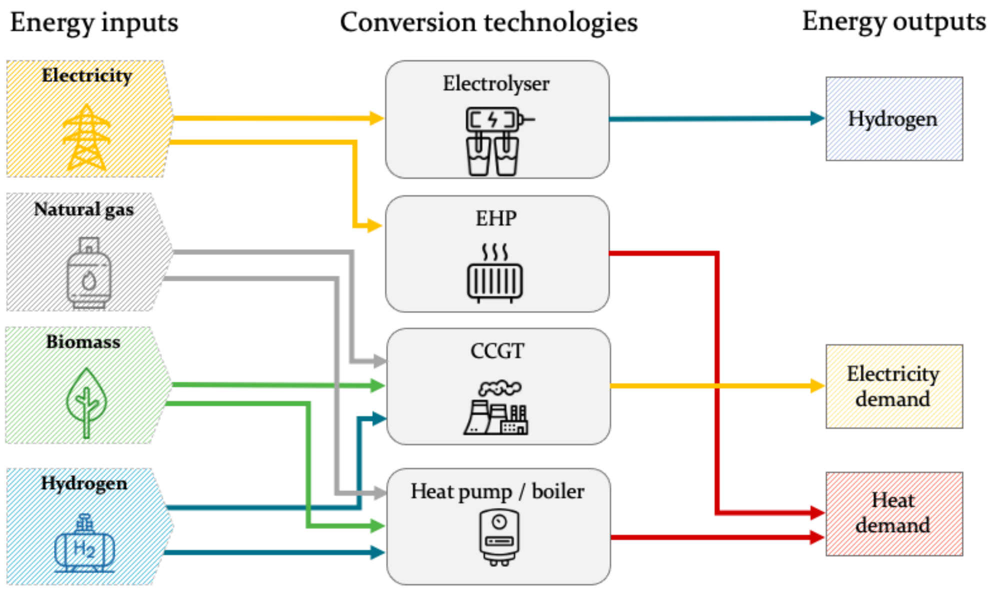


Figure 4.6: Overview conversion technologies.

4.4.4. Storage technologies

Many different storage technologies currently exist, at different levels of development; from earlier stages of R&D to more mature, deployed technologies. Lott et al. [91] analysed the maturity and readiness of several key storage technologies, based on the qualitative assessments measures of Technology Readiness Levels and Manufacturing Readiness Levels. In fig. 4.7, some of these key technologies are displayed with respect to their associated initial capital investment requirements and technology risk versus their current phase of development (i.e. R&D, demonstration and deployment, or commercialisation phases). Luo et al. [94] provided an extensive analysis of different storage technologies and characteristics. Current research indicates that no single storage technology is superior, and the optimal storage technology depends on characteristics of the energy system in question [10, 67, 158, 159]. Currently, most storage technologies have not been deployed on large-scale, with the exception of pumped-hydro storage, which has more than 100GW installed worldwide [91]. However, due to the limited availability of large natural water reserves in the Netherlands, pumped-hydro storage is not included in the model.

Based on the maturity and compatibility with the chosen final energy sources, the three storage types are included. First, electrical storage is considered. Several electrical storage technologies, especially batteries, have recently received funding support in research, development and demonstration [91]. Advanced battery technologies such as superconducting magnetic energy storage or super-capacitors are promising, but in early stages of development. The electrical storage in the model is limited to flow batteries.

Second, thermal energy storage (TES) technologies store energy for later use. Since energy usage for heating and cooling represent about 45% of the total energy use in buildings, TES can provide significant value in

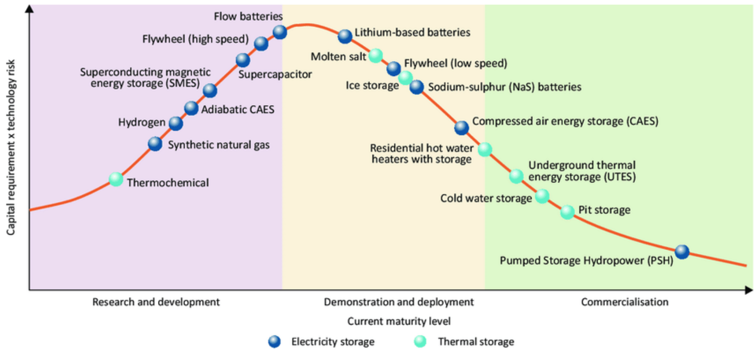


Figure 4.7: Maturity of energy storage technologies. Reprinted from [91]

optimizing the energy system [68] and is considered a competitive option for reducing heat wasted [68]. As shown in fig. 4.7, some TES technologies are currently realized at levels of deployment. Underground thermal energy storage (UTES) is frequently found in many European countries [68]: in the Netherlands, UTES is quite mature, having been used for 25 years [152]. Although other TES technologies are promising, the scope is limited to UTES.

Third, hydrogen storage is considered, which can be stored physically or material based. In physical storage, the state of matter of hydrogen can be either gas or liquid. This requires pressure tanks with high pressures (350 to 700 bar). If stored liquid at atmospheric pressure, hydrogen has to be stored at cryogenic temperatures, since the boiling point of hydrogen is around 33 Kelvin. Alternatively, hydrogen can be stored on the surfaces of solids or within solids [156]. Hydrogen storage can be used for long-term energy applications and has a high energy density, quick response times and potential use in large scale applications [91].

4.5. Overview modelling assumptions

This section list the assumptions made. First, energy export to other countries is not included to reduce the model's size. Although this would effect costs, the Netherlands is generally a net imported of energy. Second, hydrogen and biomass are modelled as foreignly imported, that is, with fixed price per MWh. Hence, it is assumed no investment in generation capacity is required. This allows to model to characteristics of biomass and hydrogen which are interesting for the scope of this thesis. Investment costs are, however, accounted for in conversion technologies (see 4.4.3). To investigate the possibilities of importing large quantities of hydrogen, several European gas operator, including Gasunie, explored the options of developing a European dedicated hydrogen infrastructure, the European Hydrogen Backbone (EHB) [148]. This network connects hydrogen supply and demand for various European countries, taking advantage of geographical favourable conditions such as high solar radiation in countries such as Spain and Italy. The network is envisioned to emerge from the mid-2020s onwards, from initially 6800 km pipeline network in 2030 to 23000 km in 2040 [148]. Third, fixed prices for electricity import are assumed. Fourth, offshore wind is not included: this is discussed in more detail in the limitations in section 6.6. Finally, the inclusion of multiple transmission networks vastly increases the number of decision variables and therefore computational time: therefore, the transmission of natural gas and heat are not considered.

4.6. Conceptual model

The previous sections described the generic approach to modelling MES energy flows and defined the system boundaries in terms of the different energy inputs, outputs, conversion technologies and storage technologies included. From this, the conceptual model can be established. The energy flows of the conceptual model of a single region is shown in fig. 4.8. The left side of the fig. shows the different energy sources considered, which function as energy inputs entering the regions energy hub , indicated by the dark grey dashed square. This area presents the region's internal energy flows, that is, the possible storage, conversion and distributions flows. The energy outputs are shown on the right side, consisting of the three types of final demands and two types of transmission export to other regions. The area with the light grey dashed line indicates the decision space of a single region.

4.6.1. Modelling of the internal energy flows

This section describes the processes associated with the energy flows. The starting point is the input of energy in the energy hub. The eight different energy inputs are modelled differently. VRES inputs (solar and wind) require capacity of generation technologies (the white pentagon arrow shape in fig. 4.8, see legend). Non-VRES on the other hand inputs do not, however these require capacities of conversion technology (grey diamond shape in fig. 4.8). Natural gas, hydrogen, biomass, foreign electricity are modelled as foreignly imported with fixed prices. Finally, cross-border electricity import is constrainted by the maximum capacity of the transmission lines. The electricity import is modelled for six nodes located in regions with a cross-border connection line. A map and list (publicly available from TenneT [137]) of cross border transmission capacities can be found in appendix B.

Before entering the energy hub of a region, the eight different energy inputs are considered similar when these are of the same energy carrier type. The trapezium in fig. 4.8 indicates the splitting or combining of energy flows. For instancElectricity generated from wind turbines and solar PV, foreign imported electricity and electricity imported from other regions are combined and thereafter enter the energy hub .

Thereafter, upon enter the energy hub (the innermost area in fig. 4.8), two processes can occur: the energy inputs can either flow to conversion technologies or the bus of that carrier. A bus can be considered a "connector" of many flows: it represents the place where inputs, flows and outputs loads of a particular energy carrier are connected [80]. Each conversion technologies has an associated conversion efficiency, which is defined as the ratio of the desired (usable) energy output to the energy input [45]. The capacities for CCGTs and boilers and heat pumps are modelled separately for each energy carrier, i.e. natural gas, hydrogen or biomass.

Finally, in addition to conversion or distribution to final demand, energy can be stored in storage technologies. Storage technologies consist of two distinct parts: the energy storage unit and the power conversion system (PCS). The storage duration of different storage technologies is in part determined by the ratio between the storage facility and converter costs [49].

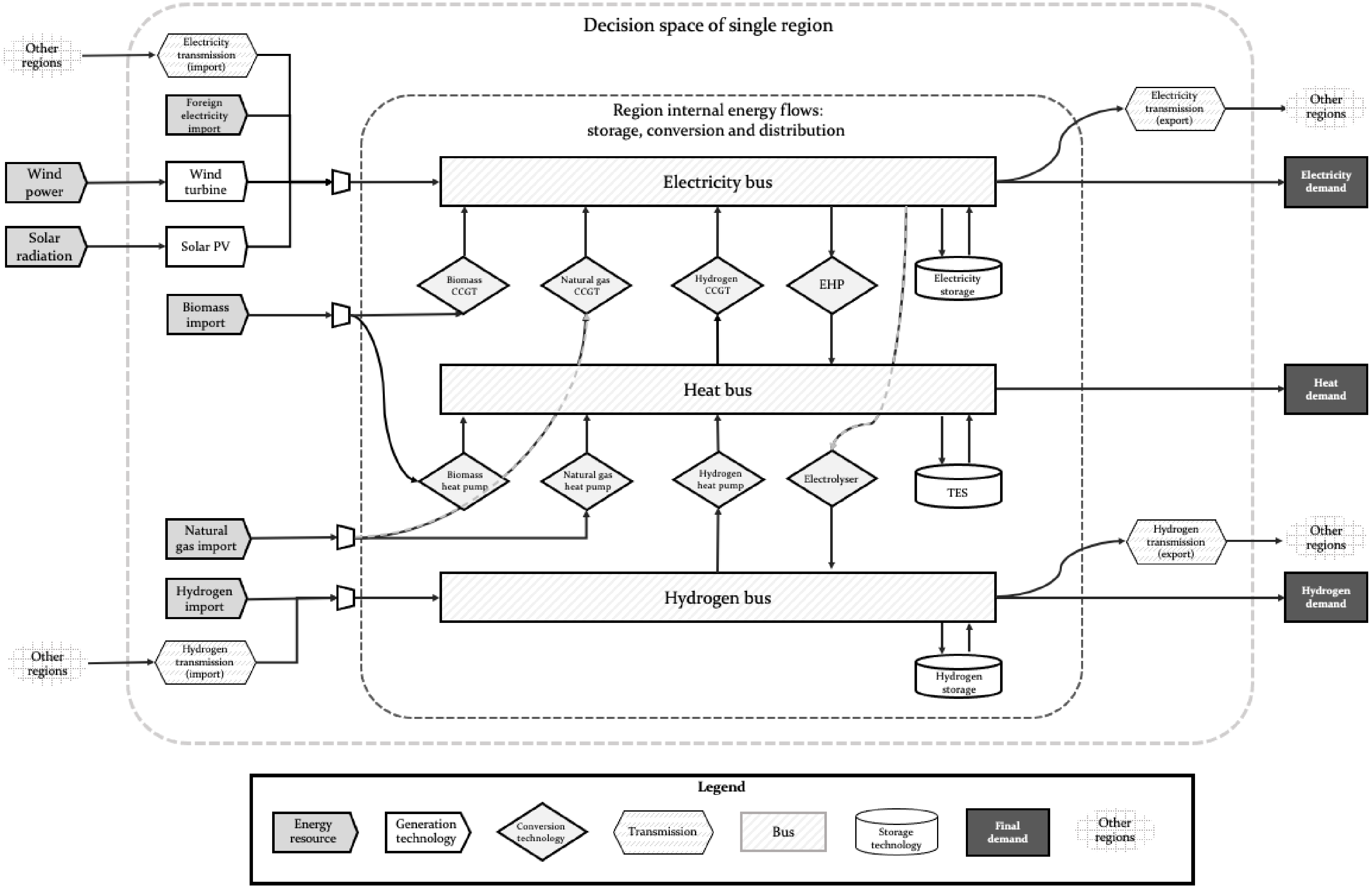


Figure 4.8: System description of energy flows of single region (node) at single point in time. Energy input is indicated on the left which is converted to other energy carriers in the centre (the energy hub) to the outputs.

4.6.2. Network description

The description in 4.8 shows the energy inputs, internal energy flows and outputs of a single region. Detailed modelling of the energy network is considered out of scope. For the structure of the network, a meshed network where adjacent polygons are connected is assumed. Fig. 4.9 illustrates how the energy hub of fig. 4.8 can be extended to a network model. Each region (henceforth node) represents an energy hub with energy in- and outputs. The connection on the right side are the set of possible electricity or hydrogen transmission lines. Each represents a single energy hub with energy in- and outputs. The set of 30 nodes and the possible connections (henceforth edges) are shown on the right side of fig. 4.9: the left side shows the energy hub description of a single node. The connection on the right side are the set of possible electricity or hydrogen transmission lines. Since the model follows a Greenfield approach, no existing network capacities are considered. The same set of possible connections and lengths of per connection are used for both network types. In contrast, the two network differ in the power loss and costs of the lines. A more detailed description of the network parameters is provided in section 5.2.2. Now that the collection of statements, assumptions and relationships are defined to describe the MES conceptually, the optimization problem can be formulated.

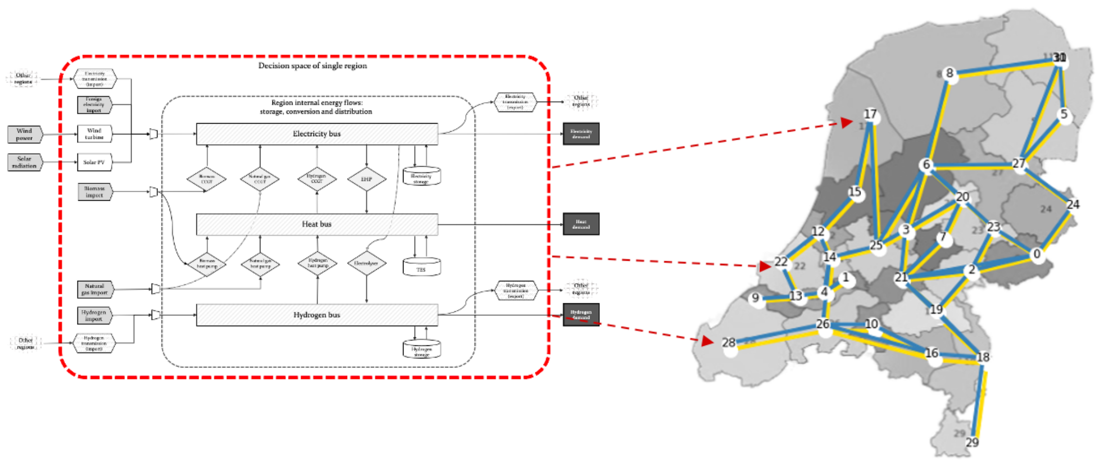


Figure 4.9: Illustration of placement of energy hubs in network

4.6.3. Optimization problem

To find the cost-optimal solution, the optimization problem has to be defined, consisting of the decision variables, constraints and the objective function [133]. The objective function is to minimize the total system costs: these consist of investment and fixed costs of the generation, conversion and storage technologies, the investment costs for electricity transmission lines and hydrogen pipelines, and the operation costs. The decision space consists of the variables for the expansion planning of GEP, NEP and SEP and variables for operation. These include the capacities of generation, conversion and storage technologies and the capacities of network transmission lines and pipelines. To meet the energy demand at each time step, the decision variables include the energy generated, converted, charged or discharged, and the transmission of energy through the network, for each time step. Finally, the constraints consist of balance constraints, capacity constraints for generation and conversion technologies, the storage constraints, national and local RES targets constraints, land-use constraints, network constraints and the non-negativity constraints. An overview of the optimization problem is given in the textbox below. The following section describes how the conceptual model can be expressed in terms of mathematical relationships.

Overview optimization problem

Decision variables:

- The energy generated of energy source z at node n at time t;
- The energy used as input for conversion technology i at node n at time t;
- The energy charging or discharging of storage conversion technology i at node n at time t;
- The energy import and export of energy carrier w form node n to node m at time t;
- The capacities of generation, conversion, storage conversion and storage technologies i at node n;
- The capacity of line n,m of network energy carrier w.

Objective function: Minimise total system costs, consisting of:

- Investment and fixed costs for the capacities of generation technologies:
- Investment and fixed costs for the capacities of conversion technologies:
- Investment and fixed costs for capacity of storage conversion technologies and storage capacities:
- Investment costs for electricity transmission lines and hydrogen pipelines;
- Variable operation costs for secondary energy sources: onshore wind turbines, solar PV panels, foreign imported hydrogen and foreign imported biomass.

Constraints:

- Balance constraints: electricity, heat and hydrogen balance;
- Capacity constraints for generation and conversion technologies;
- Storage constraints;
- National RES target constraint;
- Locally generated RES target constraint;
- Land-use constraints;
- Network constraints;
- Non-negativity constraints.

4.7. Mathematical formulation

This section will elaborate upon the mathematical formulation of the model, that is, the equations used to describe the decision variables, constraints and the objective function. First, decision variables, sets and parameters used will be given. These can then be used in order to illustrate the relations in terms of possible energy flows between the different elements using a Sankey Diagram, as shown in fig. 4.10. Second, the objective function is described. Third, the constraints are given.

4.7.1. Decision variables, sets & parameters

In order to formulate the optimization problem, the sets, parameters and variables are formulated. Fig. 4.10 shows the Sankey diagram in which the sets, parameters, decision variables and possible energy flows are indicated. The decision variables are given in table 4.1 below. In comparison to GRIM, the MES-GRIM includes decision variables for the energy generation, $Pz_{z,n,t}$, as well as a decision variable for the amount of energy converted, $Ph_{i,n,t}$. Furthermore, the domains of decision variables differ. The sets, including the notations, description and domain are shown in table 4.2. Instead of a single set of generation technologies, a set of energy sources Z and conversion technologies H are included. The set of energy sources is extended to include more sources. In addition, a set for different types of demands is included. Furthermore, the domain of capacity $K_{i,n}$ is extended towards also including conversion technologies and the domain of transmission capacity $K^{w}_{n,m}$ is extended to include also hydrogen connections. Finally, the parameters, notations, domain, description and unit are given in table 4.3.

Table 4.1: Overview of decision variables

Notation	Domain:	Description	unit
$Pz_{z,n,t}$	$z \in Z, n \in N, t \in T$	Amount of energy generated of energy source z at node n at time t	[kWh]
$Ph_{i,n,t}$	$i \in H, n \in N, t \in T$	Amount of energy used as input for conversion technology i at node n at time t	[kWh]
$CP_{i,n,t}$	$i \in SC, n \in N, t \in T$	Energy charging of storage conversion technology i at node n at time t	[kWh]
$DP_{i,n,t}$	$i \in SC, n \in N, t \in T$	Energy discharging of storage conversion technology i at node n at time t	[kWh]
$SP_{i,n,t}$	$i \in SC, n \in N, t \in T$	Stored energy of storage technology i at node n at time t	[kWh]
$K_{i,n}$	$i \in I,\ n \in N$	Capacity of conversion, storage conversion and storage technology i at node n	[kW]
$K_{z,n}$	$z \in Z, n \in N$	Capacity of generation technology i at node n	[kW]
$K^{w}_{n,m}$	$(n, m) \in E$	Capacity of line (n, m) of energy carrier w	[kW]
$P^{w,\text{exp.}}_{n,m,t}$	$w \in W, (n,m) \in E, t \in T$	Energy export of energy carrier w form node n to node m at time t	[kWh]
$P^{w,\text{imp.}}_{n,m,t}$	$w \in W, (n,m) \in E, t \in T$	Energy import of energy carrier w from node n to node m at time t	[kWh]

Table 4.2: Overview of sets

Sets		
Notation	**Description**	**Includes**
N	Set of considered nodes	30 Regional energy strategy regions
E	Set of possible electricity and hydrogen connections	50
Ω_n	Subset of E with connections to / from n	$\Omega_n \subset E$, such that $n \mid A(n,m) = 1, \forall n \in N$, where $A(n,m)$ is the adjacency matrix of neigbouring nodes
RES	Set of considered RES technologies	Onshore wind, solar PV, hydrogen, and biomass
$VRES$	Set of considered VRES technologies	Onshore wind and solar PV
S	Set of considered storage technologies	Battery, TES, and hydrogen storage
SC	Set of considered storage conversion technologies	Battery (dis)charge, TES (dis)charge, and hydrogen storage (dis)charge
H	Set of considered conversion technologies	Electrolyser, EHP, CCGT, and boilers for hydrogen, biomass and natural gas
H_{heat}	Subset of H with heat output	$H_H \subset H$: EHP, hydrogen boiler, biomass boiler and natural gas boiler
H_{CCGT}	Subset of H for CCGT technologies	$H_H \subset H$: Hydrogen CCGT, biomass CCGT and natural gas CCGT
H_{elec}	Subset of H with electricity input	$H_{elec} \subset H$: EHP, electrolyser
$H_{h2.}$	Subset of H with hydrogen input	$H_{h2.} \subset H$: Hydrogen CCGT, hydrogen boiler
H_{bio}	Subset of H with biomass input	$H_{bio} \subset H$: Biomass CCGT, biomass boiler
H_{gas}	Subset of H with natural gas input	$H_H \subset H$: Natural gas CCGT, natural gas boiler
I	Set of all considered technologies	$G \cup H \cup SC \cup S$
T	Set of considered time steps	Hours: 0 to 8760
N	Set of considered nodes	30 Regional energy strategy regions
E	Set of possible electricity and hydrogen connections	50
Ω_n	Subset of E with connections to neighboring nodes of n	$\Omega_n \subset E$
W	Set of considered network energy carriers	Electricity and hydrogen
D	Set of considered final energy demands types	Electricity, heat, and hydrogen
Z	Set of considered energy sources	Onshore wind, solar PV, hydrogen, biomass, natural gas, and foreign electricity import

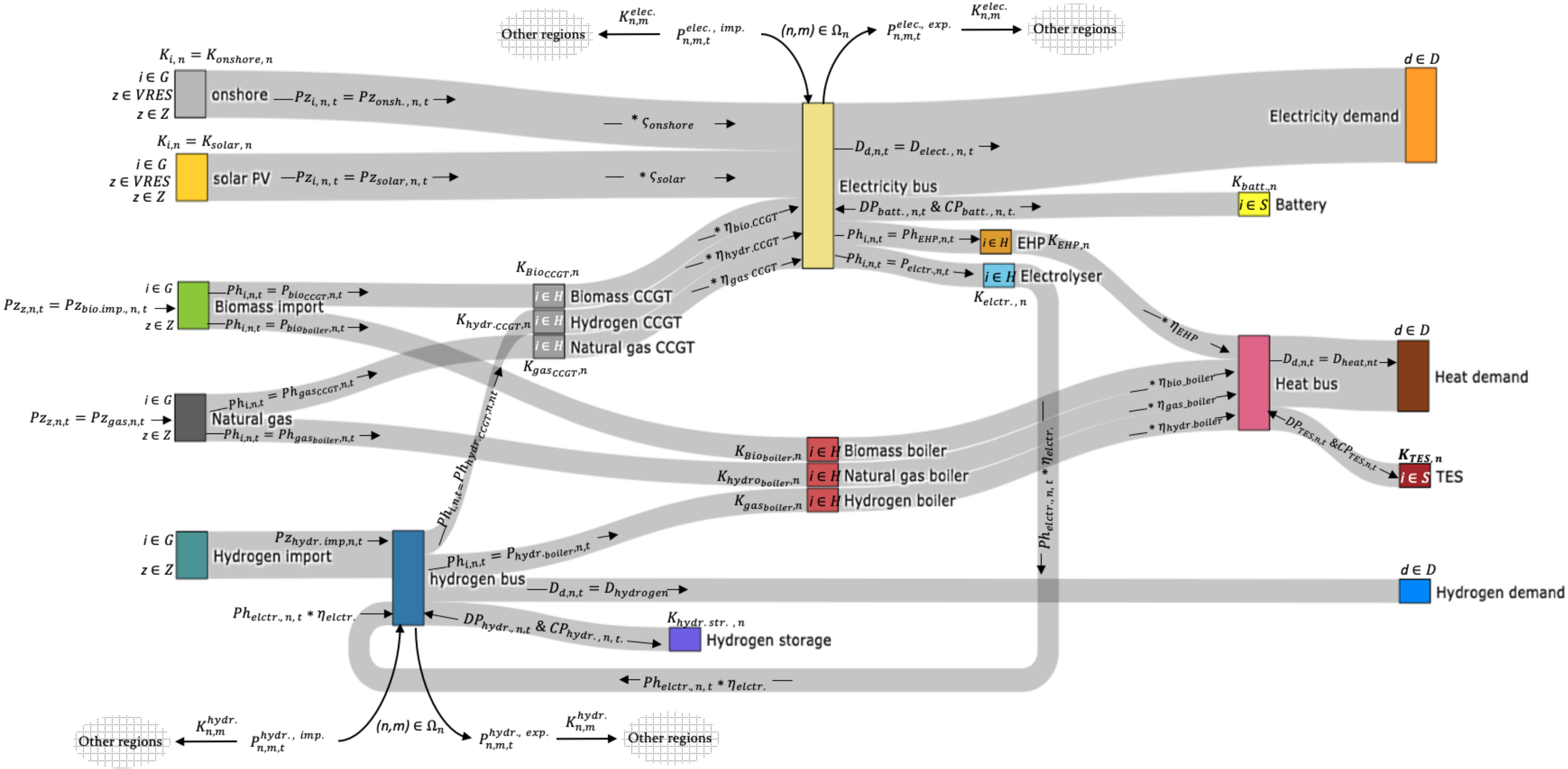


Figure 4.10: Sankey diagram, including the mathematical variables and sets for the energy flows.

Table 4.3: Overview of parameters

Parameters			
Notation	**Domain**	**Description**	**unit**
η_i	$i \in H$	Conversion efficiency of conversion technology i	[%]
$\varsigma_{i,n,t}$	$i \in$ *VRES*, $n \in N$, $t \in T$	Capacity factor for technology i at time t, for solar and wind; 1 for other generation technologies	unitless
$D_{d,n,t}$	$d \in D$, $n \in N$, $t \in T$	Demand of energy type d of node n at time t	[kWh]
$K^{\max}_{i,n}$	$i \in$ *VRES*, $n \in N$	Maximum possible installed capacity for VRES technology i at node n	[kW]
η^{in}_i	$i \in SC$	Charging efficiency of storage technology i	[%]
η^{out}_i	$i \in SC$	Discharging efficiency of storage technology i	[%]
A_i	$i \in I$	Annuity factor of generation, storage and conversion technology i	unitless
a_i	$i \in I$	Fixed Operation & Maintenance (FOM) costs of generation, conversion and storage technology i	[€/kW/yr]
b_z	$z \in Z$	Variable Operation & Maintenance (VOM) costs of energy source z	[€/kWh]
C_i	$i \in I$	Capital Expenditure (CapEx) of generation, conversion, storage conversion and storage technology i	[€/kW]
$C^w_{n,m}$	$w \in W$, *(n,m)* $\in E$	CapEx of network line *(n, m)* of network energy carrier w	[€/kWkm]
L_i	$i \in I$	lifetime of generation, storage and conversion technology	[year]
$\delta_{n,m}$	*(n, m)* $\in E$	Length of network	[m]
$\tau^w_{n,m}$	$w \in W$, *(n, m)* $\in E$	Power loss factor in line *(n, m)* of energy carrier w	[%/km]
$L^w_{n,m}$	$w \in W$, *(n,m)* $\in E$	Lifetime of line *(n, m)* of network energy carrier w	[year]
$K^w_{n,m}$	$w \in W$, *(n,m)* $\in E$	capacity of line *(n, m)* of network energy carrier w	[kW]
$A^w_{n,m}$	$w \in W$, *(n, m)* $\in E$	Annuity factor of line *(n, m)* of energy carrier w: $A_i = \frac{1-\frac{1}{(1+r)^{L^w_{n,m}}}}{r}$	unitless
f		Factor that represents extra length and extra capacity considering security constraint	unitless
ω		National RES target	[%]
ϕ		Locally generated RES target	[%]
r		Discount rate	[%]
t_{end}		Last time step in T	unitless

4.7.2. Objective function

The objective of the model is to minimize the total annualized costs of the system. A distinction is made between the fixed and variable costs.

Fixed costs The fixed costs consist of investment costs and the fixed operation and maintenance (FOM) costs. These consist of three cost components. First, The investment costs consist of Capital Expenditure (CapEx) cost C_i for installing generation, conversion, storage conversion and storage technologies for all nodes n, annualized by the annuity factor A_i. Second, the costs for FOM a_i for generation, conversion and storage technologies for all nodes n. Finally, the network investment costs consist of the CapEx costs $C^w_{n,m}$, annualized by the annuity factor $A^w_{n,m}$, for the electricity and hydrogen network. A factor of 25% is added to the network length $\delta_{n,m}$, since the direct route may not be the shortest, realistic length between nodes, due to physical barriers such as buildings, protected areas and others [151]. This possible detour is thus accounted for by adding a factor of $f = 1.25$. This leads to the following total fixed costs (eq. 4.1):

$$FC_{\text{total}} = \sum_{i\in I} \sum_{n\in N} \frac{C_i K_{i,n}}{A_i} + \sum_{i\in G\cup H\cup S} \sum_{n\in N} a_i K_{i,n} + \sum_{w\in W} \sum_{(n,m)\in E} \frac{f\delta_{n,m} C^w_{n,m} K^w_{n,m}}{A^w_{n,m}} \tag{4.1}$$

Variable costs The total variable costs consist of the cost required for generation of energy to meet the final energy demands d. The total generation is equal to the sum required to meet all the energy demands d multiplied with the VOM costs b_z of energy source z. Within the scope of this thesis, this considers the VOM costs of onshore wind, solar PV, imported natural gas, imported foreign electricity, imported hydrogen, and imported biomass. In order to meet these demands, energy sources(s) z can be converted into secondary energy carrier q, which can subsequently be converted to other final demand. The amount of energy used for production z to q, and from q to d are subject to balance constraints. The total generation cost GC_{total} is equal to the VOM costs b_z multiplied by the amount of energy generated of energy source z of all nodes summed over all time steps $t \in T$. This leads to the following total operation costs (eq. 4.2):

$$GC_{\text{total}} = \sum_{t\in T} \sum_{z\in Z} \sum_{n\in N} b_z Pz_{z,n,t} \tag{4.2}$$

Combining of the total fixed costs and total variable costs lead to the following objective function (eq. 4.3):

$$\begin{gathered}\text{Min.} \sum_{i\in I} \sum_{n\in N} \frac{C_i K_{i,n}}{A_i} + \sum_{i\in G\cup H\cup S} \sum_{n\in N} a_i K_{i,n} + \\ \sum_{w\in W} \sum_{(n,m)\in E} \frac{f\delta_{n,m} C^w_{n,m} K^w_{n,m}}{A^w_{n,m}} + \sum_{t\in T} \sum_{z\in Z} \sum_{n\in N} b_z Pz_{z,n,t}\end{gathered} \tag{4.3}$$

4.7.3. Constraints

The set of constraints to which the optimization model is subject to are described in this section. The balance constraint consists of the three balances at the busses, as indicated in fig. 4.10. These include the balance constraints for the electricity, heat and hydrogen bus. In addition, for biomass and natural gas import, the amount of import has to match the amount used as inputs for conversion technologies.

Electricity power balance constraints The energy supply of electricity has to match the demand of electricity, for all nodes, at all time steps. In other words, the sum of electricity input flows of a node has to equal the electricity output flow. The input is equal to the electricity generated from energy sources $Pz_{z,n,t}$, the electricity generated through conversion from secondary energy carriers $Ph_{h,n,t}$ (such as CCGT), the electricity discharged from storage batteries $DP_{batt,n,t}$ and the imported electricity from other nodes $P^{elec.,imp.}_{n,m,t}$. The latter is accounted for the by the power loss in the lines, which is equal to $\tau^{elec.}_{n,m}$. This input has to equal the output flows, which is equal to the electricity demand $D_{elec.,n,t}$, the amount of electricity used for conversion to other energy carriers $Ph_{h,t}$, the electricity used for charging storage batteries $CP_{batt,n,t}$ and the electricity exported to other nodes $P^{elec.,exp.}_{n,m,t}$:

$$\sum_{z \in VRES} Pz_{z,n,t} + \sum_{i \in H_{CCGT}} Ph_{i,n,t}\eta_i + DP_{batt,n,t} + \sum_{(n,m)\in\Omega_n} \left(1-\tau^{elec.}_{n,m}\right) P^{elec.,imp.}_{n,m,t}$$
$$= D_{elec.,n,t} + \sum_{i \in Hs} Ph_{i,n,t} + CP_{batt,n,t} + \sum_{(n,m)\in\Omega_n} P^{elec.,exp.}_{n,m,t} \quad \forall t \in T, \quad \forall n \in N \tag{4.4}$$

Heat balance constraints Similarly to the electricity power balance, the heating energy supply has to match the output at every time step. However, transmission of heat through the network of nodes is not considered, as well as heat generation from energy sources z. Hence, the supply of generated heat at each node n equals the sum of heat generated through conversion from secondary energy carriers $Ph_{h,n,t}$ (e.g. boiler and EHP) and the heating energy discharged from TES $DP_{TES,n,t}$, which has to equal the demand for heating energy $D_{heat,n,t}$ and the heat used for charging of TES $CP_{TES,n,t}$ for all nodes n and every time step t:

$$\sum_{i \in H_{heat}} Ph_{i,n,t}\eta_h + DP_{TES,n,t} = D_{heat,n,t} + CP_{TES,n,t} \quad \forall t \in T \quad \forall n \in N \tag{4.5}$$

Hydrogen balance constraints The supply of hydrogen has to match the demand of hydrogen at all time steps. The input consists of the foreign import of hydrogen, the hydrogen generated through electrolysis $P_{elctr.,n,t}$, the hydrogen discharged from hydrogen storage $DP_{h2,n,t}$ and the imported hydrogen from other nodes $P^{h2,imp.}_{n,m,t}$. This amount has to equal the hydrogen demand $D_{h2,n,t}$, the amount of hydrogen used for conversion to other energy carriers $Ph_{i,n,t}$ using hydrogen as input (CCGT and boiler), the hydrogen used for charging of hydrogen storage $CP_{h2,n,t}$, and the hydrogen exported to other nodes $P^{h2,exp.}_{n,m,t}$ for all nodes n and every time step t:

$$Pz_{h2.imp.,n,t} + P_{elctr.,n,t}\eta_{elctr.} + \sum_{(n,m)\in\Omega_n} (1-\tau^{h2.}_{n,m})P^{h2,imp.}_{n,m,t}$$
$$= D_{h2,n,t} + \sum_{i \in H_{h2}} Ph_{i,n,t} + \sum_{(n,m)\in\Omega_n} P^{h2,exp.}_{n,m,t} \quad \forall t \in T \quad \forall n \in N \tag{4.6}$$

Biomass import balance constraints The foreign import of biomass has to match the biomass used for conversion to other energy carriers for all nodes n at all time steps t:

$$Pz_{bio.imp.,n,t} = \sum_{i \in H_{bio}} Ph_{i,n,t} \quad \forall t \in T, \quad \forall n \in N \tag{4.7}$$

Natural gas import balance constraints The foreign import of natural gas has to match the natrual gas used for conversion to other energy carriers for all nodes n at all time steps t:

$$Pz_{gas.imp.,n,t} = \sum_{i \in H_{gas}} Ph_{i,n,t} \quad \forall t \in T, \quad \forall n \in N \tag{4.8}$$

Capacity constraints The generation of primary energy sources $Pz_{z,n,t}$ per time step cannot exceed the installed capacity. For generation from VRES, the production depends on the meteorological conditions, which are captured in the capacity factor $\varsigma_{i,t}$. The capacity is multiplied by the capacity factor of technology $\varsigma_{i,t}$, which has a value between 0 and 1:

$$Pz_{z,n,t}\varsigma_{i,t} \le K_{z,n} \quad \forall z \in Z, \quad \forall t \in T, \quad \forall n \in N \tag{4.9}$$

In addition, the conversion $Ph_{i,n,t}$ at conversion technology i cannot exceed the installed capacity of that technology:

$$Ph_{i,n,t} \le K_{i,n} \quad \forall i \in H, \quad \forall t \in T, \quad \forall n \in N \tag{4.10}$$

Storage constraints Firstly, the stored energy per time step cannot exceed the energy content of the storage unit (equation 4.11). Secondly, the energy charging and discharging per time step cannot exceed the capacity of the storage conversion (equation 4.12). Finally, the stored energy at storage technology i at time t is equal to $SP_{i,n,t}$. The stored energy at t − 1 has to be equal to the stored energy at t, minus the discharged energy, plus the charged energy, taking into account the storage conversion efficiencies (equation 4.13). Finally, the stored at the first step of the year cannot be t-1. Hence, t-1 is the last time step of the year, making the storage cyclic. Eq. 4.13 becomes 4.14:

$$SP_{i,n,t} \leq K_{i,n} \quad \forall i \in S, \quad \forall t \in T, \quad \forall n \in N \tag{4.11}$$

$$DP_{i,n,t}, CP_{i,n,t} \leq K_{i,n}, \quad \forall i \in SC, \quad \forall t \in T, \quad \forall n \in N \tag{4.12}$$

$$SP_{i,n,t} = SP_{i,n,t-1} + \eta_i^{in} CP_{i,n,t} - \frac{DP_{i,n,t}}{\eta_i^{out}} \quad \forall i \in \mathrm{S}, \quad \forall t \in \mathrm{T}, \quad \forall n \in N \tag{4.13}$$

$$SP_{i,n,0} = SP_{i,n,t_{end}} + \eta_i^{in} CP_{i,n,0} - \frac{1}{\eta_i^{out}} DP_{i,n,0}, \quad \forall i \in S, \quad \forall n \in N \tag{4.14}$$

National RES target constraint A RES target constraint is added to indicate the minimum percentage of RES in the final energy mix. The RES target is specified by ω, ranging between 0 and 1.

$$\omega \sum_{z \in Z} \sum_{n \in N} \sum_{t \in T} P_{z,n,t} \leq \sum_{z \in RES} \sum_{n \in N} \sum_{t \in T} P_{z,n,t} \tag{4.15}$$

Locally generated RES target constraint In addition to the national RES target constraint, a locally generated RES target is added to indicate the minimum percentage of locally RES generated energy in the final energy mix (more details on the two types of RES targets is given in section 5.4). The locally generated RES target is specified by ϕ, ranging between 0 and 1.

$$\phi \sum_{z \in Z} \sum_{n \in N} \sum_{t \in T} P_{z,n,t} \leq \sum_{z \in VRES} \sum_{n \in N} \sum_{t \in T} P_{z,n,t} \tag{4.16}$$

Level of sector integration constraint To analyse the implications of MES as compared to a separated energy system, the level of sector integration is varied. This is modelled with a constraint that sets the maximum allows capacities for EHP and electrolysers for all nodes n to zero:

$$\sum_{i \in H_{elec}} \sum_{n \in N} K_{i,n} \leq 0 \tag{4.17}$$

Network constraints The network consists of two energy carriers, an electricity and a hydrogen network. First, for both networks w, the flow over transmission lines (electricity) or through pipelines (hydrogen) cannot exceed the installed capacity of that line (equation 4.18). Secondly, the import from node n to node m (that is, the flow of import going from m to n) is equal to the export from m to n (equation 4.19). Similarly, the electricity transmission line or hydrogen pipeline from n to m is equal to the line from m to n (equation 4.20

$$0 \leq P_{n,m,t}^{w,imp.}, \quad P_{n,m,t}^{w,exp.} \leq K_{n,m}^{w} \quad \forall (n,m) \in E, \quad \forall t \in T, \quad \forall w \in W \tag{4.18}$$

$$P_{n,m,t}^{w,imp.} = P_{m,nt}^{w,exp.}, \quad \forall (n,m) \in E, \quad \forall t \in T, \quad \forall w \in W \tag{4.19}$$

$$K_{n,m}^{w} = K_{m,n}^{w}, \quad \forall (n,m) \in E, \quad \forall w \in W \tag{4.20}$$

Non-negativity constraints All decision variables must be equal to or larger than zero.

$$0 \leq Pz_{z,n,t}, K_{z,n} \quad \forall z \in Z, \quad \forall n \in N, \quad \forall t \in T \tag{4.21}$$

$$0 \leq Ph_{i,n,t} \quad \forall i \in H, \quad \forall n \in N, \quad \forall t \in T \tag{4.22}$$

$$0 \leq SP_{i,n,t}, CP_{i,n,t}, DP_{i,n,t} \quad \forall i \in SC, \quad \forall n \in N, \quad \forall t \in T \tag{4.23}$$

$$0 \leq K_{i,n}, \quad \forall i \in I, \quad \forall n \in N \tag{4.24}$$

$$0 \leq K_{n,m}^{w} \quad \forall (n,m) \in E, \quad \forall w \in W \tag{4.25}$$

4.7.4. Modelling structure

Now that the conceptual model is described, the system boundaries are determined and the model is translated into a set of mathematical equations, the model is theoretically able to be run and provide outcomes. Fig. 4.11 shows the model flow diagram of the extended model. The next chapter discusses the translation of the conceptual, mathematical model into the workable model which is used to generate useful modelling outcomes. This consists of the input data, as shown on the right side of fig. 4.11.

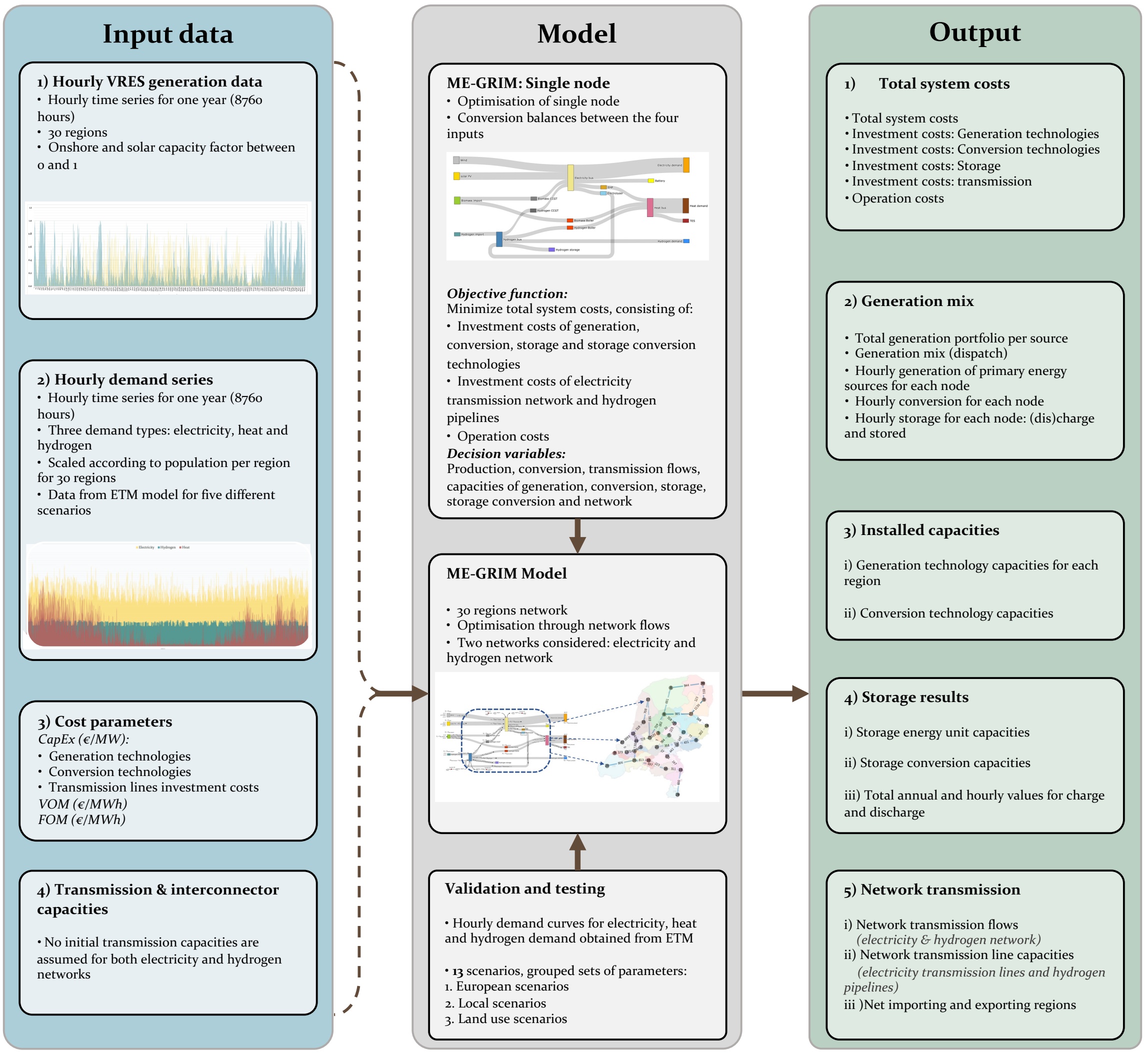


Figure 4.11: Model flow diagram

5
Model formalization

In the previous chapter, the conceptual model was formulated. However, the conceptual model in and of itself is not able to produce useful outcomes. This requires the translation of the mathematical, conceptual model into the final, workable model which can be used to generate modelling outcomes that are useful, and subsequently can be used to obtain insights. This formalization of the conceptual model requires the following. First, the data input and values for parameters are determined. These are described in the first section. Second, the verification of the model will be addressed. Third, the experimental design is explained, resulting in the set of scenarios used to run the model. Finally, the computational settings used to run the model are described.

5.1. Data input

As indicated on the left side of the model overview in fig. 4.11, the data required for the model consists of four types of data: the hourly data for VRES capacity factors, the available land for VRES generation technologies, the hourly demand profiles, and finally values for the (costs) parameters. The data collection and pre-processing are described in this section. The first two data inputs are similar than those found in GRIM. The methods used to obtain the input data will be described briefly. Thereafter, the values of spatio-temporal demand profiles and costs parameters and are discussed.

5.1.1. VRES hourly capacity factors

In order to model the intermittent character of VRES supply, the input data consists of location-specific VRES hourly potential, i.e. the wind or solar potential for each node n at each time step t for one year. The data is obtained from Wang et al. [151], in which also a more detailed description of the data gathering and process methodology can be found. The hourly values for wind are based on meteorological measurements of wind speeds, measured at hub height. KNMI [81] provide data sets for the hourly wind speed in the Netherlands for different heights with a 2.5 km horizontal resolution. In order to convert the wind speed data to the hourly capacity factor, the power curve of a Vestas V90 3MW wind turbine was used at a height of 80 m. The hourly values for solar are based on levels of solar irradiation. The solar data is obtained from Pfenninger and Staffell [120] for each of the 30 regions for the year 2015. The data for solar and wind VRES potentials are normalized between 0 and 1 (the capacity factors $\sigma_{i,n,t}$). An example of the hourly capacities of onshore and wind over a full year is shown in fig. 5.1.

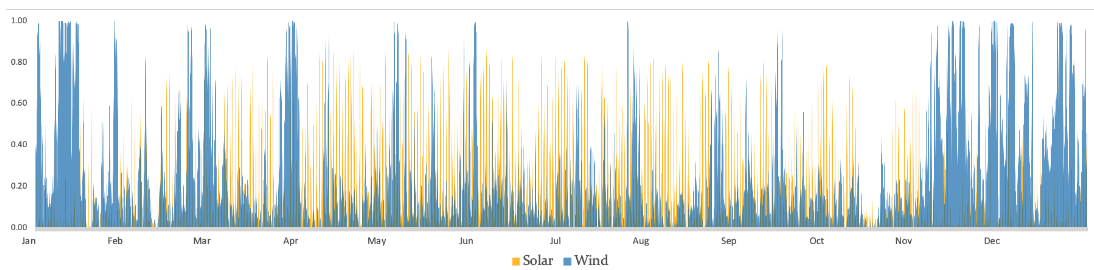


Figure 5.1: Hourly capacity factor of onshore wind and solar for full year (8760 hours)

5.1.2. Land cover assessment

In addition to the location-specific hourly VRES potential, each region is assigned with a maximum allowed capacity. In order to determine the maximum capacity per region, Wang et al. [151] developed a land cover assessment approach. This approach is generically applicable; a more detailed description of the land cover assessment approach can be found in Appendix C. In appendix C, the procedure to obtain the land use capacities for the Netherlands is also specified in more detail. Hereafter, the land cover assessment approach is briefly summarized.

First, the total available area is calculated (left map of fig. 5.2). Once the total area is determined, the next step involves the exclusion of areas not suitable for VRES generation instalment, such as nature reservation areas. The remaining land area can be considered available for VRES development: for the Netherlands, this available land for VRES is equal to 77.35% of the total land (centre map in fig. 5.2). This is referred to as moderate exclusion. A more strict exclusion can be applied, based on the social resistance, mainly for wind energy. In addition, the remaining area is classified based on the Corine Land Cover (CLC) database [1]. Each CLC class is assigned with a suitability factor. Based on the CLC classes, some land can be partially excluded. In the strict scenario, exclusion based on social resistance as well as the partial exclusion based on suitability factors per type of CLC class is applied (right map in fig. 5.2). For the Netherlands, this results in 30.40% of the available land. Finally, the total available capacity (MW) per region can be calculated using the capacity density per technology (5 MW/km^2 for wind [32], and 30 MW/km^2 for solar [58]). This leads to 58.23 GW of potential wind capacity and 379 GW of potential solar capacity [151].

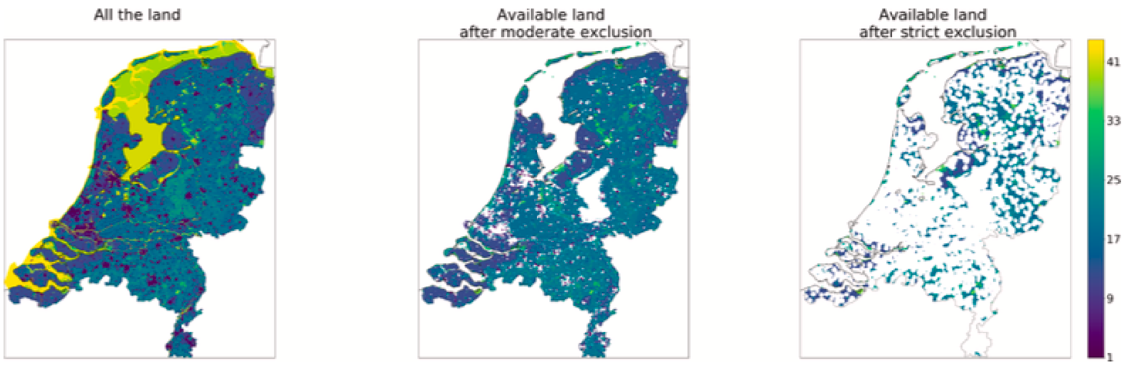


Figure 5.2: Available land in the Netherlands for VRES instalment. The white area represents excluded area, or area not in the Netherlands. The colored area represent different CLC classes. Left to right: all the land, the available land after moderate exclusion and the available land after strict exclusion. Reprinted from [151]

5.1.3. Spatio-temporal demand profiles

The data for hourly demand profiles consists of three types of demand: electricity, heating and hydrogen demand. In order to obtain values for future demand, the Dutch system operators developed four scenarios. The scenarios outline how the energy transition can develop in the Netherlands from 2030 to 2050 (labelled II3050). The scenarios are based on four types of governance: European, International, National or Regional governance [107]. The demand profiles used in this thesis are based on the II3050 European governance scenario. Relative to the other scenarios, this is a mediocre scenario without any extreme values, for instance for total demand or import. The scenario implies reaching carbon-neutrality, mainly through a European CO2 tax. A medium to strong growth in solar and wind energy is expected, as well as medium degree of electrification. Well-developed European markets for hydrogen result in large-scale usage of (blue) hydrogen, including in industry. Similarly, higher shares of biomass results from a well-developed European markets for biomass. In addition, there is a lot of energy import, of both electricity and hydrogen. Import levels are, however, not as excessive as in the international scenario. The values for the total annual demand are 236 TWh for electricity demand, 77.8 TWh for heat demand and 113 TWh for hydrogen. In order to obtain the temporal demand profiles from these total annual values, the Energy Transition Model (ETM)[76] was consulted. The ETM is an open-source and fact-based energy model, which allows exploring future energy scenarios. Numerous settings can be adjusted manually. For this thesis, the II3050 European scenario is used as input for the Energy Transistion Model (ETM)[76], from which hourly demand profiles are derived. Fig. 5.3

shows the hourly demand profiles and demand sub-categories of (a) electricity; (b) heating; (c) Hydrogen as obtained from [76].

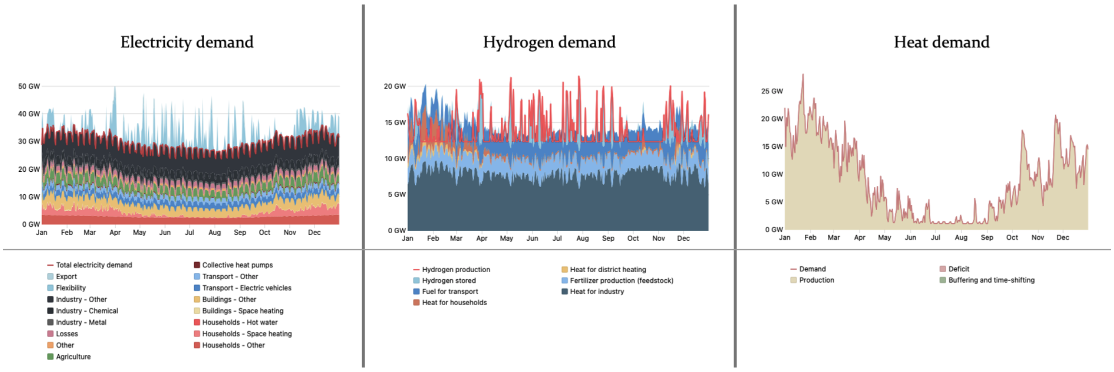


Figure 5.3: ETM hourly demand profiles for scenario II3050 European Governance for sub-categories of electricity, hydrogen and heat demand. Obtained from [76]

In order to obtain demand profiles which are suitable for usage in the model, the data from the ETM is pre-processed. As shown in fig. 5.3 the demand profiles from ETM for electricity and hydrogen are made up of several sub-categories. First, for the hourly electricity and hydrogen demand profiles, several of these sub-categories (i.e. final uses) were excluded from the data, since some of these are calculated endogenously in the optimization model. For example, electricity storage demand, electricity used for heating, hydrogen used to meet the electricity demand (through CCGT) or hydrogen used to meet heating demand (through boiler or heat pump) are all calculated endogenously in the model and hence need to be excluded from the input data. A complete list of the elements removed per demand profile is given in Appendix D. Secondly, in order to obtain the hourly power demand per region, the demands for electricity, household heat and hydrogen are scaled according to the population per region. The shares of population per region is given in Appendix E.

5.1.4. Costs parameters

The costs parameters consist of two categories: the fixed costs and variable costs. In turn, the fixed costs parameters consist of the CapEx costs and lifetimes for generation, conversion and storage technologies. For the variable costs, three parameters are considered: the FOM costs, VOM costs of the energy sources, and the efficiencies. Table 5.1 list the values used for costs parameters. The values are often in a range. The range per costs parameters can be found in Appendix F. Hereafter, first, the fixed costs are discussed. Thereafter, the variable costs are described in more detail.

5.1.5. Fixed costs

The fixed costs consist of the CapEx and lifetime. For onshore, a range of 1075 [130] to 1103 [43] was found. A value of 1100 was used. For solar PV, a relatively low CapEx value of 425 €/kW was chosen. Although seemingly low in comparison to current values, solar investment costs have significantly dropped in recent years. Whereas between 2008 and 2012 of 3000 € /kW where common values for solar PV CapEx, in 2015 this reduced to 1725 € /kW [131]. Recent data show that prices in Germany for small PV instalments (below 10 kW) in 2012 were below 1600 € /kW [**?** **?**]. Average price reductions have been around 15% annually since 15% with a learning rate of about 20% [131]. Therefore, for the long timespan the IPCC forecast a more significant price reduction from 2015 to 2050 solar PV (65%) compared to wind (25%) [57].

Network cost parameters It is assumed that the nodes in the region are similar for the electricity and hydrogen networks, that is, the same set of 30 nodes are used for. In addition, the same edges between these nodes exists for both networks. However, the costs parameters for both network differ. For electricity transmission costs parameters, network cable costs range from € 3000 per MW/km to € 50000 per MW/km [106]. For the transmission and distribution losses, the average of 2014 in the Netherlands was equal to 4.77% [108]. Since all of the network lines in the model are less than 100km, a loss factor of 5% /100km is used [151].

Hydrogen transmission lines can be constructed by either retrofitting of existing gas infrastructure pipelines through coating or the installation of new hydrogen pipelines [148], the former being much less costly. Cost

Table 5.1: Estimations of costs parameters, efficiencies and lifetime for generation, conversion, & storage technologies, fuels, and network costs. Based on [9, 31, 43, 76, 114, 130, 151, 153]

Technology	CapEx (€/kW)	FOM (€/kW/yr)	VOM (€/MWh)	Efficiency (%)	Lifetime (years)
Onshore	1100	45	0.015	-	25
Solar PV	425	21	0.01	-	25
Hydrogen, fuel	-	-	52.25	-	-
Biomass, fuel	-	-	45.26	-	-
Natural gas, fuel	-	-	27.6	-	-
Foreign electricity import	-	-	38.5	-	-
Electrolyser	965	30	-	72	30
EHP	1390	10	-	90	15
CCGT, hydrogen fired	800	11.3	-	70	30
CCGT, biomass fired	2327	90	-	48.7	33
CCGT, natural gas fired	800	20	-	60	30
Boiler, hydrogen fired	1300	40	-	60	25
Boiler, biomass fired	750	26	-	65	25
Boiler, natural gas fired	1300	40	-	60	15
Battery storage unit	650	0.9	-	-	10
Battery conversion	450 €/kWh	-	-	90 (in/out η)	-
TES storage unit	3340	0.7	-	-	30
TES conversion unit	100 €/kWh	-	-	75 (in/out η)	-
Hydrogen storage unit	2400	0.04	-	-	25
Hydrogen storage conversion	60 €/kWh	-	-	100 (in/out η)	-
Network: Electricity	10000 €/MW/km	-	-	5 %/100 km	-
Network: Hydrogen	82 €/MW/km	-	-	1.75%/100 km	-

estimations range from €2.5 to €3.36 Million / km for new hydrogen pipelines and €0.25 to €0.64 Million / km for retrofitted pipelines [148]. Assuming a pipeline with a diameter of 48-inch (1.22m) (one of the most common pipeline types in the EU [148]) with a capacity of 13 GW capacity (LHV), as well as the medium estimations for the costs values, this equals to €211/MW/km for new pipelines and €38 / MW/ km for retrofitted pipelines. Assuming 75% of hydrogen pipelines being retrofit and 25% new pipelines, the average is equal to about €82 / MW / km. The network losses, including the energy used for compression purposes, equal to 0.15 to 0.2% / 100km [148]. For both electricity and hydrogen networks, a lifetime of 40 years is assumed [70].

5.1.6. Variable costs

The total operation costs consist of the VOM costs of energy sources. Since hydrogen and biomass can be converted to both electricity and heat, the value for VOM differs for each use. The fuel price of hydrogen or biomass, given in €/kg, is multiplied with conversion efficiency to electricity or heat of that technology in order to obtain the values given in €/ MWh.

Hydrogen variable costs Generation of green hydrogen, that is, from VRES through electrolysis, is very expensive and currently makes up a small percentage of the overall hydrogen production. The variable costs for hydrogen in this thesis is based on blue hydrogen. Values ranging from €1.5 to €3.2 /kg were found [76, 78]. In this thesis a value of €2/kg is used with a conversion factor of approximately 39 kWh/kg for higher heating value (HHV) and 33 kWh/ kg for the lower heating value (LHV) [82]. With a conversion efficiency for CCGT of about 70% and foreign transporting costs equalling to €21/MWh [31], this is in line with costs parameter values for electricity generation from hydrogen (in €/MWh) found in literature. For example, Gnanapragasam and Rosen [48] found values from €40.5/MWh for grey hydrogen to SMR to €157/MWh for blue or green hydrogen from RES, whereas [78] found values from €41,02 to €58.97 /MWh. The ETM uses values from €30,26 to €82,05 to MWh [76].

Biomass variable costs The fuel costs of biomass is dependent on which biomass resource streams is considered. Research organisation TNO investigated over 30 different biomass streams, which can be categorized into four categories: 1. *wet biomass*, including residues from the food and beverage industry, agricultural residual streams, sewage sludge, aquatic biomass, cultivated grain products; 2. *Dry biomass*, such as residual streams from forestry (tree tops, stumps, bark, branches), recycled waste wood, residual streams from agriculture (straw) and fast-growing bio-energy crops (elephant grass, willow, poplar); 3.*Oil-containing biomass*:

rapeseed, sunflower seeds, oil palm, used frying fat, and finally 4).*Biogenic waste*. In the Netherlands, most boilers run on woody biomass [24], with direct combustion being the most common methods of producing heat from biomass [153]. In a direct combustion system, the biomass is burned to generate hot gas, which is subsequently either used directly to provide heat or fed into a boiler to generate hot water or steam. The overall efficiency of generation from biomass is influenced by several factors, such as biomass moisture content, combustion air distribution, operating temperature and pressure, and others[153]; a typical biomass system operating on fuel with a moisture content of 40% has a net efficiency of about 60% to 65% [76, 153]. Although the wood can be dried prior to increase efficiency, this is not typically done in practice, considering the additional equipment and higher initial cost required [153].

5.2. Model verification

Modelling is always subject to errors. These can range from obvious errors to subtle logical mistakes, which may cause the model to produce erroneous outcomes [111]. Therefore, it is important to verify the implemented model, in which it is addressed whether the model is build as intended. Verification, in contrast to validation, is centred around the question on whether the model is build right. Validation, on the other hand, is centred around the question whether the model is build around the right thing. The validation is discussed in section 6.5. The purpose of this section is thus to provide evidence that the conceptual model, as described in chapter 4, , corresponds with the model implementation which produces the outcomes. The following activities were conducted in the verification process.

Continuous integration and testing First, for every change made in the model, the outcomes were tested to see whether these lead to changes in the outcomes. The easiest way to check whether a change in the model leads to different outcomes is through the exact value of the model objective. The objective function is to minimise the total system costs, which translates to a very high number, often in the domain of millions or billions. Since the optimization model gives an exact number for the total costs, it can safely be deducted that if a change is made to the model, and the objective value does not change, the change is not in force in the model. Nevertheless, this does not give an indication on whether the change incorporated given is indeed accurate. Therefore the changes were assessed to regression errors. The model was incrementally build up in steps, each incorporating new elements, such as storage or the inclusion of hydrogen network. For each of these steps, the outcomes were carefully assessed to verificate whether a single change to the model gave expected outcomes.

Pedigree The model has a history of use in other cases. The model upon which the model presented in this thesis is an extension, GRIM, vouches to some extend for the correctness of the model.

Other Other than the verification steps described above, the model was verified by including function which were run after every scenario run. First, a function was included to check the overall energy balance, for all three types (i.e., electricity, heat, hydrogen), for every time step. In addition, the energy balance for each separate node was checked. - Second, it was checked whether the energy generated of energy source z did not exceed the installed generation capacity of that energy source, for all nodes over all time steps. Third, it was check whether import or export over transmission line did not exceed the installed capacity of that line. Fourth, it was checked whether the storage charge or discharge did no exceed the installed storage conversion capacity. Similarly, it was checked whether the total stored energy was never higher than the installed capacity for energy storage. Fifth, it was checked whether the import and export over transmission line was equal.

5.3. Experimental design

The previous sections described how the conceptual model can be translated into a workable model: the parameters are defined, and it is verified whether the model is preforming as intended. In order to obtain valuable outcomes, the experimental design needs to be constructed which can be used to run the optimization model. The goal of the model is not to provide general descriptions of the system, but to answers specific questions. Therefore, the modelling problem statement of this thesis was formulated in section 2.2. The model can be used to evaluate the impact of different inputs, in terms of four components: the system costs, generation mix, the role of storage and the network flows and capacities. This section first describes the different input variables. Thereafter, the sets of input variables are given, i.e., the scenarios.

National RES target In order to analyse the implications of a future energy system with reduction in GHG emissions, different targets of RES shares were analysed. Increasing targets of RES are especially interesting to investigate in detail for several reasons. First, this allows to analyse the implications on the generation mix and system costs when more RES enter the energy system. With increasing share of VRES, it is more difficult to meet demand for every time step due to the intermittent character, as opposed to conventional energy generation. These could, for example, lead to a sharp increases in total system costs. Secondly, it allows analysing which of the options to increase system flexibility are the preferred, cost-optimal options. Included in the model are storage, transmission and increased integration between different energy sectors through electrolysis or EHP. Five levels of increasing RES target are considered: 0% - 20% - 50% - 80% - 100%. The RES target is added as a constraint (see eq. 4.15)

Locally generated RES target In addition to the overall RES target, the Dutch government set the target to provide more than 70 percent of electricity needs from wind and solar energy [112]. Although not explicitly mentioned that these should be generated domestically, realistically due to limited cross-border transmission line capacity this implies that a large share will have to be generated locally from wind or solar. Furthermore, in addition to the Locally generated RES target set in the Dutch climate agreement, high shares of hydrogen and biomass import can lead to very different outcomes. In scenarios without a Locally generated RES target, shares of hydrogen and biomass import can be significant. This would imply a very well-developed cross border hydrogen infrastructure, exceeding the ambitions of EHB [148]. The values are based on the 70% target of RES. Hence, the values for the Locally generated RES targets are 0%, 14%, 35%, 56& and 70% in respect to the overall RES target levels. The locally generated RES target is added as a constraint (see eq. 4.16).

Level of sector integration In order to analyse the implications of a MES compared to a non-integrated energy system (NIES), the level of sector integration is varied. Referring to fig. 4.8, this is implemented by excluding two conversion technologies: EHP and electrolyser. By comparison a MES scenario with a NIES scenario, the potential benefits of a MES can be investigated. This could be reflected in the total system costs, generation mix and ability to increase system's flexibility. This input variable is binary, meaning that sector integration is not allowed at all, or sector integration is fully unconstrained. This is modelled as a constraint whereby the capacities of EHP and electrolyser are either zero or unconstrained (see eq. 4.17).

Land-use limitations More land-intensive generation technologies like solar PV and onshore wind can be limited by the available land-use, especially in a densely populated country such as the Netherlands. In order to account for this maximum VRES capacities, a constraint is added to model the maximum allowed capacities for solar and onshore in the regions. The land cover assessment method for the Netherlands is described in section 5.1.2 and Appendix C. Three levels of land-use limitations can be imposed: no exclusion, i.e. all the land is available for instalment of VRES, moderate exclusion (77.85% of total area) and strict exclusion (30.40% of total area). The scenarios are limited to no exclusion, or strict exclusion.

5.3.1. Constructed scenarios

The variable options for the runs of the optimization are two levels of sector integration, five levels of national RES targets and locally generated RES targets, and two levels for the maximum land-use, in total accounting for fifteen scenarios which could be constructed. These are shown in table 5.2.

The scenarios are divided in three groups. First, the "MES" scenarios refer to scenarios where no limitations are imposed on sector integration, and no limitations on land-use. Five different levels of RES targets are considered. Second, the "NIES" scenarios refer to the scenarios where no sector integration is allowed. Similar to the MES scenarios, land-use is not restricted. The outcomes of these scenarios can be compared with MES scenarios. As such, the implications of sector coupling can be studied. Five levels of RES targets are included to provide a comprehensive comparison. Third, the "MES w/LR" scenarios are similar to the MES scenarios, however strict restrictions are implied on the land-use available for onshore and solar capacities per region. Before the results are presented and discussed in the next chapter, the computational set-up used to run the model and the associated implications is described in the next subsection.

5.3.2. Computational settings

The computational set-up used to run the model can have implications on the outcomes of the model. The optimization model was written in Python, using the Pyomo package for linear optimization formulation.

Table 5.2: Scenarios used to run the optimization model

Scenario group	Scenario name	RES target	Local RES target	Sector integration	Land-use restrictions
MES scenarios	MES 0	0%	0	✓	none
	MES 20	20%	14%	✓	none
	MES 50	50%	35%	✓	none
	MES 80	80%	56%	✓	none
	MES 100	100%	70%	✓	none
NIES scenarios	NIES 00	0%	0%	✗	none
	NIES 20	20%	14%	✗	none
	NIES 50	50%	35%	✗	none
	NIES 80	80%	56%	✗	none
	NIES 100	100%	70%	✗	none
MES with land-use restrictions	MES w/ LR 0	0%	0%	✓	strict
	MES w/ LR 20	20%	14%	✓	strict
	MES w/ LR 50	50%	35%	✓	strict
	MES w/ LR 80	80%	56%	✓	strict
	MES w/ LR 100	100%	70%	✓	strict

Other packages used include Pandas and Numpy. The mathematical optimization solver software used was Gurobi [2]. Other solvers, such as CPLEX could also be used, however, these can lead to significant increase in computational time. The model was run on a 4 core, 28 GB RAM Linux Azure D12 series cloud computer.

For these settings, not all scenarios could be run for a full year. In general, the more "stricter" scenarios are computationally more demand. That is, it is more difficult to find the global optimum if more constraints are implied — specifically RES targets and land-use constraints. A large decision space is common in MES optimization models due to the multi-input and multi-output character, adding an additional layer of computational complexity, leading to very large number of variables and non-zeros. Therefore, trade-offs are common in MES optimization models [16], such as on the spatial coverage and resolution, the temporal coverage and resolution, degree of linearization, level of detail or total number of the energy sectors incorporated. With the computational set-up described above, the maximum allowed number of time steps per scenario is around 600 hours[1]. In order to account for the intermittent VRES characters, the temporal resolution of the model (hourly) was not altered. Instead, the temporal horizon was reduced. To cover for seasonal fluctuations, the total run is a combination of four different time periods throughout the year of 120 hours each:

1. 360 - 480 hours: January (winter)
2. 2520 - 2640 hours: April (spring)
3. 4680 - 4800 hours: July (summer)
4. 6840 - 6960 hours: October (autumn)

In turn, the results are adjusted for the reduced time horizon by extrapolating the obtained values to a year, (i.e., by multiplying these with 8760 / (4×120). In order to assess the implications of this reduced time horizon, several scenarios were run for different time horizons: for all of these, the difference in total system costs was relatively small, in the range of 10%. The MES 0 scenario was run for a time span of 4380 hours, thus covering half a year as well as the reduced time series as described above; the difference in results was also below 10%.

The next chapter will discuss the results obtained from the ten scenarios run with the optimization model.

[1] Numerous options were tested to decrease computational times, such as Gurobi object scaling, scale flagging, bar homogeneousity, loosening of Markowitz tolerance and rearranging of the decision variables and objective function order. None of these resulted in significant decrease in computional time.

6

Results & Discussion

In this chapter, the results from the optimization model, based on the runs of the experimental design, are presented and discussed. The model provides the cost-optimal investment and operation based on varying levels of sector integration, RES targets and land-use limitations. The model produces three outcomes: the total system costs, the energy mix, and finally the spatial distribution of generation, conversion, storage and transmission.

The results are analysed by comparing the three groups of scenarios. In turn, this allows to analyse the implications of two important components: the level of sector integration and the land-use restrictions. The analysis of the results is structured as follows. In the first section, the system costs are investigated. The difference in costs between MES and NIES scenarios is analysed to determine the benefits of sector integration. Then, the MES scenarios without land-use restrictions are compared with the MES scenario with land-use restrictions. To investigate the differences in price between a MES and a NIES, the energy mix is analysed in more depth. This is presented in the second section, consisting of the installed capacities of generation, conversion and storage technologies (the generation mix), the hourly generation and conversion of different energy sources and conversion technologies and the storage charged or discharged, the energy balances for electricity, hydrogen and heating sector, and the cross-sector utilization. In the third section, the spatial components are presented and discussed. Here, the implications of land-use restriction on the spatial distribution and network transmission flows and capacities are further investigated. The validation is addressed in the fourth section. In the fifth section, implications of the results are discussed. Since the results are prone to assumption and choices made, the limitations of the outcomes and applicability are also discussed here. The sixth and final section provides suggestions for future research.

6.1. Average cost of energy

Fig. 6.1 shows the average cost energy costs (€/MWh) and the values per cost component for each scenario. The total system costs consist of the investment costs of generation and conversion technologies, investment costs in storage, operation costs, and network investment costs. Numerical values for each component per scenario can be found in Appendix G. The average energy cost is obtained by dividing the total system costs by the total amount of MWh generated. Across all scenarios, the average costs increases with higher RES targets. Operation costs make up the largest share of total costs for lower RES targets. However, from RES targets of 80% and higher, investment costs for generation and conversion technologies increase significantly, and present the largest shares in total costs. From a RES target of 50% and higher, investment is made in storage technologies. Investment in both electricity and hydrogen networks increase with higher RES targets as well. Hereafter, first the difference in cost components between MES and NIES scenarios is discussed, and then the costs of MES and MES w/LR senarios are compared.

6.1.1. Implications of sector integration on costs

The implications of increasing sector integration are assessed by comparing the scenarios without sector integration (NIES) with sector integration (MES) of the same RES target. The average energy cost provides a good indication of the benefits of integrating energy sectors for the energy system as a whole. The results in fig. 6.1 show that for all RES targets, the average energy costs is lower in the MES scenarios compared

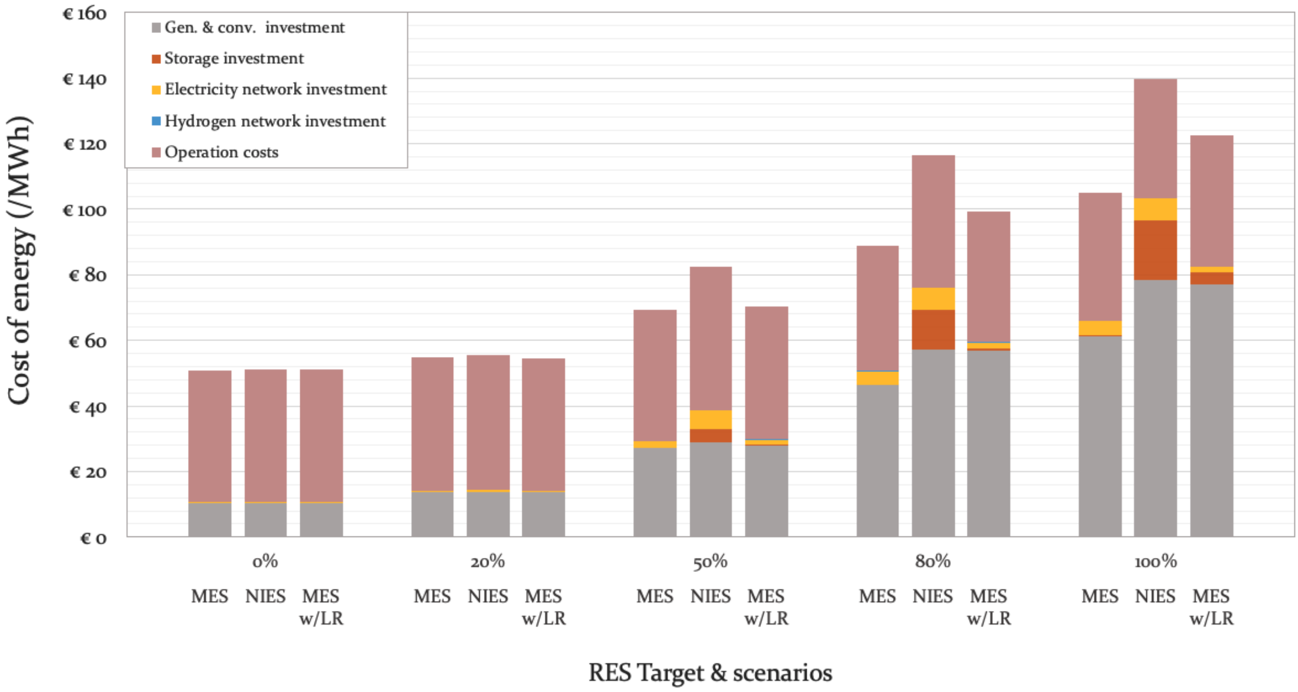


Figure 6.1: Average cost of energy (€/MWh) for each scenario and the share per cost component

to the NIES scenarios. Hence, increasing integration between different sectors leads to improved economic efficiency of the overall system. These findings are in line with other studies found [17, 42, 44, 63, 95, 127, 143]. Furthermore, the average energy costs savings are highest with increasing RES targets. For a 50% RES target, the average energy costs of the MES scenario (69.32 €/MWh) is about 16% lower than of the NIES scenario (82.60 €/MWh). This difference increases for higher RES targets: for 80% RES, this amounts to 23.9% and for a 100% the decrease is 24.8%.

The average energy cost reflects the overall economic efficiency of the system. The higher average energy costs in the NIES scenarios indicates that it is increasingly difficult to find an optimal solution to meet the demand at all times. However, the average energy cost in and of itself does not provide rationale as to why the costs are lower. Investigation of specific costs components allows highlighting which particular investment costs are reduced due to increased sector integration. For the 50% RES target scenarios, increased sector coupling leads to 16% reduction in total costs, as compared to NIES scenarios. About one third of the savings are a result of less storage investment. Furthermore, sector integration leads to a reduction in electricity network investment, which also accounts for about a third in savings. Operation costs savings account for about a quarter. Savings in generation and conversion technology amount to 11.5% of total savings. When the RES target increases to 80%, savings in generation and conversion technologies become more significant. For RES target of 80%, this cost component amounts to 43.7%.

In the fully renewable scenario, the savings are significant. In absolute terms, most savings are made in capacity needed for generation and conversion technologies. Overall, the demand can be met much more cost-efficiently, leading to a reduction in electricity network investment of 57.8%. Similarly, whereas storage investment costs amount to just 0.36% of total costs for the MES 100 scenarios, respectively, the storage costs are significantly higher for the NIES scenarios: 13.03% of total costs are needed for storage.

Since the solution is always optimal and the average energy costs are lower in the MES scenarios, it can be deducted that integration of energy sectors is a cost-efficient approach to provide system flexibility. Sector integration leads to reduction in investment of generation capacity, storage capacity or electricity and hydrogen network capacity to meet the demand. For lower RES target, savings in generation and conversion capacity, storage capacity and network capacity are all significant. For higher RES target, savings are particularly high for generation and conversion investment, but also for storage. Although to a less extent, savings are also made in electricity network expansion. This is in line with findings of TenneT and Gasunie [138], who indicate that increased sector coupling could lead to significant savings in network expansion.

6.1.2. Implications of land-use restrictions on costs

In order to assess the implications of restrictions on land-use, the total costs of MES and MES w/LR scenarios are compared. For RES targets of 0 and 20%, the differences in average energy costs are insignificant (€0.20 /MWh and €0.31 /MWh). In these scenarios, the land-use restriction do not lead to a lot of land area being maximumly utilized since onshore and solar PV capacities are low. Hence, deviations from the optimal locations of VRES generation capacities are not required. For a RES target of 50%, imposing land-use restrictions leads to a costs increase of just €0.88 /MWh (+1.26%). For a RES target of 80%, however, the difference increases to €10.64 / MWh (+11.99%). For a RES target of 100%, land use restrictions results in cost increase of €17.55 (+16.69%). In particular, investment in storage increases significantly. Also, investment costs in generation and conversion costs increase. Since the total amount energy of energy generated is similar, this indicates that deviations from the optimal locations for generation can have lead to significant increases in investment costs. Interestingly, the average energy cost is lower in the MES w/LR scenarios than in the NIES scenarios. In order to investigate this difference in more detail, the next section will investigate the differences in terms of energy mix between scenarios.

6.2. Energy mix

Fig. 6.2 shows the total installed capacities of all generation and conversion technologies for increasing RES targets, for the three different scenarios. In addition to the total installed capacity over all nodes per scenario, the installed capacity per individual node can be investigated. This is presented in the next section, where the spatial distribution of the different technologies are analysed in more detail in order to identify differences across regions. Two conversion technologies are not invested in across all scenarios: CCGT using biomass fuel and heat pump or boiler using hydrogen, due to the poor conversion efficiencies compared to competing conversion technologies.

At a RES target of 0%, shares of natural gas CCGT are high, with natural gas accounting for 40% of total energy supply. With increasing RES targets, overall installed capacity also increases. At a RES target of 20%, investment is made in onshore. At this level of RES target, EHP also appears in the generation mix, taking away shares of natural gas boiler in the supply of heat. However, although EHP takes some share in heating supply in higher RES scenarios, biomass is dominant in the supplying of heat and is invested in relatively consistently across all scenarios. Electrolysis is invested in as well from a RES target of 20% and higher. Hereafter, the implications of sector integration will be investigated in more detail by comparing the MES with NIES scenarios. Thereafter, the MES scenarios are compared with the MES w/LR scenarios to investigate the implications of imposing land-use restrictions.

As discussed in section 6.1.1, the MES scenarios lead to an overall more efficient energy system in terms of total costs. When comparing the NIES scenarios with the MES scenarios in terms of the generation mix, it can be observed that the total installed capacities do not differ significantly for RES targets of 50% or lower. The differences between the two scenarios become mostly apparent for RES target of 80% and higher. Total installed capacity is about 27.7% higher in the NIES 80 scenario compared to the MES 80 scenario. For a RES target of 100%, this difference amounts to 36.3%.

Meeting the demands is increasingly difficult for higher RES targets in the NIES scenario. To provide system flexibility, increased sector integration reduces the need to invest in additional storage and transmission (transmission is discussed in more detail in section 6.4). Therefore, storage investment is much higher in the NIES scenarios as compared to the MES scenarios, in particular battery storage. Also, more investment in generation technologies of solar PV and onshore wind is needed. Therefore, installed capacity of onshore wind increase by a factor of 1.2 in the NIES scenario, where solar PV capacity more than doubles. By increasing sector integration, this need for more generation capacity and storage capacity is reduced by the possibility of other conversions. Therefore, in contrast to the NIES scenarios, the cost-optimal solutions found in MES scenarios show a mixture of different conversion, storage and generation technologies.

Nevertheless, sector integration alone is not enough. MES is especially beneficial in combination with other flexibility measures. The MES scenarios shows that, especially in an energy system with higher shares of RES, storage will still play a moderate role in providing system flexibility. The scenarios with more sector integration show higher investment in hydrogen storage investment and a decrease in battery investment. This preference for hydrogen storage in the MES scenarios is due to the increased capacity of electrolysers in the energy mix, highlighting the complementary benefits of hydrogen storage with the increased electrolyser installed capacity.

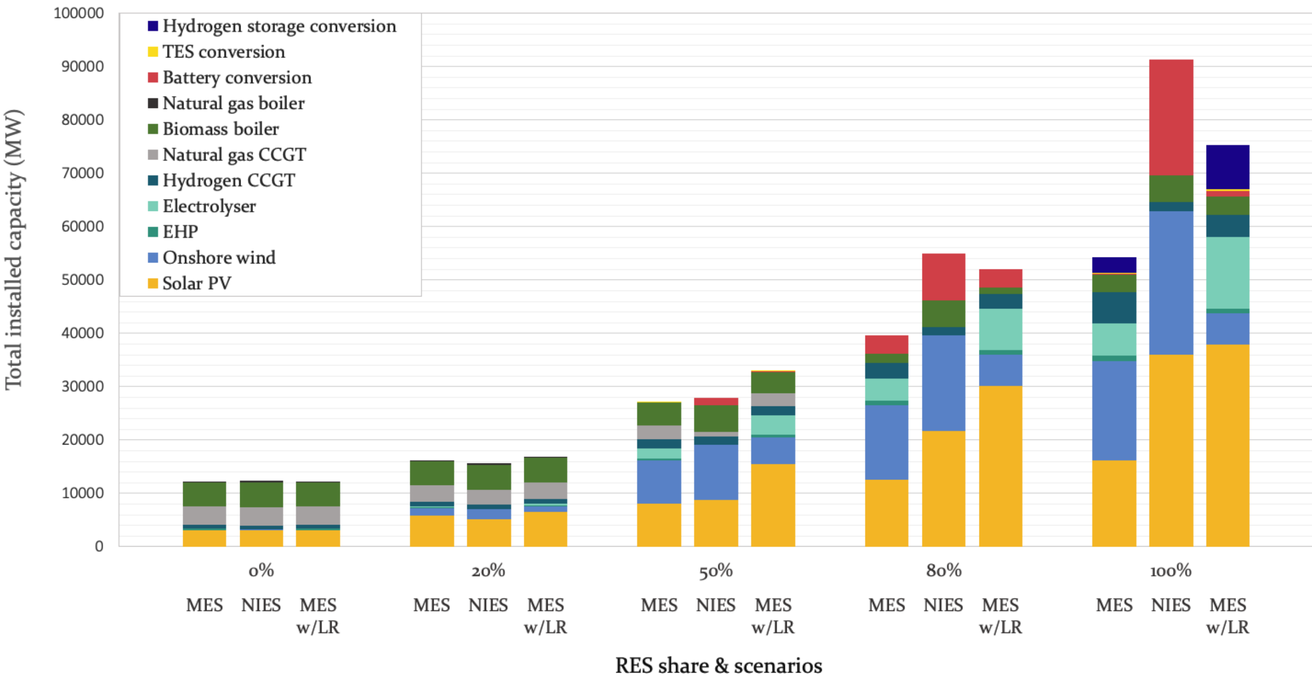


Figure 6.2: Total installed capacity in MW per generation and conversion technologies for all scenarios

For lower RES target, the imposing of land-use restrictions does not lead to a different optima. That is, in a MES with RES targets, the amount of land used for solar PV and onshore wind does not exceed the imposed maximum for all of the 30 regions. This changes for a RES target of 50% and higher. In particular, shares of solar are relatively high in scenarios with land-use restrictions. This is due to the land-use constraints and the difference in capacity factors of wind energy opposed to solar. In order to meet all three types of demand in scenarios with high RES targets, the maximum amount of land available for onshore is reached more quickly than for solar PV, due to the difference in capacity density: 30 MW/km^2[58]) for solar PV, compared to 5 MW/km^2 for wind [32] (more detail can be found in section 6.3.1). In order to compensate for this decrease in onshore generation capacity, investment is made in solar PV, ultimately leading to higher investment costs. Furthermore, electrolysers investment is higher in scenarios with land-use restrictions. Electrolysers has relatively high investment costs and low efficiencies, however this is outweighed by the benefits electrolysis can provide in balancing and storage. Imposing of land-use restriction results in a different energy mix: shares of onshore are lower when land-use restrictions are imposed. Share of solar, on the other hand, are relatively higher.

6.2.1. Energy balances

In addition to the installed capacities, the model provides hourly energy balances for electricity, hydrogen and heating. Fig. 6.3 shows the annual energy balance for electricity for a fully renewable MES scenario (MES100). The total demand consists of exogenous electricity demand, amounting to 51.3% of total electricity, input for EHP (8.1%), charging of battery storage (0.7%), and a large share of electricity is used for generation of hydrogen in electrolysers (39.9%). VRES supply for electricity is high, with most electricity generation originating from onshore (53.3 %), where solar PV amount to 33% solar PV. Hydrogen CCGT provides 13.2% of total electricity, whereas the final 0.5% is supplied by discharge from battery storage.

The energy balances for hydrogen and heat are shown in fig. 6.4. Compared to the electricity balance, storage shares are high. About 32.4% of total annual hydrogen demand is supplied by discharging of hydrogen storage. Furthermore, a significant amount of hydrogen is supplied by electrolysis (43.1%). The remaining hydrogen is imported (24.5%). Heat demand is lower than exogenous hydrogen and electricity demand, where around two third is supplied by biomass (65%) and about a third by EHP (34%). Since heat is largely covered by biomass, fluctuations are less troublesome and shares of TES are low.

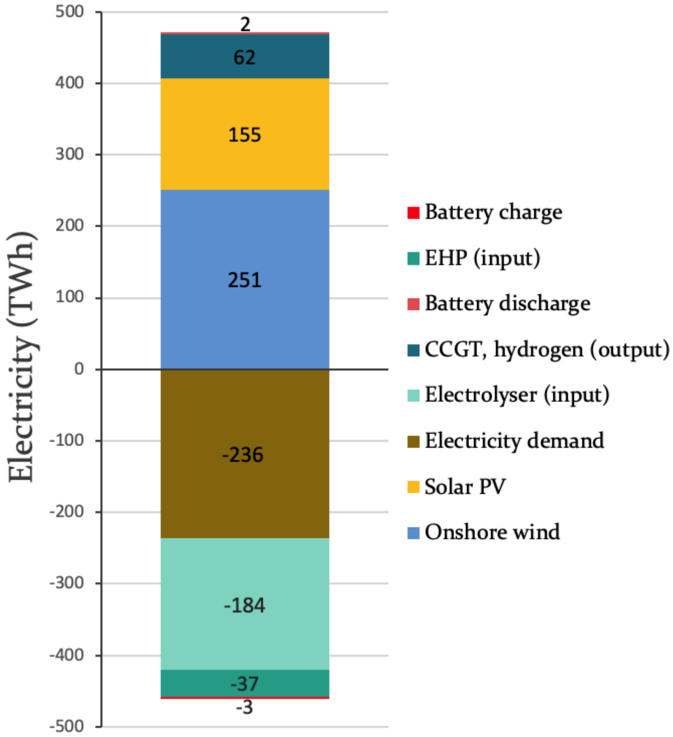


Figure 6.3: Annual electricity balance for fully renewable MES

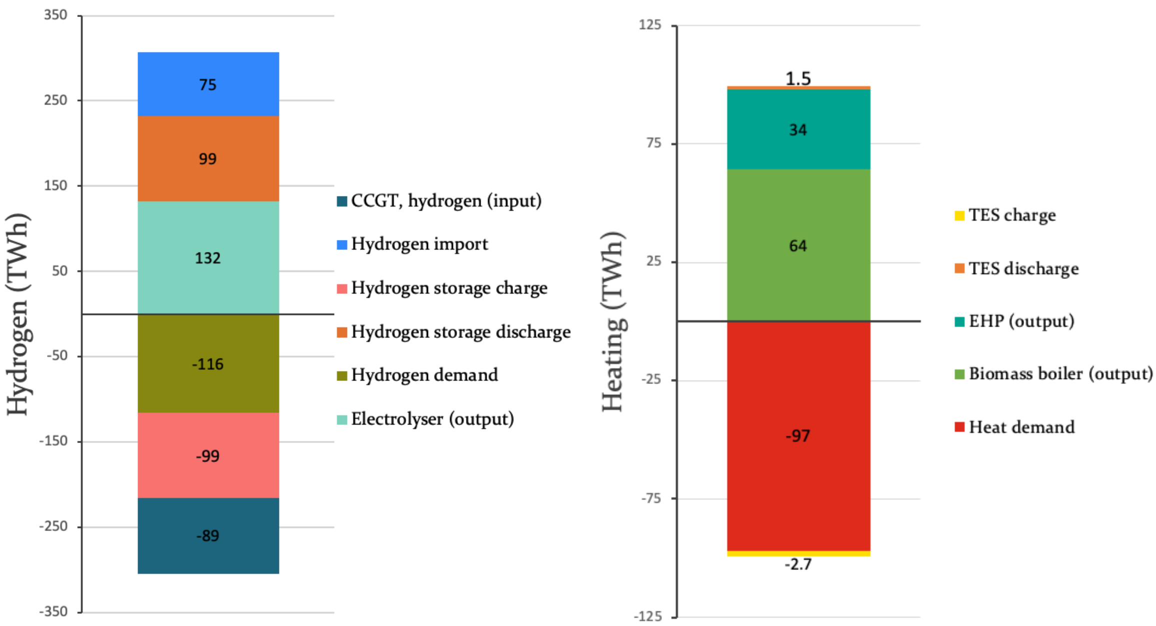


Figure 6.4: Annual hydrogen and heating balance for fully renewable MES

6.2.2. Cross-sector utilization

The different energy sectors of electricity, hydrogen and heating are integrated. Fig. 6.5 illustrates the cross-sector utilization of different energy sectors. The electricity and hydrogen energy sectors are integrated through electrolysis. In the MES 100 scenario, electrolysis is heavily invested in, with electrolysis accounting for about 64% of hydrogen supply compared to 36% import. The electricity and heating sectors are integrated through EHP. Since the total annual heat demand (97 TWh) is lower than the total annual hydrogen (113 TWh) or electricity (236 TWh) demand, the total cross-sector utilization of electricity in heating is smaller. EHP amounts to about a third of total heat supply. In contrast to electricity, heat can be generated when effectively when needed using biomass. Finally, hydrogen and electricity sectors are also integrated through hydrogen CCGT. Hydrogen CCGT is used when it is difficult to meet electricity demand with solar or onshore. To analyse how sector integration increases system flexibility, the hourly energy generation and conversion is investigated in the next paragraph.

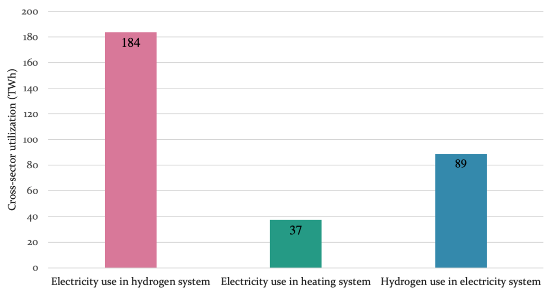


Figure 6.5: Cross-sector utilization of hydrogen, electricity and heating sectors

6.2.3. Hourly generation, conversion and discharge

Fig. 6.6 shows the hourly energy generation, conversion and discharge related to the electricity power balance. That is, the generation $Pz_{i,n,t}$ for solar, onshore, and foreign electricity import, the conversion $Ph_{i,n,t}$ output for CCGT of natural gas and hydrogen, and the storage discharge $DP_{i,n,t}$ for battery, for 480 hours in a year. For a RES target of 100%, onshore and solar are better utilized in the MES scenario due to increased shares of hydrogen CCGT. To illustrate this, the input of electrolyser $Ph_{elctr.,n,t}$ and the amount of hydrogen used to charge hydrogen storage $CP_{h2,n,t}$ are also shown in fig. 6.6. It shows that these two values are high in hours when solar and onshore is also high. Hydrogen storage is accumulated in times of high supply of solar and onshore, which is used in hydrogen CCGT is high when the solar or onshore supply is low. As a result, in the MES scenario the output of hydrogen CCGT amounts to 62.18 TWh, compared to 7.51 TWh for the NIES 100 scenario. These hours are thus troublesome and in the NIES scenario require investment of more expensive battery storage (the read or increased generation capacity. In line with findings of Meibom et al. [100], who showed that sector integration in a (North European) power system leads to an increase in capture of wind power potential, ultimately leading to a lower energy price.

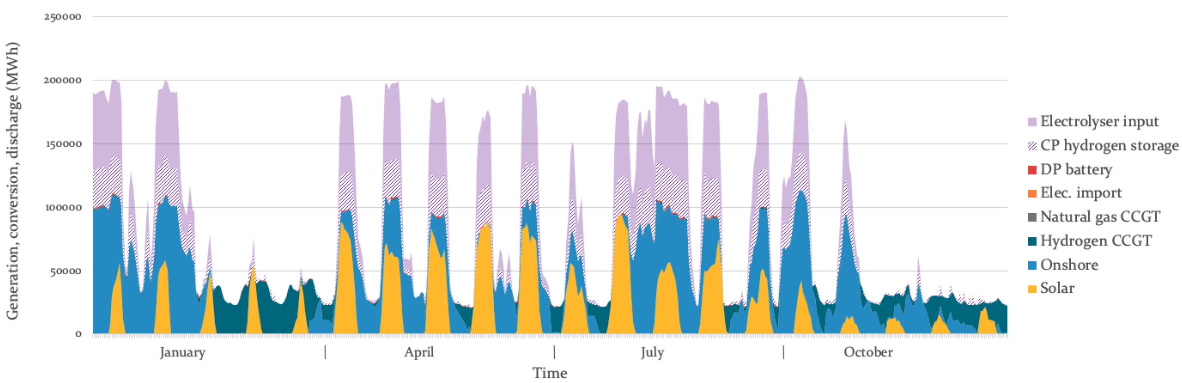


Figure 6.6: Total annual (left, pie chart) and hourly (right, area) generation, conversion and discharge of electricity for RES target of 100% for the MES scenario. Plotted for the hours 360 - 480 hours (January, winter), 2520 - 2640 (April, spring), 4680 - 4800 (July, summer) and 6840 - 6960 (October, autumn)

6.3. Spatial implications

In addition to the costs and energy mix, the model produces the installed capacities of generation, conversion and storage technologies per region, and the transmission capacities and flows of the electricity and hydrogen networks. Since assuming unlimited available land for solar and onshore can lead to unrealistic fraction of land usage, this section will analysed the difference in spatial implications as a result of imposing land-use restrictions. This section first compares the spatial components of the electricity sector. Here, the installed capacities per region of solar PV and onshore wind technologies between scenarios with and without land-use restrictions are compared, along with the transmission of electricity and hydrogen between these regions. In contrast to onshore and solar PV, technologies related to the hydrogen sector do not have a significant impact on the available land in a region, and no land-use restriction are not imposed on hydrogen or heating technologies. The NIES scenarios are not considered in the spatial analysis, since it was concluded in section 6.1 that the MES scenarios lead to a more cost-efficient optimum.

Fig. 6.7 shows the installed capacities of solar PV and onshore per region, and the installed capacities for electricity network lines, for the fully renewable scenarios. The scenarios without land-use restrictions are shown on the left, whereas the scenarios with land-use restrictions are shown on the right. The installed capacities of generation and conversion technologies for the fully renewable scenario without land-use restrictions can be found in Appendix H. Values for the scenario with land-use restrictions can be found in Appendix I.

When land-use restrictions are not imposed, the installed capacities are geographically very centred in a few regions. For both solar PV and onshore wind, the imposing of land-use restrictions leads to a much more evenly spread distribution of capacities. However, the total installed capacity of solar PV is higher in the scenarios with land-use restriction, due to a decrease in onshore capacity. This implies that the maximum allowed onshore capacity per region is quickly when imposing of land-use restrictions. In order to compensate for this loss in onshore capacity, additional solar PV is required. For solar PV, maximum land-usage is not reached as quickly, partly due to the higher capacity density of solar PV. Therefore, the total installed capacity of solar PV as well as the average installed capacity of solar PV per region is higher in the scenario with land-use restriction. Hereafter, the spatial distribution of solar PV and onshore will be discussed.

6.3.1. Spatial distribution of solar PV

Although the imposing of land-use restrictions leads more solar PV per region on average - 3554 MW with, scenarios compared to 9287 MW without land-use restrictions - the capacities are more evenly spread. Without imposing land-use restrictions, highest installed capacity of solar PV are found in regions Noord- en Midden Limburg (41880 MW) and region Zuid-Limburg (39077 MW). The total installed capacity of solar PV of these two regions accounts for almost half of the total installed capacity. Other regions with high solar PV capacities are Rotterdam & Den Haag (16237 MW) and Noord-Holland Noord (14835 MW). 70% of total installed solar PV capacities is installed in these regions.

When land-use restrictions are imposed, concentration of solar PV capacity is spread more evenly. Solar PV is found in all regions, and no regions with extraordinary high capacities are found. The region with the highest installed capacity is Friesland, with 53307 MW, equalling to 14.1% of the total. Other regions with high capacities in these scenarios are Groningen (30589 MW, 8.1%), Drenthe (29487 MW, 7.8%), and West Overijssel (25108 MW, 6.6%). In comparison to the scenario without land-use restrictions, where 70% of solar PV was concentrated in four regions, in this scenario the four highest regions amount to 36.6% of total solar PV capacity.

In the scenario without land-use restrictions, solar PV is higher in regions with high annual capacity factors. Fig. 6.8 shows the annual capacity factor for solar and onshore. Highest average capacity factors for solar PV are found in southern areas, such as Noord- en Midden Limburg and Zuid-Limburg, which also show higher solar PV capacity in the MES 100 scenario. However, the difference in solar capacity factors between regions is relatively small, with capacity factors ranging from 0.11 to 0.14. Fig. 6.7 also shows some installed solar PV capacity in Noord-Holland Noord and Rotterdam & Den Haag, which are regions with relatively lower solar capacity factors. Investment in solar PV is high in these regions, due to higher electricity demand. Apparently, the avoiding of additional electricity transmission lines outweighs the higher solar radiation in these regions. When land-use restrictions are imposed, solar capacity is higher in regions with more available area for solar. The regions with high solar PV capacities in this scenario are generally larger and have lower population density.

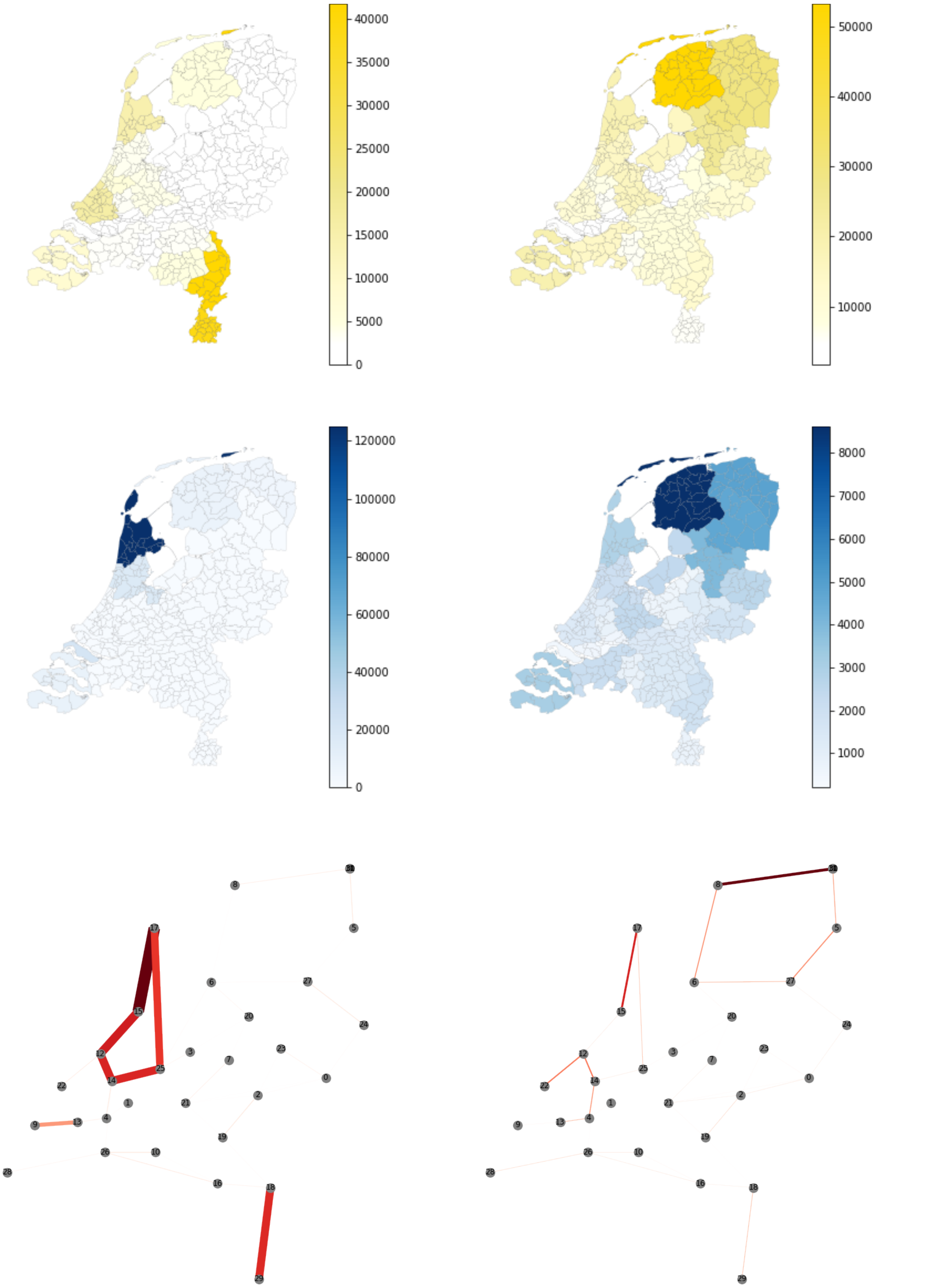
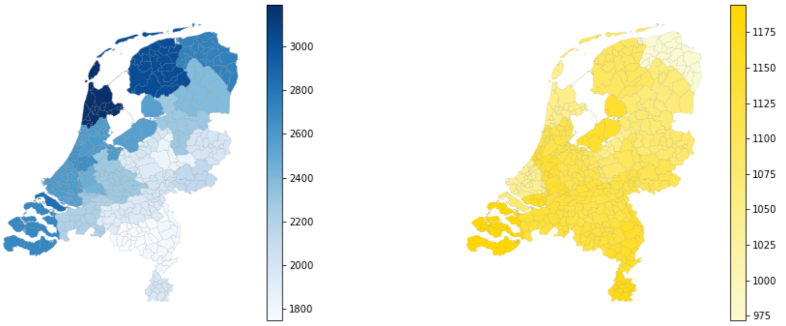


Figure 6.7: Spatial distribution of solar PV and onshore wind capacities, and installed capacity per electricity network line for fully renewables scenarios. Left: no land-use restrictions. Right: with land-use restrictions



(a) onshore (b) solar

Figure 6.8: Capacity factor map for a) onshore wind and b) solar

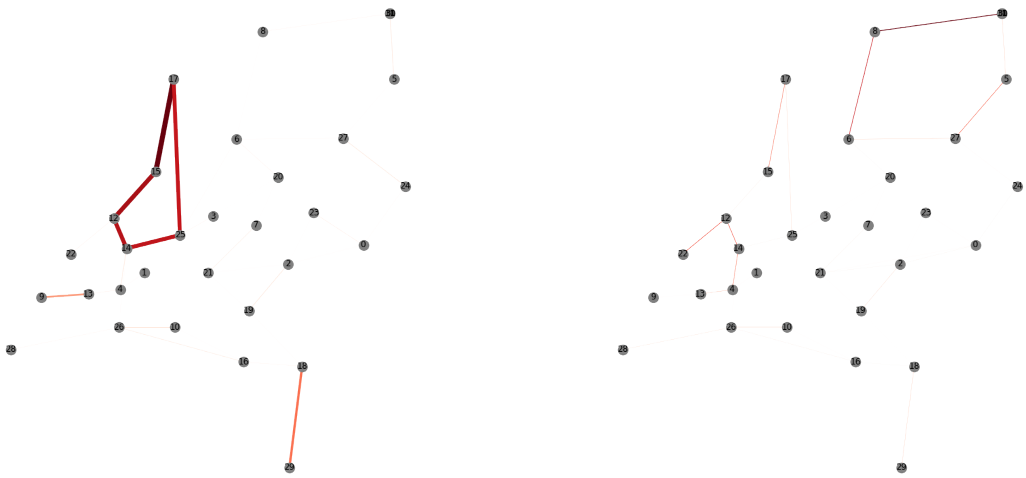
6.3.2. Spatial distribution of onshore wind

Whereas imposing land-use restrictions lead to an increase in capacity for solar PV, the capacity of onshore decreases as a result of land-use restrictions. The average per region is 1845 MW for the MES with land-use restriction scenarios compared to 3488 MW for the MES scenarios. The highest installed capacity in a single region does not exceed 9000 MW when imposing land-use restrictions. In contrast, the maximum capacities for the MES scenarios are extremely high. In the fully renewable scenario without land-use restrictions, the highest capacity of a single region is found in Noord-Holland Noord, with a capacity of 125 214 MW. This is equal to 67.6% of total installed capacity in this scenario. This indicates that not imposing land-use restrictions in a MES leads an unrealistically high capacities of onshore wind. In contrast to solar PV, the discrepancy between regions in terms of favourable wind conditions is high: onshore capacity factors range from 0.20 to 0.36. Therefore, onshore investment is especially high in the western and northern coastal regions. Onshore investment generally capitalizes more on the spatial differences, explaining the high centrality of onshore investment: the optimization model invests in regions with the highest annual wind in order to maximise the return on investment costs.

If land-use restrictions are imposed, average installed capacities are much lower and the capacities are spread much more evenly. In fact, in the fully renewable scenario, there is no region without onshore capacity. The highest values for onshore are found in Friesland (8632 MW, 14.8% of total), Groningen (4870 MW, 8.4%), Drenthe (4696 MW, 8.1%) and West-Overijssel (4017 MW, 6.9%). Together, these four regions account for 38.2% of total onshore capacity. As shown in fig. 6.7, these regions are mostly large, densely populated, coastal regions situated in the North and East, with relatively high annual wind capacity factors.

6.3.3. Electricity transmission

Fig. 6.7 shows the capacities of electricity transmission lines for the fully renewable scenario. The total installed electricity transmission line capacity is higher when land-use restrictions are not in place: the average over all lines is 2209 MW per line without land-use restrictions, compared to 693 MW with land-use restrictions. This quadrupling of electricity line capacity is a result of the centrality of onshore and solar PV. When land-use restrictions are imposed, onshore and solar PV capacities are spread much more evenly, hence less transmission capacity between regions is required. This shows that the benefits of maximally utilizing the regional advantages of certain areas outweighs the additional network investment costs.



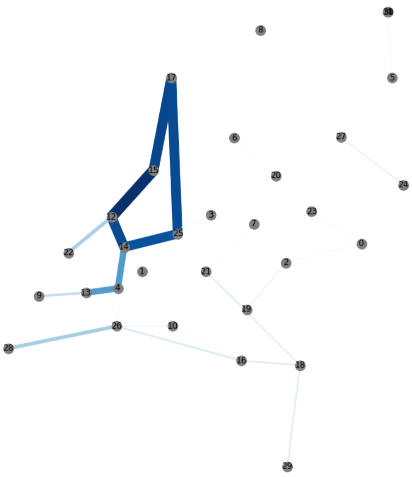
(a) Without land-use restrictions (b) With land-use restrictions

Figure 6.9: Average energy flow of electricity per line for scenarios with a RES target of 100%

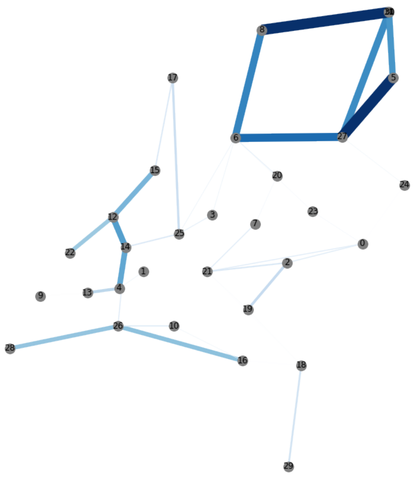
In addition to the installed capacities, fig. 6.9 illustrates the average flows per line of electricity for the fully renewable scenarios. Since import and export are modelled separately, the highest value was taken in order to indicate the type of transmission flow that causes the most stress on the line. The average load per line (average annual flow divided by the installed capacity) over all lines is lower when land-use restrictions are implied: 22.61%, compared to 36.14%. In general, lines with high capacities also have higher average flows. Fig. 6.7 and fig. 6.9 give an indication of bottlenecks in the electricity grid. For the scenario without land-use restrictions, six connections have particularly high capacities and flows, exceed capacities of 11000 MW. Bottlenecks can occur mainly in regions with high demand, centred in the North-Western regions. When land-use restrictions are imposed, stress on the grid is much less significant. Capacities do not exceed 5000 MW. The higher transmission capacities are found in regions with higher onshore and solar PV capacities in the North-Western regions.

6.3.4. Hydrogen network

Fig. 6.10 shows the installed capacity of hydrogen pipelines for the fully renewable scenarios with (right) and without (left) land-use restrictions. Investment costs of hydrogen transmission are much lower than electricity (82 €/MW/km compared to 10000 €/MW/km). Average capacity over all lines is 2734 MW for scenario without land-use restrictions, compared to 3448 MW with land-use restrictions. Fig. 6.10 shows that hydrogen transmission pipelines are installed in regions with high onshore or solar PV capacities: in particular Noord-Holland Noord for scenario without land-use restriction, and Groningen, Friesland and Drenthe for scenario with land-use restriction. Investment in electrolyser is also high in these regions, in order to transport hydrogen to regions.



(a) Without land-use restrictions



(b) With land-use restrictions

Figure 6.10: Installed capacity of hydrogen pipelines for scenarios with a RES target of 100%

6.4. Validation

After the optimization model is run for a number of experiments, the results are to be validated. Validation is the process that concerns with the fitness for purpose of the model [111]. The aim of this chapter is to give insight in the dependency, or sensitivity of the outcomes when changing the model's variables, parameters, assumptions and chosen data [105]. To determine the degree of dependency of the model's variables and parameters, the following processes were conducted.

Outcome validation The first step, sometimes referred to as classic validation, assesses how well the model outcomes represent the real world. The degree of mismatch between an experiment run and the real world is a measure for the validity. However, since the model describes a system that does not exist, a full one-on-one representation of reality is not possible. In addition, the model is a simplified representation of reality, as well as a Greenfield model. Thus, when determining the validation, to analyse to what degree the results are valid the outcomes are compared on the orders of magnitude, however is not to be expected that the model outcomes are exactly the same [105]. Two outcomes of the model are compared to real world values and other studies: the system costs (in particular, the average energy costs and the generation mix. It is assessed how much the model outcomes differ from reality and other studies, why there could be a difference and what the implications of these are (i.e., whether and why it matters).

System costs The average energy costs differs per scenario, ranging from €50.92 / MWh (scenario MES 0) to €122.72 / MWh (scenario MES w/LR 100). Higher average energy costs are found in scenarios with higher RES targets. Also, the average energy costs are lowest in the MES scenarios (€55 to 105 /MWh), moderate in the land-use scenarios (€70 to 120 / MWh) and highest in the scenarios (€70 to 140 / MWh). In 2018 the share of renewable in the Netherlands was equal to 7.4% [73]. The current costs are best compared to scenarios with lower RES shares. The average wholesale price for electricity in 2015 in the Netherlands was €40 / MWh. Average prices have been increasing in recent years: from about €35 / MWh in 2016, to €39.3 /MWh to in 2017 and €52.5 EUR/MWh in 2018 [73]. The costs found in the model for low RES share scenarios are comparable to these real-world prices.

The costs of scenarios with higher RES targets can be compared with other studies. However, the model configuration as used in this study does not allow calculating the different costs for the three types of demand (electricity, heat and hydrogen). This is because it is not possible to determine which costs can be attributed to which energy demand. Although it is possible to directly allocate some costs to a specific final demand (such as investment costs in biomass heat pumps or boilers), certain costs cannot [1]. Especially troublesome are the combination of storage, network flows and the many conversion possibilities that can occur in an integrated energy system: a single unit of energy is indistinguishable, consequently making it difficult to follow the flow of energy (see fig. 4.8 and **??**). This makes it infeasible to pinpoint exactly which investment costs and network costs are made for which demand in particular. The average costs of energy is compared to the electricity costs or the hydrogen costs. Koirala et al. [82] studied the Dutch energy infrastructure for 2050, looking into the interweaving of electricity, hydrogen and methane system under high RES targets. They found an average annual electricity price of 148 €/MWh, an average annual hydrogen price of 63 €/MWh and an average annual methane price of 146 €/MWh. These annual average prices for electricity, hydrogen and methane are relatively high due to the high RES target considered, as well as the high biomass import price assumption of 76 €/MWh. The results of the MES scenarios with high RES targets, show values for average energy costs in comparable orders of magnitude (€122.72 /MWh). Energieonderzoek Centrum Nederland evaluated the implication of the Dutch Energy Agreement. Simulation runs with electricity marker model COMPETES, (based on the assumed gas, coal and CO2 prices), which analysed recent and expected development of the electricity generation capacity in the Netherlands, resulted in a wholesale electricity price of 57 €/MWh. Although lower than values found in this study, the price is for 2030 and refers to the wholesale price, which does not consider capital cost. The energy price is expected to increase with higher shares of RES.

Energy generation mix Currently, the Dutch energy supply shows high shares of natural gas and oil. In 2018, 90% of TPES came from conventional energy sources: natural gas (42%), oil (37%), coal (11%). Bioenergy and waste accounted for 5.4%, nuclear 1.3%, wind 1.2%, solar 0.5%, geothermal 0.1% and finally 0.9% electricity imports [73]. The total energy generated per source as resulting from the optimization model are shown in fig. 6.2. The generation mix differs per scenario. The scenario with the lowest RES target, EU 0, shows a comparable shares of natural gas (40.3%). However, the current situation and the scenarios are not suitable to compare, since coal, oil and nuclear were not included in the optimization model. The shares of biomass, hydrogen, solar and onshore differ per scenario. Koirala et al. [82] found that significant hydrogen storage is required to cover for seasonal imbalances between supply and demand, spanning 48% of the annual hydrogen demand. The results of the land-use 80 and land-use 100 scenarios show compared shares of hydrogen storage to meet the demand, respectively 40.5% and 43.1%.

6.5. Discussion of the results

This section discusses the findings and reflects on real-world implications. First, the implications on costs and the energy mix of sector integration are discussed. Thereafter, the land-use implications are discussed.

6.5.1. Implication of sector integration

A consensus is that with forecasted increased RES uptake, electrification and decarbonization, the energy system of the future can benefit from interactions between different energy sectors. This thesis investigates the implications of integrating electricity, heating and hydrogen sectors, given increasing RES targets. The model presented in this thesis considers the overall optimization whilst incorporating different energy sectors, and also optimizing investment of different technologies, network, and storage. The results, based on a case study of the Dutch energy system, are in line with other MES investment studies, showing that the energy system as a whole can benefit from increased sector integration. In particular, a MES compared to a NIES results in increased system flexibility, lowering of energy costs, and avoiding investment in storage and network expansion. The model in this thesis differs from current models found in literature. In particular, the model is able to capture operational and three expansion planning components (GEP, NEP and SEP) simultaneously, whilst also considering different spatio-temporal VRES profiles and land-use restrictions. In addition, it is able to incorporate three different sectors. This ultimately leads to a more comprehensive and complete representation. These findings are of value for system operators in X ways:

First, the results show how system integration can lead to significant reduction in average energy costs. This reduction in costs increases with increasing VRES uptake, up the 36.3% in fully renewable scenarios. Cross-sector utilization is highest for usage of electricity in hydrogen system, and for usage of hydrogen in electricity

[1] The total system costs consists of 36 elements: investment in 16 different generation, conversion, storage and storage conversion technologies; FOM costs of 13 different generation, conversion and storage technologies; operation costs of 5 different energy carriers; investment costs in 2 different networks, consisting of 50 connections and costs of lost load.

system. By carefully consider the optimal levels of electrolysis, EHPs, and hydrogen CCGT, system operator can mitigated significant investments in additional generation, transmission and storage can be mitigated.

Second, three options to increase the energy systems flexibility were included in the model: storage, network transmission and increased energy sector integration [2]. Sector integration is a cost-effective approach to increase in the systems' ability to provide flexibility by capturing VRES oversupply, which can subsequently be used to meet heating or hydrogen demand. Additionally, oversupply can be captured and stored as hydrogen, which is much more cost-efficient than battery storage. This is in line with findings of [41], who found that hydrogen storage, especially in a hydrogen-based integrated energy system, can lead to much lower total system costs than a system reliant on large battery storage.

However, sector integration alone is not sufficient, especially for higher RES targets. No single flexibility option alone is sufficient; all scenarios with high RES targets showed investment in all three option. Therefore, system operators should consider the combination of storage, network transmission (of both electricity and hydrogen) and integration of different energy sectors simultaneously. This leads to a more cost-optimal energy system compared to investing more in a single option, since a combination of different flexibility options provides complementary advantages. Here, the spatial distribution of generation, conversion and storage technologies and transmission are important to consider. The findings of this study are in line with findings provided by the Dutch TSO, who concluded that adequately located electrolysers and gas storages are very potent solutions in reducing additional electricity lines [138]. Regarding the optimal level of sector coupling, they conclude that this is dependent upon the degree of RES uptake; higher RES are more advantageous for high investment in electrolysis. However, their study is limited to a single time step, consideration of VRES integration, GEP and SEP are not considered. This study builds upon this by considering a more comprehensive analysis of the energy system.

Third, although increasing sector integration leads to an overall reduction in capacity of 27.7% for a RES target of 80% and even 36.3% for a RES target of 100%, significant increases in total generation capacity are still required in order to meet all three types of energy demands of electricity, hydrogen and heat in a fully renewable energy system. To illustrate, in 2018 total installed capacity of solar in the Netherlands amounted to 4300 MW [73]. For scenarios with RES targets of 100, the total required solar capacity ranges up to 38000 MW. This thus amounts to an increase of 8.8 times. Also, in all scenarios, the cost-optimal investment portfolio consist of a mix of different energy sources. For the Dutch future energy system with RES targets of 80% and higher shares of onshore increase significantly. In the MES scenario 100, onshore generation accounts for 43.2% of total energy supply. Biomass places a significant role for meeting heat demand.

6.5.2. Land-use implications in a multi-energy system

The results show that not considering restrictions on land-usage for solar PV and onshore leads to high concentration of solar PV or onshore wind capacities in certain regions. Especially for onshore, this results in unrealistically high capacities of onshore wind turbines in coastal regions (such as Noord-Holland Noord). Although to less extent, also for solar PV almost half of the total installed solar capacity is found in just two out of 30 regions (Noord-en Midden Limburg and Zuid-Limburg). In perspective, the current geographical distribution of solar in the Netherlands is much more even: no single region has a share larger than 10%. The highest amount is found in Friesland, with a share of about 6%. Regarding onshore, currently 36.5% of total installed capacity is located in Flevoland and 11.18% is located in Zeeland.

Hence, system operator should account for limitations imposed by land-use restrictions. As is the case in Germany, suboptimal distribution of supply and demand can lead to very high dispatching costs. Failing to account for more realistic limitations on the available amount of land for solar PV and onshore wind turbines per region, will lead to significant increases in overall costs of energy. This is mostly significant for RES target of 80% and higher. For the Dutch case study and a fully renewable scenario, costs increase amounts to 16.69%.

This study builds upon the work of Wang et al. [151] and shows how the spatial distribution of generation technologies can have significant effect on the overall system costs. This work extends upon this by incorporating also different types of demand and other generation, conversion and storage and transmission networks. The results of this work show that by incorporating also heat and hydrogen demand, maximums on the available amount of land for onshore are quickly reached in fully renewable scenarios. In consequence, the imposing of land-use restrictions result in an increase decrease of market share from onshore, and an increase in solar.

[2] Although an option of lost load was included in the model (with a value of €23000 / MWh) for all scenarios, this was never needed, implying that the demand could be met through the flexibility options

Besides the spatial distribution of the electricity sector, this study highlights the relevance of spatial distribution of hydrogen sector. High investment in onshore or solar PV in a region is often paired with high investment in electrolysis in that region as well as hydrogen transmission capacity to distribute the produced hydrogen to other regions. Finally, whereas it could be expected that imposing land-use constraints on solar and onshore would lead to a *decrease* in installed capacities, it actually leads to an *increase* in total installed capacities. This because the cost-optimal geographical investment lay-out deviates from what is actually possible in terms of available land. In turn, requiring more total capacity and thus also more total land-use.

6.6. Limitations

Although the model shows results comparable with those found in other studies, from which useful insights could be deducted, models are always a simplified representation of reality due to modelling choices and assumptions made. This section discusses some of the limitations as well as their implications on the results of this thesis. By understanding these limitations, conclusions can be drawn from the research more carefully. First, limitations of the model will be discussed. Following from these are suggestions for future research.

First, not all possible generation and conversion technologies were considered in this thesis, for example offshore wind and nuclear. The results showed that land-use limitations for onshore were reached for some of the highly renewable scenarios. The aim of this study is to investigate the role of sector integration. Important for sector integration is how system flexibility can be improved, for different seasons and specifically also on an hourly temporal scale. Whereas offshore and onshore win differ on the costs components and available wind, it is assumed that the VRES character of wind is also captured through onshore. Nevertheless, incorporating offshore wind in the model would enable to analyse whether offshore can aid in providing this loss in onshore capacity. These could be considered in future studies.

Secondly, the modelling approaches imposed some limitations. The greenfield approach poses both an advantage as well as a disadvantage. Considering existing generation and conversion technologies, transmission capacities, etc. could lead to different model outcomes. The network transmission was simplified, however more detailed flow formulation methods could be included for a more realistic representation. Taxes, carbon prices and subsidies to stimulate renewable technology deployment were not considered in the model. Thirdly, the hydrogen and biomass importation prices were fixed, however in reality these fluctuate significantly through the year [76]. These could be modelled more realistically by having varying prices, for example based on historical annual fluctuations. In addition, the foreign import of energy from biomass and hydrogen was modelled mainly as a way to represent the shares of biomass and hydrogen in the final energy mix. This allowed to easily include these two energy carriers in the system and thence analyse the cost-optimal energy mix and the future role of hydrogen and biomass, as well as interactions with other elements such as storage and transmission. In order to do so, the assumption was made that no CapEx costs are associated with foreignly imported hydrogen and biomass. However, imported hydrogen and biomass indeed need to be transported from other countries and also distributed within the country. In order to more accurately include these in the costs calculation, costs could be accounted for by including CapEx costs to the border, as well as from the border. For hydrogen, however, this is highly speculative, since precise network flows are currently not in place. Fourth, estimations of future demand profiles are dependent on numerous assumptions and path dependencies. Future studies could analyse different demand profiles. In particular, the spatial distribution of demand could be based on more accurate values based on real-world energy demand, or scaled according to industrial clusters. As a result of the spatial resolution, the internal transmission infrastructure of energy final energy demands, that is, the distribution within the region itself, is not considered.

Third, the use of optimization models limits the description of the energy system in a discrete manner. Parameters for the investment and operation costs are fixed. Furthermore, optimization models neglect market imperfections [42, 59]; in reality, investment decisions are not made purely based on lowest costs [54]. Therefore, in addition to a cost-optimal objective function, future research could optimize based on environmental, technical or reliability criteria.

6.7. Future research

Based on the results of this research and the limitations, several suggestions for future research are provided. First, in addition to the cost-optimal system configuration from the perspective of the system operator, the design of future energy systems should consider a broader perspective. The work presented in this paper could be extended by investigating different objective functions. For example, the environmental performance or the trade-off between environmental and economical objectives [38], the system resilience, or even multi-objective analysis, such as [154], [86] or [40]. In addition, a more consumer oriented perspective could result in a more exhaustive analysis. For instance, the minimization of costs compared to welfare maximization could be analysed. This would also allow to analyse other flexibility options, such as demand flexibility.

Second, ranging values for the costs parameter values could be analysed. The developments related to the EHB presents a particular interesting case to be analysed in more detail. For instance, future studies could analyse in more detail the implications of varying levels of EHB deployment, and include for example varying prices throughout the year. Furthermore, other generation technologies, in particular offshore wind, could be included. The implications of MES could be analysed more deeply by considering other generation and technologies. In particular, other sector coupling options such as SMR and biomass gasification could provide interesting results.

Finally, institutional aspects could be analysed in more detail. Different alignments of technological and institutional features can determine the performance of the energy system. A more complete assessment of reformations needed to the energy infrastructure and the role of different actors could be taken into account explicitly [85]. The consequences of changing generation technologies for the economic organisation of an energy system, the responsibilities related to load balancing and implications of taxes and subsidies are examples of relevant topics to be addressed. In particular, the ensuring of sufficient investment capital for generation, conversion and storage technologies could prove to be troublesome in MES with high shares of VRES. In the following and final chapter, the answers to the research questions are provided to conclude the thesis.

7 Conclusion

This chapter present the conclusion following from this thesis. First, the answer to the research questions are given. The research is composed of one main research question and five sub research questions. To rehearse, the main research question formulated is shown below. The sub research questions will be answered first, before answering the main research question. The combination of the answers to the sub research question and the main research question allow formulating recommendation for decision makers, especially system operators and other (policy related) energy system planners. These policy recommendations are presented in the second section. The final section discusses the academic and social relevance of this work.

"What are the cost-optimal designs of multi-energy systems integrating electricity, heating, and hydrogen sectors, given different RES targets?"

7.1. Answers to sub research questions

In order to adequately answer the main research question, sub research question have been constructed. The results from these sub research questions either formed a knowledge base required to build upon, such as relevant frameworks and boundaries, or actual results. Together, the answers of the sub research questions allow constructing an answer for the main research question. Therefore, prior to answering the main research question, the sub research questions will be discussed.

Sub question 1: *Which modelling aspects need to be considered when designing an optimal MES, and how are these reflected in literature?*

This sub research question is covered in chapter 2. Energy planning models are widely used, and various different modelling types can be found in the literature. In general, energy planning models can be categorized in several categories, each with different limitations, advantages and intended uses. The model approach in this thesis is a bottom-up optimization model. Furthermore, ten modelling aspects were identified to categorize and analyse the current body of literature on MES modelling. In the literature study, several aspects were discussed, including their implications on the modelling of a MES. The modelling scope should capture both operational and planning of the energy system, in order to account for the stochastic characteristics of VRES in a highly renewable energy system. In addition, a MES model would ideally capture all three expansion planning elements (GEP, NEP and SEP) to provide a holistic analysis on the provision of system flexibility. The spatial resolution should be at least regional to account for the spatial VRES supply profiles and regional limitations on VRES potential. To account for VRES integration, the time step size should be at least hourly. In addition, in order to account for weekly and seasonal differences, an annual horizon is preferred.

Sub question 2: *How can the GRIM be extended towards a multi-energy carrier model, in terms of the mathematical relationships?*

The relationships and constraints of the model are described threefold: the objective function, the decision variables and the constraints. The objective function is the minimization of total system costs of a multi energy system on country level scale, consisting of the investment and fixed costs for the capacities of generation, conversion and storage technologies, the investment costs for electricity transmission and hydrogen network line and the variable operation costs for primary energy sources. The decision variables include the energy generated $Pz_{i,n,t}$ of technology *i*, at node *n*, at time step *t*, the energy converted $Ph_{i,n,t}$ of technology *i*, at node *n*, at time step *t*, the energy charged $CP_{i,n,t}$ and discharged $DP_{i,n,t}$ of storage technology *i*, at node *n*, at time step *t*, the energy flows to other nodes $P^{imp}_{w,(n,t),t}$ and $P^{exp}_{w,(n,t),t}$ of network carrier w (hydrogen or electricity) over line *(n,m)* at time step *t*. Furthermore, the investment decision space consist of decision variables for the capacities $K_{i,n}$ of generation conversion and storage technologies *i*, at node *n*, and the capacities of electricity and hydrogen transmission (pipe)lines $K^{w}_{(n,m)}$ over line *(n,m)*. Finally, the constraints consist of power balance constraint, capacity constraints, storage constraints, RES target constraints, network constraints and non-negativity constraint. In addition, depending on the scenario additional constraints were included, namely a maximum importation capacity constraint, land-use constraints and RES target constraint. An overview of the mathematical equations used to describe each of these is shown in section 4.6.

Although the mathematical formulation of the optimization problem is, in essence, a sufficient description for the optimization algorithm, some constraints require additional clarification (in particular the energy balance constraints). Within a MES, multiple energy carriers are integrated, with different conversion possibilities. In consequence, several energy flows are possible and the formulation of appropriate energy balances can be challenging. The multi energy model is described using busses for the three different types of demand: an electricity bus, hydrogen bus and heating bus. To illustrate this, fig. 4.10 shows a description of a single node and the model, as extended to the 30 nodes. The left figure shows the energy flows (in grey) with the three power balance busses (electricity, hydrogen and heat). Hence, within a single node, all three energy balances must be met at every time step. Each energy hub represents a single node. The right side shows the placement of the nodes when extending to a network. The node balances for an individual node are extended to also include import or export.

Sub question 3: *How can the conceptual model be translated to a workable model?*

The conceptual model, as described in the chapter 4, is generic, and prior to being used requires the values for data input. These include the VRES hourly capacity factors and available area for onshore wind turbines and solar PV per region; these two data inputs are obtained from Wang et al. [151]. Furthermore, the hourly demand profiles of electricity, heating and hydrogen for each of the 30 regions need to be developed. These are obtained from the ETM, pre-processes, and scaled according to population. Furthermore, the values for cost-parameters are defined, as described in section 5.1.4. Finally, different scenarios are constructed to analyse the model outcomes, based on differences in RES targets, level of sector integration and land-use restrictions.

Sub question 4: *What are the implications of increased integration between different energy sectors on the energy costs, generation mix, and spatial distribution?*

The optimization results showed a lower average price for the MES scenarios. Since less investment has to be made in either generation, storage, or network capacity, it can be deducted that integration of energy sectors is a very cost-efficient approach to provide system flexibility. Hence, increasing integration between different sectors can lead to improved economic efficiency of the overall system. In the 50% RES target scenarios, the MES scenario leads to 17% reduction is total costs, as compared to separated scenarios. The reduction for electricity network investment costs is about 173%. The same is true for the 100% RES target scenario, where, MES leads to a reduction in network investment of about 137%. Similarly, whereas storage investment costs amount to 0 and 0.36% for the MES 50 and MES 100 scenarios, the storage costs significantly increase for the separated scenarios: here, the shares are 4.78% for a RES target of 50% and even 13.03% for a RES target of 100%.

After the construction of the optimization model, different scenarios were constructed and run to analyse the implications of different input variables and constraints. First, higher RES target generally lead to an increase in total system costs and average energy price. Whereas the operation costs generally decrease for scenarios with higher RES targets, due to a decrease in fuel costs, the investment costs increase. This is to be expected since VRES generally have a much lower operation costs, but higher investment costs than conventional energy sources. Storage costs increase as well with increasing RES targets. For most scenarios storage costs represent a small share in overall costs for most scenarios. However, storage appears to become increasingly important from RES targets of 80% and higher, especially in scenarios considering land use restrictions. Similarly, network investment costs also increase with higher RES targets.

Second, for the land use scenarios, investment in onshore decreases at the expense of increasing solar capacity. For all scenarios, a mix of different energy sources is found. In almost all scenarios (even with no RES target, hydrogen places an important role). Interestingly, shares of hydrogen are relatively low in land use scenarios. Third, RES targets significantly influence the installed capacities of generation and conversion technologies.
Overall, higher RES targets lead to a significant increase in total installed capacity. Besides, the portfolio of both generation and conversion technologies changes significantly between scenarios (i.e., which technologies are invested). EHP and especially electrolyser capacity increases with higher RES targets in scenarios. Obviously, natural gas based CCGT and heat pump or boiler capacities decrease with higher RES targets. In the local scenarios, the solar generation capacity is very concentrated in the southern regions and onshore in the coastal regions. Generation is much more evenly spread in the land use scenarios.

Fourth, the role of storage increases with higher RES targets. Storage is increasingly invested in the local and land use scenarios. Especially high investments are found for batteries in the separated scenarios and hydrogen storage in land use scenarios, due to the complementary advantages when combining this with high shares of VRES and electrolysis. Storage usage differs among the seasons. Hydrogen storage usage is higher in autumn and winter, whereas battery and TES storage are higher in spring and summer.

Fifth, network investment increases with higher RES targets. As more energy is generated from VRES, transmission both of electricity and hydrogen increasingly outweigh network investment cost. This implies that for future energy system, higher stress on the grid can be expected, indicating the necessity for careful network expansion planning. Reason for this is found, in the large spatial difference of generation, especially for onshore.

7.2. Answer to the main research question

In order to determine the cost optimal transmission, generation and storage investment in a multi-energy system combining electricity, hydrogen, natural gas and biomass energy carriers under different RES target scenarios, an optimization model was constructed. The optimization model was run for nine different scenarios. These scenarios differed on the overall RES target, local RES target and maximum land usage for solar PV and onshore. The objective of the optimization model was set to minimize total systems costs, consisting of operation costs and of investment costs in storage, generation and conversion technologies, as well as transmission flows and investments. For all scenarios, the optimum was found given constraints, such as power constraints and capacity constraints. Given the objective, the capacities of these technologies and transmission (pipe)lines of electricity and hydrogen networks, as well as operational elements such as energy generations, conversion, import and export flows and storage charge and discharge were optimally varied.

In essence, the answer to the main research question (the cost-optimal lay out) consists of the combination of numerical values of the following elements:

- The installed capacities of all technologies i for all nodes n
- The amount of energy generated, converted, discharged and charged for all time steps t for all nodes n
- The amount of energy electricity and hydrogen import or export over all lines n,m for all time steps t
- The installed capacities of electricity transmission lines and hydrogen pipelines for all lines n,m

The cost optimal lay-outs for each of the nine scenarios are given and described in (chapter 6). The next section will restate some of the most important conclusions which can be drawn based on the results.

7.3. Insights & policy recommendations

Based on both the outcomes of the optimization model and the qualitative assessment of these, several insights and policy recommendations followed.

First, the model presented in this thesis provides a more comprehensive and complete analysis on the benefits of MESs. The total system costs and the related average price per energy generated are expected to increase with higher: the results show that increasing sector integration can lead to significant savings in total costs, especially with higher VRES uptake. In order to increase the energy systems flexibility to cope with the intermittent supply of VRES, three approaches were considered in this work: storage, network transmission and increasing energy sector integration.

The results show that sector integrations allows for a much more effective capture of solar and onshore supply, leading to significant reductions in investment of generation, storage and network transmission capacities. Furthermore, the results show that each options can provide benefit, and no single options is superior. A combination of storage, network transmission and integrated of different energy sectors is better than investing more in a single option. Especially apparent is the combination of electrolysers investment, VRES generation capacity, hydrogen storage and hydrogen transmission. These can result in much lower total system costs than for example large battery storage.

Secondly, decision makers should consider the spatial distribution of generation, conversion and storage technologies in combination with network expansion in order to determine the cost-optimal energy system investments. Limitations on available land for solar and onshore could lead to increase in average energy prices. Since investment in energy infrastructure and generation technologies cover long time spans, planning of the energy system is path dependent and could lead to a lock-in situation. Neglecting limitations on land availability for VRES technologies will lead to significant increases in total system costs, and different generation portfolios (which and how much technology is installed). For the Netherlands, imposing land use constraint showed a decrease of market share from onshore and increase in solar.

Third, total generation capacity has to increase significantly in order to reach a carbon-free energy system. For all scenarios, the cost-optimal investment portfolio consists of a mix of different energy sources.

7.4. Academic and social relevance

This section discussed the academic and social relevance of this research.

First, the model developed in this thesis builds upon existing energy system modelling literature, in particular MES modelling. Although literature on both the operational and planning stages energy system and MES optimization is extensive, the literature review conducted in chapter 2 showed that the implications of increasing integration between different energy sectors is not yet fully captured in optimization modelling. None of the literature focuses on the implications on transmission, generation and storage expansion planning within a multi-energy system consisting of electricity, natural gas, hydrogen and biomass sectors. More specifically, an approach to calculate the cost-optimal operation and investment of transmission and generation profiles in a modelling set-up that covers a country level spatial area, an annual temporal horizon and an hourly time resolution is currently not available. The model developed in this thesis can be considered a unique approach in the field of energy system planning. The results of this thesis show the effectiveness of this modelling approach and show how this can provide unique insights compared to other models. It shows that the spatial resolution should be at least regional to account for the spatial VRES supply profiles and regional limitations on VRES potential.

Second, this thesis builds on existing energy planning literature by providing a case study of the future energy system of the Netherlands. The results provide an extensive and broad analysis of cost-optimal generation, conversion, storage and transmission investment. The results of this thesis are in line with those found in for example [82] and [138]. However, the study conducted by TenneT and Gasunie [138] is limited to the network perspective and does not consider time series, and the results of Koirala et al. [82] are limited to the operational perspective and hence investment decision were not considered. The result from this thesis present more robust analysis on the cost-optimal investment decisions of both generation and conversion technologies.

Finally, a thesis within the Complex Systems Engineering and Management (CoSEM) program typically covers issues found in the public and private domain with high societal relevance, in which design engineering and technology elements are addressed. The design of future energy system involves complex technical issues in terms of optimal generation, transmission and storage, as well as institutional issues and issues concerned with investment decision. The subject covered in this thesis has clear design components which were investigated from both a technological as well as institutional perspective. Hence, this thesis fit well in the scientific CoSEM domain.

Bibliography

[1] CORINE Land Cover — Copernicus Land Monitoring Service, . URL https://land.copernicus.eu/pan-european/corine-land-cover.

[2] Gurobi - The fastest solver, . URL https://www.gurobi.com/.

[3] Nationaal Programma Regionale Energiestrategie - Regionale Energiestrategie, . URL https://www.regionale-energiestrategie.nl/default.aspx.

[4] Salvador Acha, Arthur Mariaud, Nilay Shah, and Christos N. Markides. Optimal design and operation of distributed low-carbon energy technologies in commercial buildings. *Energy*, 142:578–591, January 2018. ISSN 0360-5442. doi: 10.1016/j.energy.2017.10.066. Place: Oxford Publisher: Pergamon-Elsevier Science Ltd WOS:000424854900050.

[5] International Energy Agency. CO2 Emissions from Fuel Combustion: Overview – Analysis, July 2020. URL https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview.

[6] International Energy Agency. Key World Energy Statistics 2020 – Analysis, 2020. URL https://www.iea.org/reports/key-world-energy-statistics-2020.

[7] Mads Almassalkhi and Ian Hiskens. Optimization Framework for the Analysis of Large-scale Networks of Energy Hubs. January 2011.

[8] Kerstine Appunn. Re-dispatch costs in the German power grid, 2016. URL https://www.cleanenergywire.org/factsheets/re-dispatch-costs-german-power-grid.

[9] World Nuclear Association. Heat values of various fuels - World Nuclear Association. URL https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx.

[10] Marc Beaudin, Hamidreza Zareipour, Anthony Schellenberglabe, and William Rosehart. Energy storage for mitigating the variability of renewable electricity sources: An updated review. *Energy for Sustainable Development*, 14(4):302–314, December 2010. ISSN 0973-0826. doi: 10.1016/j.esd.2010.09.007. URL https://www.sciencedirect.com/science/article/pii/S0973082610000566.

[11] N. M. J. P. van Beeck. Classification of Energy Models. 1999. URL https://research.tilburguniversity.edu/en/publications/classification-of-energy-models. Publisher: Operations research.

[12] I. van Beuzekom, M. Gibescu, and J. G. Slootweg. A review of multi-energy system planning and optimization tools for sustainable urban development. In *2015 IEEE Eindhoven PowerTech*, pages 1–7, June 2015. doi: 10.1109/PTC.2015.7232360.

[13] George E. P. Box and Norman R. Draper. *Empirical model-building and response surfaces.* Empirical model-building and response surfaces. John Wiley & Sons, Oxford, England, 1987. ISBN 978-0-471-81033-9. Pages: xiv, 669.

[14] Andy Brown. Hydrogen as a Fuel for Gas Turbines, 2020. URL https://www.thechemicalengineer.com/features/hydrogen-as-a-fuel-for-gas-turbines/.

[15] T. Bruckner, I.A. Bashmakov, Y Mulugetta, H Chum, A de la Vega Navarro, J Edmonds, B Faaij, B Fungtammasan, A Garg, E Hertwich, D Honnery, D Infield, M Kainuma, S Khennas, S Kim, H.B. Nimir, K Riahi, N Strachan, R Wiser, and X Zhang. Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical report, IPCC, 2014.

[16] Benjamin Böckl, Matthias Greiml, Lukas Leitner, Patrick Pichler, Lukas Kriechbaum, and Thomas Kienberger. HyFlow—A Hybrid Load Flow-Modelling Framework to Evaluate the Effects of Energy Storage and Sector Coupling on the Electrical Load Flows. *Energies*, 12(5):956, January 2019. doi: 10.3390/en12050956. URL https://www.mdpi.com/1996-1073/12/5/956. Number: 5 Publisher: Multidisciplinary Digital Publishing Institute.

[17] Tomislav Capuder and Pierluigi Mancarella. Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options. *Energy*, 71:516–533, July 2014. ISSN 0360-5442. doi: 10.1016/j.energy.2014.04.097. URL http://www.sciencedirect.com/science/article/pii/S0360544214005283.

[18] Xinyu Chen, Michael B. McElroy, and Chongqing Kang. Integrated Energy Systems for Higher Wind Penetration in China: Formulation, Implementation, and Impacts. *Ieee Transactions on Power Systems*, 33(2):1309–1319, March 2018. ISSN 0885-8950. doi: 10.1109/TPWRS.2017.2736943. Place: Piscataway Publisher: Ieee-Inst Electrical Electronics Engineers Inc WOS:000425530300014.

[19] Giovanni Cinti, Arianna Baldinelli, Alessandro Di Michele, and Umberto Desideri. Integration of Solid Oxide Electrolyzer and Fischer-Tropsch: A sustainable pathway for synthetic fuel. *Applied Energy*, 162: 308–320, January 2016. ISSN 0306-2619. doi: 10.1016/j.apenergy.2015.10.053. URL https://www.sciencedirect.com/science/article/pii/S0306261915012805.

[20] Seán Collins, John Paul Deane, Kris Poncelet, Evangelos Panos, Robert C. Pietzcker, Erik Delarue, and Brian Pádraig Ó Gallachóir. Integrating short term variations of the power system into integrated energy system models: A methodological review. *Renewable and Sustainable Energy Reviews*, 76:839–856, September 2017. ISSN 1364-0321. doi: 10.1016/j.rser.2017.03.090. URL https://www.sciencedirect.com/science/article/pii/S1364032117304264.

[21] D. Connolly, H. Lund, B. V. Mathiesen, and M. Leahy. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, 87(4):1059–1082, April 2010. ISSN 0306-2619. doi: 10.1016/j.apenergy.2009.09.026. URL http://www.sciencedirect.com/science/article/pii/S0306261909004188.

[22] Aad Correljé. Natural Gas - A tale of three markets. In *The Routledge Companion to Network Industries*. Routledge, November 2015. ISBN 978-1-317-66807-7. Google-Books-ID: 55f4CgAAQBAJ.

[23] Aad Correljé and L.J. Vries. Hybrid Electricity Markets: The Problem of Explaining Different Patterns of Restructuring. In *Competitive Electricity Markets*, page 28. January 2008. ISBN 978-0-08-047172-3. doi: 10.1016/B978-008047172-3.50006-4. Journal Abbreviation: Competitive Electricity Markets.

[24] Marcel Cremers, Jeroen Daey Ouwens, Bart Strengers, TNO, and Plan voor de Leefomgeving. Conceptadvies SDE++ 2020 - Verbranding en vergassing van biomassa. Technical report, Den Haag, 2019.

[25] Athanasios S. Dagoumas and Nikolaos E. Koltsaklis. Review of models for integrating renewable energy in the generation expansion planning. *Applied Energy*, 242:1573–1587, May 2019. ISSN 0306-2619. doi: 10.1016/j.apenergy.2019.03.194. URL https://www.sciencedirect.com/science/article/pii/S0306261919306117.

[26] Martín David, Carlos Ocampo-Martínez, and Ricardo Sánchez-Peña. Advances in alkaline water electrolyzers: A review. *Journal of Energy Storage*, 23:392–403, June 2019. ISSN 2352-152X. doi: 10.1016/j.est.2019.03.001. URL https://www.sciencedirect.com/science/article/pii/S2352152X18306558.

[27] Steven J. Davis, Nathan S. Lewis, Matthew Shaner, Sonia Aggarwal, Doug Arent, Inês L. Azevedo, Sally M. Benson, Thomas Bradley, Jack Brouwer, Yet-Ming Chiang, Christopher T. M. Clack, Armond Cohen, Stephen Doig, Jae Edmonds, Paul Fennell, Christopher B. Field, Bryan Hannegan, Bri-Mathias Hodge, Martin I. Hoffert, Eric Ingersoll, Paulina Jaramillo, Klaus S. Lackner, Katharine J. Mach, Michael Mastrandrea, Joan Ogden, Per F. Peterson, Daniel L. Sanchez, Daniel Sperling, Joseph Stagner, Jessika E. Trancik, Chi-Jen Yang, and Ken Caldeira. Net-zero emissions energy systems. *Science*, 360(6396): eaas9793, June 2018. doi: 10.1126/science.aas9793. URL https://www.science.org/lookup/doi/10.1126/science.aas9793. Publisher: American Association for the Advancement of Science.

[28] C. De Jonghe, B. F. Hobbs, and R. Belmans. Integrating short-term demand response into long-term investment planning. Working Paper, Faculty of Economics, April 2011. URL https://www.repository.cam.ac.uk/handle/1810/257248. Accepted: 2016-08-11T15:25:47Z.

[29] T. H. J. De Pater. *Towards a cost-optimal European power system for a renewable future: An assessment of the best planning scale, complementary options and policy implications.* PhD thesis, Delft University of Technology, 2016. URL https://repository.tudelft.nl/islandora/object/uuid%3A4e43ef3b-0a5e-4ccf-9352-2eea4ac3370c.

[30] Jaon Deign. Germany's Maxed-Out Grid Is Causing Trouble Across Europe, 2020. URL https://www.greentechmedia.com/articles/read/germanys-stressed-grid-is-causing-trouble-across-europe. Section: Wind.

[31] CE Delft. Waterstofroutes Nederland. Blauw, groen en import. Technical report, 2018. URL https://ce.nl/publicaties/waterstofroutes-nederland-blauw-groen-en-import/.

[32] P. Denholm, M. Hand, M. Jackson, and S. Ong. Land Use Requirements of Modern Wind Power Plants in the United States. Technical Report NREL/TP-6A2-45834, National Renewable Energy Lab. (NREL), Golden, CO (United States), August 2009. URL https://www.osti.gov/biblio/964608-LaTU8c/.

[33] Ibrahim Dincer and Canan Acar. Review and evaluation of hydrogen production methods for better sustainability. *International Journal of Hydrogen Energy*, 40(34):11094–11111, September 2015. ISSN 0360-3199. doi: 10.1016/j.ijhydene.2014.12.035. URL https://www.sciencedirect.com/science/article/pii/S0360319914034119.

[34] Ottmar Edenhofer, Ramón Pichs Madruga, Y. Sokona, United Nations Environment Programme, World Meteorological Organization, Intergovernmental Panel on Climate Change, and Potsdam-Institut für Klimafolgenforschung, editors. *Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, New York, 2012. ISBN 978-1-107-02340-6 978-1-107-60710-1. OCLC: ocn759914978.

[35] Omar Ellabban, Haitham Abu-Rub, and Frede Blaabjerg. Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*, 39: 748–764, November 2014. ISSN 1364-0321. doi: 10.1016/j.rser.2014.07.113. URL https://www.sciencedirect.com/science/article/pii/S1364032114005656.

[36] European and Environment Agency. Europe's onshore and offshore wind energy potential — European Environment Agency, 2009. URL https://www.eea.europa.eu/publications/europes-onshore-and-offshore-wind-energy-potential.

[37] EWEA. *Large Scale Integration of Wind Energy in the European Power Supply: Analysis, Issues and Recommendations : a Report.* European Wind Energy Association, 2005. Google-Books-ID: Xo9THAAACAAJ.

[38] Enrico Fabrizio, Marco Filippi, and Joseph Virgone. Trade-off between environmental and economic objectives in the optimization of multi-energy systems. *Building Simulation*, 2(1):29–40, March 2009. ISSN 1996-8744. doi: 10.1007/S12273-009-9202-4. URL https://doi.org/10.1007/S12273-009-9202-4.

[39] Enrico Fabrizio, Vincenzo Corrado, and Marco Filippi. A model to design and optimize multi-energy systems in buildings at the design concept stage. *Renewable Energy*, 35(3):644–655, March 2010. ISSN 0960-1481. doi: 10.1016/j.renene.2009.08.012. URL http://www.sciencedirect.com/science/article/pii/S0960148109003577.

[40] Tobias Falke, Stefan Krengel, Ann-Kathrin Meinerzhagen, and Armin Schnettler. Multi-objective optimization and simulation model for the design of distributed energy systems. *Applied Energy*, 184: 1508–1516, December 2016. ISSN 0306-2619. doi: 10.1016/j.apenergy.2016.03.044. URL https://www.sciencedirect.com/science/article/pii/S0306261916303646.

[41] Samira S. Farahani, Cliff Bleeker, Ad van Wijk, and Zofia Lukszo. Hydrogen-based integrated energy and mobility system for a real-life office environment. *Applied Energy*, 264:114695, April 2020. ISSN 0306-2619. doi: 10.1016/j.apenergy.2020.114695. URL https://www.sciencedirect.com/science/article/pii/S0306261920302075.

[42] Meisam Farrokhifar, Yinghui Nie, and David Pozo. Energy systems planning: A survey on models for integrated power and natural gas networks coordination. *Applied Energy*, 262:114567, March 2020. ISSN 0306-2619. doi: 10.1016/j.apenergy.2020.114567. URL https://www.sciencedirect.com/science/article/pii/S0306261920300799.

[43] Michaela Fürsch, Simeon Hagspiel, Cosima Jägemann, Stephan Nagl, Dietmar Lindenberger, and Eckehard Tröster. The role of grid extensions in a cost-efficient transformation of the European electricity system until 2050. *Applied Energy*, 104:642–652, April 2013. ISSN 0306-2619. doi: 10.1016/j.apenergy.2012.11.050. URL https://www.sciencedirect.com/science/article/pii/S0306261912008537.

[44] Paolo Gabrielli, Matteo Gazzani, Emanuele Martelli, and Marco Mazzotti. Optimal design of multi-energy systems with seasonal storage. *Applied Energy*, 219:408–424, June 2018. ISSN 0306-2619. doi: 10.1016/j.apenergy.2017.07.142. URL http://www.sciencedirect.com/science/article/pii/S0306261917310139.

[45] Global Energy Assessment GEA. *Global Energy Assessment: Toward a Sustainable Future*. Cambridge University Press, August 2012. ISBN 978-0-521-18293-5. Google-Books-ID: MZ3DklIQuT0C.

[46] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klockl, G. Andersson, and K. Frohlich. Energy hubs for the future. *IEEE Power and Energy Magazine*, 5(1):24–30, January 2007. ISSN 1558-4216. doi: 10.1109/MPAE.2007.264850. Conference Name: IEEE Power and Energy Magazine.

[47] Martin Geidl and Göran Andersson. A modeling and optimization approach for multiple energy carrier power flow. pages 1–7, July 2005. doi: 10.1109/PTC.2005.4524640.

[48] N. V. Gnanapragasam and M. A. Rosen. A review of hydrogen production using coal, biomass and other solid fuels. *Biofuels*, 8(6):725–745, November 2017. ISSN 1759-7269. doi: 10.1080/17597269.2017.1302662. URL https://doi.org/10.1080/17597269.2017.1302662. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/17597269.2017.1302662.

[49] Philipp Grünewald, Tim Cockerill, Marcello Contestabile, and Peter Pearson. The role of large scale storage in a GB low carbon energy future: Issues and policy challenges. *Energy Policy*, 39(9):4807–4815, September 2011. ISSN 0301-4215. doi: 10.1016/j.enpol.2011.06.040. URL https://www.sciencedirect.com/science/article/pii/S0301421511004964.

[50] Elisa Guelpa and Vittorio Verda. Compact physical model for simulation of thermal networks. *Energy*, 175:998–1008, May 2019. ISSN 0360-5442. doi: 10.1016/j.energy.2019.03.064. URL http://www.sciencedirect.com/science/article/pii/S0360544219304682.

[51] Elisa Guelpa, Aldo Bischi, Vittorio Verda, Michael Chertkov, and Henrik Lund. Towards future infrastructures for sustainable multi-energy systems: A review. *Energy*, 184:2–21, October 2019. ISSN 0360-5442. doi: 10.1016/j.energy.2019.05.057. URL https://www.sciencedirect.com/science/article/pii/S0360544219309260.

[52] B Gupta. Status and progress in solar thermal research and technology. *Energy*, 12(3-4):187–196, March 1987. ISSN 0360-5442. doi: 10.1016/0360-5442(87)90076-4. URL http://www.sciencedirect.com/science/article/pii/0360544287900764. Publisher: Pergamon.

[53] J. Haas, F. Cebulla, K. Cao, W. Nowak, R. Palma-Behnke, C. Rahmann, and P. Mancarella. Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review. *Renewable and Sustainable Energy Reviews*, 80:603–619, December 2017. ISSN 1364-0321. doi: 10.1016/j.rser.2017.05.201. URL https://www.sciencedirect.com/science/article/pii/S1364032117308377.

[54] Lisa M. H. Hall and Alastair R. Buckley. A review of energy systems models in the UK: Prevalent usage and categorisation. *Applied Energy*, 169:607–628, May 2016. ISSN 0306-2619. doi: 10.1016/j.apenergy.2016.02.044. URL https://www.sciencedirect.com/science/article/pii/S0306261916301672.

[55] Emma S. Hanley, JP Deane, and BP Ó Gallachóir. The role of hydrogen in low carbon energy futures–A review of existing perspectives. *Renewable and Sustainable Energy Reviews*, 82:3027–3045, February 2018. ISSN 1364-0321. doi: 10.1016/j.rser.2017.10.034. URL https://www.sciencedirect.com/science/article/pii/S1364032117314089.

[56] Adam Hawkes and Matthew Leach. Impacts of temporal precision in optimisation modelling of micro-Combined Heat and Power. *Energy*, 30(10):1759–1779, July 2005. ISSN 0360-5442. doi: 10.1016/j.energy.2004.11.012. URL https://www.sciencedirect.com/science/article/pii/S036054420400475X.

[57] J.A Hayward, P.W Graham, and Peter Campbell. Projections of the future costs of electricity generation technologies. Technical report, CSIRO, 2011.

[58] Gang He and Daniel M. Kammen. Where, when and how much solar is available? A provincial-scale solar resource assessment for China. *Renewable Energy*, 85:74–82, January 2016. ISSN 0960-1481. doi: 10.1016/j.renene.2015.06.027. URL https://www.sciencedirect.com/science/article/pii/S0960148115300501.

[59] Andrea Herbst, Felipe Toro, Felix Reitze, and Eberhard Jochem. Introduction to Energy Systems Modelling. *Swiss Journal of Economics and Statistics*, 148(2):111–135, April 2012. ISSN 2235-6282. doi: 10.1007/BF03399363. URL https://doi.org/10.1007/BF03399363.

[60] Simon Hilpert, Cord Kaldemeyer, Uwe Krien, Stefan Günther, Clemens Wingenbach, and Guido Plessmann. The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling. *Energy Strategy Reviews*, 22:16–25, November 2018. ISSN 2211467X. doi: 10.1016/j.esr.2018.07.001. URL http://arxiv.org/abs/1808.08070. arXiv: 1808.08070.

[61] J. D. Holladay, J. Hu, D. L. King, and Y. Wang. An overview of hydrogen production technologies. *Catalysis Today*, 139(4):244–260, January 2009. ISSN 0920-5861. doi: 10.1016/j.cattod.2008.08.039. URL https://www.sciencedirect.com/science/article/pii/S0920586108004100.

[62] Thomas Hoppe. Workshop 3: Sub questions and research approach, July 2020.

[63] G. Huang, F. Wen, M. A. Salam, Z. Dong, Y. Zheng, and R. Zhang. Optimal collaborative expansion planning of integrated electrical and natural gas energy systems. In *2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, pages 378–383, November 2016. doi: 10.1109/ISGT-Asia.2016.7796415. ISSN: 2378-8542.

[64] Yu Huang, Shuqin Li, Peng Ding, Yan Zhang, Kai Yang, and Weiting Zhang. Optimal Operation for Economic and Exergetic Objectives of a Multiple Energy Carrier System Considering Demand Response Program. *Energies*, 12(20):3995, January 2019. doi: 10.3390/en12203995. URL https://www.mdpi.com/1996-1073/12/20/3995. Number: 20 Publisher: Multidisciplinary Digital Publishing Institute.

[65] J. Hörsch and T. Brown. The role of spatial scale in joint optimisations of generation and transmission for European highly renewable scenarios. In *2017 14th International Conference on the European Energy Market (EEM)*, pages 1–7, June 2017. doi: 10.1109/EEM.2017.7982024. ISSN: 2165-4093.

[66] Jonas Hörsch, Henrik Ronellenfitsch, Dirk Witthaut, and Tom Brown. Linear optimal power flow using cycle flows. *Electric Power Systems Research*, 158:126–135, May 2018. ISSN 0378-7796. doi: 10.1016/j.epsr.2017.12.034. URL https://www.sciencedirect.com/science/article/pii/S0378779617305138.

[67] H. Ibrahim, A. Ilinca, and J. Perron. Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, 12(5):1221–1250, June 2008. ISSN 1364-0321. doi: 10.1016/j.rser.2007.01.023. URL https://www.sciencedirect.com/science/article/pii/S1364032107000238.

[68] IEA. Energy Conservation through Energy Storage Programme. Technical Report final report, Annex 20, 2011.

[69] IEA. The Future of Hydrogen. Technical report, IEA, Paris, 2019. URL https://www.iea.org/reports/the-future-of-hydrogen.

[70] IEA. IEA G20 Hydrogen report: Assumptions, June 2019.

[71] IEA. Renewables 2020. Technical report, 2020. URL https://www.iea.org/reports/renewables-2020.

[72] International Energy Agency (IEA). Iron and Steel Technology Roadmap – Analysis. URL https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[73] International Energy Agency (IEA). The Netherlands - Countries & Regions. Technical report, 2018. URL https://www.iea.org/countries/the-netherlands.

[74] International Energy Agency (IEA). Cement – Analysis, 2020. URL https://www.iea.org/reports/cement.

[75] International Energy Agency (IEA). International Shipping – Analysis, 2020. URL https://www.iea.org/reports/international-shipping.

[76] Quintel Intelligence. Energy Transition Model. URL https://energytransitionmodel.com/.

[77] IPCC. Mitigation of Climate Change. In *Mitigation of Climate Change*. 2014.

[78] ISPT. HyChain II model evaluates import costs renewable electricity, hydrogen and hydrogen carriers, June 2019. URL https://ispt.eu/news/hychain-ii-model-evaluates-import-costs-renewable-electricity-hydrogen-and-hydrogen-carrier

[79] J. K. Kaldellis and M. Kapsali. Shifting towards offshore wind energy—Recent activity and future development. *Energy Policy*, 53:136–148, February 2013. ISSN 0301-4215. doi: 10.1016/j.enpol.2012.10.032. URL https://www.sciencedirect.com/science/article/pii/S0301421512008907.

[80] Samir S. Khalse and Dhondiram M. Kakre. Computer Oriented Load Flow Study of Five Bus, 2014.

[81] KNMI. Royal Netherlands Meteorological Institute (KNMI). URL https://www.knmi.nl/home.

[82] Binod Koirala, Sebastiaan Hers, Germán Morales-España, Özge Özdemir, Jos Sijm, and Marcel Weeda. Integrated electricity, hydrogen and methane system modelling framework: Application to the Dutch Infrastructure Outlook 2050. *Applied Energy*, 289:116713, May 2021. ISSN 0306-2619. doi: 10.1016/j.apenergy.2021.116713. URL https://www.sciencedirect.com/science/article/pii/S0306261921002336.

[83] Nikolaos E. Koltsaklis and Athanasios S. Dagoumas. State-of-the-art generation expansion planning: A review. *Applied Energy*, 230:563–589, November 2018. ISSN 0306-2619. doi: 10.1016/j.apenergy.2018.08.087. URL https://www.sciencedirect.com/science/article/pii/S0306261918312583.

[84] Lukas Kriechbaum, Gerhild Scheiber, and Thomas Kienberger. Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges. *Energy, Sustainability and Society*, 8(1):35, November 2018. ISSN 2192-0567. doi: 10.1186/s13705-018-0176-x. URL https://doi.org/10.1186/s13705-018-0176-x.

[85] Rolf W. Künneke. Aligning institutions and technologies in energy systems 1. In *Energy as a Sociotechnical Problem*. Routledge, 2018. ISBN 978-1-315-18631-3. Num Pages: 17.

[86] M. La Scala, A. Vaccaro, and A. F. Zobaa. A goal programming methodology for multiobjective optimization of distributed energy hubs operation. *Applied Thermal Engineering*, 71(2):658–666, October 2014. ISSN 1359-4311. doi: 10.1016/j.applthermaleng.2013.10.031. URL https://www.sciencedirect.com/science/article/pii/S1359431113007400.

[87] F Li. *Spatially explicit techno-economic optimisation modelling of UK heating futures.* Doctoral, UCL (University College London), July 2013. URL https://discovery.ucl.ac.uk/id/eprint/1400217/. Pages: ?-? Publication Title: Doctoral thesis, UCL (University College London).

[88] Xiwang Li and Jin Wen. Review of building energy modeling for control and operation. *Renewable and Sustainable Energy Reviews*, 37:517–537, September 2014. ISSN 1364-0321. doi: 10.1016/j.rser.2014.05.056. URL https://www.sciencedirect.com/science/article/pii/S1364032114003815.

[89] Xuezhi Liu and Pierluigi Mancarella. Modelling, assessment and Sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems. *Applied Energy*, 167:336–352, April 2016. ISSN 0306-2619. doi: 10.1016/j.apenergy.2015.08.089. URL http://www.sciencedirect.com/science/article/pii/S0306261915010259.

[90] Imperial College London. Unlocking the potential of Energy Systems Integration | Energy Futures Lab | Imperial College London. Technical report, 2018. URL https://www.imperial.ac.uk/energy-futures-lab/reports/briefing-papers/paper-2/.

[91] Melissa Lott, Sang-Il Kim, Cecilia Tam, David Elzinga, Steve Heinen, Luis Munuera, and Uwe Remme. *Technology Roadmap: Energy storage.* March 2014.

[92] H. Lund and B. V. Mathiesen. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. *Energy*, 34(5):524–531, May 2009. ISSN 0360-5442. doi: 10.1016/j.energy.2008.04.003. URL https://www.sciencedirect.com/science/article/pii/S0360544208000959.

[93] Henrik Lund and Ebbe Münster. Integrated energy systems and local energy markets. *Energy Policy*, 34(10):1152–1160, July 2006. ISSN 0301-4215. doi: 10.1016/j.enpol.2004.10.004. URL http://www.sciencedirect.com/science/article/pii/S0301421504003118.

[94] Xing Luo, Jihong Wang, Mark Dooner, and Jonathan Clarke. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, 137:511–536, January 2015. ISSN 0306-2619. doi: 10.1016/j.apenergy.2014.09.081. URL https://www.sciencedirect.com/science/article/pii/S0306261914010290.

[95] P. Mancarella. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, 65:1–17, February 2014. ISSN 03605442. doi: 10.1016/j.energy.2013.10.041. URL https://linkinghub.elsevier.com/retrieve/pii/S0360544213008931.

[96] P. Mancarella, G. Andersson, J.A. Peças-Lopes, and K.R.W. Bell. Modelling of integrated multi-energy systems: Drivers, requirements, and opportunities. In *2016 Power Systems Computation Conference (PSCC)*, pages 1–22, June 2016. doi: 10.1109/PSCC.2016.7541031.

[97] Pierluigi Mancarella and Gianfranco Chicco. Distributed multi-generation systems: Energy models and analyses (Manchester eScholar - The University of Manchester). *Energy/Electrical Power*, 2009. URL https://www.escholar.manchester.ac.uk/uk-ac-man-scw:144504.

[98] Eduardo A. Martínez Ceseña, Nicholas Good, Angeliki L. A. Syrri, and Pierluigi Mancarella. Techno-economic and business case assessment of multi-energy microgrids with co-optimization of energy, reserve and reliability services. *Applied Energy*, 210:896–913, January 2018. ISSN 0306-2619. doi: 10.1016/j.apenergy.2017.08.131. URL https://www.sciencedirect.com/science/article/pii/S0306261917311352.

[99] R. McKenna, S. Hollnaicher, and W. Fichtner. Cost-potential curves for onshore wind energy: A high-resolution analysis for Germany. *Applied Energy*, 115:103–115, February 2014. ISSN 0306-2619. doi: 10.1016/j.apenergy.2013.10.030. URL https://www.sciencedirect.com/science/article/pii/S0306261913008507.

[100] Peter Meibom, Juha Kiviluoma, Rüdiger Barth, Heike Brand, Christoph Weber, and Helge V. Larsen. Value of electric heat boilers and heat pumps for wind power integration. *Wind Energy*, 10(4):321–337, 2007. ISSN 1099-1824. doi: https://doi.org/10.1002/we.224. URL http://onlinelibrary.wiley.com/doi/abs/10.1002/we.224. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.224.

[101] Y. G. Melese, P. W. Heijnen, and R. M. Stikkelman. Designing Networked Energy Infrastructures with Architectural Flexibility. *Procedia Computer Science*, 28:179–186, January 2014. ISSN 1877-0509. doi: 10.1016/j.procs.2014.03.023. URL https://www.sciencedirect.com/science/article/pii/S1877050914000866.

[102] Mohammad Mohammadi, Younes Noorollahi, Behnam Mohammadi-ivatloo, and Hossein Yousefi. Energy hub: From a model to a concept – A review. *Renewable and Sustainable Energy Reviews*, 80: 1512–1527, December 2017. ISSN 1364-0321. doi: 10.1016/j.rser.2017.07.030. URL https://www.sciencedirect.com/science/article/pii/S1364032117310985.

[103] Simon Moser and Stefan Puschnigg. Supra-Regional District Heating Networks: A Missing Infrastructure for a Sustainable Energy System. *Energies*, 14(12):3380, January 2021. doi: 10.3390/en14123380. URL https://www.mdpi.com/1996-1073/14/12/3380. Number: 12 Publisher: Multidisciplinary Digital Publishing Institute.

[104] Machiel Mulder, Peter L Perey, and José L Moraga. *Outlook for a Dutch hydrogen market: economic conditions and scenarois*. Centre for Energy Economics Research, University of Groningen, 2019. ISBN 978-94-034-1567-3 978-94-034-1566-6. OCLC: 8089228949.

[105] David J. Murray-Smith. Case Study: Development and Testing of a Simulation Model of Two Interconnected Vessels. In David J. Murray-Smith, editor, *Testing and Validation of Computer Simulation Models: Principles, Methods and Applications*, Simulation Foundations, Methods and Applications, pages 127–145. Springer International Publishing, Cham, 2015. ISBN 978-3-319-15099-4. doi: 10.1007/978-3-319-15099-4_9. URL https://doi.org/10.1007/978-3-319-15099-4_9.

[106] Netbeheer Nederland. Basisinformatie Energie-infrastructuur, 2019. URL https://www.regionale-energiestrategie.nl/Nieuws/1305967.aspx.

[107] Netbeheer Nederland. Integrale Infrastructuurverkenning 2030-2050. Technical report, 2021. URL https://www.tennet.eu/nl/bedrijf/publicaties/ii3050/.

[108] Economics T. Netherlands. Netherlands Electric Power Transmission And Distribution Losses Percent Of Output. URL https://tradingeconomics.com/netherlands/electric-power-transmission-and-distribution-losses-percent-of-output-wb-data.html.

[109] Marcus Newborough and Graham Cooley. Developments in the global hydrogen market: The spectrum of hydrogen colours. *Fuel Cells Bulletin*, 2020(11):16–22, November 2020. ISSN 1464-2859. doi: 10.1016/S1464-2859(20)30546-0. URL https://www.sciencedirect.com/science/article/pii/S1464285920305460.

[110] Pavlos Nikolaidis and Andreas Poullikkas. A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews*, 67:597–611, January 2017. ISSN 1364-0321. doi: 10.1016/j.rser.2016.09.044. URL https://www.sciencedirect.com/science/article/pii/S1364032116305366.

[111] I. Nikolic, Z. Lukszo, E. J. L. Chappin, Martijn Warnier, J. H. Kwakkel, P. W. G. Bots, and F. M. Brazier. Guide for Good Modelling Practice in policy support. 2019. doi: 10.4233/uuid:cbe7a9cb-6585-4dd5-a34b-0d3507d4f188. URL https://repository.tudelft.nl/islandora/object/uuid%3Acbe7a9cb-6585-4dd5-a34b-0d3507d4f188. Publisher: TUD / TPM.

[112] Ministry of Economic Affairs. Energierapport Transitie naar Duurzaam. rapport, January 2016. URL https://www.rijksoverheid.nl/documenten/rapporten/2016/01/18/energierapport-transitie-naar-duurzaam. Last Modified: 2020-07-21T12:11 Publisher: Ministerie van Algemene Zaken.

[113] U.S. Department of Energy. Heat Pump Systems. URL https://www.energy.gov/energysaver/heat-pump-systems.

[114] U.S. Department of Energy, James Vickers, David Peterson, and Katie Randolph. Cost of Electrolytic Hydrogen Production with Existing Technology, 2020. URL https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf.

[115] Torben Ommen, Wiebke Brix Markussen, and Brian Elmegaard. Comparison of linear, mixed integer and non-linear programming methods in energy system dispatch modelling. *Energy*, 74:109–118, September 2014. ISSN 0360-5442. doi: 10.1016/j.energy.2014.04.023. URL `https://www.sciencedirect.com/science/article/pii/S0360544214004368`.

[116] Vishwamitra Oree, Sayed Z. Sayed Hassen, and Peter J. Fleming. Generation expansion planning optimisation with renewable energy integration: A review. *Renewable and Sustainable Energy Reviews*, 69:790–803, March 2017. ISSN 1364-0321. doi: 10.1016/j.rser.2016.11.120. URL `https://www.sciencedirect.com/science/article/pii/S1364032116308711`.

[117] Praveen Panna. Accelerating the Energy Transition: The Renewable Energy Business Environment in the top-7 Emitting Countries. 2019. URL `https://repository.tudelft.nl/islandora/object/uuid%3A4e1f828c-79e9-4063-bde4-159d28926b08`.

[118] G. Papaefthymiou, B. Hasche, and C. Nabe. Potential of Heat Pumps for Demand Side Management and Wind Power Integration in the German Electricity Market. *IEEE Transactions on Sustainable Energy*, 3 (4):636–642, October 2012. ISSN 1949-3037. doi: 10.1109/TSTE.2012.2202132. Conference Name: IEEE Transactions on Sustainable Energy.

[119] Stefan Pfenninger. Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability. *Applied Energy*, 197:1–13, July 2017. ISSN 0306-2619. doi: 10.1016/j.apenergy.2017.03.051. URL `https://www.sciencedirect.com/science/article/pii/S0306261917302775`.

[120] Stefan Pfenninger and Iain Staffell. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy*, 114:1251–1265, November 2016. ISSN 0360-5442. doi: 10.1016/j.energy.2016.08.060. URL `https://www.sciencedirect.com/science/article/pii/S0360544216311744`.

[121] Stefan Pfenninger, Adam Hawkes, and James Keirstead. Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews*, 33:74–86, May 2014. ISSN 1364-0321. doi: 10.1016/j.rser.2014.02.003. URL `http://www.sciencedirect.com/science/article/pii/S1364032114000872`.

[122] Sannamari Pilpola and Peter D. Lund. Analyzing the effects of uncertainties on the modelling of low-carbon energy system pathways. *Energy*, 201:117652, June 2020. ISSN 0360-5442. doi: 10.1016/j.energy.2020.117652. URL `https://www.sciencedirect.com/science/article/pii/S0360544220307593`.

[123] Kris Poncelet. Long-term Energy-system Optimization Models - Capturing the Challenges of Integrating Intermittent Renewable Energy Sources and Assessing the Suitability for Descriptive Scenario Analyses. January 2018. URL `https://lirias.kuleuven.be/1745696`.

[124] Hassan Qudrat-Ullah. *The Physics of Stocks and Flows of Energy Systems: Applications in Energy Policy*. Springer, December 2015. ISBN 978-3-319-24829-5. Google-Books-ID: fWoiCwAAQBAJ.

[125] Jonathan Reynolds, Muhammad Waseem Ahmad, and Yacine Rezgui. Holistic modelling techniques for the operational optimisation of multi-vector energy systems. *Energy and Buildings*, 169:397–416, June 2018. ISSN 0378-7788. doi: 10.1016/j.enbuild.2018.03.065. URL `https://www.sciencedirect.com/science/article/pii/S0378778817340240`.

[126] Dermot Roddy. *Advanced Power Plant Materials, Design and Technology - 1st Edition*. 2010. ISBN 978-1-84569-515-6. URL `https://www.elsevier.com/books/advanced-power-plant-materials-design-and-technology/roddy/978-1-84569-515-6`.

[127] Mark F. Ruth and Benjamin Kroposki. Energy Systems Integration: An Evolving Energy Paradigm. *The Electricity Journal*, 27(6):36–47, July 2014. ISSN 1040-6190. doi: 10.1016/j.tej.2014.06.001. URL `https://www.sciencedirect.com/science/article/pii/S1040619014001195`.

[128] Hugh Saddler. South Australia makes fresh power play to end blackouts, 2017. URL `https://energypost.eu/south-australia-makes-fresh-power-play-bid-end-blackouts/`.

[129] Nicolae Scarlat, Jean-François Dallemand, and Fernando Fahl. Biogas: Developments and perspectives in Europe. *Renewable Energy*, 129:457–472, December 2018. ISSN 0960-1481. doi: 10.1016/j.renene.2018.03.006. URL https://www.sciencedirect.com/science/article/pii/S096014811830301X.

[130] David P. Schlachtberger, Tom Brown, Stefan Schramm, and Martin Greiner. The Benefits of Cooperation in a Highly Renewable European Electricity Network. *Energy*, 134:469–481, September 2017. ISSN 03605442. doi: 10.1016/j.energy.2017.06.004. URL http://arxiv.org/abs/1704.05492. arXiv: 1704.05492.

[131] Andreas Schröder, Friedrich Kunz, Jan Meiss, and Roman Mendelevitch. Current and Prospective Costs of Electricity Generation until 2050. page 105, 2013.

[132] Anna Schwele, Adriano Arrigo, Charlotte Vervaeren, Jalal Kazempour, and François Vallee. *Coordination of Electricity, Heat, and Natural Gas Systems Accounting for Network Flexibility.* June 2020.

[133] Hossein Seifi and Mohammad Sadegh Sepasian. *Electric Power System Planning: Issues, Algorithms and Solutions.* Power Systems. Springer-Verlag, Berlin Heidelberg, 2011. ISBN 978-3-642-17988-4. doi: 10.1007/978-3-642-17989-1. URL https://www.springer.com/gp/book/9783642179884.

[134] Alessandra Sgobbi, Wouter Nijs, Rocco De Miglio, Alessandro Chiodi, Maurizio Gargiulo, and Christian Thiel. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. *International Journal of Hydrogen Energy*, 41(1):19–35, January 2016. ISSN 0360-3199. doi: 10.1016/j.ijhydene.2015.09.004. URL https://www.sciencedirect.com/science/article/pii/S0360319915301889.

[135] Kais Siala and Mohammad Youssef Mahfouz. Impact of the choice of regions on energy system models. *Energy Strategy Reviews*, 25:75–85, August 2019. ISSN 2211-467X. doi: 10.1016/j.esr.2019.100362. URL https://www.sciencedirect.com/science/article/pii/S2211467X19300495.

[136] N. Sriram and M. Shahidehpour. Renewable biomass energy. volume 249, pages 612–617 Vol. 1, July 2005. doi: 10.1109/PES.2005.1489459.

[137] TenneT. Grid maps. URL https://www.tennet.eu/company/news-and-press/press-room/grid-maps/.

[138] TenneT and Gasunie. Phase II — Pathways to 2050. Technical report, 2019.

[139] Godfrey T. Udeh and Patrick O. Udeh. Comparative thermo-economic analysis of multi-fuel fired gas turbine power plant. *Renewable Energy*, 133:295–306, April 2019. ISSN 0960-1481. doi: 10.1016/j.renene.2018.10.036. URL https://www.sciencedirect.com/science/article/pii/S0960148118312205.

[140] (UN) United Nations. The Paris Agreement | UNFCCC. URL https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[141] (UN) United Nations Paris Agreement. Paris Agreement. Technical report, 2015.

[142] L van Cappellen. *Variable network tari s in the LV-network: Analysing the effects on household network cost and power ows in the low voltage electricity network.* PhD thesis, Eindhoven University of Technology, 2020.

[143] Luc van Nuffel, Joao Gorenstein Dedecca, Tycho Smit, and Koen Rademaekers. Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise? Technical report, ITRE committee - European Parliament, Brussels, 2018. URL http://www.europarl.europa.eu/supporting-analyses.

[144] Bert van Wee and David Banister. How to Write a Literature Review Paper? *Transport Reviews*, 36(2):278–288, March 2016. ISSN 0144-1647. doi: 10.1080/01441647.2015.1065456. URL https://doi.org/10.1080/01441647.2015.1065456. Publisher: Routledge _eprint: https://doi.org/10.1080/01441647.2015.1065456.

[145] Andrea Vian, Fabio Bignucolo, and Michele De Carli. Modelling and Optimization Approach of Residential Energy Hub: The GHOTEM Project. In *2019 1st International Conference on Energy Transition in the Mediterranean Area (SyNERGY MED)*, pages 1–6, May 2019. doi: 10.1109/SyNERGY-MED.2019.8764149.

[146] L.J. Vries, A.F. Correljé, H.P.A. Knops, and Reinier van der Veen. *Electricity: Market design and policy choices.* 2019.

[147] P. H. Wagner and M. Wittmann. Influence of Different Operation Strategies on Transient Solar Thermal Power Plant Simulation Models with Molten Salt as Heat Transfer Fluid. *Energy Procedia*, 49: 1652–1663, January 2014. ISSN 1876-6102. doi: 10.1016/j.egypro.2014.03.174. URL `https://www.sciencedirect.com/science/article/pii/S1876610214006286`.

[148] Anthony Wang, Kees van der Leun, Daan Peters, Maud Buseman, and Gas For Climate. European Hydrogen Backbone. Technical report, July 2020. URL `https://www.h2knowledgecentre.com/content/researchpaper1676`. Publisher: Hydrogen Knowledge Centre.

[149] Ligang Wang, Mar Pérez-Fortes, Hossein Madi, Stefan Diethelm, Jan Van herle, and François Maréchal. Optimal design of solid-oxide electrolyzer based power-to-methane systems: A comprehensive comparison between steam electrolysis and co-electrolysis. *Applied Energy*, 211:1060–1079, February 2018. ISSN 0306-2619. doi: 10.1016/j.apenergy.2017.11.050. URL `https://www.sciencedirect.com/science/article/pii/S0306261917316367`.

[150] Ligang Wang, Ming Chen, Rainer Küngas, Tzu-En Lin, Stefan Diethelm, François Maréchal, and Jan Van herle. Power-to-fuels via solid-oxide electrolyzer: Operating window and techno-economics. *Renewable and Sustainable Energy Reviews*, 110:174–187, August 2019. ISSN 1364-0321. doi: 10.1016/j.rser.2019.04.071. URL `https://www.sciencedirect.com/science/article/pii/S1364032119302928`.

[151] Ni Wang, Remco A. Verzijlbergh, Petra W. Heijnen, and Paulien M. Herder. A spatially explicit planning approach for power systems with a high share of renewable energy sources. *Applied Energy*, 260: 114233, February 2020. ISSN 0306-2619. doi: 10.1016/j.apenergy.2019.114233. URL `http://www.sciencedirect.com/science/article/pii/S0306261919319208`.

[152] Jos Wassink. Can underground heat storage replace gas in the Netherlands?, 2018. URL `https://www.delta.tudelft.nl/article/can-underground-heat-storage-replace-gas-netherlands#`.

[153] WBDG and U.S. Department of Energy. Biomass for Heat, September 2016. URL `https://www.wbdg.org/resources/biomass-heat`.

[154] F. Wei, Q. H. Wu, Z. X. Jing, J. J. Chen, and X. X. Zhou. Optimal unit sizing for small-scale integrated energy systems using multi-objective interval optimization and evidential reasoning approach. *Energy*, 111:933–946, September 2016. ISSN 0360-5442. doi: 10.1016/j.energy.2016.05.046. Place: Oxford Publisher: Pergamon-Elsevier Science Ltd WOS:000384776900078.

[155] Margot P.C. Weijnen and Ivo Bouwmans. Innovation in networked infrastructures: coping with complexity. *International Journal of Critical Infrastructures*, 2(2-3):121–132, January 2006. ISSN 1475-3219. doi: 10.1504/IJCIS.2006.009432. URL `https://www.inderscienceonline.com/doi/abs/10.1504/IJCIS.2006.009432`. Publisher: Inderscience Publishers.

[156] Lara Welder, D. Severin Ryberg, Leander Kotzur, Thomas Grube, Martin Robinius, and Detlef Stolten. Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. *Energy*, 158:1130–1149, September 2018. ISSN 0360-5442. doi: 10.1016/j.energy.2018.05.059. URL `https://www.sciencedirect.com/science/article/pii/S036054421830879X`.

[157] Manuel Welsch, Dimitrios Mentis, and Mark Howells. Long-Term Energy Systems Planning : Accounting for Short-Term Variability and Flexibility. pages 215–225. Elsevier, 2014. URL `http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-181267`.

[158] Mohammed Yekini Suberu, Mohd Wazir Mustafa, and Nouruddeen Bashir. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Renewable and Sustainable Energy Reviews*, 35:499–514, July 2014. ISSN 1364-0321. doi: 10.1016/j.rser.2014.04.009. URL https://www.sciencedirect.com/science/article/pii/S1364032114002366.

[159] Haoran Zhao, Qiuwei Wu, Shuju Hu, Honghua Xu, and Claus Nygaard Rasmussen. Review of energy storage system for wind power integration support. *Applied Energy*, 137:545–553, January 2015. ISSN 0306-2619. doi: 10.1016/j.apenergy.2014.04.103. URL https://www.sciencedirect.com/science/article/pii/S0306261914004668.

A

MES literature review search terms

Table A.1 list the search terms used for the literature review on MES optimization models and the number of results per database per search term. In addition to these search terms, snowballing technique was used. First, studies from other domains dealing with other types of multi-energy systems were excluded, such as computer science articles. Second, studies focussing on the optimization of single buildings for short time spans (up to 24 hours) were excluded.

Table A.1: Search terms used for literature research and number of hits for Scopus and Web of Science

Search term	Hits: Scopus	Hits: Web of Science
"multi energy system" AND "optimization" AND "investment"	39	23
"multi energy system" AND "optimization" AND "investment" AND "model"	30	14
"multi energy system" AND "investment" AND "model"	48	21
"integrated energy system" AND "optimization" AND "investment"	81	55
"integrated energy system" AND "optimization" AND "investment" AND "model"	71	46
"integrated energy system" AND "investment" AND "model"	144	70

B
Cross border electricity transmission capacities

Table B.1 list the import regions, the cross-border connected country, and the capacity of the electricity transmission lines. The total cross-border electricity import capacity is the sum of all import countries.

Table B.1: Cross-border electricity import capacities

	Importing region	Exporting country	Capacity (MW)
0	Achterhoek	Germany	1125
9	Goeree-Ovelakee	UK	1000
11	Groningen	Germany	1125
11	Groningen	Denmark	700
11	Groningen	Norway	700
18	Noord-en Midden Limburg	Germany	1125
18	Noord-en Midden Limburg	Belgium	2000
24	Twente	Germany	1125
28	Zeeland	Belgium	2000

Fig. B.1 shows a map of HV-network of the Netherlands and where the cross-border transmission lines are located.

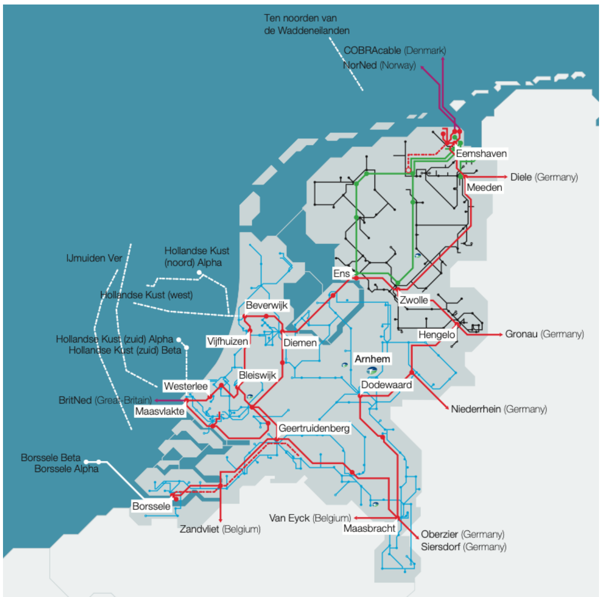


Figure B.1: TenneT's HV-network in the Netherlands, for 2012. Reprinted from [137]

C

GRIM land cover assessment procedure

Here, the land cover assessment procedure from Wang et al. [151] to obtain the maximum VRES potential per region is explained. The procedure follows five steps.

First, the total available area per region is calculated. For the Netherlands, the 30 regions are not administrative units (e.g., provinces), and therefore the polygons of these regions are not directly available in databases. The municipality polygons are obtained from the OpenStreetMap project and combined.
Second, the available area is divided into 44 CLC classes [1]. In the third and fourth steps, the available area of land km^2 for VRES instalment is assessed. This is done two-fold: some area of land is totally excluded, whereafter the remaining available area can be partially excluded, based on the suitability factor $\alpha_{i,c}$. [1].

The third step is the full exclusion of some land areas which are not available for VRES development, such as urban fabrics, airports, rice fields, water bodies or national parks. Although nature reserves are not a CLC class, they can be identified in the form of polygons. For the Netherlands, since most of the nature reserves in the Netherlands are small monuments, only the two largest reservations, Veluwe and Waddenzee are excluded. Furthermore, existing wind turbines are to a large extent built along the roads or highways and at the construction sites, such as the Rotterdam Port area. Therefore, the transport area is not excluded. In addition to physical conditions, more strict exclusion can be applied based on social acceptance. This is especially relevant for wind turbines. In this stricter exclusion, all the land in the built environment, i.e. all the CLC classes of Artificial Surface, is excluded. Furthermore, the area in their 2 km radius is excluded as well. The remaining land area is considered available for VRES development. For the Netherlands, this available land for VRES is equal to 77.35% of the total land (the centre map in fig. 5.2).

The fourth step is partial exclusion of some land. The remaining land can be considered suitable to some degree, and is partially excluded based on the land cover class. The resolution of land cover data is not fine enough to assess the land cover of scale of individual wind turbines or solar panels. Therefore, a suitability factor $_alpha_{i,\,c}$ is applied, for which the value depends on the technology i and the land cover class c [99]. Then, the suitability factors are applied on the available area, resulting in the suitable areas. In addition, stricter exclusion is applied based on social resistance for wind energy. This leads to exclusion of the built environment, i.e. all the CLC classes of Artificial Surface. In addition, the 2km radius is excluded as well. Since solar panels can be build on rooftops, a suitability factor of 0.3 is given to discontinuous urban fabric for solar panels. For all the other CLC land classes, the suitability factors for wind turbines and for solar panels are similar. After the assignment of suitability factors, the suitable areas for technology i at location n for CLC class c are obtained using the following equation (eq. C.1):

$$S_{i,n,c} = S_{unit}\,B_{n,c}\alpha_{i,c}, \forall i \in VRES, \forall n \in N, \forall c \in CLC \tag{C.1}$$

Here, i is either wind or solar energy, and $B_{n,c}$ is the number of grid cells. S_{unit} is the area of a grid cell, S_{unit} = 0.01 km^2.

[1] Instead of these two separate, also a suitability factor of zero could be applied. However, dividing the exclusion in two steps, allows to explicitly give two different ways to exclude land. Namely, in the first step, land can be excluded based on surface conditions, social acceptance and local spatial policies. Then, in the second step, suitability factors can be changed depending on the local surface conditions, such as the height of trees in forests, the slope of the area, or others. In this way, by changing the exclusion criteria and the suitability factors, the approach provides a flexible way to use VRES potential constraint based on location-specific conditions.

Table C.1 shows the details of the land cover assessment for the Netherlands, including the CLC classes available for VRES development, the available area per CLC class, the percentages per CLC class in terms of the total area of the country, suitability factor for each available CLC class, suitable areas and percentages of them in terms of the total area of the country. The suitable areas for wind and solar energy in the Netherlands are 11646 km^2 and 12633 km^2, respectively, occupying 28.02% and 30.40% of the total land of the Netherlands (the right map in fig. 5.2).

Table C.1: The land cover characteristics of the available and the suitable land for VRES development in the Netherlands. Reprinted from [151]. The suitability factors are based on [151] and [99].

CLC class	Available area (km2)	Percentage	Suitability factor	Suitable area (km2)	Percentage
2 Discontinuous urban fabric	3288.10	7.91%	0.3	986.43	2.37%
3 Industrial or commercial units	807.18	1.94%	0.8	645.74	1.55%
7 Mineral extraction sites	46.25	0.11%	0.5	23.13	0.06%
8 Dump sites	21.49	0.05%	0.5	10.75	0.03%
9 Construction sites	153.67	0.37%	0.3	46.10	0.11%
12 Non-irrigated arable land	7366.88	17.72%	0.4	2946.75	7.09%
15 Vineyards	0	0	0.1	0	0
16 Fruit trees and berry plantations	71.63	0.17%	0.1	7.16	0.02%
18 Pastures	10089.93	24.28%	0.6	6053.96	14.57%
20 Complex cultivation patterns	5304.71	12.76%	0.1	530.47	1.28%
21 Land principally occupied by agriculture, with significant areas of natural vegetation	1136.94	2.74%	0.1	113.69	0.27%
23 Broad-leaved forest	568.16	1.37%	0.3	170.45	0.41%
24 Coniferous forest	1146.76	2.76%	0.3	344.03	0.83%
25 Mixed forest	725.17	1.74%	0.3	217.55	0.52%
26 Natural grasslands	475.29	1.14%	0.6	285.17	0.69%
27 Moors and heathland	246.85	0.59%	0.6	148.11	0.36%
29 Transitional woodland-shrub	13.62	0.03%	0.5	6.81	0.02%
30 Beaches, dunes, sands	143.04	0.34%	0.3	42.91	0.10%
32 Sparsely vegetated areas	0	0	0.8	0	0
35 Inland marshes	364.74	0.88%	0.1	36.47	0.08%
36 Peat bogs	80.21	0.19%	0.1	8.02	0.02%
37 Salt marshes	96.69	0.23%	0.1	9.67	0.02%
Sum	32147.31	77.35%	n.a.	12633.38	30.40%

The fifth and final step is to calculate the maximum VRES capacity based on the available land. For this, the capacity density β_i is needed, which is defined as the maximum potential installed capacity per unit area. Values used for the capacity density β_i are 5 MW/km2 for wind [32], and 30 MW/km2 for solar [58]. The maximum VRES capacity is calculated according to the following equation (eq. C.2):

$$K_{i,n}^{\max} = \sum_{c \in CLC} S_{i,n,c} \beta_i, \forall i \in VRES, \forall n \in N \tag{C.2}$$

This leads to 58.23 GW of potential wind capacity and 379 GW of potential solar capacity.

D

Data pre-processing ETM demand profiles

In order to obtain demand profiles which are suitable for usage in the model, the demand data obtained from the ETM was pre-processed. From the hourly electricity and hydrogen demand profiles, several sub-categories (i.e. final uses) were excluded from the data, since some of these are calculated endogenously in optimization model (such as electricity storage demand, electricity used for heating, hydrogen used to meet the electricity demand (through CCGT) or hydrogen heating demand (through boiler or heat pump) are all calculated endogenously in the model and hence were excluded from the input data. Below, all of the elements removed from the demand profiles from ETM and the total amount of TWh of energy are shown for electricity (D.1) and hydrogen (D.2)

D.1. Overview categories excluded from ETM: electricity demand

Table D.1: Overview categories excluded from ETM: electricity demand

Category	ETM column name	Total annual energy (TWh)
Buildings, heating	buildings_space_heater_collective_heatpump_water_water_ts_electricity.input (MW)	1.61
Buildings, heating	buildings_space_heater_electricity.input (MW)	0.00
Storage	energy_flexibility_mv_batteries_electricity.input (MW)	3.68
Storage	energy_flexibility_pumped_storage_electricity.input (MW)	0.00
Storage	energy_heat_flexibility_p2h_boiler_electricity.input (MW)	0.00
Storage	energy_heat_flexibility_p2h_heatpump_electricity.input (MW)	0.00
Heating	energy_heat_heatpump_water_water_electricity.input (MW)	2.69
Heating	energy_heat_well_geothermal.input (MW)	0.05
Hydrogen P2G	energy_hydrogen_flexibility_p2g_electricity.input (MW)	20.40
Export	energy_interconnector_1_exported_electricity.input (MW)	2.44
Export	energy_interconnector_2_exported_electricity.input (MW)	0.00
Export	energy_interconnector_3_exported_electricity.input (MW)	0.00
Export	energy_interconnector_4_exported_electricity.input (MW)	0.00
Export	energy_interconnector_5_exported_electricity.input (MW)	0.00
Export	energy_interconnector_6_exported_electricity.input (MW)	0.00
Export	energy_offshore_sequestration_co2_electricity.input (MW)	0.00
Network losses	energy_power_hv_network_loss.input (MW)	14.90
Heating	households_space_heater_electricity.input (MW)	0.00
Heating	households_space_heater_heatpump_air_water_electricity.input (MW)	3.53
Heating	households_space_heater_heatpump_ground_water_electricity.input (MW)	0.69
Heating	households_space_heater_hybrid_heatpump_air_water_electricity.input (MW)	5.93
Heating	households_space_heater_hybrid_hydrogen_heatpump_air_water_electricity.input (MW)	2.96
Heating	households_water_heater_heatpump_air_water_electricity.input (MW)	1.00
Heating	households_water_heater_heatpump_ground_water_electricity.input (MW)	0.19
Heating	households_water_heater_hybrid_heatpump_air_water_electricity.input (MW)	0.00
Heating	households_water_heater_hybrid_hydrogen_heatpump_air_water_electricity.input (MW)	0.00
Electrolyser	industry_aluminium_electrolysis_bat_electricity.input (MW)	1.25

D.2. Overview categories excluded from ETM: hydrogen demand

Table D.2: Overview categories excluded from ETM: hydrogen demand

Category	ETM column name	Total annual energy (TWh)
Export	energy_export_hydrogen.input (MW)	0.0
Heating	energy_heat_burner_hydrogen.input (MW)	1.2
Storage	energy_hydrogen_storage.input (MW)	14.2
CHP	energy_power_combined_cycle_hydrogen.input (MW)	0.0
CCGT	energy_power_turbine_hydrogen.input (MW)	0.0
Heating	households_space_heater_hybrid_hydrogen_heatpump_air_water_electricity.input (MW)	4.3
Heating	households_water_heater_hybrid_hydrogen_heatpump_air_water_electricity.input (MW)	2.4

E

Population distribution

The percentages of population per region used for the spatial distribution of demand are shown in table E.1.

Table E.1: Population share per region

	Region	Population share
0	Achterhoek	1.67%
1	Alblasserwaard	0.50%
2	Arnhem/Nijmegen	2.53%
3	Amersfoort	1.20%
4	Drechtsteden	1.54%
5	Drenthe	3.08%
6	Flevoland	2.23%
7	FoodValley	1.80%
8	Friesland	3.13%
9	Goeree- Overflakkee	0.92%
10	Hart van Brabant	2.62%
11	Groningen1	1.90%
12	Holland Rijnland	2.59%
13	Hoeksewaard	0.45%
14	Midden-Holland	1.49%
15	Noord-Holland Zuid	9.80%
16	Eindhoven	4.24%
17	Noord-Holland Noord	3.44%
18	Noord-en Midden Limburg	3.94%
19	Noord-oost Brabant	3.83%
20	Noord Veluwe	1.12%
21	Rivierenland (Fruitdelta)	1.76%
22	Rotterdam / Den Haag	16.63%
23	Stedendriehoek / Cleantech region	1.84%
24	Twente	3.42%
25	U10/U16	3.89%
26	West Brabant	5.37%
27	West Overijssel	3.14%
28	Zeeland	3.35%
29	Zuid Limburg	2.79%
30	Groningen2	1.90%
31	Groningen3	1.90%

F

Specification of cost parameters

For some costs parameters, a range was found in literature. Table F.1 list the range per parameter.

Table F.1: Estimations of costs parameters and efficiencies for generation, conversion, and storage technologies and network costs

Technology	**CapEx** (€ / kW)	**FOM** (€ / kW / yr)	**VOM** (€ / MWh)	**eta** (%)	**Lifetime** years
Onshore	1075 [130] to 1103 [43])	35 [130] to 45 [151]	0.015 [151]	-	25 [43]
Solar PV	425 [130]	21 [151] to 25 [130]	0.01 [151]	-	25 [43]
Hydrogen, fuel	-	-	52.25 [31]	-	-
Biomass, fuel	-	-	45.26 [130]	-	-
Natural gas, fuel	-	-	27.6	-	-
Foreign electricity import	-	-	38.5 [76]	-	-
Electrolyser	670 to 1260 [114]	30	-	72 [104]	30
EHP	1390	10	-	90	15
CCGT, hydrogen fired	774 [76] to 2400 [151]	11.33 [76]	-	60 to 80 [76][9]	20 [151] to 30 [43]
CCGT, biomass fired	1951 [130], 2390 [43] , 2640 [151]	90 [130, 151] to 120 - 165 [43]	-	48.7 [130]	30 [43] to 33 [151]
CCGT, natural gas fired	800	20	-	60	30
Boiler, hydrogen fired	1300	40	-	60	25
Boiler, biomass fired	500 - 1500 [153]	26	-	60 - 0.65 [153]	25
Boiler, natural gas fired	1300	40	-	0.6	15
Battery storage unit	650	0.9	-	-	10
Battery conversion	450 €/kWh	-	-	90 (in/out η)	-
TES storage unit	3340	0.7	-	-	30
TES conversion unit	100 €/kWh	-	-	75 (in/out η)	-
Hydrogen storage unit	2400	0.04	-	0.6 - 0.65 [153]	25
Hydrogen storage conversion	60 €/kWh	-	-	100 (in/out η)	-
Network: Electricity	10000 €/MW/km	-	-	5 %/100 km (power loss factor)	-
Network: Hydrogen	82 €/MW/km	-	-	1.75%/100 km (power loss factor)	-

G

Cost specifications per scenario

Table G.1

RES target	0%			20%			50%			80%			100%		
Scenario:	**MES**	**MES w/LR**	**NIES**	**MES**	**MES w/LR**	**NIES**	**MES**	**MES w/LR**	**NIES**	**MES**	**MES w/LR**	**NIES**	**MES**	**MES w/LR**	**NIES**
Gen. & conv. Investment	6017	6017	6055	7770	7781	7785	15045	15804	16315	25906	38856	32677	35542	72004	47051
Storage investment	0	0	0	0	0	0	0	2146	133	119	8188	479	217	16736	2263
Electricity network investment	216	216	240	331	406	290	1139	3118	730	2259	4565	993	2589	6143	917
Hydrogen network investment	0	0	0	0	0	1	34	0	252	50	0	54	30	0	47
Operation costs	23726	23726	23849	23085	23182	23145	22105	23860	23457	21285	27636	22931	22677	33556	24562
Total	29960	29960	30143	31186	31369	31221	38323	44927	40887	49618	79245	57134	61055	128438	74839
Average energy costs (/MWh)	€ 50.92	€ 50.92	€ 51.24	€ 54.79	€ 55.40	€ 54.59	€ 69.39	€ 82.60	€ 70.26	€ 88.71	€ 116.58	€ 99.34	€ 105.17	€ 139.87	€ 122.72
Shares															
Gen. & conv. Investment	20.1%	20.1%	20.1%	24.9%	24.8%	24.9%	39.3%	35.2%	39.9%	52.2%	49.0%	57.2%	58.2%	56.1%	62.9%
Storage investment	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.8%	0.3%	0.2%	10.3%	0.8%	0.4%	13.0%	3.0%
Electricity network investment	0.7%	0.7%	0.8%	1.1%	1.3%	0.9%	3.0%	6.9%	1.8%	4.6%	5.8%	1.7%	4.2%	4.8%	1.2%
Hydrogen network investment	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.6%	0.1%	0.0%	0.1%	0.0%	0.0%	0.1%
Operation costs	79.2%	79.2%	79.1%	74.0%	73.9%	74.1%	57.7%	53.1%	57.4%	42.9%	34.9%	40.1%	37.1%	26.1%	32.8%
Per MW/h:															
Gen. & conv. investment	€ 10.2	€ 10.2	€ 10.3	€ 13.7	€ 13.7	€ 13.6	€ 27.2	€ 29.1	€ 28.0	€ 46.3	€ 57.2	€ 56.8	€ 61.2	€ 78.4	€ 77.2
Storage investment	€ 0.0	€ 0.0	€ 0.0	€ 0.0	€ 0.0	€ 0.0	€ 0.0	€ 3.9	€ 0.2	€ 0.2	€ 12.0	€ 0.8	€ 0.4	€ 18.2	€ 3.7
Electricity network investment	€ 0.4	€ 0.4	€ 0.4	€ 0.6	€ 0.7	€ 0.5	€ 2.1	€ 5.7	€ 1.3	€ 4.0	€ 6.7	€ 1.7	€ 4.5	€ 6.7	€ 1.5
Hydrogen network investment	€ 0.0	€ 0.0	€ 0.0	€ 0.0	€ 0.0	€ 0.0	€ 0.1	€ 0.0	€ 0.4	€ 0.1	€ 0.0	€ 0.1	€ 0.1	€ 0.0	€ 0.1
Operation costs	€ 40.3	€ 40.3	€ 40.5	€ 40.6	€ 40.9	€ 40.5	€ 40.0	€ 43.9	€ 40.3	€ 38.1	€ 40.7	€ 39.9	€ 39.1	€ 36.5	€ 40.3

H

Installed capacities per region for fully renewable scenarios without land-use restrictions

The total installed capacities and shares of solar, onshore, EHP, electrolysers, hydrogen CCGT and biomass boiler per region are shown in table H.1 for the fully renewable scenario without land-use restrictions.

Table H.1: Without land-use restrictions

Region		solar		onshore		EHP		electrolyser		CCGT_hydro		boiler_bio	
0	Achterhoek	0	0.0%	0	0.0%	207	1.9%	0	0.0%	734	1.2%	504	1.6%
1	Alblasserwaard	415	0.3%	14	0.0%	55	0.5%	0	0.0%	282	0.5%	160	0.5%
2	Arnhem/Nijmegen	1513	0.9%	0	0.0%	350	3.2%	0	0.0%	1006	1.7%	759	2.3%
3	Amersfoort	1186	0.7%	0	0.0%	150	1.3%	0	0.0%	763	1.3%	360	1.1%
4	Drechtsteden	425	0.3%	0	0.0%	171	1.5%	0	0.0%	64	0.1%	498	1.5%
5	Drenthe	840	0.5%	0	0.0%	312	2.8%	0	0.0%	1479	2.5%	1076	3.3%
6	Flevoland	614	0.4%	0	0.0%	223	2.0%	0	0.0%	1172	2.0%	748	2.3%
7	FoodValley	852	0.5%	0	0.0%	195	1.8%	0	0.0%	629	1.1%	594	1.8%
8	Friesland	5282	3.3%	7448	4.0%	463	4.2%	2106	3.5%	2064	3.5%	936	2.9%
9	Goeree-Overflakkee	1453	0.9%	21794	11.8%	115	1.0%	5992	10.0%	589	1.0%	284	0.9%
10	Hart-van-Brabant	28	0.0%	0	0.0%	358	3.2%	0	0.0%	821	1.4%	755	2.3%
11	Groningen1	0	0.0%	4543	2.5%	710	6.4%	0	0.0%	2890	4.9%	1722	5.3%
12	Holland-Rijnland	5905	3.6%	0	0.0%	375	3.4%	0	0.0%	1121	1.9%	714	2.2%
13	Hoeksewaard	0	0.0%	206	0.1%	68	0.6%	0	0.0%	216	0.4%	118	0.4%
14	Midden-Holland	3220	2.0%	0	0.0%	199	1.8%	0	0.0%	17	0.0%	434	1.3%
15	Noord-Holland Zuid	3735	2.3%	16889	9.1%	902	8.1%	0	0.0%	5170	8.7%	3366	10.4%
16	Eindhoven	5018	3.1%	0	0.0%	414	3.7%	0	0.0%	2519	4.3%	1419	4.4%
17	Noord-Holland Noord	14836	9.1%	125214	67.6%	614	5.5%	34536	57.4%	2422	4.1%	767	2.4%
18	Noord-en Midden Limburg	41880	25.8%	0	0.0%	544	4.9%	7144	11.9%	5155	8.7%	1124	3.5%
19	Noord-oost Brabant	2986	1.8%	0	0.0%	353	3.2%	0	0.0%	2025	3.4%	1319	4.1%
20	Noord-Veluwe	0	0.0%	0	0.0%	127	1.1%	0	0.0%	610	1.0%	354	1.1%
21	Rivierenland (Fruitdelta)	920	0.6%	0	0.0%	230	2.1%	0	0.0%	546	0.9%	511	1.6%
22	Rotterdam &Den-Haag	16237	10.0%	0	0.0%	1391	12.5%	0	0.0%	9627	16.3%	6061	18.7%
23	Stedendriehoek / cleantechregio	408	0.3%	0	0.0%	160	1.4%	0	0.0%	1063	1.8%	654	2.0%
24	Twente	4	0.0%	0	0.0%	248	2.2%	0	0.0%	1930	3.3%	1350	4.2%
25	U10/U16	4243	2.6%	0	0.0%	334	3.0%	0	0.0%	3784	6.4%	1390	4.3%
26	West-Brabant	2874	1.8%	0	0.0%	529	4.8%	0	0.0%	2330	3.9%	1815	5.6%
27	West-Overijssel	0	0.0%	0	0.0%	363	3.3%	0	0.0%	1867	3.2%	981	3.0%
28	Zeeland	8211	5.1%	9092	4.9%	552	5.0%	3899	6.5%	2248	3.8%	885	2.7%
29	Zuid-Limburg	39077	24.1%	0	0.0%	385	3.5%	6502	10.8%	4070	6.9%	806	2.5%

I

Installed capacities per region for fully renewable scenarios with land-use restrictions

The total installed capacities and shares of solar, onshore, EHP, electrolysers, hydrogen CCGT and biomass boiler per region are shown in table I.1 for the fully renewable scenario with land-use restrictions.

Table I.1: With land-use restrictions

Region		solar		onshore		EHP		electrolyser		CCGT_hydro		boiler_bio	
0	Achterhoek	11023	2.9%	1748	3.0%	163	1.9%	3661	2.7%	380	0.9%	560	1.6%
1	Alblasserwaard	3401	0.9%	536	0.9%	57	0.7%	1636	1.2%	171	0.4%	161	0.5%
2	Arnhem/Nijmegen	8362	2.2%	1191	2.0%	233	2.7%	2616	1.9%	674	1.6%	865	2.4%
3	Amersfoort	4071	1.1%	600	1.0%	116	1.3%	1294	1.0%	493	1.2%	417	1.2%
4	Drechtsteden	1709	0.5%	213	0.4%	117	1.4%	60	0.0%	386	0.9%	561	1.6%
5	Drenthe	29488	7.8%	4696	8.1%	359	4.2%	11958	8.9%	1729	4.2%	982	2.8%
6	Flevoland	15297	4.0%	2418	4.2%	185	2.1%	4540	3.4%	782	1.9%	793	2.2%
7	FoodValley	4604	1.2%	678	1.2%	144	1.7%	1188	0.9%	603	1.5%	645	1.8%
8	Friesland	53308	14.1%	8632	14.8%	454	5.3%	25016	18.6%	1877	4.6%	874	2.5%
9	Goeree-Overflakkee	3025	0.8%	487	0.8%	67	0.8%	1302	1.0%	306	0.7%	341	1.0%
10	Hart-van-Brabant	5811	1.5%	834	1.4%	248	2.9%	1736	1.3%	859	2.1%	889	2.5%
11	Groningen1	30589	8.1%	4870	8.4%	500	5.8%	9404	7.0%	3655	8.9%	2010	5.7%
12	Holland-Rijnland	6992	1.8%	1038	1.8%	253	2.9%	1516	1.1%	969	2.4%	879	2.5%
13	Hoeksewaard	3343	0.9%	532	0.9%	56	0.6%	2327	1.7%	141	0.3%	136	0.4%
14	Midden-Holland	5339	1.4%	824	1.4%	141	1.6%	860	0.6%	247	0.6%	507	1.4%
15	Noord-Holland Zuid	14883	3.9%	2048	3.5%	663	7.7%	3964	2.9%	4159	10.2%	3700	10.5%
16	Eindhoven	9736	2.6%	1363	2.3%	318	3.7%	2898	2.2%	1955	4.8%	1552	4.4%
17	Noord-Holland Noord	18706	4.9%	2908	5.0%	429	5.0%	7134	5.3%	580	1.4%	1023	2.9%
18	Noord-en Midden Limburg	12416	3.3%	1864	3.2%	423	4.9%	4084	3.0%	1574	3.9%	1307	3.7%
19	Noord-oost Brabant	9270	2.4%	1341	2.3%	291	3.4%	2787	2.1%	1644	4.0%	1397	4.0%
20	Noord-Veluwe	3516	0.9%	547	0.9%	105	1.2%	815	0.6%	450	1.1%	382	1.1%
21	Rivierenland (Fruitdelta)	8743	2.3%	1376	2.4%	172	2.0%	3595	2.7%	568	1.4%	591	1.7%
22	Rotterdam &Den-Haag	10603	2.8%	1308	2.2%	995	11.5%	120	0.1%	7545	18.5%	6438	18.2%
23	Stedendriehoek / cleantechregio	7825	2.1%	1204	2.1%	162	1.9%	2648	2.0%	745	1.8%	659	1.9%
24	Twente	16762	4.4%	2595	4.5%	302	3.5%	5064	3.8%	1462	3.6%	1223	3.5%
25	U10/U16	15822	4.2%	2392	4.1%	299	3.5%	5683	4.2%	1424	3.5%	1418	4.0%
26	West-Brabant	14209	3.7%	2146	3.7%	420	4.9%	5287	3.9%	1901	4.7%	1955	5.5%
27	West-Overijssel	25108	6.6%	4017	6.9%	290	3.4%	10282	7.6%	1168	2.9%	1078	3.1%
28	Zeeland	19532	5.2%	3112	5.3%	458	5.3%	9612	7.1%	1274	3.1%	973	2.8%
29	Zuid-Limburg	5509	1.5%	718	1.2%	226	2.6%	1482	1.1%	1151	2.8%	1018	2.9%