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Sustainable energy in Noord-Brabant
renewable energy scenarios in an agent-based model of the province's energy system

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Sustainable Energy in Noord-Brabant

Renewable energy scenarios in an agent-based model of the province's energy system

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Table of Contents

List of Figures 5

List of Tables...6

List of Abbreviations..7

Abstract..8

1. Introduction 11

2. Modelling renewable energy and transitions...14

  2.1. Renewable energy models 14

  2.2. Model debate 16

  2.3. Transition theory 17

  2.4. Socio-technical energy transition models...20

3. Agent-based modelling 24

  3.1. Agent-based energy transition models..27

  3.2. Multi-method modelling 28

  3.3. Verification and validation of agent-based models 29

4. Model structure...31

  4.1. Requirement priorities 31

  4.2. Agent types and environment 31

  4.3. Energy carriers...33

  4.4. Energy Demand 34

    4.4.1. Industry & Agriculture 34

    4.4.2. Built Environment...35

    4.4.3. Electric vehicles 35

    4.4.4. Smart charging..35

  4.5. Energy Generation...36

    4.5.1. Heat generation...36

    4.5.2. Renewable electricity generation 36

    4.5.3. Conventional electricity generation...37

  4.6. Storage 37

  4.7. Balancing algorithm..39

  4.8. CO_2 emission calculations...40

  4.9. Cost calculations..40

  4.10. Out of scope energy technologies 41

  4.11. Software tool - AnyLogic...42

  4.12. Visualization 42

5. Data and Assumptions...44

5.1. Data gathering 44
5.2. Energy Demand 45
  5.2.1. Conventional Transport 45
  5.2.2. Electric Transport 46
5.3. Heat 46
  5.3.1. Conventional Heat 46
  5.3.2. Heat networks 46
  5.3.3. Residual heat 47
  5.3.4. Geothermal heat 47
  5.3.5. Heat pumps 49
  5.3.6. Biomass 49
5.4. Electricity 50
  5.4.1. Conventional Electricity generation 50
  5.4.2. PV 50
  5.4.3. Wind 51
  5.4.4. Batteries 52
  5.4.5. Hydrogen 52
5.5. CO_2 54
5.6. Costs 55
5.7. Weather input 55
6. Verification and validation 57
7. Analysis 59
7.1. Scenarios 59
7.2. Output 61
8. Results 62
8.1. Current 67
8.2. 50% Renewable Electricity 67
8.3. 50% Renewable Energy 68
8.4. 100% CCGT 68
8.5. 100% Wind 69
8.6. 100% Solar 70
8.7. 100% In Brabant 71
8.8. Cost optimized 71
8.9. Socio-economical potential 72
8.10. Renewable heat 73
8.11. Smart charging 74

- 8.12. Storage assumptions ... 75
- 8.13. CO_2 pricing ... 77
- 8.14. Renewable energy growth ... 78
- 8.15. Interactive discussion tool ... 80

9. Conclusions ... 81
10. Discussion ... 85
11. Limitations and recommendations for future research ... 87
12. Bibliography ... 89
13. Appendix ... 111
    - A. ODD Elements ... 111
    - B. NEDU demand profile examples ... 111
    - C. Schematic representation of model algorithm ... 114
    - D. List of cost assumption ... 115
    - E. List of Input parameters ... 116
    - F. Model output all scenarios ... 118

List of Figures

Figure 1: A dynamic multi-level perspective on technology transitions.. 19
Figure 2 Methodological requirements for socio-technical energy transition (STET) models. 21
Figure 3: Generic architecture ABM. 24
Figure 4: A sketch of the system that is represented by the AMIRIS model. 28
Figure 5: Simulation modelling methods. 29
Figure 6: Schematic overview of the model 33
Figure 7: EV load without (left) and with (right) smart charging 36
Figure 8: Value of storage in each step of the energy value chain 38
Figure 9: Storage technologies compared on rated power, energy content and charge discharge time. 38
Figure 10: Snapshot of balancing modules in model runtime 40
Figure 11: Snapshot of the visual model during simulation 43
Figure 12: Medium segment price and battery costs in EU 46
Figure 13: Potential for geothermal district heating: 48
Figure 14: LCOH geothermal heat project Groningen compared to literature sources and gas heat price in 2017. 48
Figure 15: Underground hydrogen storage possibilities: Reprinted from (Schiebahn et al., 2015)......53
Figure 16: Global weighted average capacity factors for new onshore wind power capacity.............58
Figure 17: Annual Energy consumption in different scenarios in GWh. 63
Figure 18: Energy costs of different scenarios (in Mln. € annually) 63
Figure 19: Energy costs of different scenarios (in €/kWh)..64
Figure 20: Electricity annual system costs (in Energy costs of different scenarios (in € Mln. annually)64
Figure 21: Electricity costs (in €/kWh) 65
Figure 22: Battery required capacity and total conversion per scenario (MWh annually) 65
Figure 23: Hydrogen required capacity and total conversion (in MWh annually) 66
Figure 24: Capacity use of batteries and hydrogen. 66
Figure 25: Comparing full heat supply by either heat networks or heat pumps (in Mln. € annualy)....74
Figure 26: The annaul battery costs for a system with regular EVs versus Smart charging EVs. 75
Figure 27: Storage costs (in € Mln. annually) assumptions..77
Figure 28: System costs compared to CO_2 prices for the cost optimized and 100% CCGT scenarios ...78
Figure 29: Percentage renewable energy in different scenarios. 79
Figure 30: Annual CO_2 emission of projected and goal scenarios..79
Figure 31: NEDU demand profile Electricity E2, 10-16th of April 112
Figure 32: NEDU demand profile Electricity E3, 10-16th of April 112
Figure 33: NEDU demand profile Electricity averages, 10-16th of April 113
Figure 34: NEDU natural gas demand profile temperate independent, 10-16th of April 113
Figure 35: NEDU natural gas demand profile depended on 2017 temperatures, 10-16th of April 113
Figure 36: Schematic representation of the energy balancing algorithm amongst energy carriers ...114

List of Tables

Table 1: Requirements derived from renewable energy models 15
Table 2: Requirements for Socio-Technical Energy Transition (STET) Models.....................................21
Table 3: Model requirements across scales and domains derived from a theoretic perspective.........23
Table 4: Model structure of agents and modules..32
Table 5: Energy demand forecast per sector of Noord-Brabant..45
Table 6: Assumptions on electricity and heat share of total demand in absolute figures and percentage 45
Table 7: Cost assumptions...55
Table 8: Average capacity factors of onshore wind and PV in Brabant. 58
Table 9: General baseline parameter settings...59
Table 10: Scenario characteristics 60
Table 11: 2030 Heat cost assumptions..73
Table 12: Range of cost assumptions for storage technologies in 2030..76
Table 13: Scenario setting forecasted growth 78
Table 14: List of main conclusions of the scenarios..83
Table 15: 2030 cost assumptions including sources 115

List of Abbreviations

ABM	Agent-based model(ling)
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture, usage and storage
CHP	Combined heat and power
CO_2	Carbon dioxide
DES	Discrete-event simulation
DoI	Diffusion of Innovation
EV	Electric vehicle
GHG	Greenhouse gas
ICE	Internal combustion engine
IEA	International energy agency
LCOE	Levelized costs of energy
LCOH	Levelized costs of heat
LULU	Locally unwanted land use
MLP	Multi-level perspective
NEV	Nationale energie verkenning (Dutch national energy forecast)
NIMBY	Not in my back yard
OPEX	Operational expenditure
PLC	Product-life cycle
PV	Photovoltaics
RE	Renewable energy
RES	Renewable energy system
REM	Renewable energy model
SC	Smart charging
SCOP	Seasonal coefficient of performance
SD	System dynamics
STET	Socio-technical energy transition (model)
TT	Technological trajectories
V2G	Vehicle to grid
WEO	World energy outlook
WWS	Wind, water and solar

Abstract

The energy transition can be seen as a complex web of problems, solutions, developments and effects interact across multiple scales and domains. From the technological challenge of temporally and spatially matching all energy carriers; to economic questions regarding costs and benefits; political questions of energy equality or spatial planning; and societal debate about local changes. Each of these effects is caused by different solutions to different subsets of the energy system, while these subsets are in no way structured. They tend to overlap or interacting, often reinforcing one effect and hindering others. Now enter the field of energy policy. Policy makers have to juggle between all these tensions while CO_2 targets are more and more pressing. In other words, there is a lot at stake in a complex and uncertain web. How can policy makers come to a comprehensive overview upon which informed decisions can be made?

The province of Noord-Brabant faces this challenge as well. They have ambitious renewable energy and CO_2 reduction targets, but miss the overview to make a comprehensive plan to achieve these goals. The main question leading from this is: *What are the economic, spatial, societal and CO_2 emission effects of choices in renewable energy, storage and conversion technologies towards reaching the climate goals of the Province of Noord-Brabant?*

To answer this, a renewable energy model of the province of Noord-Brabant has been made, showing the effects of choices and trade-offs towards the 2030 energy system. The model provides a broad overview of different sectors, domains and energy carriers. As the research question implies, the effects are not only analyzed on techno-economic aspects, but also on spatial requirements and socio-economic transition paths. This combination leads to a comprehensive overview of the energy transition.

The model is based on requirements from the field of renewable energy research. Two general directions within this field are techno-economic renewable energy models and socio-economic transition models. The first focus on the a technologically balanced economic optimum of a renewable energy system. The second focus on social and economic factors that influence transitions, such as the power of incumbent firms. Both approaches simplify certain aspects of the energy transition. Techno-economic models are generally based on economic optimization. Not only does this neglect a large part of the factors that matter to policy makers, it also results in less reliable assumptions. Socio-economic transition models do incorporate these factors, providing analytic concepts to socio-economical change. However, they exclude the techno-economic tradeoffs influencing the energy transition. Although both fields find factors affecting the energy transition, an overview is lacking.

Socio-technical energy transition (STET) models are proposed to be the solution to this problem. STET models are a combination of techno-economic and socio-economic research. Increasing the relevance of techno-economical models with the socio-economic concepts. This can be done by either, using these concepts to analyze techno-economic results, or by quantifying and directly integrating these concepts in a quantified energy system model.

Agent-based modelling (ABM) is argued to be the most suited method to create STET models. Starting with individual agents, who can be grouped in agent populations. All agent types (individual agents and populations) interact with each other in the model environment. This multi-level, bottom-up method aligns closely to the complex interactions across multiple scales and domains in socio-technical energy transition models. The environment can be defined in continuous time and geographical space. The multi-level characteristics of ABM enable a combination between system dynamics (SD) like continuous flows and feedback loops (such as a balancing energy grid), and discrete event simulation

(DES) event-based dynamics (such as event-based driving patterns). In this sense, ABM is the basis of the multi-method modelling approach, combining the best of all three.

We have made an agent-based model of potential energy systems of Noord-Brabant. Relevant (renewable) sources, consumption sectors, storage and conversion technologies have been modelled bottom-up. They interact in the environment, which ensures a balanced system on an hourly basis for all energy carriers at all times. The balancing algorithm first balances heat demand and supply to determine the electricity demand from heat pumps. Then, (if applicable) the EV smart charging schedules are determined. Followed by gas power production. The remaining imbalance is covered by batteries (daily imbalance) and hydrogen (seasonal imbalance).

A thorough analysis of trend reports has been performed to acquire well-informed assumptions on energy technologies and consumption patterns. The model design and assumptions are described in detail. Thereafter, the model is validated by the indirect-calibration approach. Meaning that the bottom-up generated results of the model are compared to measured aggregate statistics.

To analyze the effects of choices and trade-offs in renewable energy technologies a scenario analysis is performed. A wide range of scenarios throughout the energy transition creates an overview of the most important effects and dynamics. The scenarios are based on two main pillars; the electrification of non-electric sectors (heat and transport), and the transformation from fossil fuel energy generation to renewable energy generation.

The most important effects are:

1. Electrification of heat and transport strongly reduces energy use and enables use of renewable sources.
2. 100% renewable energy systems are economically competitive in scenarios with 2030 forecasts of fossil-fuel, CO_2, renewable energy sources and storage prices. The cost-optimized renewable scenario is close to €200 million cheaper than the second cheapest option of gas power.
3. In order to achieve this competitiveness a balanced mix between PV and (offshore) wind is required, making optimal use of daily (batteries) and seasonal (hydrogen in salt caverns) storage.
4. The economic optimal system relies on wind (>60% of all energy generation). PV is cheaper than wind in low shares, until storage costs outweigh this difference (at around 23% of all energy generation).
5. Storage assumptions are still highly uncertain, while they have a major impact on the optimal system design. Cheap storage enables more flexibility in system design choices as there is less difference between PV and wind.

The agent-based structure of the model has enabled a clear overview, increasing its utility for policy makers. The model is used in an interactive session with policy makers, increasing their understanding of energy system dynamics to create a fruitful debate on how to obtain the renewable energy goals. To create a clear yet engaging overview for this session the model is geographically defined on the map of Brabant, with representative numbers of wind turbines and acres of PV plants. Furthermore, effects could be demonstrated by adjusting scenario settings during parameter runtime. When presenting the model these factors combined contributed to an increased understanding of renewable energy systems by policy makers. The model served in political debate as a sort of common ground, structuring the discussion based on a shared understanding and comparable figures.

As this is a first integration of a balancing renewable energy model with STET concepts using agent-based modelling, there is a lot of room for future research. First, the technological scope is already large (covering energy, heating and transport) but could of course be included. The most important techno-economical areas for future research are: including grid and transportation costs; detailing heat demand and insulation requirements; vehicle to grid smart charging; and increased sector coupling such as combined heat and power. Also concepts from STET models such as actor agency and transition paths are and important topic for future research.

1. Introduction

Many countries, provinces and municipalities are urged to address issues of climate change. After the Paris Climate Agreement nations have set targets to reduce their greenhouse gas (GHG) emissions. The energy and mobility sector are currently based on burning fossil fuels, making them two of the biggest sources of CO_2 emissions. Therefore, specific goals aimed at renewable energy and mobility are set. However, the requirements and effects of this goal are usually unclear in terms of: land-use, costs, social factors and technological progress. The energy transition is accompanied by numerous social, economic and technical trade-offs, all interacting in a complex web. With the introduction of decentralized energy generation technologies, local or domain specific renewable energy (RE) characteristics have increasingly entered policy making. The spatial requirements of renewables are completely different from fossil fuels. Think of NIMBY (Not In My Back Yard) arguments in the case of wind turbines or LULU (Locally Unwanted Land Use) debate about farmland versus utility scale photovoltaics (PV) plants (Schively, 2007). Energy transportation is also affected by this decentralization. Scales vary from local micro-grids to offshore wind turbines which directly convert electricity to hydrogen to reduce transportation costs (Wijk & Hellinga, 2018). The trade-offs between these solutions are often unclear, while they have tremendous effects upon shaping a renewable energy system. In short, the transition towards a 100% renewable energy system (RES) is highly complex and the result is still largely unknown.

Policy makers have set ambitious targets but do not know how to achieve those targets. They are faced with a broad range of requirements; from general costs and benefits to specific local circumstances and social inclusion. These solutions each have their own characteristics and effects. From small scale local initiatives to global technological development, even varying between or combining different energy types. Within all these developments policy makers lack a system overview and tool for exploration. The lack of this knowledge the more important because of the key role policy makers have in achieving an affordable, reliable and socially inclusive energy transition. As the international energy agency (IEA) states in their last '*World Energy Outlook*' (WEO): "Affordability, reliability and sustainability are closely interlinked: each of them, and the trade-offs between them, require a comprehensive approach to energy policy." (IEA, 2018). To implement this comprehensive approach, the WEO states "robust data and well-grounded projections about the future are essential foundations for today's policy choices" (IEA, 2018). In other words, comprehensive, scientific models based on well-researched data including learning curves and price predictions are necessary to develop an efficient, affordable and reliable renewable energy system.

The province of Noord-Brabant initiated this research based on a similar sentiment. They have been working on renewable energy policies within the province, but are faced with a wide range of domains, projects and criteria, without having an adequate and comprehensive system overview. The new provincial climate goals of 50% renewable energy in 2030 and 100% in 2050 (Provincie Noord-Brabant, 2016b) increased the urge of such an overview, and are the direct motive of this thesis. A first investigation resulting in the report '*Brabant op 100% wind, water en zon*' (Hoekstra, 2018) gave insight in technological trends and special requirements for a 100% wind, water and solar (WWS) based renewable energy system in the province. The next phase is described here. It is focused on structuring these technological trends and spatial requirements in an interactively adjustable, time and spatially defined model. The model is used further investigate and explain the effects of renewable energy technologies.

The required overview is not only a political desire, it is also the connects to a fierce scientific debate. Numerous researchers are investigating and modelling 100% RESs. The necessity of models in the political and societal renewable energy debate is widely underlined. However, it did result in a scientific dispute focusing on specific technological assumptions or system structure choices. This is valuable as the models are critically reviewed by energy system researchers and domain experts. However, it does not help policy makers comprehend an overview of a radically different energy system. Furthermore, renewable energy models (REM) usually exclude social, political and institutional factors affecting a future renewable energy system (Diesendorf & Elliston, 2018; Lund, 2014). A more valuable direction is to identify all technological, economic, social and political factors and demonstrate the effect critical choices and assumptions.

This political and scientific lacuna leads to a set of requirements to be investigated. The research focusses on the province of Noord-Brabant specifically, but also has broader implications for the RES debate. The first requirement to the RES is that it ensures energy security at all times at all places. To achieve this with intermittent renewable energy sources, supply, demand, conversion and storage need to be aligned and temporally balanced. Second, the objective of climate goals is to reduce CO_2, so on top of investigating levels of renewable energy generation, CO_2 emissions per energy source should be included. Third, insights on the feasibility and costs of such a system on provincial scale need to be provided. Fourth the system should take important societal and spatial requirements into account to analyze the validity of the investigated scenarios. These main requirements have led to the following research question:

What are the economic, spatial, societal and CO_2 emission effects of choices in renewable energy, storage and conversion technologies towards reaching the climate goals of the Province of Noord-Brabant?

A digital representation, or 'digital twin' (Grieves & Vickers, 2017), of the province's energy system is made to answer this question. The energy transition can be described as a complex system. Numerous social, economic, geographical and technological factors influence the system, resulting in dynamic, nonlinear, interlinked and emergent effects at multiple scales. Creating a digital representation of sustainable energy systems is highly relevant in research to large-scale integration of sustainable energy technologies in modern societies. The geographic, climatological, social and economic characteristics of a country, province or region result in specific mixes of sustainable energy technologies to achieve potential 100% renewable energy systems. As it is very costly and time consuming to test all possible mixes of technologies in reality, modelling is the best way to investigate the viability of different system solutions. Models can help policy makers in two ways; by exploring the system effects of renewable possibilities within a given set of requirements and by creating a clear, interactive, spatially and temporally defined overview to increase system understanding and structure political, societal and scientific debate.

The first sub-goal is to be able to integrate the complex, multi-level and multi-dimensional characteristics in a model. Agent-based modelling (ABM) is argued to be the most suitable method to fulfill these requirements. This is a novel method to the field of renewable energy models. Therefore, the use of ABM in these models is assessed, demonstrated and discussed.

The introduction of ABM to renewable energy models results in the first sub-question: *How can agent-based modelling be used in renewable energy modelling?*

The second sub-goal is using this model in policy making. The use of models to increase societal and political understanding in the renewable energy debate is often underestimated (Holtz et al., 2015). The province's policy makers realized an integral model was required to obtain a clear and viable system overview. They enabled a collaborative research including policy makers, landscape architects and technology experts. This diverse set of inputs was the foundation of the renewable energy models described in this thesis. Furthermore, the model is used in policy making and an interactive brainstorm session in the province’s State Council. Therefore, the results are not just aimed at a new RES design, but also at providing insight to the politicians who are trying to shape the energy transition hands-on. This results in another requirement; a collaboratively made comprehensive model, while maintaining a clear yet engaging system overview.

The need for models in energy policy translates in the second sub-question: *How can renewable energy models be used in a comprehensive yet engaging way in renewable energy policy making?*

The priority of integration of requirements is based on these questions. First and foremost, a feasible and viable REM is made, capable of investigating the effects of system choices. Second, this model is improved for demonstrative purposes by creating an interactive, visual representation. Third, the connection between transition theories and ABM features is integrated in the model.

To answer the research questions the following research is composed. In the second chapter a review of existing energy and transition models is performed. Many renewable energy models focus on techno-economic system analysis, resulting in a lack of social, institutional and political factors. To overcome this lacuna transition theories are investigated. From the combination of policy makers, renewable energy models and transition theories a broad range of model requirements is formulated. In chapter three agent-based modelling is introduced and described as the most suited method to integrate all these model requirements. From this theoretical background on energy and transition models and the ABM method a new model is made specifically for the province. Chapter 4 thoroughly explains the model structure. After which chapter 5 is dedicated to the data and assumptions. In the sixth chapter the model’s verification and validation is discussed. The last chapters focus on the scenario analysis. By means of scenarios the effects of choices in system design and socio-technical trade-offs are analyzed. Chapter 7 is a description of the scenario analysis. The results of this analysis are interpreted in chapter 8. The final conclusions answering the research questions are drawn up in chapter 9. Their implications are interpreted in the discussion (chapter 10). Finally, limitations and recommendations for future research are given in chapter 11.

2. Modelling renewable energy and transitions

This chapter establishes a set of requirements for a comprehensive and for policy makers useful renewable energy transition model. The set of requirements is the basis upon which the modelling method and model structure are chosen. To obtain this set of requirements different types of renewable energy models are reviewed. First, conventional renewable energy models are reviewed. Typically, these are techno-economic cost optimization models balancing renewable energy sources to demand. An often-stated lacuna in these models is the lack of spatial, political, social and institutional factors, while these are critically important to policy makers. Therefore, the second section of this chapter covers transition theories and socio-economical transition models. Lastly, the two methods are combined in the field of socio-technical energy transition (STET) models. These models combine a detailed techno-economical system with in-depth socio-economical concepts. This makes STET models the comprehensive overview energy policy makers can rely on. The requirements resulting from the renewable energy models, transition theories and STET models are summarized in table 3.

2.1. Renewable energy models

Like politicians, scientists have been debating renewable energy systems for years. Many models illustrate the effects of different setups or assumptions on 100% renewable or low-carbon energy (or just electricity) systems. The field is diverse, as the model structure, assumptions and analysis depend on different requirements originating from different research questions and goals. Differences can be found in scale, objective, integrated domains and technologies and general model structure or algorithm. This first part focusses on models with a similar objective; investigating regional or national renewable energy systems on a techno-economic basis, including supply-demand balancing. This requires an overview scale (national or regional). In terms of simulation time-steps, Brown et al. (2018) argue the minimum required step correlates to the geographic scale. As small wind or solar varieties (e.g. a local cloud) average out over large distances. Making one-hour timesteps sufficient for long term, large-scale energy system planning. Furthermore, there is a minimum simulation runtime of a year to be able to balance seasonal storage demands.

Connolly, Lund, Mathiesen, and Leahy (2010) reviewed 37 computer tools for modelling. A wide variety of tools is included, varying on scales in domains or the entire energy system, geographic area, timeframe and time-step or objective. Of the 37 just seven are able to simulate 100% RES. Of these seven, four use time-steps of one hour or less while the other three use annual time-steps. As part of the objective of the model is to simulate storage requirements, at least hourly time-steps are needed. Making just four out of 37 comparable to the objective of Noord-Brabant. The models that are able to simulate 100% RES with one-hour timesteps are SimREN, Mesap PlaNet, H_2RES, and EnergyPLAN.

SimREN uses a bottom-up approach, simulating multiple spatial layers of demand and supply all based on actual weather data. It has been used to model 100% renewable scenarios for Japan (Harry Lehmann et al., 2003) and 100% renewable electricity in Catalonia (Peter et al., 2007). MESAP PlaNet is a combination of linear (SD like) flow balancing equations and a cost calculation module. This enabling large-scale overview simulations as used in Greenpeace’s global energy outlook (Teske et al., 2011). H_2RES is a load balancing model based on hourly energy demand and renewable generation. It does not include emission reduction and costs and transport only partially. A 100% RES in Portugal (Krajačić, Duić, & Carvalho, 2011) has been simulated with it, but the main focus is on smaller regions or islands. EnergyPLAN is one of the most appearing models in literature. It is a high-level, techno-economic load management tool deterministically simulating RES with different options in regulation strategies (D. Connolly et al., 2010). The model has been applied in 95 publications of which 15 include high-RES scenarios (Østergaard, 2015). Amongst others 100% RES in Denmark (Lund & Mathiesen, 2009), Ireland (D. Connolly, Lund, Mathiesen, & Leahy, 2011), Finland (Child & Breyer, 2016), and Macedonia (Ćosić, Krajačić, & Duić, 2012) are analyzed.

More recently an overview by Cochran, Mai, and Bazilian (2014) cites a number of the aforementioned studies and adds countries including: Australia (Elliston, Diesendorf, & MacGill, 2012; Elliston, MacGill, & Diesendorf, 2013), New Zealand (Mason, Page, & Williamson, 2010, 2013). Other energy system research includes the world's largest contributors to global warming the U.S.A (Becker et al., 2014) and China (Liu, Lund, Mathiesen, & Zhang, 2011) , North-East Asia (Bogdanov & Breyer, 2016) European networks (Rodriguez, Becker, & Greiner, 2015; Schlachtberger, Brown, Schäfer, Schramm, & Greiner, 2018; Schlachtberger, Brown, Schramm, & Greiner, 2017), global storage (Pleßmann, Erdmann, Hlusiak, & Breyer, 2014) and even generic energy systems (David Connolly & Mathiesen, 2014). Most of these studies vary in system design due to local and environmental factors, or due to research set-up, broadly differentiating between several solutions to cover renewable intermittency issues. Some include non-renewable sources such as 'firm low-carbon electricity sources' like nuclear (Sepulveda, Jenkins, de Sisternes, & Lester, 2018) or fossil fuels with CCS (Koo, Han, & Yoon, 2011; Lund & Mathiesen, 2012).

Studies with 100% renewable energy result in different optimal scenarios based on system design and local circumstances. General differences are:

- Large amounts of biomass combined with hydropower and hydrogen storage (all EnergyPLAN models; a.o. (Lund & Mathiesen, 2009))
- Hydropower, storage and super grids from just wind water and solar (WWS) sources (Jacobson, Delucchi, Cameron, & Mathiesen, 2018)
- Sector coupling across energy carriers (also called smart energy systems) and transmission grid expansions with long-term, large-scale thermal and hydrogen storage (Brown, Schlachtberger, Kies, Schramm, & Greiner, 2018; Lund, Mathiesen, Connolly, & Ostergaard, 2014; Schlachtberger et al., 2017).

From this wide variety of renewable energy models, a number of important requirements can be deducted. With the objective of an overview of the entire provincial energy system, including intermittent sources and spatial limitations the most important requirements are displayed in Table 1. First of all, the model timesteps can be no larger than an hour to adequately cover intermittent energy sources leading to supply-demand imbalance and storage requirements. Second, as renewable sources depend on local weather characteristics and transportation of energy is an important cost driver in renewable energy systems spatially defined energy production and consumption is important. Third, the scale of a provincial overview requires a multi-level, bottom-up model combining al domains, energy carriers and scales. Starting by modelling domain specific consumption patterns and energy source specific production patterns and combining this in a balanced energy system.

Table 1: Requirements derived from renewable energy models

Requirement	**Scale**
Hourly (weather based) balancing of supply and demand	Temporal
Regional and local demand, supply, distribution and conversion balance	Spatial
An integral overview including cross-domain, cross-scale interlinkages	Multi-level system

Although these requirements are important to create a well function energy model, they do not cover the entire range of factors relevant to model users such as policy makers. The following section on the debate around these techno-economic models and the incorporation of transition theories integrates the lacking factors. At the end of this chapter table 1 will be expanded into table 3, including all requirements for a fully comprehensive renewable energy transition model.

2.2. Model debate

The 100% RES studies mentioned in the previous paragraph are subject to a fierce scientific debate. Even though all of these studies underline the feasibility of multiple 100% renewable energy designs there is still a fierce discussion regarding this feasibility. A dispute arose after Clack et al. (2017) published a critical review of Jacobson, Delucchi, Cameron, and Frew (2015) study of 100% WWS in 50 U.S states. The debate is formed by critical reviews of renewable energy systems (Clack et al., 2017; Heard, Brook, Wigley, & Bradshaw, 2017; Procter, 2018; Trainer, 2012) and responses by 100% RES advocates (Brown, Bischof-Niemz, et al., 2018; Delucchi & Jacobson, 2012; Jacobson & Delucchi, 2018; Jacobson, Delucchi, Cameron, & Frew, 2017).

The most important critiques are the feasibility of forecasted assumptions (mostly regarding storage and costs) and the system design (e.g. ‘firm’ resources like nuclear or fossil fuels with CCS versus batteries and long-term storage). These have been rebutted in a comprehensive response to 100% RES criticism by Brown et al. (2018). He is able to address these concerns even within current technological constraints, while the entire energy transition is bound to be accompanied with radical innovations enabling more renewable energy.

There are two sides to this debate. It is beneficial, as a wide range of peer-reviewed feedback is given upon which models can be improved. However, it also discredits some important research towards renewable energy goals. The critics misinterpret the value of 100% RES studies. They often take part in this discussion based on linear transition thinking. However, combining the exponential growth curves of multiple renewable energy technologies does not lead to a linear transition.

The energy transition is a dynamic, messy and complex process towards a completely revised system. In this complex transition one development could accelerate another, decelerate the next and shift an entire paradigm in the following. This means that investigating potential relationships and dynamics is important. It also means that using one model to contradict another is incorrect, as no dynamic stands on its own. In other words, the transition path cannot be separated from the final goal when stating optimal system designs, as it greatly influences this design.

Battery prices give a good example of these dynamics. Over recent years their costs have been reduced rapidly, mainly due to a strong development of the automotive industry (with Tesla’s Gigafactory as frontrunner (Lambert, 2017)). Although this dynamic started from the automotive industry, it is highly beneficial to the PV industry as it reduces storage costs at high levels of PV penetration. In other words, the development of both EV and PV in the energy system cannot be separated from battery development. Similarly, scenarios including high levels of EV and PV penetration should assume different battery characteristics in comparison to scenarios including high levels of biomass and nuclear energy.

They are valuable by showing, investigating and comparing the effects of potential solutions. This helps policy makers to make informed choices on the required direction of the transition path. Currently, modelers often take the position of a politician instead of a researcher, as they state which system is best. Instead, models should show the advantages, disadvantages and requirements of certain system designs. The question should be changed. From stating whether a 100% RES is feasible, to asking what is required to create a viable 100% renewable energy system.

When taking this perspective, the viability of renewable energy models can be analyzed in a much broader sense. Stepping away from the endless discussion on forecasted assumptions to a broad perspective on how to obtain a 100% RES. The viability does not only concern techno-economic factors. As 100% renewable electricity system modelers put it in another response to critics "*We find that the principal barriers to 100%RElec are neither technological nor economic, but instead are primarily political, institutional and cultural*" (Diesendorf & Elliston, 2018). So why do renewable energy modelers not change their perspective away from the techno-economical solutions they have been offering for years and include social, cultural and institutional factors of change?

The answer to this question lies in the complexity of the energy transition. To include these factors requires not only an overview of all the domain in the energy transition, but also the knowledge about socio-economic factors of change. This study provides the first step, analyzing the most important requirements and dynamics in multiple domains and scales. Opening up the potential for an informed debate about different system designs between different stakeholders (policy makers, spatial planners and technology experts).

2.3. Transition theory

Transition theories are added to the scope of analysis based on the critiques regarding renewable energy models. There are at least two levels in which transition theory can contribute to the field of 100% renewable energy systems. One is by focusing on specific domain or technology development. The other is focused on analytical frameworks of system change, such as the multi-level perspective (MLP).

Forecasting specific domain or technological trends is important to create accurate assumptions. Currently, this is often done by observing variables or cost components and their historical trends, usually described as learning curves (J. Mayer, 2015; Trancik et al., 2015). This focus could be expanded by taking theories of innovation into account. Historic trends generally result in logarithmic cost reduction and adoption rates, corresponding to the theoretical S-curve, diffusion and life-cycle models (Levitt, 1965; Mansfield, 1961; Rogers, 2010). However, these models have their limitations. They cannot describe new radical or disruptive system innovation, as they are limited within one (existing) technological trajectory (Dosi, 1982). By identifying the development and diffusion phase of multiple (competing and complementing) technologies within one technological system radical system change can be better understood and forecasted. Mapping this trajectory with proxy factors like patents (Fontana, Nuvolari, & Verspagen, 2009; Lee & Su, 2008; T. Mayer, Kreyenberg, Wind, & Braun, 2012; Verspagen, 2007) or high-scale cost reduction mechanisms such as 'Economies of scale' or 'learning by doing' (Kavlak, McNerney, & Trancik, 2018) is already common. Combining this mapping of technological trajectories to paradigm shifts and adding it to bigger picture system integration can improve the forecasting and assumptions of renewable energy models sharply.

On the system level, socio-economic and institutional factors are identified as major influences of change. The lack of these factors compromises the feasibility of REM results. Social, spatial or institutional factors are accounted by general statements. For example, the required space is just a fraction of a region's size without looking at spatial planning (e.g. (Jacobson, Delucchi, Bauer, et al., 2017)). Such factors are important to provincial policy makers as they are obliged to translate national targets to local projects on for example wind energy (RVO, 2018).

Looking at the aforementioned renewable energy models, the system approach is starting to pave way for the introduction of transition theories. The most comprehensive system approach to achieve a 100% renewable energy system is made by Lund (2014). By dividing the research question in a technical aspect and a social and political aspect he adds societal aspects to the techno-economic focus of general RES models. The basis of this study is the techno-economic model EnergyPLAN which is combined with a theoretic framework of socio-economic transition barriers. For this reason, the 'Choice Awareness' theory is introduced; stating that different organizations see things differently. It is than deducted that incumbent organizations will limit societal choices from their perspective. Being aware of the choices outside the scope of incumbent organizations is the first step towards collective change (Lund, 2014). Lund indicates this is a 'non-comprehensive' approach, focusing only on what he believes to be the key factor in the energy transition; the power of incumbent organizations.

Lund's notion of the power of incumbent organization aligns to the socio-economic transition theory of the multi-level perspective (MLP). In this theory the resistance of incumbent organizations, usually called the 'regime', towards system change is widely acknowledged and seen as one of the biggest obstacles towards radical system change (Geels, 2012, 2014; Geels & Schot, 2007).

MLP is rooted in evolutionary theory, which is closely related to the evolutionary component of technological trajectories (Dosi & Nelson, 1994) and the introduction of the 'regime' (R. Nelson & Winter, 1982). Social constructs were added to this evolutionary perspective (Belt & Rip, 1987) together with the concept of multi-level analysis (Rip & Kemp, 1998) to form a comprehensive analytical framework for transition analysis. This comprehensiveness aligns with both, policy makers' desire to provide a system overview including technical, economical, spatial and social components, and the by renewable energy modelers earlier mentioned political, institutional and cultural barriers (Diesendorf & Elliston, 2018).

The multi-level perspective is not only suited because of its comprehensiveness. It is most valuable in defining the scale and phase of specific developments (e.g. the difference in power between a small, local geothermal-heat feasibility study and the global price of natural gas). This has proven to be a hurdle for politicians, who often focus on niche-developments with limited potential. Also, they are part of the regime itself and have the power to alter institutional or legislative barriers.

In short, MLP describes the social-technical system at three levels; the landscape, regimes and niches (see Figure 1). The socio-technical 'regime' is formed by the dominant technology, actors, institutions and infrastructure and the 'set of rules' they follow. Regimes can be exceptionally strong due to the interlinking forces across the domains (technical, societal, political, institutional and infrastructural) that together form the system. Regimes are influenced from macro and the micro level developments (see Figure 1). Macro-level developments include large-scale structural trends from the societal system in which the regime is embedded and are described by the landscape level. Factors like oil prices, political movement, environmental pressure and normative values are part are part of the landscape. The micro-level is formed by technological niches. These niches form opportunities for new innovations and developments to incubate in a protected space. When innovations mature they stand a better change of competing with incumbent socio-technical regimes (Geels, 2002). Analysis has shown that developments at all three levels need to reinforce each other to break through incumbent regime forces and result in a transition (Verbong & Geels, 2007).

Verbong and Geels have analyzed the Dutch electricity regime (2007). At that time the analysis resulted in a pessimistic attitude as many renewable energy technologies were still in early development phases, incumbent regime forces were strong and landscape pressure still relatively week. The state "We do not expect such a transition to take off in the next 10 years" (Verbong & Geels, 2007). Now, over 10 years later, the analysis is starting to differ. Landscape pressures have been increasing over time (although current political movement in many countries contradicts this). Technological niches have matured, several regime actors are getting involved in the technologies and they are in some cases competing without (financial) protection (Huijben & Verbong, 2013).

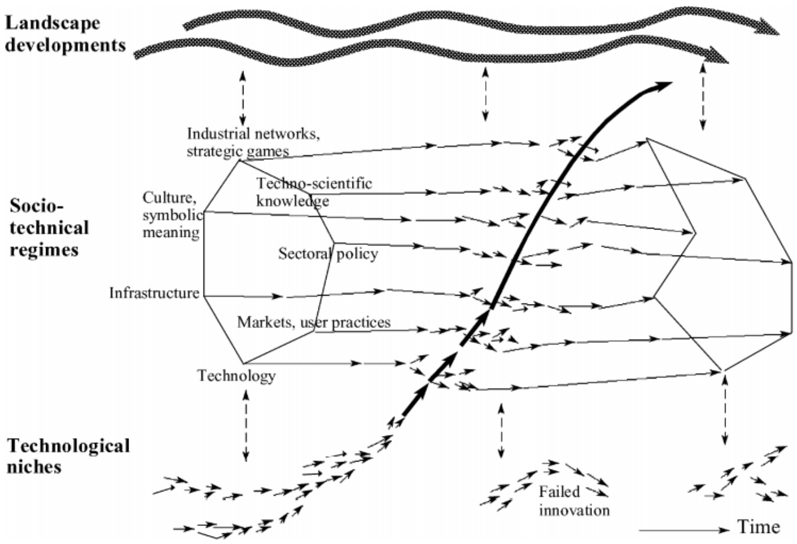


Fig. 5. A dynamic multi-level perspective on TT.

Figure 1: A dynamic multi-level perspective on technology transitions. Reprinted from (Geels, 2002).

Based on the MLP multiple transition pathways have been identified (Geels & Schot, 2007) and applied to the Dutch electricity system (Verbong & Geels, 2010). The *transformation* and r*econfiguration* pathways are deemed most likely (although also the *de-alignment and re-alignment* is feasible). The two most likely pathways are both formed by relatively slow transitions. The *transformation* pathway describes a slow technical transformation from incumbent regime actors adopting niche technologies on economic criteria and political mitigation. This is an important notion as it excludes radical change. Model scenarios including large levels of electrification (in transport especially) require a fast adoption of electric vehicles (EVs), which only aligns with this pathway if incumbent fuel suppliers adopt this technology. Something which is actually happening, albeit gradually (NOS, 2017; Shell, 2017). The *reconfiguration* pathway is formed due to stronger landscape pressures, leading to more radical system change. As the need for renewable energy increases, policy becomes more dominant leading to more international cooperation resulting in a European supergrid (also something of which elements are currently visible (European Commission, 2018)). The supergrid idea is interesting as it is also seen as one of the most cost effective renewable energy systems in modelling multiple renewable energy models (Brown, Schlachtberger, et al., 2018; Jacobson et al., 2015; Rodriguez et al., 2015; Schlachtberger et al., 2018).

The fact that signs of multiple pathways are visible indicates a '*sequence of transition pathways*' (Geels & Schot, 2007). This sequence of pathways starts with an initial *transformation* pathway in which incumbent actors try to maintain their position with increasing landscape pressure. However, if these landscape pressures keep on rising, the initial pathway could transform into any of the other pathways, depending on the state of niches and the power of incumbent actors.

Taking the different kinds of pressures resulting in different pathways into account strengthens the viability of renewable energy models. The importance of analyzing socio-economical actors with the MLP is underlined by the fact that differences amongst countries are already visible energy transition pathways (Geels et al., 2016). Some models incorporate a number of these characteristics (landscape pressures like oil prices are usually included) while for example IEA looks at different policy scenarios (IEA, 2018).

The applicability of the MLP (or any other transition theory identifying transition structures (Rotmans & Loorbach, 2009)) in renewable energy models is multifold. First, it helps to verify if potential techno-economically optimized scenarios are viable from a socio-economical point of view. (E.g. NIMBY arguments make any model relying on large shares of onshore wind power useless for the goal of policy advise). Second, the MLP could give direction to interesting RES scenarios to be modelled, like quantifying the differences between the aforementioned pathways. Third, improve system and technological assumptions of the model by identifying key drivers and incumbent forces affecting socio-technological development.

The above-mentioned applications all show how to use the analytical framework in order to analyze or improve renewable energy model results. However, this can be taken one step further. The final goal is to directly integrate these concepts in energy transition models. This not only improvs the models itself, but also greatly enhancing the usability in policy making and other types of transition management (Holtz et al., 2015).

2.4. Socio-technical energy transition models

The novel field of socio-technical energy transition (STET) models actually makes the combination between transition models and renewable energy models. STET models are focused on three pillars (see table 2). The techno-economic detail accounts for a well modeled techno-economic system like a renewable energy model. The explicit actor heterogeneity and the transition pathway dynamics are based on transition theories. Actors (stakeholders) should be able to 'act' based on certain patterns or environmental inputs. This acting of actors in a techno-economic system leads to the eventual transition pathway. Which could take any form depending on the speed of development and the reaction of actors. The requirements of table 2 are visually represented in figure 2.

Most current STET models are oriented at looking at the interaction between technical systems, actor interaction and policy measures. A good example is the agent-based model of the Dutch electricity system in transition (Kwakkel & Yücel, 2014). By incorporating all these dynamics, they have been able to simulate lock-in effects if the start of the business cycle of investment in energy generation capacity was missed. A rapid reduction in costs of renewable technologies afterwards would have far smaller effects. This is a conclusion which might seem trivial and logic, as why would you invest in new renewable energy capacity if you have enough capacity lasting for the next 20 years. Trivial as it is, it is neglected in all aforementioned renewable energy models.

Table 2: Requirements for Socio-Technical Energy Transition (STET) Models. Adapted from(Li, Trutnevyte, & Strachan, 2015)

Techno-economic detail	A disaggregated portfolio of technology options with different price and performance characteristics
	Bounded systems with operational or resource constraints
Explicit actor heterogeneity	Multiple explicit actors with differentiated selection criteria or behavioral parameters
	Actors that possess agency to shape transitions
Transition pathway dynamics	Assessment of normative goals
	Time horizons sufficient for exploring long-term socio-technical change, path dependencies
	Radical alternatives to incumbent status quo technology or behavior options

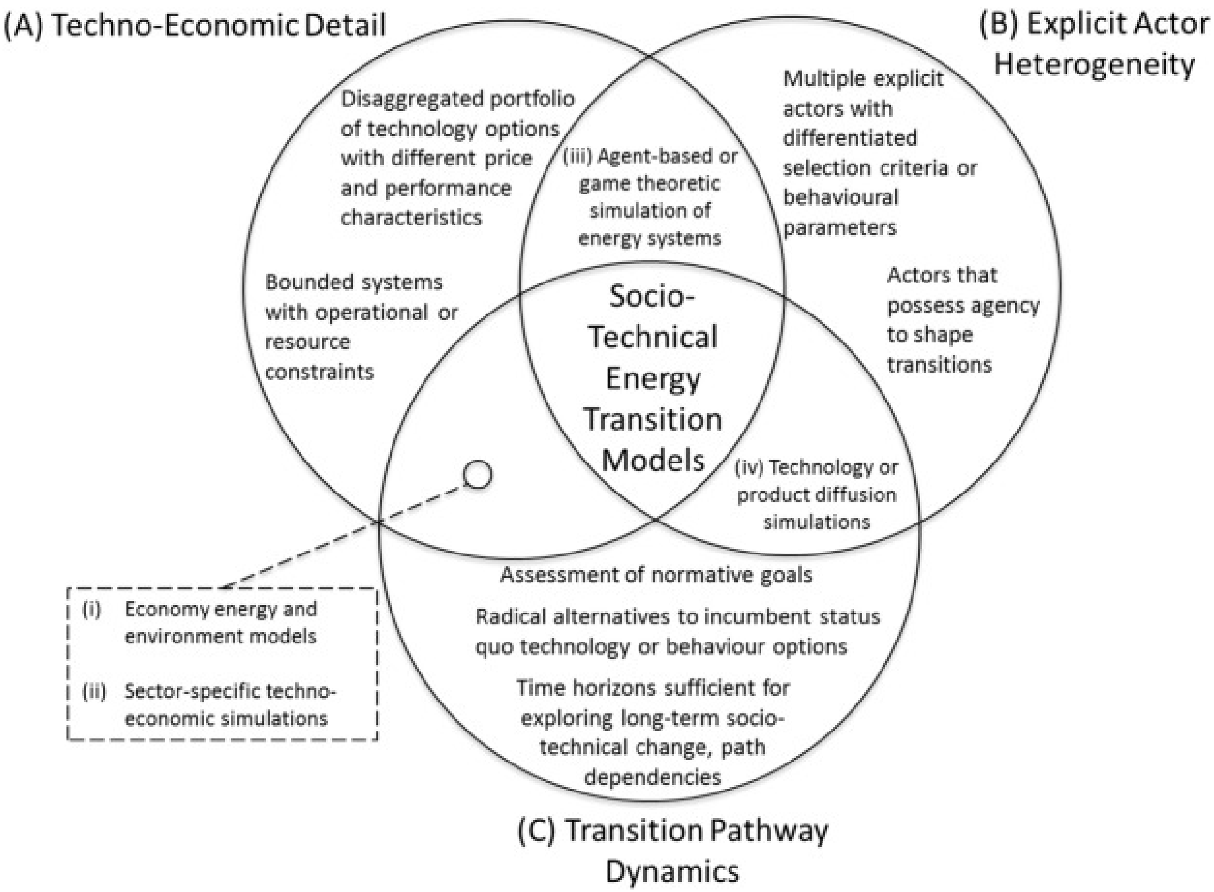


Figure 2 Methodological requirements for socio-technical energy transition (STET) models. Reprinted from (Li et al., 2015)

The downside to integrating these concepts in renewable energy models is the lack of quantification. Quantifying transition concepts is widely acknowledged to be difficult (Holtz et al., 2015; Li et al., 2015). However, taking on the challenge is required in order to provide insightful, comprehensive policy advice on the energy transition. Neglecting concepts which could make or break a certain trajectory is certainly an oversimplification in STET modelling. It is therefore important to all critical factors into account.

STET models can be seen as an integration of renewable energy models into transition models. Increasing the level of techno-economic detail to make full function renewable energy models while still including the transition theory aspects. Bridging the gap from the analytical frameworks used in transition theory to quantitative models, adhering to the requirements of policy makers who state that REMs neglect social and institutional factors while transition theories are difficult to use in quantitative policy making.

As mentioned before, the goal of this literature review of renewable energy models and transition theories is to find the most important requirements for a comprehensive and politically useful renewable energy model. The list of requirements is broad, ranging over multiple domains, temporal and spatial scales and levels of analysis. It starts with creating a sufficiently detailed techno-economic renewable energy model. This means a spatially defined and temporally balanced model. Furthermore, when making future assumptions and forecasts they should be based on transition theories, as these developments are subject to numerous factors. Furthermore, the MLP states that underlying socio-economic forces should be understood to be able to model a viable transition pathway. Lastly, all these influences should be combined in a comprehensive, interlinked yet clear and engaging system overview to use in policy making. Naturally this results in a multi-level model, enabling all the scales and detail while retaining clarity. Table 3 has been made to structure the wide range of requirements mentioned across renewable energy models and transition theories. The table is categorized based on the variety in scales, domains and theoretic background. As STET is a combination of the aforementioned theories, it is not used to explain the theoretic background.

This comprehensive, multi-level system perspective might seem excessive. A model should always be a schematic representation of reality. Complexity is required, not for the sake of complexity but because real transitions are complex. So, to model a valid representation of a transition, complexity is required. If exact results on very specific system parts would be required, more detailed and exact models would be useful. However, as the objective is towards exploring broad future scenarios and their effects, it is important to take all relevant factors in account. Therefore, the requirements from table 3 serve as the basis upon which the model of the energy system in Noord-Brabant is made.

To conclude this chapter; To create an accurate system overview useful to policy makers, it is of critical importance to integrate all relevant aspects of the energy transition into a model. The techno-economic REMs are a good start, focusing on different technological system designs to create a balanced and affordable renewable energy system. However, to increase the viability of these models and increase their usefulness in policy making, they should be appended with transition theories. In the field of STET models this integration is made; however, these models have not yet found their way to the ongoing renewable energy system debate.

This theoretic section on energy and transition models is followed by a chapter on how this wide variety of requirements can be incorporated into a single model using agent-based modelling. After explaining the method in chapter 3, chapter 4 on model structure will focus on how these requirements are implemented in the actual model.

Table 3: Model requirements across scales and domains derived from a theoretic perspective

Requirement	Scale	Domains	Theory
Hourly (weather based) demand and supply balance	Temporal (hourly)	Technological	REM
Forecast of costs and technological learning curves, technological trends, and incumbent resistance	Temporal (annual)	Techno-economical	TT/DoI/ PLC/MLP
Regional and local demand, supply, distribution and conversion balance	Spatial	Techno-economical	REM
Spatial planning - Which technology fits where in the landscape. Social factors (NIMBY) included.	Spatial	Societal	MLP
An integral overview including cross-domain, cross-scale interlinkages	Multi-level system	Techno-economical	REM
Identifying underlying actors and processes of transition, adoption and emergence.	Multi-level system	Societal	MLP
A quantified and visualized narrative towards feasible (socially, economically and technologically) 100% RES solutions	Quantitative and visual	Political	REM/MLP

REM = Renewable Energy Models, TT = Technological trajectories, DoI = Diffusion of Innovation, PLC = Product life-cycle, MLP = Multi-Level Perspective.

3. Agent-based modelling

This chapter explains how the requirements formulated in the last chapter point to agent-based modeling. This choice is explained in this chapter by describing agent-based modeling, how it can be used in energy transition models and how this can be combined with system dynamics and discrete event simulation. The next chapter will define the resulting model structure and the chapter after that will detail the process of data gathering and determining assumptions.

The literature review on renewable energy models depicts a debate in renewable energy modelling focused on technological and economic assumptions. However, the methodological approach is not discussed, and usually not even specified. Methodology sections of the above mentioned 100% REM describe the model structure instead of the theoretic methodology. The models are generally equilibrium based, aimed at techno-economic optimization. Although some RES modelers have indicated the challenges outside of the techno-economic optimum, this was not connected to questioning the methodological approach. By broadening the scope from REM to STET, questioning the theoretical approach becomes almost inevitable. The complexity of integrating all aforementioned requirements (table 3) is virtually impossible to fit into currently used method. Especially combining the interlinkages and feedback loops across multiple scales and domains, while maintaining a clear and presentable overview. Hoekstra, Steinbuch & Verbong (2017) acknowledge this by explicitly stating the potential of agent-based modelling as a method in energy transition models.

ABM is a novel method in the field of renewable energy modelling. The models are based on defined agents and the effects of their actions and interactions. The modelled system is built up from individual agents, agent populations and the environment they interact in (see figure 3 for a schematic overview). Agent actions are determined by a set of rules. All agents of a similar type are part of one agent population. Agents in a population can be defined by a combination of individual and population characteristics. If multiple types of agents and multiple agent populations are used ABM is naturally a multi-level method. The agent-population-environment structure enables the combination of in-depth, domain specific research on the characteristics of a certain agent, including heterogenous agents within a population, with system overview results. Furthermore, it is spatially and temporally defined, as agents (and agent behavior) can be modelled time and space dependent. This multi-level design with continuous time and space enables clear visualization while maintaining a high level of detail. Lastly, the interdependencies between all agents, agent populations, agent types and the environment are easily integrated, approaching the complexity of reality in simulations.

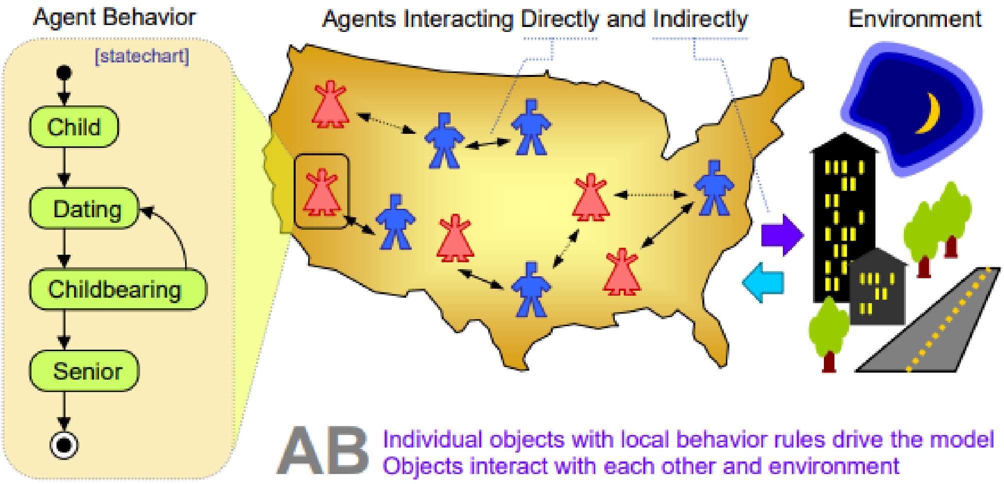


Figure 3: Generic architecture ABM. Adapted from (Borschev & Filippov, 2004)

Agent-based modelling originates from cellular automata. An automaton is a self-operating machine automatically following a set of instructions or predetermined rules. Modelling automata according to a set of rules defining their behavior in time and space has resulted in complex dynamics, including the phenomena of reproduction. The earliest example of this John Conway's 'Game of Life' (Gardner, 1970). This game of life was a game designed on a grid of cells evolving over time. With every time step the state of the cell would alter according to a few simple rules based on the state of its neighboring cells. Cells could have two states, either dead or alive, and could at every time step either live on, die or reproduce (dead becomes alive again). Based on the initial rules and grid setting, over numerous model steps highly complex patterns occur. These patterns replicate, reproduce and even interact creating a complex system of emergence, interaction and decay (Macal & North, 2005). These dynamics fit remarkably well with ecology. Large scale population dynamics occur when individual organisms interact and replicate or reproduce with other individuals of this population, or they are shaped by outside factors.

The complex, emergent, bottom-up patterns do not only align to biology, but also fields such as social sciences (Epstein & Axtell, 1996), economics (Tesfatsion, 2006), climate mitigation policies (Lempert, Scheffran, & Sprinz, 2009) and diffusion of innovation (Alkemade & Castaldi, 2005; Kiesling, Günther, Stummer, & Wakolbinger, 2012). All these form a perfect basis for agent-based socio-technical energy transition models (Li et al., 2015).

The rapid spread of ABM in recent years can be explained due to a unique mix of characteristics. Many socio-economic sciences have been indicted of oversimplification of complex patterns. ABM enables the modeler a free and dynamic framework reducing a lot of constraints of other modelling methods. Combining the best of both DES (event based) and SD (time based) characteristics, while additionally giving agency to the actors involved.

Agent-based modelling enables a wide range of possibilities. The following list depicts the benefits of ABM over other modelling methods. These benefits align closely to the aforementioned requirements (table 3). Each number of the list is specified in the section afterwards.

1. Domain specific integration (renewable energy solutions and their technological, economical, societal, political, institutional, spatial and emission characteristics)
2. Multi-level connections
3. Continuous and discontinuous developments (time based and event based)
4. Continuous space
5. Agent heterogeneity
6. Actor agency

1. Domain specific integration (renewable energy solutions and their technological, economical, societal, political, institutional, spatial and emission characteristics) – The interlinked mix of energy consumption, storage and demand on multiple energy types or carriers is complex and the effects differ across multiple criteria. Research and expertise are commonly domain or criteria focused, making comprehensive system analysis difficult. The agent-based structure enables modular, domain specific integration. This suits renewable energy systems as each technology can be modelled bottom-up, focusing on its specific characteristics. Only after a domain or sector is modelled in detail, one has to think of how it is connected to the system as a whole, or any other domains or sectors specifically.

2. Multi-level connections – The notion of levels or scales is highly important in renewable energy and transition modelling. Scale exists from multiple points of analysis:

- Techno-economic (e.g. individual wind turbine – wind farm – electricity system)
- Transition (niche – regime – landscape)
- Spatial (LV – MV – HV grids, small-scale local energy storage vs large-scale storage)
- Temporal (Hourly grid balancing to annual technological development)
- Societal (individual drivers of technology adoption to (inter)national societal developments)

Combining these very different levels of scale has been a challenge across renewable energy models. However, due to the spatial and temporal continuity and the event and time-based possibilities, it is possible to integrate all scales. For example, earlier models often differentiate between investigating long term effects of renewable energy policy or calculating storage requirements in a balanced system, focusing on either one or the other. Using ABM, a combination can be made of the continuous balancing calculations and the discrete policy measures. This improves the investigation to the system effects of policy measures. Note that within this comprehensibility, focus should remain on the most important factors required for the research objective. ABM just enables a far wider range of possible factors.

3. Continuous and discontinuous developments (time based and event based) – The temporal characteristics are also relevant on two scales, hourly load and demand management and annual socio-technical development. Hourly load and demand management perfectly combine the characteristics of DES and SD. A lot of load balancing can be seen as system dynamics; stocks, rates and flows. However, part of demand management is on the micro-scale event based. When does a person decide to take their car for example. Such events are important when looking at the effects of demand side management on storage. In the case of transition management examples of the difference between continuous and discontinuous scale are general technological development trends versus specific policy measures.

4. Continuous space –Space is increasingly relevant as transportation of energy is a key factor in renewable energy generation. Transition from a centralized grid with both electricity and natural gas connections to smart combinations of energy carriers, (de)centralized sources and storage. ABM enables geographically mapped agents, which is not only suitable for visualization but also for transportation and agent heterogeneity. For example, a wind turbine capacity factor can be depended on local wind conditions. Furthermore, the geographical mapping is important in the using the model to aid political debate. Geographically visualized models address spatial and social effects. Spatial planning is amongst the main concerns of local policy makers. Dutch energy policy will be based on regional energy strategies, which every municipality has to determine. These strategies are a complex mix of techno-economic requirements and socio-spatial optimization. An often-heard concern by policy makers is for example reducing nuisance of infrastructural development required to enable the energy transition. In other words, if a street has to be refurbished to adapt to the grid, be sure to take all (near) future developments into account such that the grid can sustain these developments.

5. Agent heterogeneity – agents within a population are heterogenous. The relevance of this is dependent on the objective. Looking at a provincial scale for example, aggregates are usually enough. However, when investigating smart charging, heterogeneity in EV use must exist. In all cases of 'smart' demand-supply management, heterogeneity is a necessity. It becomes especially important when zooming in to local-scale smart-grid management. And as these characteristics can be critical to the techno-economic optimization, they are relevant for an overview analysis as well. In this model the level of detail of heterogenous agents is still limited as demand side management is only applied at EV use. In more comprehensive models this could be further expanded.

6. Actor agency – Smart agents can act based on a set of rules, objectives and patterns. Social, political, economic or institutional stakeholders can be added to the model. In traditional economic models, stakeholders act rationally. Transition models should include effects of bounded rationality, technological diffusion, societal constraints, etc.

To sum up these points; The multi-level structure of ABM aligns closely to both the bottom-up modelling of renewable energy sources in REMs and the socio-economic concepts of the multi-level perspective. Making it the best fit for socio-technical energy transition models.

3.1. Agent-based energy transition models

Although ABM has characteristics suitable to renewable energy system modelling, it is still uncommon in the field. In the mentioned energy model software tool overview ABM is described as a novel and complex modelling technique, and used in just one out of 37 tools (D. Connolly et al., 2010). The tool using ABM is called EMCAS and described as a techno-economic model of the electricity sector. EMCAS is developed by the U.S. Department of Energy Office backed Argonne National Laboratory. The developers remark similar disadvantages regarding traditional models as Hoekstra et al. (2017). They note "the implicit assumption of a centralized decision-making process built into many of the global optimization and equilibrium-based power systems analysis tools developed over the last two decades limits their ability to adequately analyze the forces prevalent in today's emerging markets" (Argonne National Laboratory, n.d.). In other words, bottom-up analysis is required to truly grasp the dynamics and course of action of all involved stakeholders and the system effects. EMCAS has a different focus than the model described later on in this thesis as it simulates energy markets and the stakeholders involved but does not integrate 100% RES. In terms of method EMCAS is further developed as agent-based, where this model is multimethod (see section 3.2.). EMCAS identifies stakeholders within the electricity market as agents and let them interact based on their own set of objectives, decision-making rules and behavioral patterns (Argonne National Laboratory, n.d.).

In recent years the number of ABM renewable energy models has been expanded. Modelling multiple aspects of renewable energy systems from local energy distribution (Fichera, Pluchino, & Volpe, 2017), to a model on distributed energy management (Lagorse, Paire, & Miraoui, 2010) and a conceptual model of integration within the current electricity market (Carlos Sousa, Kokkinogenis, Rossetti, & Saraiva, 2013). Also in specific technological domains within RESs, ABM is being used, mainly in simulating smart or microgrids (Basir Khan, Jidin, & Pasupuleti, 2016; Coelho, Weiss Cohen, Coelho, Liu, & Guimarães, 2017; Khan & Wang, 2017; Moghaddam et al., 2011; Oyarzabal et al., 2005; Pipattanasomporn, Feroze, & Rahman, 2009). In recent years some studies have included concepts from the field of transition modelling. Kraan, Kramer, and Nikolic (2018) include bounded rationality leading to heterogenous investor behavior in their analysis to investments in renewables. Deissenroth, Klein, Nienhaus, and Reeg (2017) directly link to the multi-level perspective in an analysis on the effects of actors and policy interventions. See figure 4 for a representation of their AMIRS model. They state ABM has the ability to examine "the impact of policy instruments considering the complex interplay between the regulatory framework, the actors, and the technoeconomic regime" (Deissenroth et al., 2017). Their conclusions hold the possible emergence of niches within the electricity market based on heterogeneous actors and the need to take incumbent, intermediate actors into account when modelling actor and policy interactions. The results of this model are comparable to the claims made by Hoekstra et al. (2017). The most obvious increase in agent-based models is in STET models. 7 out of the 14 models mentioned by (Li et al., 2015) are agent-based, showing that the requirements of STET models and the capabilities of ABM align closely. It enables a combination of discrete events and system dynamics, which simplifies integrating event-based policy measures in continuously balanced energy systems. Also, it enables connections on all levels and domains, from individual agents to landscape effects specified to defined locations and times. Lastly, smart agents can be modelled as heterogenous actors possessing agency. In other words, individual agents or agent populations can react differently based on a wide range effects (e.g. environmental, political or societal pressures, institutional obstacles or the emergence of niche technologies. All these trends should be included in an optimal energy transition model for the explorative future energy system studies and the quantification of transition paths.

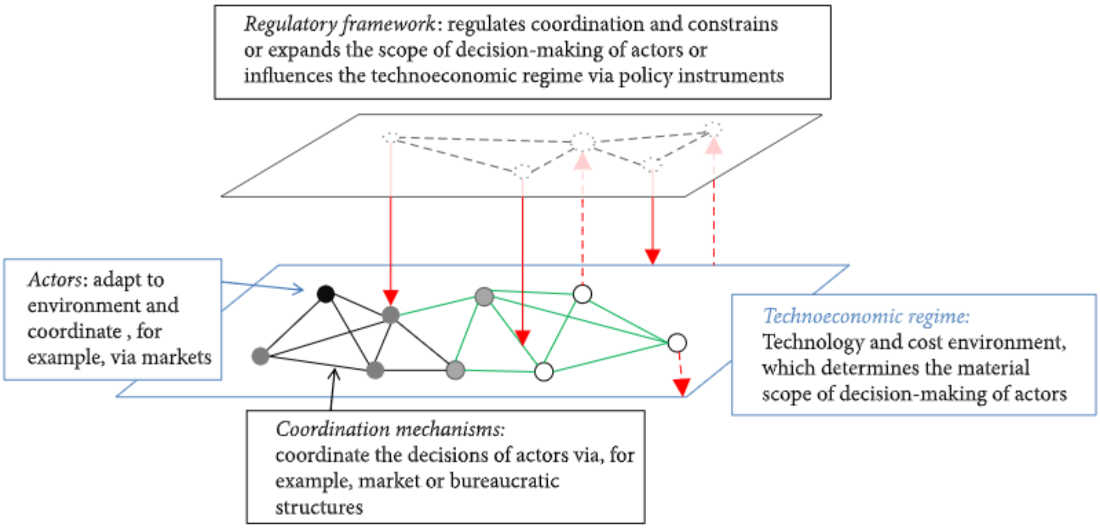


Figure 4: A sketch of the system that is represented by the AMIRIS model. Reprinted from (Deissenroth et al., 2017)

3.2. Multi-method modelling

STET models like (Deissenroth et al., 2017; Kraan et al., 2018; Kwakkel & Yücel, 2014) show that ABM is a suitable method. However, their goal and scope are very different from the objective of the Noord-Brabant model explained later. These models focus on the socio-technical system aimed at market integration and energy policy instruments, not at balancing 100% renewable energy supply and demand. As this scope is so comprehensive, modelling every aspect in detail is a challenge. Different modelling methods can provide a shortcut in creating the right level of detail for each domain of the energy system. Therefore, discrete-event simulations (DES) and system dynamics (SD) are brought into the picture of a multi-method model.

Combing discrete-event and system dynamics in an agent-based model has a number of advantages. In comparison to the other methods ABM has much more degrees of freedom. However, this also makes agent-based modelling a time-consuming process. On top of this, when modelling an energy system, not all specific technological domains require things like bottom-up, actor heterogeneity and agency. Many system components will be detailed enough to answer the research question by taking some shortcuts to top-down system dynamics or discrete event simulation. In other words: "*Create Hybrid Models When Needed*" (Hoekstra et al., 2017). In short, agents modelled according to DES or SD principles can exist within a general ABM. Depending on the scope and objective of the model certain domains have been interpreted according to either one of these methods. In this ABM can be seen as the bridge between the micro/meso-level scale of DES and the macro-scale of SD (see figure 5.) The final model includes both, the macro-level flows and feedback loops typical for system dynamics and the micro-level, object oriented, stochastically or statistically determined discrete event simulation. However, unlike DES the model runs in continuous time and interlinks the SD and DES components. Further specifications on the method of specific parts of the model are given in the 'Model Structure' section.

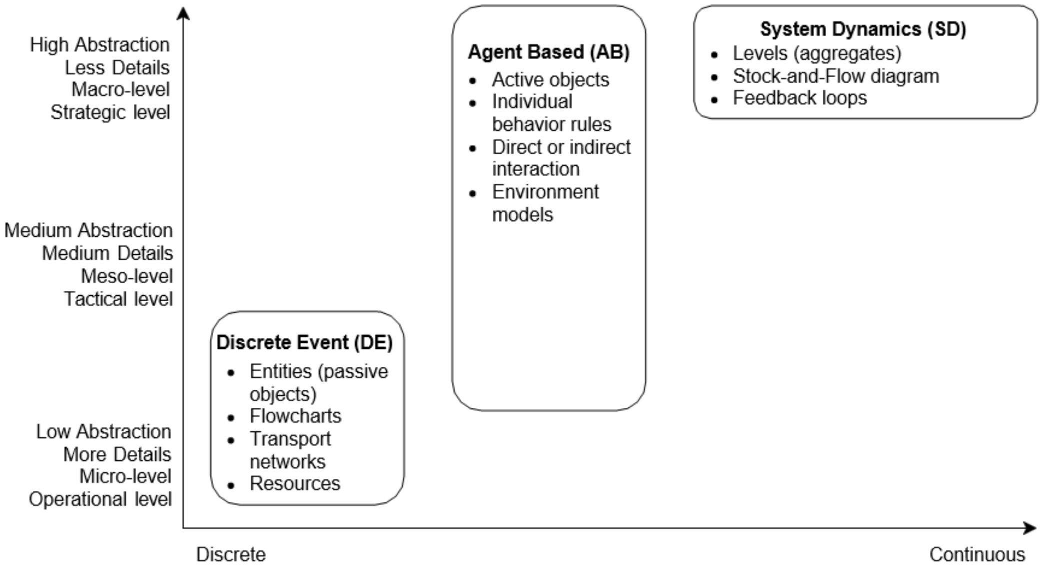


Figure 5: Simulation modelling methods. Adapted from (Borschev & Filippov, 2004)

3.3. Verification and validation of agent-based models

Verification and validation are a challenge for ABM. In this section the theoretic background of verifying and validation complex renewable energy models in general, and agent-based models in specific is covered. In Chapter 6 the model will be validated using the concepts described in this section.

In complex, interdependent models, uncertainty rises exponentially with the number of variables. Even general renewable energy models are described as difficult to validate (Lund, 2014), let alone models with the added complexity of ABM. A sensitivity analysis on a wide range of important parameters is required to obtain acceptable confidence intervals for exact quantitative results (Deissenroth et al., 2017). Even then, a quantitative analysis of ABMs is subject to large levels of uncertainty. Most important is keeping the purpose of the model in mind (Lund, 2014). When modelling a radically different future energy system, of course results won't be exact predictions. However, if the objective is identifying effects and trade-offs, this is not a problem. Complex (agent-based) models are highly suited to identify and compare dynamics, trends and system designs, but should not focus on exact results. In the words of the famous economist Keynes "It is better to be roughly right than precisely wrong."

Solutions to verify and validate ABMs to the best possible extent are proposed in the ODD (Overview, Design concepts, and Details) protocol which focusses on standardization of explicit model descriptions (Grimm et al., 2010). These concepts have been considered as much as possible by explicitly describing overview concepts such as: Purpose entities, scales and processes; design concepts such as agent interactions, collectives and stochastics; and Details such as initial settings, input data and sub-models. For a complete overview of ODD elements see Appendix A.

The most frequently used method of verification of stochastically based ABMs is by replication: Are similar results replicated over simulations (Ormerod & Rosewell, 2009)? However, in this model the level of stochastically based agents is limited. Making verification more a matter of checking if results adhere to the expected outcomes. This is possible by taking system components apart and analyzing their results.

Validation is a more delicate undertaking as it largely depends on the research question and objective. Having a clear understanding of what to explain and for what purpose is the most crucial factor in validation (Grimm et al., 2010; Ormerod & Rosewell, 2009; Windrum, Fagiolo, & Moneta, 2007). Three major theoretic approaches to empirical validation of ABM have been proposed: Indirect Calibration; Werker-Brenner; and the history-friendly approach (Windrum et al., 2007). All are aimed at calibrating and validating the model with empirical data. The Indirect Calibration and Werker-Brenner approach are based on aggregating bottom-up agent-based effects and comparing them macro-scale empirical data. The difference lies in whether this macro data is first used to calibrate and then to validate (Werker-Brenner) or first to validate and then indirectly calibrate afterwards (indirect calibration). In this case a simplified form of indirect calibration has been used as it is the most straightforward validation procedure, which is well suited to determine whether the model results are realistic. It is a four-step process (Windrum et al., 2007):

1. Identification of macro-effects to be reproduced by micro agent behavior
2. Build the model according to micro-scale underlying principles
3. Empirical macro-scale evidence is compared to aggregate micro-scale simulation results
4. Further research to the causes of any differences in the comparison in step 3 should be examined to either update the model or explain invalid behavior

Note that of course complete empirical validation is not possible, as the model is able to simulate scenarios of which no empirical evidence exists (e.g. a future 100% RES in Brabant). Therefore, this method has been applied to scenarios showcasing current behavior and trends. For example, renewable energy generation at current levels should result in currently measured CO_2 emissions and individual driving patterns should add up to currently aggregated annually driven kilometers.

The history-friendly approach differs from the other two in the sense that it does not compare aggregated micro-scale simulation to macro-scale empirical evidence. Instead, it comperes time scales, looking at historical evidence and comparing this to simulation results. An example of this would be modelling technological development based on multiple underlying factors and comparing those to historic development patterns. Evolutionary theories of innovation are a good example of this way of thinking, and this verification method is similar to the methods used by the PV and Fuel cell studies mentioned in the theoretic section (Kavlak et al., 2018; T. Mayer et al., 2012; Verspagen, 2007). Although relevant to making agent-based models of technological trajectories, it has not yet been included in this model as technological development is currently assumed instead of modelled.

To validate a number of important variables a simplified sensitivity analysis has been performed in the form of a scenario. Research shows that the costs of long-term storage solutions are is still uncertain, as the required technologies are relatively immature at the required scale. Therefore, a range of storage assumptions is used to test the effects. This will be further discussed in the storage assumptions scenario.

Although these methods are derived from ABM literature, there are similarities to the validation of other renewable energy models. As all REMs tend to be relatively broad and complex, verification and validation is always a challenge. Similar to the ODD concept, energy models tend to have a detailed design and assumption description. Examples are: EnergyPLAN (Lund, 2014) and the 100% WWS Roadmap (Jacobson, Delucchi, Bauer, et al., 2017). Furthermore, the EnergyPLAN model uses reference scenarios to validate model results to official statistics (Lund, 2014). These reference scenarios are similar to Indirect Calibration, as both compare model output to measured statistics.

4. Model structure

The origin, concepts and connection to energy transition models of agent-based modeling are explained in the previous chapter. This chapter will continue by describing the model made of Noord-Brabant’s provincial energy system. System design choices are justified based on the research questions and requirements.

Starting with a description of the agent environment by using a schematic overview of energy flows in the model. Based on these energy flows the distinction and interaction between energy types and carriers is explained. Then the agents and modules that embody energy demand and generation are specified. Based on the supply-demand differences the storage types and balancing algorithm are introduced and smart-charging is described to show the potential of supply-demand management. From this setup outputs are calculated like CO_2 emissions, annual system costs and system costs per kWh. Next to the technologies used in the model design, it is also important to specify implicit assumptions about technologies excluded. Lastly, the visualization and integration of the model in the modelling software is explained. The assumptions corresponding to sections of the model are highly important. Therefore, the entire next chapter is devoted to them.

4.1. Requirement priorities

The requirements indicated from the literature review to energy and transition models serve as the basis upon which the model is built. Completely fulfilling all these requirements results in an optimal combination of techno-economical and socio-economical energy models. However, as this is a first combination ABM and 100% RES model, requirements have been prioritized. This ranking is derived from the main objective of the model: Analyzing system effects of renewable energy technologies in an agent-based model with the ability to illustrate a quantified narrative for policy makers. To analyze the system effects a balanced renewable energy model is required with viable assumptions. The results should be assessed on technological, economic, social and political criteria and presented in a clear overview to policy makers. Therefore, the first focus lies a creating a balanced renewable energy model within the socio-economic constraints given by the province and spatial planners.

The sub-goals of showing the potential of ABM with the integration of socio-economic aspects towards a comprehensive STET model is of secondary importance. Integrating concepts derived from transition models in renewable energy models is part of the justification of using ABM as a method. However, not all STET requirements are fully integrated in the model (e.g. agents are relatively simple, with little reaction to the environment). The model should therefore be seen as a first integration of ABM in renewable energy models, enabling future developments towards a comprehensive combination of renewable energy and transition models.

4.2. Agent types and environment

Every ABM has an environment in which agents interact and where aggregates and results are calculated. In the software used this environment is called the *main.*

Nine agent types live in the environment. Four relating to energy consumption: *Agriculture; Built Environment; EVs;* and *Industry*. Three describe energy generation: *PV; Renewable Heat;* and *Wind Turbines*. The remaining two are storage methods: *Battery;* and *H2 Storage Tank*. These agents all have their own characteristics that are contributing to the entire energy system. They will be further specified in the rest of this chapter.

Not all specific generation types have been formally specified in agents. Simple agents without a location and a population of just one are directly programmed in the main, and are called modules. Theoretically speaking, there is no difference between a simple, individual agent without a specified location and a module. The simple reason for not making them agents is that the Personal Learning Edition of the software package limits the number of agents. All agents and modules are structured in table 4

Table 4: Model structure of agents and modules

Type	Agents	Modules
Energy Consumption	Agriculture	Other transport
	Built environment	
	EVs	
	Industry	
Energy Generation	PV	Offshore wind
	Renewable heat	Gas turbines
	Onshore wind turbines	Gas boilers
		Heat pumps
Energy Storage	Battery	
	H2 Storage Tank	

For the scenario analysis and presentation purpose of the model a number of parameters can be adjusted before or during model runtime. These include the amount of heat and electricity generation sources, the number of EVs, and whether smart charging and storage options are selected or not. To be able to run all scenarios freely the annual energy demand and supply are not automatically balanced. These should be manually balanced by selecting the right amount of energy generation sources that match the specific demand. When the annual supply and demand are matched, the balancing algorithm ensures a stable energy system at all times. The algorithm will be further explained in the next section.

The requirement of annually balancing supply and demand does result in a minimal simulation time of a year. Within this year the model has the ability to cover the full range of annual imbalance by seasonal storage. At the end of each simulated year, annual consumption, generation, storage, costs and emissions can be calculated.

The consumption, generation and storage agents and modules have been combined in a schematic representation (figure 6) of the model. Note, for the sake of simplicity this diagram does not adhere to the multi-level approach. It is structured to show the relationships within the energy system, not to show which of these are modelled as agents, populations or modules.

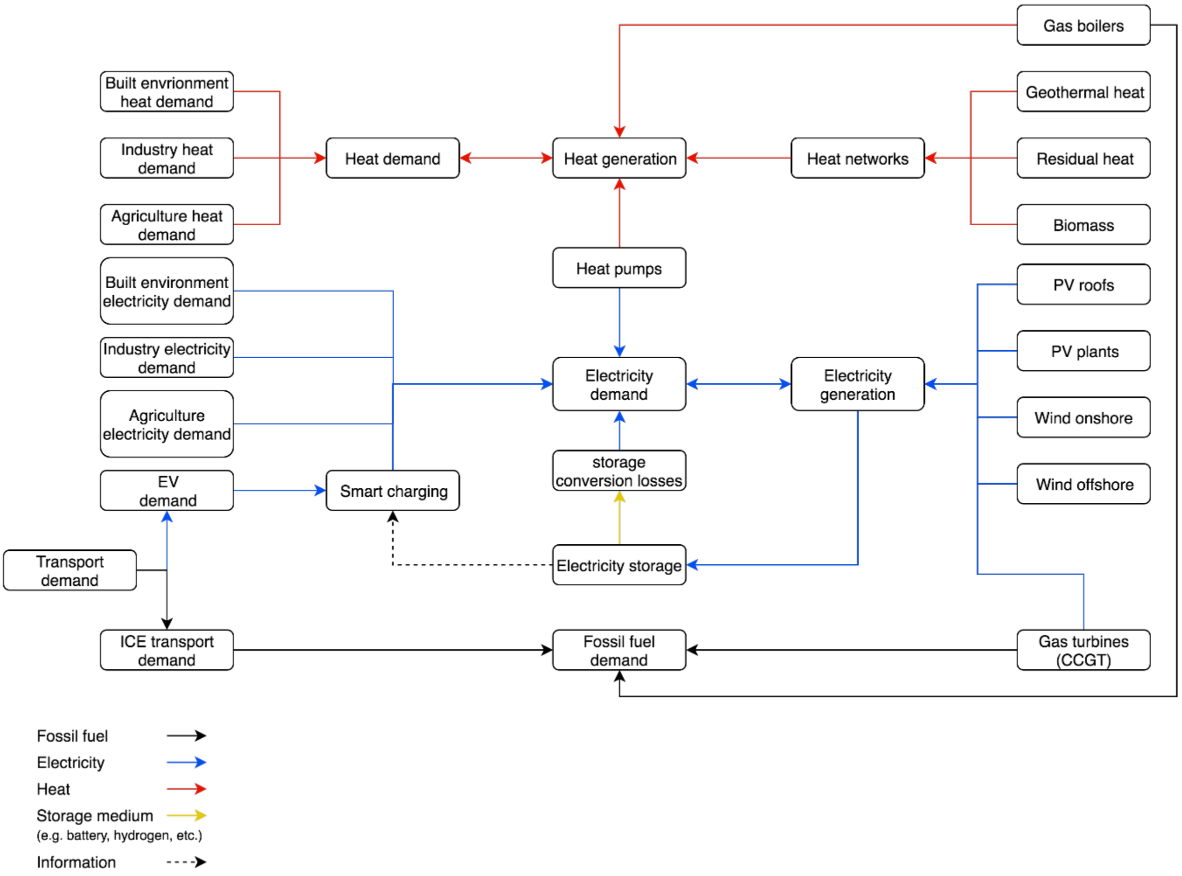


Figure 6: Schematic overview of the model

4.3. Energy carriers

Five types of energy carriers are considered in this model: electricity; heat; natural gas; hydrogen; and fossil fuels for transport. This division is important for several reasons. First, in a balanced energy system, all energy carriers should be balanced. Converting energy between one or another often results in conversion losses and added costs. Second, all energy carriers require a different infrastructure (grid and appliances). Although grid effects are not yet integrated in the model, this is a noteworthy distinction. Third, future predications of energy usage vary amongst energy carriers. Heat demand is considered to decrease due to increased insulation and improved efficiency in industry. Fuels are also expected to decrease due to increasing numbers of EV's and heat pumps. Electricity on the other hand, is expected to increase. Not only due to electrification of other energy carriers, also because of increased usage of other electrical appliances.

As said, a big challenge is creating an optimum amongst multiple energy carriers and sectors. In many 100% RES models this combination is an underdressed topic, mainly focusing on the electricity sector. Recently, the potential of combining these sectors is becoming more and more apparent, shown by the focus on 'sector coupling' (such as coupling transport and heat to electricity) (Brown, Schlachtberger, et al., 2018), or the shift from smart electricity grids to 'smart energy systems' (Lund, 2014; Mathiesen et al., 2015). As electricity is currently the most renewable generated type of energy, and efficient for transport (EVs) and heating (heat pumps), this model focusses on large scale electrification of energy demand. The possibility to adjust settings on the number of EVs and heat pumps enables scenario analysis of this electrification.

The combination of different energy carriers has it effects on comparing energy consumption. As each carrier has conversion losses, which are not always accounted for in energy consumption statistics. Primary energy consumption is the energy required to make the system work. This means all fossil fuels and their conversion losses are considered. Shifting these to renewables largely reduces the primary energy consumption. Next to the primary energy consumption, also the final energy consumption can be misleading. Final energy consumption is all energy used by consumers. This includes for example car fuels. As EVs are more efficient than combustion engine cars, they reduce the final energy demand as well. Furthermore, it means that the heat generated by heat pumps is subtracted from the final consumption, as only the electricity required to create this heat is relevant. Lastly, of course storage conversion losses have to be taken into account.

To analyze a 100% RES the following is needed: All energy carriers should be matched; the entire heat demand should be covered by either renewable heat or heat pumps; the entire transportation sector should be electrified; and the resulting electricity demand including the conversion losses from the storage solutions needs to be covered by renewable resources.

4.4. Energy Demand

Demand per energy carrier is divided into four sectors: Built environment; transport; industry; and agriculture. This is done to make more accurate, sector and carrier specific, forecasts of energy of energy savings (See the '*klimaattafels*' (Klimaatakkoord, 2018) for the current goals, and '*Brabant op 100% wind, water en zon*'(Hoekstra, 2018) on assumptions regarding predicted energy usage per carrier per sector).

After assuming the aggregate energy demand per carrier per sector it is important to use a temporal demand profile in order to create dynamic demand patterns. To do this the annually predicted demand profiles of NEDU are used (NEDU, 2017). These profiles include quarterly (electricity) or hourly (gas) data on the fraction of energy used within that period over the total energy used. NEDU is a facilitator in supplying information to different companies within the energy sector. These profiles are generated separately for electricity and gas and divided amongst categories of grid connection size. These categories have been assumed differently per sector. In the case of electricity, built environment is assumed to have the smallest grid connection type, agriculture the middle and industry the biggest. In the case of gas there are only two categories. Built environment is mostly connected to the smallest connection, and industry and agriculture both to the biggest. Furthermore, gas demand profiles have been made temperature independent. This has been adjusted to 2017 temperatures to obtain the actual demand profiles corresponding to the weather data. Demand is matched to the weather-based supply of wind and solar to determine storage requirements. For detailed graphs of electricity and gas demand profiles see appendix B.

4.4.1. Industry & Agriculture

The demand by industry and agriculture is determined in two simple agents. There is no accurate data available on exact location and company or region-specific demand profiles of industrial agricultural energy demand. Also, due to the scale of the model and the province's goals of total energy supply and demand, aggregate and average characteristics of energy demand are sufficient. In other words, the agent type consists of a single agent, representing all the energy demand by agriculture in Brabant. Energy consumption in this agent is divided amongst a share of heat use and a share of electricity use which are modelled according to their NEDU demand profiles. These two agents could be turned into heterogenous populations in future studies.

4.4.2. Built Environment

The built environment is slightly differently integrated. The built environment is an agent population consisting of 214 agents, each representing a village, city or municipality. Each agent is characterized by parameters such as their name, coordinates, inhabitants and number of households. By using the coordinates of the towns, it is possible to geographically distribute the energy consumption. This is done for visualization purposes at the moment and can include transmission and distribution in the future. Similar to agriculture the heat and electricity consumption pattern of the built environment is shaped by NEDU gas and electricity profiles.

4.4.3. Electric vehicles

In the case of transportation only the electric vehicles have been modelled into a separate agent. Other modes of transportation have been implemented as a module in the environment. Creating a dedicated agent for EVs is important because the potential of supply-demand management by smart charging. First, the structure of EVs is explained, followed by the smart charging algorithm.

EVs consumption patterns show agent-based dynamic patterns. The final output parameter to the rest of the energy system is the electricity demand load at a certain time. To obtain this load the average amount of kilometers driven a day is simulated in multiple trips. The total amount of electric cars is represented in an agent population. Theoretically it would be possible to create 1.3 million agents (as there are 1.3 million cars in the province). However, due to computational limits is has been decided to represent the behavior of these 1.3 million cars in a representative amount of 50 separate agents. With this number of agents, dynamic patterns can be simulated while remaining within computational limits. Amongst the individual agents a driving schedule is calculated based on stochastics of when certain trips are made. Three main types of trips have been identified; day (commuting) trips, evening trips and weekend trips. All have their own stochastic distribution of distance and departure times. Each of the 50 agents will obtain a moment and time of making a trip each day, thus simulating an already quite complex and distributed behavioral pattern amongst the agents in the population. As said, the only resultant is the variable of aggregate EV demand load on the entire system. When simulating this it shows that the demand of EV's often extend the already existing peaks in household electricity demand and is not matched to electricity generation. This is a result of people just plugging their EV in when they arrive home from work or after any trip without having an incentive or system which manages the loading scheme. A good solution to this is smart charging.

4.4.4. Smart charging

To show the system effects of demand management a smart charging module has been implemented. Smart charging is a concept based on charging your car when electricity prices are low. Those prices serve as a proxy for the difference between supply and demand. With high levels of renewables those differences will fluctuate tremendously, making smart charging beneficial. As a proxy of this the model uses the difference between supply and demand to decide when one would be charging. In other words, all EV owners would charge their EV when charging is cheapest, unless of course, they have scheduled trips during these hours of the day. This creates a negative feedback loop; due to growing demand of EV's when the price is lowest, the price will rise, having effect on the amount of EV's being charged.

Creating truly dynamical smart charging based on the consumption patterns turned out to be not possible within constraints of this assignment. Therefore, it is based on an hourly average of number of to the grid connected cars, generated by simulating the EV's driving patterns. This is statically implemented to determine EV's maximum charging load every hour of the day. These maxima serve as the boundaries for electricity charged at the most favorable moments of the day. It is important to note that this section has been implemented in the *main* environment, thus does not consist of individual agents. Ideally this section would be directly implemented to the EV agent type, creating different, dynamic patters for individual agents within the population. An example of how smart charging is based on the imbalance between supply and demand can be seen in figure 7. In scenarios with extreme penetrations of PV, the smart charging loads follow the daily solar peaks.

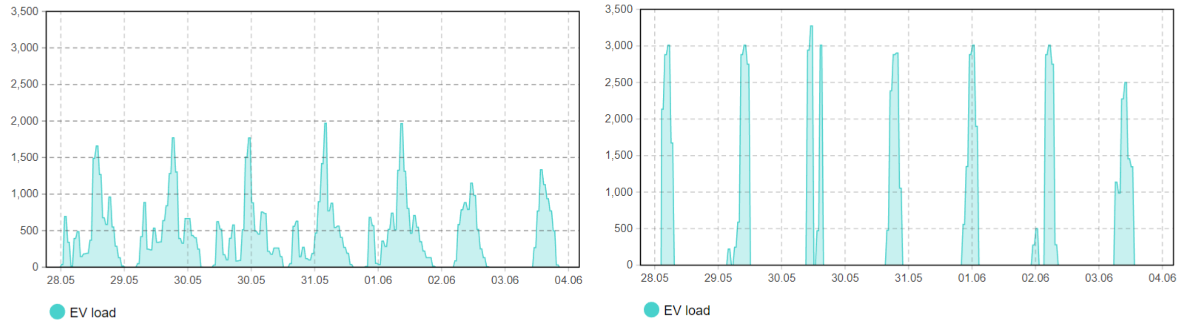


Figure 7: EV load without (left) and with (right) smart charging in a scenario with high levels of PV. Smart charging peaks align to solar peaks as those result in the highest supply-demand mismatch.

4.5. Energy Generation

The different energy generation sources are structured based on energy carriers. An important distinction in energy generation technologies is whether a technology is supply driven or demand driven. The best example of demand driven technologies is conventional electricity generation; the amount of electricity produced by gas turbines is based on the electricity demand. On the other hand, supply driven technologies like wind turbines and PV are based on the supply side of wind and solar. If the wind blows or the sun shines, they will produce electricity in disregard of any demand. The same distinction is made in other energy models regarding 'firm' generation (or storage) to complement intermittent renewable energy technologies (Jenkins, Luke, & Thernstrom, 2018; Sepulveda et al., 2018).

4.5.1. Heat generation

All renewable and non-renewable heat generation is assumed to be demand driven. Residual heat and geothermal heat are combined in heat networks. Biomass is assumed to be dominantly used for heating, with an annual maximum capacity not larger than the residual waste streams of the province itself. Heat pumps and heat networks can be adjusted during model runtime and are used as variables in the scenario analysis. When these sources do not add up to the total required heat demand gas boilers fill in as the non-renewable source for the remaining heart requirement.

4.5.2. Renewable electricity generation

All renewable electricity generation methods consider are supply driven technologies. The 'firm' resources required according to above mentioned sources is in 100% RES scenarios covered by long-term large-scale storage. The renewable sources are wind (onshore and offshore) and PV. Based on hourly weather statistics (windspeed and solar insolation) from the Royal Netherlands Meteorological Institute (KNMI). These can be combined with power curves and efficiency into an expected power output.

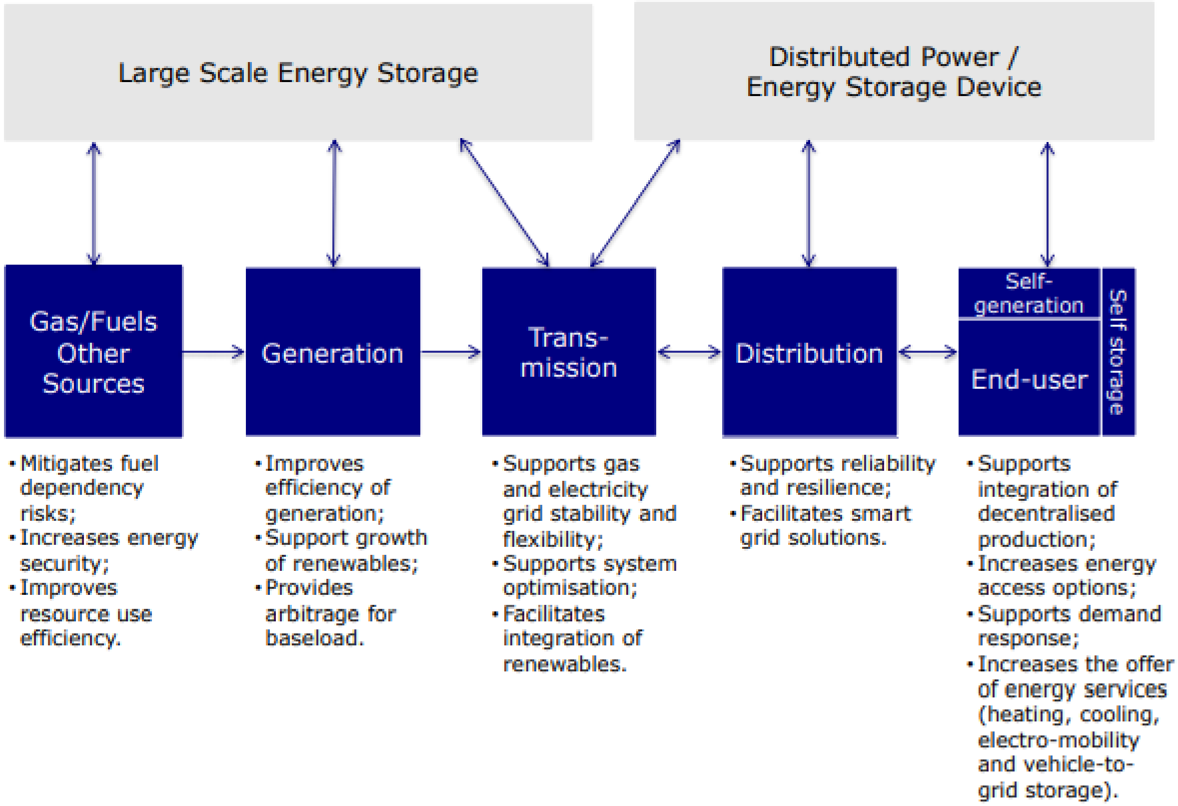
4.5.3. Conventional electricity generation

To be able to run non-100% renewable, current or business as usual (BAU) scenarios, a conventional type of electricity generation can be used. Combined-cycle gas turbines (CCGT) is the only type of conventional electricity generation is integrated in the model. Looking at the goal of simulating 2030 scenarios this assumption is based on the plans to phase out coal before 2030 (Wiebes, 2018). Furthermore, gas is often seen as a ‘transition fuel’ to supply either a base demand, or work as ‘gas peaker plant’ in scenarios with high shares of renewables (BNEF, 2017). Conventional electricity generation can either be used to generate a baseload, or match supply and demand at low levels of renewables. In the model, gas consumption is calculated after the renewable supply and demand (either based on smart charging or not). The installed capacity of gas turbines can be adjusted according to the scenario settings. The model compares the potential capacity with the supply-demand imbalance and generate electricity if the mismatch is between zero and the installed capacity.

4.6. Storage

If the installed capacity of gas turbines is capped enough, or even zero in case of a 100% renewable system, there will still be a remaining temporal imbalance between supply and demand. Note this imbalance is only temporal, annual electricity consumption and generation should be matched. To balance this difference between supply and demand storage is required. Two types of storage are implemented, based on the functions and characteristics storage can have in 100% RESs. One is for large scale, long term seasonal balance, while the other matches daily intermittent generation and demand peaks (see figure 8). Different technologic characteristics are important for these purposes. Daily storage can be relatively expensive per capacity (kWh) but should be able to ramp up and down very fast. Seasonal on the other hand, is cheaper to store over longer periods (per kWh) but conversion or charge/discharge rate is relatively slow or expensive. Large amounts of PVs will generate a lot of electricity on sunny summer days around noon, but little in winter and none at night. Creating two types of storage requirements. First, the day-and-night gap needs to be bridged by intraday storage, second the summer-winter gap needs to be bridged by inter-seasonal storage. Based on figure 9, batteries represent daily storage and hydrogen seasonal storage.

Battery storage is used for intraday balancing. Batteries will be charged during the PV peaks around noon and discharged during the consumption peaks in the late afternoon. The algorithm calculates and stores the supply-demand imbalance over the entire day and makes sure these peaks are shaved. However, when simulating a 100% renewable energy system one will notice that even after the battery storage, there will be a remaining energy surplus on summer days and shortage on winter days. This is covered by introducing hydrogen. On days with a lot of renewable electricity generation, the part which is not used on that day will be used for electrolysis to generate hydrogen, which is used in a fuel cell on days with an energy shortage.



- Mitigates fuel dependency risks;
- Increases energy security;
- Improves resource use efficiency.

- Improves efficiency of generation;
- Support growth of renewables;
- Provides arbitrage for baseload.

- Supports gas and electricity grid stability and flexibility;
- Supports system optimisation;
- Facilitates integration of renewables.

- Supports reliability and resilience;
- Facilitates smart grid solutions.

- Supports integration of decentralised production;
- Increases energy access options;
- Supports demand response;
- Increases the offer of energy services (heating, cooling, electro-mobility and vehicle-to-grid storage).

Figure 8: Value of storage in each step of the energy value chain. Reprinted from (Ugarte et al., 2015)

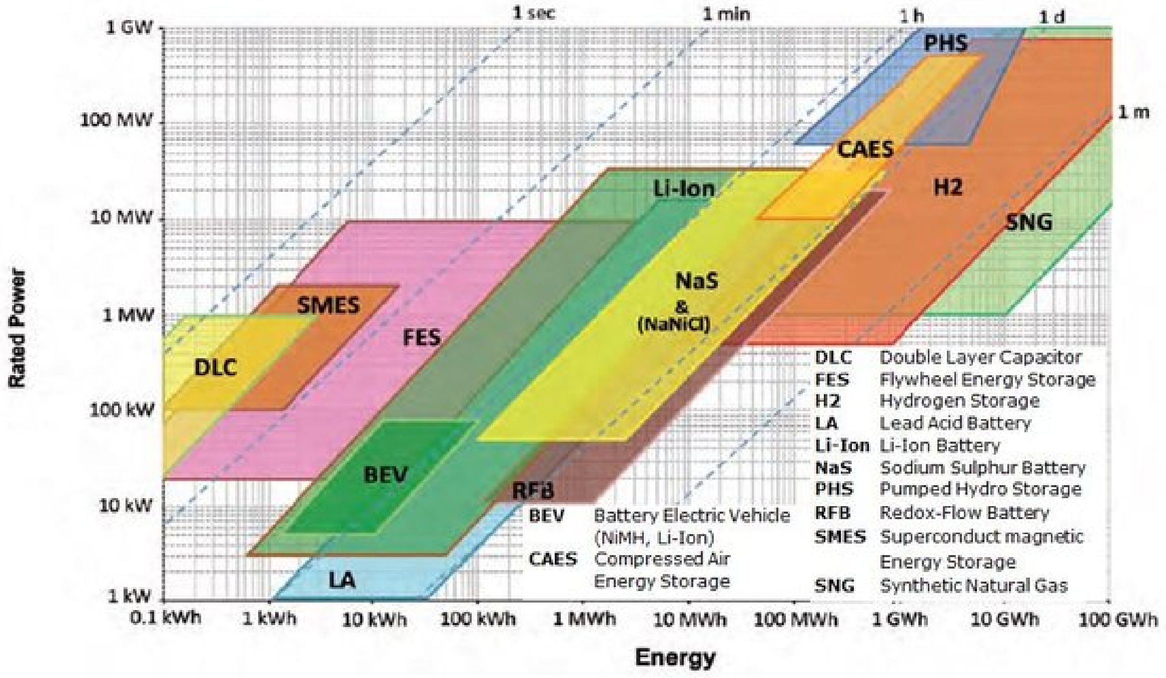


Figure 9: Storage technologies compared on rated power, energy content and charge discharge time. Reprinted from (IEC, 2011)

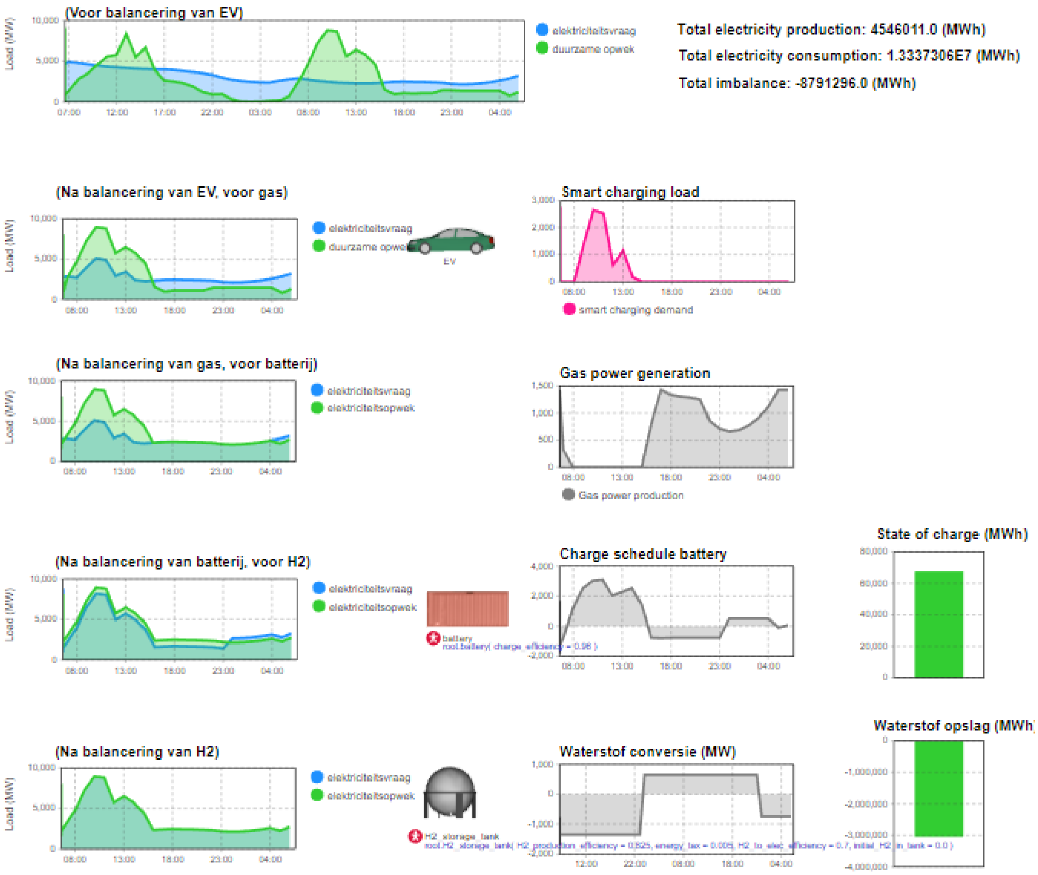
4.7. Balancing algorithm

The electricity flows (see figure 6 at the start of this chapter) are balanced in a ‘priority order’ scheme. The balancing algorithm is structured per energy carrier. As the number of heat pumps and EVs effect the electricity demand, they are calculated first. Heat is manually balanced by adjusting the settings for heat networks and heat pumps to fulfill the renewable heating requirements.

The specific electricity balancing algorithm is more advanced, as different types of storage and demand management are taken into account. Typically, this would be done by a market-based merit order. However, the goal is not to find the cost-optimum system design but to show the effect of renewable energy technologies, for which the priority order is a simpler and suitable method. The priority order essentially balances the supply and demand by ordering which type of electricity generation, supply-demand matching or storage is used. The following order is applied:

1. The algorithm compares demand without smart charging to renewable electricity generation.
2. The smart charging load is matched to the imbalance as far as possible (charging during an excess of renewable electricity).
3. The amount of electricity generated by gas turbines is determined. It is capped at a pre-set maximum capacity and will fill the imbalance as long as this is lower this capacity.
4. At high levels of renewables and low levels of gas turbines, this capacity is not sufficient and storage is required.
5. The inter-day imbalance is smoothed by battery capacity, leaving a stable shortage or surplus over the day.
6. The remaining intra-day imbalance is covered by hydrogen (or any other seasonal storage technology).

This order is depicted in figure 10 (a snapshot from the model during runtime), showing that the imbalance slightly reduces with each step, until demand and supply are matched after the hydrogen step. See appendix B for a schematic representation of the model algorithm. A lot of options are implied to enable the analysis of multiple different scenarios.



Total electricity production: 4546011.0 (MWh)

Total electricity consumption: 1.3337306E7 (MWh)

Total imbalance: -8791296.0 (MWh)

Figure 10: Snapshot of balancing modules in model runtime

4.8. CO$_2$ emission calculations

The final goal of creating a renewable energy system is of course reducing the emissions of the energy system. This is not just an important factor of analysis, but also to explain the effect of certain technologies on emission reduction to policy makers in order for them to take measures which are as effectively as possible to combat global warming. To calculate this each energy generation method is characterized with a certain CO$_2$ output per kWh, which is multiplied with the amount of kWh used by each generation method. It is then compared to the emissions in 1990, the reference year of the climate goals. To be able to visualize the effects in a sensible manner a graph is made showing the 48-hour average CO$_2$ emissions per energy carrier multiplied and expanded to an annual scale. The 48-hour average is used to reduce short term peaks and give insight in the long-term effect. The annual scale is used in order to make the values recognizable to policy makers. However, it does result in an above average visualization in winter and below average in summer. Of course, the final results used in analysis (instead of visualization) are the annual aggregates.

4.9. Cost calculations

Costs can only be calculated on an annual basis. In order to calculate costs, seasonal storage should be balanced, which of course only happens annually. After one year has been simulated, aggregates of all types of generated, consumed and stored energy, CO$_2$ emissions and costs are made. Costs are calculated based on energy source specific levelized cost of energy (LCOE) or combinations of capital expenditure (CAPEX), operational expenditure (OPEX) and lifetime. Furthermore, costs of all technologies are aggregated to annual system costs or divided by final energy demand into system costs per kWh.

4.10. Out of scope energy technologies

After addressing how the model is constructed and what is included, it is equally important to address what is excluded. Being clear not only on what is included, but also on what is excluded enables a fair comparison to other energy models, and explicitly states some of the implicit assumptions made in terms of system design.

Although a system overview as comprehensive as possible is desired, the number of renewable energy solutions is nearly infinite. Therefore, focus points have been applied. The renewable energy system is focused on electrification of transport and heating demand, covered by wind, water and solar (WWS) electricity generation. Previous research has shown that this is techno-economically feasible (Jacobson, Delucchi, Bauer, et al., 2017; Schlachtberger et al., 2018) and policy makers identified it as the most socio-politically desired system if possible within techno-economic and spatial limits. Out of scope technologies are nuclear and fossil fuel including carbon capture, utilization and storage (CCUS).

Nuclear is not a realistic option to be built before 2030, and if the Netherlands would decide on building a nuclear power plant, it will certainly not be within the province of Noord-Brabant. Furthermore, currently built nuclear power plants are more expensive than renewables and therefore unviable (MIT, 2018). Any other types of nuclear often heard in RES debate (thorium, fusion or fission) are not commercially expected before 2050 (MIT, 2018) and therefore useless in attaining 2030 climate goals. However, policy makers (initiated by the PVV), have commissioned further research to the potential of thorium molten salt reactors in Noord-Brabant. Even though, the unviability has been thoroughly explained in to '*Brabant op 100% wind, water en zon*' (Hoekstra, 2018) and similar research in the province of Noord-Holland is negative regarding the opportunities of thorium to attain transition goals (ECN, 2015). Therefore, it would be good to include multiple types of nuclear future developments of the model, as it could lead to a more clear comparison of nuclear versus wind, water and solar.

Looking at other 'firm' technologies, a biomass fired power plant (already partially happening in the Amer plant (RWE, n.d.)) would be most likely in Brabant. On the national scale aded gas turbines with CCUS could contribute further. Brabant itself does not have a lot of carbon storage possibilities so this would result in similar provincial arguments as offshore wind, e.g. out of provincial jurisdiction. However, because of the political focus on WWS technologies, these have not been further investigated.

A similar argument holds for transmission and distribution, which is not included in the model. According to prior research it accounts for around 10-15% of the total costs (Brown, Bischof-Niemz, et al., 2018). This is certainly significant, but, not the focus of this model. As this is a first exploratory system overview and focus lies on the generation and storage technologies itself, grid connections have not been a priority. If this would be expanded in future research, the agent-based, geographically defined environment is very suited for implementing such spatial measures in future models.

Lastly, system design is optimized on relatively cheap storage. An important limitation of this is that curtailment of excess energy during solar or wind peaks is not possible in the model. Many other renewable energy models design systems with a large overcapacity of energy generation assuming that it will be partially curtailed during the most extreme imbalances. The trade-off in this system design is building increased energy generation capacity in opposition to storing all excess energy even during the highest peaks. Or in other words, increased capacity which is sometimes curtailed can be cheaper than increased storage and conversion capacity. Further cost optimization would be possible if for example some extreme solar peaks could be curtailed, instead of modelling the required storage capacity and charge or discharge rate at the most extreme production peaks.

4.11. Software tool - AnyLogic

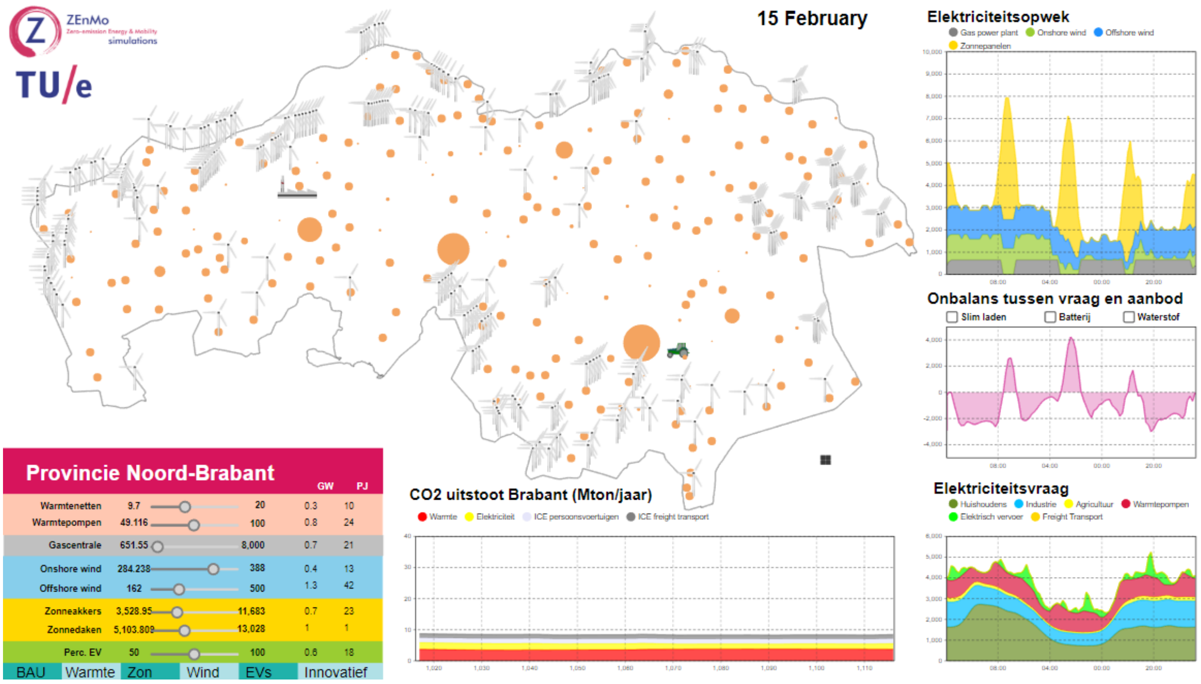
The model is developed using the modelling software AnyLogic 8.3.2. AnyLogic is a simulation application which is unique in its kind as it provides a fully integrated multimethod modeling environment. AnyLogic supports discrete event, agent-based and system dynamics or any combination thereof. The software supports visual modelling techniques such as state or action charts, which can be further extended by Java code.

The environment or landscape in which the agents interact is called the '*Main'* in AnyLogic. Individual agents, agent types and agent populations usually interact in the *Main* environment. The *Main* can be an environment of continuous space and time. This gives it an edge over ABM software that uses discrete space or time and enables multi-method modelling. AnyLogic has two manners to integrate geographic information system (GIS). The modeler can either upload Shapefiles or use the integration from maps provided by AnyLogic with amongst others the online service 'OpenStreetMaps'.

4.12. Visualization

Geographically defining agents and visualizing them on a map is important when using renewable energy models for explanatory purposes, and perfectly fits the features of ABM. The visualized part of the environment is formed by a geographical map (shapefile) of the province of Noord-Brabant. The location and amount of wind turbines are displayed on this map, as well as the size of the total area of PV fields. Cities and villages are scaled to number of inhabitants (see figure 11).

Another model aspect for the discussion tool purpose is the interactive control panel. The most important renewable energy choices have (during runtime) adjustable parameter settings. Those include: district heating, heat pumps, onshore wind, offshore wind, commercial rooftop PV, utility scale PV and percentage of electrified transportation, smart charging, battery storage and hydrogen storage. Interactively adjusting these settings creates a quantified and visualized narrative. Policy makers are navigated throughout the energy transition, explaining choices in renewable heating, different generation methods and their effects on storage. The accompanied graphs of electricity generation, demand and imbalance and CO_2 emissions helps to convey this message.



Provincie Noord-Brabant

			GW	PJ
Warmtenetten	9.7	20	0.3	10
Warmtepompen	49.116	100	0.8	24
Gascentrale	651.55	8,000	0.7	21
Onshore wind	284.238	388	0.4	13
Offshore wind	162	500	1.3	42
Zonneakkers	3,528.95	11,683	0.7	23
Zonnedaken	5,103.809	13,028	1	1
Perc. EV	50	100	0.6	18

Figure 11: Snapshot of the visual model during simulation

This past chapter explained how the Noord-Brabant energy system model was made and how it works. The agent-based structure was introduced showing the relations between al agents and agent populations. All energy generation, consumption and storage technologies are represented in these agents. The agents where further explained by describing the structure of each of them. Lastly, the simulation software and visual representation of the model was discussed. The clear yet comprehensive visuals help policy makers to get a full grasp of the complex dynamics of the energy transition.

5. Data and Assumptions

In this section a detailed description of the literature review to determine the data and assumptions on which the model is based is given. The section starts by explaining how the data is obtained. Than all assumptions are described in more detail per demand sector and generation technology. Lastly, all acquired cost assumptions are combined in one, clear table (table 7).

5.1. Data gathering

The input-parameters and system or algorithm design of the model are based on a review of literature, technology reports and forecasts studies. Energy demand is prognosed from scaling national prognosis to the size of Brabant while excluding transport and heating electrification measures, as those are separate parameters in the model. Energy generation potential is a combination of the spatial study of the architectural company HNS and technological potential. Cost assumption are based on forecasts at the first target year 2030. Although the theoretic section states cost and efficiency assumptions should be scenario depended, based on underlying technological development drivers and scenario requirements, it is not yet taken into account in this first model. The provincial scale is not big enough to make significant cost reduction effects in global industries, reducing the importance of this requirement for this specific objective.

Energy system design assumptions have been discussed with policy makers of the province of Noord-Brabant, cooperatively shaping the system by combining their socio-political knowledge with researched techno-economic assumptions. Furthermore, the usefulness of the model in political debate is assessed based on the results and comments of the model presentation to the State Council and conversations with policy makers afterwards.

The province has several existing reports documenting the opportunities of sustainable energy technologies within its boundaries. This has been used as a starting point for data gathering. Furthermore, they are actively collaborating in providing insights in relevant sectors for energy saving and local sustainability initiatives. Lastly there is a team of landscape architects involved in the research providing insight into suitable locations and area sizes which could potentially be designated for sustainable energy generation. This is combined with more general reports by national and international energy or policy agencies such as the '*Nationale Energie Verkenning'* (NEV) or technology specific reports. Altogether resulting in a set of assumptions on which the model will be based. The following section is strongly connected to '*Brabant op 100% wind, water en zon*' (Hoekstra, 2018) in which a lot of the assumptions have been described.

The model is a broad overview of the entire 2030 energy system. The challenge of this broad scope is maintaining enough level of detail to represent a viable system. Parameters have been critically assed at an adequate level of detail. The pitfall lies in endlessly researching and optimizing parameters, which on one hand is tremendously important, while on the other could result in getting lost in the details while losing sight of overall trends. Especially smart combinations between those energy carriers are difficult to quantify at this scale. Parameter relevance has been assessed on the criteria of making equal comparisons to achieve the goal of researching different scenario settings. In other words, all scenarios should be based on similar basic parameter settings. All costs for example, are based on levelized cost of energy (LCOE), a method to compare the average total costs over the lifetime based on the energy output of an energy generation technology.

5.2. Energy Demand

Acquiring detailed assumptions on sector and energy carrier specific demand was a two-step process. The first task was to map the current energy demand on provincial scale. In this the '*Klimaatmonitor'* was the most important source. This is a monitoring portal from the Dutch government accounting climate and energy measures on a local, regional or provincial scale. They acquire data from numerous national reports and governmental registers and scale it down to give insight to local circumstances. The sum of all indicators accounts for about 92-94% of the Dutch final energy demand (Klimaatmonitor, 2017). Sectors like flying and non-domestic shipping are not taken into account, along with a few big emitters or energy consuming companies who could be traced and appeal to trade secret protection.

The second step is forecasting the demand trends per sector from the most recent data of the '*Klimaatmonitor'* to 2030. This process is better described in '*Brabant op 100% wind, water en zon*' (Hoekstra, 2018). In short it is based on multiple national trend reports. From these reports, distinctions between the type of energy saving measures are distilled, as a number of these measures (EVs and heat pumps) are separate indicators in the model, while this electrification of heat and transport is one of the most important drivers of energy demand reduction. In general, it is assumed that efficiency gains balance increased demand due to economic growth and more appliances. The most important difference is the division of demand, with an increase in electricity (due to more appliances, even without electrifying heating and transport) and a decrease in heating demand (due to insulation in the built environment and efficiency gains in industry). The resulting forecasted assumptions are depicted in table 5, with a breakdown between electricity and heat in table 6.

Table 5: Energy demand forecast per sector of Noord-Brabant.

Energy demand (PJ)	2015 (PJ)	2030 (PJ)
Built environment	104	92
Transport	81	* n.a.
Industry	70	70
Agriculture	23	22

** Transport forecast is not relevant as the amount of EVs will vary in the scenario analysis*

Table 6: Assumptions on electricity and heat share of total demand in absolute figures and percentage

Energy demand 2030 (PJ)	Electricity (PJ)	Heat (PJ)	Electricity (%)	Heat (%)
Built environment	43	49	47	53
Industry	24	46	34	66
Agriculture	3	19	15	85

5.2.1. Conventional Transport

To compare scenario's with and without full electrification of transport, the costs and emissions of non-electrified transport must be calculated. As fuel prices are very volatile and depend on numerous exogenous factors, the weighted, all fuel European average price excluding taxes of the period 1980-2017 has been assumed at 0.384 €/L (EEA, 2017). 2030 oil price predictions range widely, even amongst credible sources. Scenarios will be run and compared ranging from a 114% increase (minimum of 'Low Oil Price Case' 50-70$/barrel (IEA, 2017)), a 164% case (The World Bank, 2017) and even a 252% case, which might seem like a lot but is the actual assumption used in the NEV 2017 (K. Schoots, M. Hekkenberg, & Hammingh, 2017) between an with a price increase of 45% similar to the predicted 2017-2030 crude oil prices increase (The World Bank, 2017). As this is an all-fuel average, no division between modes of transport and type of fuel consumption is required.

5.2.2. Electric Transport

Energy consumption and emissions of transport are categorized in two categories; personal transportation by car and freight or non-car transport. Personal transport is predicted to make up around 49% of the entire transport energy consumption and 48% of its CO_2 emissions in the NEV 2015 (Geilenkirchen, Broeke, & Hoen, 2016). The main reason to categorize these modes of transport is because of the differences in electrification and potential smart charging strategies. Using EV's and smart charging is amongst the most cited demand side load management measures. However, smart charging strategies would be very different between personal transport and commercial transport. Commercial transport companies will optimize their fleet usage on other parameters than electricity price. Personal transportation, on the other hand, is very suited for load management. As most cars are used only moderately, while having a lot of battery capacity, they offer a lot of flexibility.

EV's calculation is based on the amount of passenger vehicles in the province; 1,309,461 in 2015 (CBS, 2018a) and the average amount of kilometers driven 13,091 a year, resulting in 35.86 a day (CBS, 2017). Electric vehicles follow dynamic, bottom up generated driving patterns. The parameters on which these patterns are based are copied from the '*SparkCity*' model. (Hoekstra & Hogeveen, 2017)

Freight and non-car personal transport is also assumed to get electrified. In general, electricity is a more efficient fuel for transportation modes than fossil fuel. Amongst all different sectors (light-duty, medium-duty and heavy-duty trucks, and busses) a conversion factor of 0.3 (Jadun et al., 2017) has been assumed.

Looking at a cost comparison between EV's and ICE's, the assumption is no added investment costs are required, in 2030 there will be price parity between for most segments (see figure 12) (BNEF, 2018). Estimating similar battery costs reduction as (Linesh Sundrani, 2017).

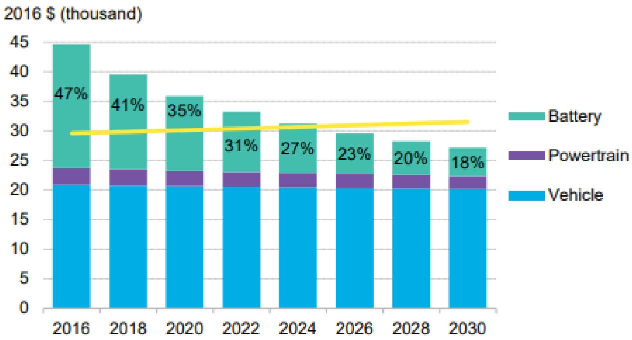


Figure 12: Medium segment price and battery costs in EU. Reprinted from (Soulopoulos, 2017).

5.3. Heat

In the model heat is generated by conventional sources such as gas boilers, heat networks supplied by either geothermal or residual heat, heat pumps or biomass. Each of these sources is further specified.

5.3.1. Conventional Heat

Conventional heat is assumed to be generated by gas (condensing) boilers. These boilers can achieve an efficiency of 96% on the top energetic value ('*bovenwaarde*') of gas (TNO, 2010). A similar gas price of 0.32 €/kWh is used.

5.3.2. Heat networks

Heat networks and district heating are assumed as a combination of geothermal heating and residual heat. The reason to combine geothermal and residual heat is because they are often seen as supplementary sources for heat networks. Also, residual heat is seen as a transition source, to optimize current heat generation. However, if industrial efficiency increases and renewable energy generation phases out coal and gas, residual heat could become scarce. Geothermal heat could than fill up the gap that that occurred due to reduced residual heat. Both are also formed by similar characteristics. Heat is difficult to transport without big losses. Therefore, geothermal and residual heating is based on a tight spatial connection between local supply and demand.

The introduction of heat networks is a complex matter, next to technological uncertainty in the case of geothermal heating and efficiency gains of residual heat sources, the main challenge is socio-economical and results are uniquely case depended. Division of costs, dependencies and social and economic equality are uncertain and project depended (Joosten, 2018).

5.3.3. Residual heat

Currently about 3.1 PJ of residual heat is being used in Brabant (Klimaatmonitor, 2017). This could theoretically be expanded to over 5 PJ (Provincie Noord-Brabant, 2016a) however, hesitations often arise due to the lock-in effects of residual heat. The currently biggest heat network in Brabant for example, is currently supplied by residual heat from the *Amercentrale*, a coal fired power plant which has been scheduled for closing already (Menkveld, Matton, Segers, Vroom, & Kremer, 2017; Provincie Noord-Brabant, 2016a). A good perspective on the effect of heat networks if supplied by residual heat is given after the introduction of a recent district heating project in Rotterdam where residual heat from Shell Pernis oil refinery is used to heat a neighboring district. The refinery emits 4.3 megaton annually, while the district heating reduces emissions from residential gas boilers which add up to 0.035 megaton. In other words, the scale is incomparable, and if this heat network creates a minimal lock-in effect it will already be net inefficient.

5.3.4. Geothermal heat

Geothermal heat is still highly uncertain. Some general studies have been done to identify possible rock layers, indicating that in general there is a lot of potential. However, only a few regions within the province have investigated the potential as this is quite a costly endeavor and companies often cannot bear the risk. See figure 13 for maps on geothermal heat potential, a large part of the Netherlands is still identified as unknown. Also, issues regarding groundwater supply hinder geothermal heat in Brabant. The few investigations did however find promising results, mainly connected to regions with high heat demands such as greenhouses in West-Brabant or clusters of cities. Also, geothermal heat could be a future alternative for current heat networks fueled by residual heat of non-sustainable factories.

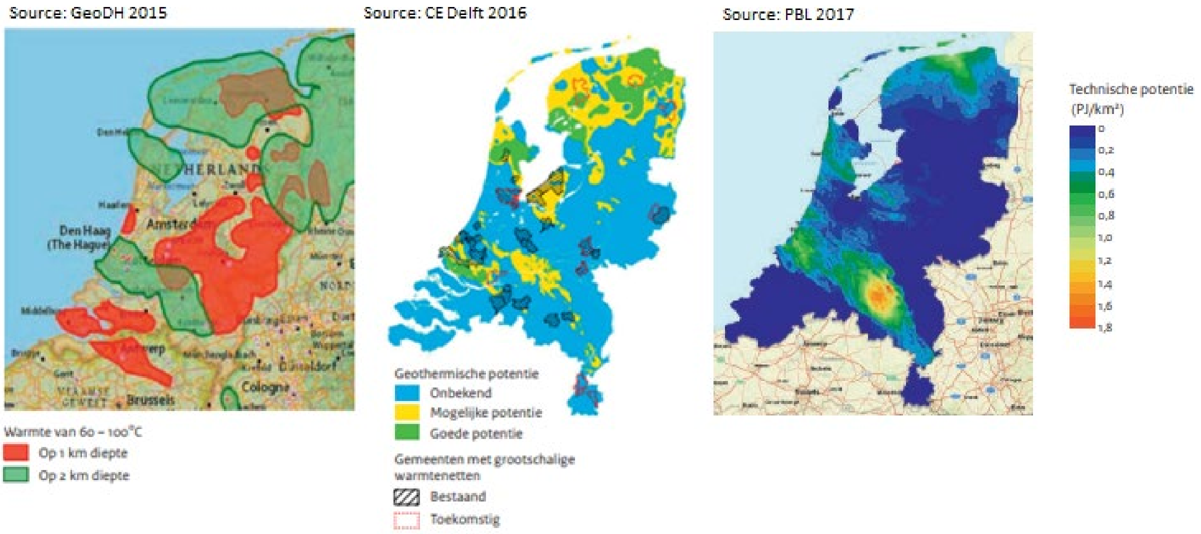


Figure 13: Potential for geothermal district heating: Adapted from the NEV (K. Schoots et al., 2017) and (Hoogervorst, 2017)

Even though uncertainty is high, assumptions have been made to be able to integrate this into the model. Geothermal energy is potentially a large renewable source, and unlike wind and solar, independent of weather conditions. This way it could benefit from high energy prices in the winter as other sources require storage and geothermal energy does not. Also, when taking grid costs into account, electricity grid enlargement is more expensive than creating district heating infrastructure. PBL even predicts higher amount of heat supply by district heating than by heat pumps, and has envisioned a nationwide heat network (even though they understand the uncertainty) (Hoogervorst, 2017).

The most important assumption made is that geothermal energy is only used to generate heat. With higher underground temperatures electricity generation is also possible, however, this is less efficient in Dutch geological structure. As said, geothermal heat is still highly uncertain. This is also reflected in cost estimates (see figure 14). In this case, LCOH of geothermal heat is assumed at 48.3 €/MWh, the average between extensive research on a geothermal plant in Groningen (Daniilidis, Alpsoy, & Herber, 2017), standardized costs used by PBL (Hoogervorst, 2017) and IEA estimates (International Energy Agency, 2011).

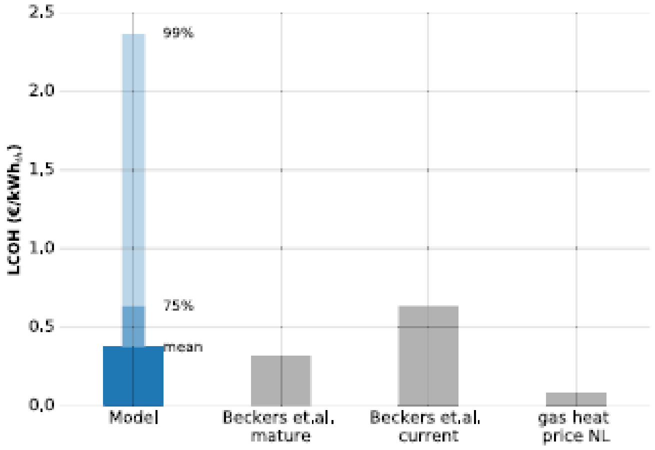


Figure 14: LCOH geothermal heat project Groningen compared to literature sources and gas heat price in 2017. Reprinted from (Daniilidis et al., 2017)

5.3.5. Heat pumps

Heat pumps are essential to the electrification of heat generation. Heat pumps work similar to an inverted fridge. They subtract heat from outside air (air source heat pump (ASHP)) or ground or geothermal water (water source heat pump (WSHP)), compress and transfer this into for example buildings. Their efficiency is mostly dependent on the difference in temperature between the heat source and destination. To get a realistic indication of efficiency over an entire year the Seasonal Coefficient of Performance is used (SCOP). As SCOP is highly dependent on temperature it is important to use assumptions regarding similar climatological conditions. A study by the U.S. National Energy Laboratory predicts efficiency increases in multiple climate zones. Technical developments are increasing efficiency even in cold climates. The Netherlands are classified within the moderate climate zone (ANSI/ASHRAE/IESNA Class V = IECC Class IV (ANSI/ASHRAE/IESNA, 2007; Jadun et al., 2017)). Even in cold areas (between -19 °C to 9 °C) a SCOP of 3.2 can already be achieved in efficient buildings (Safa, Fung, & Kumar, 2015). Despite having numerous different types of heat pumps; for industrial, commercial or personal usage creating either hot air, hot water or a combination of those, an average SCOP of 4 is assumed (Jacobson et al., 2018; Jadun et al., 2017). Meaning that for every kWh of electricity they use they generate 4 kWh of heat.

Taking the entire energy system brings further difficulties resulting from the differences in energy carriers. Most studies report LCOEs based on just electricity, forgetting about the cost of other energy types. This has led to a dedicated concept for heat which is used in heat related cost assumptions; levelized costs of heat (LCOH). A study by the U.S. National Renewable Energy Laboratory (NREL) identifies a big cost difference between residential heat pumps and commercial heat pumps (Jadun et al., 2017). This has been scaled to the heat demand in Brabant for commercial and residential use, resulting in an average CAPEX of 319 $/kW. The main point of interest however, is the increased CAPEX in comparison to current heating. Currently heat pumps can be more than 4 times the price of comparable gas boilers. Learning rates are promising. IEA reported an average price of 563 $/kW in 2007 (IEA, 2011) for residential ASHP to 427 $/kW in 2017 (Jadun et al., 2017), a 24% reduction. TNO is working at an industrial heat pump to increase residual heat at 200 €/kW (ECN/TNO, n.d.) A typical heat pump in the Netherlands costs around €8000 (Naber, Schepers, Schuurbiers, & Rooijers, 2016). Excluding taxes, dividing this by the heating capacity and using predicted cost reduction of 25% (IEA, 2011) results in an average CAPEX of 474 €/kW. In the model the main criterium is added investment costs on top of regular gas boiler costs. Therefor the average gas boiler costs are subtracted from this, resulting in a fair comparison between scenarios including gas boilers or heat pumps.

5.3.6. Biomass

There are two ways in which biomass is used to generate energy. The first is directly using biomass to generate heat, like burning wood in a fireplace or on large scale in a combustion plant to generate electricity and heat and feed it into a heat network, which is currently happening as co-fuel in the '*amercentrale*'. In total over 7 PJ of energy is currently obtained this way in Noord Brabant (Klimaatmonitor, 2017). Although often accounted as 'green', this kind of energy is under heavy debate. Recent research shows that burning local residual biomass is carbon positive within six years. However, if the biomass is made from cut trees, this takes up to 21 years (Hanssen, Duden, Junginger, Dale, & Hilst, 2017).

These second way is by using biomass in a bio-digester. Bio-digesters can produce electricity, heat and biogas, depended on the type. Although this seems promising, this type of biomass is faced with similar lock-in effects as residual heat. Biomass used in bio-digesters is often a residual of intensive farming, creating lock in effects for this sector and less incentive to reduce or upcycle waste. To define the available amount of biomass, only absolute waste streams (without any other possible usage) are considered. This results in an estimated 14 PJ in 2030 (Posad, 2016).

5.4. Electricity

Renewable electricity is mainly generated by wind and solar. Conventional electricity is generated by gas turbines. Furthermore, the assumptions regarding electricity storage are explicated.

5.4.1. Conventional Electricity generation

All conventional electricity is generated by conventional CCGT plants without combined heat and power (CHP) and carbon capture and storage (CCS). In this case taking the LCOE is not applicable as it is highly dependent on the gas price, capacity factor and even CO_2 price taken into account. As these are variables within the model, the base parameters should consist of capital expenditures (CAPEX) and operational expenditures (OPEX). CAPEX is assumed at 925 €/kW divided over a lifetime of 30 years and fixed OPEX 38.5 €/kW (Kost, Shammugam, Jülch, Nguyen, & Schlegl, 2018; Rodriguez et al., 2015). Variable OPEX consitst mainly of natural gas costs, assumed at 0.032 €/kWh (K. Schoots et al., 2017; Kost et al., 2018). An average CCGT plant is assumed to convert 62% of the energetic value of natural gas into electricity in 2030 (Kost et al., 2018).

5.4.2. PV

Solar energy is an important energy source for 100% Renewable systems. The biggest advantage of solar is the rapidly decreasing price, making it at many locations already the cheapest source of electricity. From a political and spatial planning point of view it is also a very attractive energy source. Solar panels can be integrated on already occupied spaces for building and infrastructure, results in little discussion and can even be designed as landmarks (Hoekstra, 2018). In general, the yield per square meter is much higher than for example wind (if all space in between turbines within a wind farm is calculated) or biomass. The big downside of solar is of course intermittency. The sun doesn't shine at night and far less in winter. Finding an optimal balance between these arguments is an important goal of this model.

The most important assumption on solar energy is the fact that only PV generated electricity is considered. Other alternatives are; concentrated solar power (CSP) which is less suitable for the Dutch climate (IRENA, 2018) and solar thermal collectors (STC). In the form of hot water panels they are highly efficient (Tian & Zhao, 2013) and together with large-scale seasonal thermal storage already heating multiple Danish towns (Epp, 2017). However, as the focus of the model is on large scale electrification, they have not been integrated in the model.

Integrating all PV electricity production is based on hourly solar insulation data (KNMI, 2018a). The overall system efficiency of PV production is assumed at about 17% (20% PV panel efficiency and 97% AC/DC conversion efficiency). This is a level already average for crystalline silicon wafer based modules in 2017 (IRENA, 2018) and so a very modest assumption. Note that this should be the average efficiency of all modules in 2030 (so not only new modules).

Unlike most politicians and reports, who think in MWp installed capacity, the input parameters for PV are based on area size. This is a direct result from the cooperation with spatial planners (from both HNS and the province itself). Based on the spatial input, the total installed capacity and costs are resultants of the model simulation. The most important assumptions regarding PV will be specified in this section, for further details see *Brabant op 100% Wind, Water en Zon* (Hoekstra, 2018).

PV on roofs (residential)

Two programs which model the availability and suitability of roof area exists in the Netherlands; Zonnekaart and ZonAtlas. Both have investigated PV-roof potential numerous Dutch municipalities. Deloitte has combined this, with GeoDMS software from Object Vision and geo-data and PV calculations from Map Gear, into a report calculating the entire potential of the Netherlands (Deloitte, 2017). Scaling this down to Noord-Brabant results in a potential 13 thousand hectares of roof surface. This is assumed to be the maximum area, the exact are is varied amongst scenarios. Costs vary based on residential or commercial scale. In this case residential scale costs are assumed for the entire roof surface as no division between those could be made based on the roof surface data.

PV plants

The total available and suitable area for PV plants (fields) is investigated by HNS in the first part of the assignment from the province. The most important ideas from HNS are usage of designated urban expansion area '*stedelijke uitbreidingsgebieden*', designated nature area, '*Nog niet gerealiseerde natuur (NNB)*', accompanying infrastructure and floating-PV on open water. When these designated areas are finally developed, the urban areas could include PV's on their surface design. They also introduced the idea of PV plants as a landmark, to improve public opinion and increase possible locations. Altogether the maximum identified potential area is 11.5 thousand hectares (Hoekstra, 2018). Note, this is from a spatial planning perspective. Current agricultural fields have not been taken into consideration but might turn into PV plants because of economic reasons.

PV plants hold the current lowest electricity price per kWh. When used in regions close to the equator, efficiency rises thus costs reduce. A current project (up to 5 GWp by 2030) in Saudi Arabia will sell energy at $24/MWh. Comparable LCOEs could be achieved in Europe around in 2035-2050 (J. Mayer, 2015)

5.4.3. Wind

Wind power generation is calculated by using the power curves from existing wind turbine models together with KNMI statistics on wind speeds. The turbines power curve is set on hub wind speeds. Meaning that the wind speed at hub height must be calculated. General KNMI data is at 10-meter height, while hub heights vary around 100m or higher. To do this the following formula is required:

$$v(z) = v(10) * \left(\frac{z}{10}\right)^{a}$$

$v(z) =$ windspeed at height z
$v(10) =$ reference windspeed at the measured height 10m
$z =$ required height (turbine hub height)
$a =$ wind shear exponent

The wind shear exponent is a result of the surface roughness. It is very important in wind speed calculations, smooth surfaces like the sea or open fields have far better windspeeds than forests or cities. On land, the wind shear exponent is dependent on the surrounding environment and has been assumed at an average 0.25 (ranging from 0.14 for cut grass to 0.43 for woodlands) (Gipe, 2004). Offshore the exponent is dependent of the sea roughness and closeness to the shore assumed at an average of 0.08 (typically ranging between 0.07 and 0.09 for offshore calculations (DNV, 2014)

Onshore

Similar to PV efficiency assumptions, wind turbines are also assumed at current technological levels. In fact, three different types of actually existing turbines have been selected. Again, note that these values should be the average in 2030. Currently, old and relatively low wind turbines reduce average efficiency and capacity factor (CF) levels. Especially onshore turbine development is focused on creating more efficient turbines (as larger turbines are faced political and logistical obstacles) by introducing for example variable pitch of rotor blades to increase efficiency at low wind speeds and reduce cut-in wind speed. By replacing old turbines with new turbines large efficiency gains can be made.

HNS has investigated what kind of spatial division would be optimal, while taking social and technical (e.g. Turbines need to be separated by five times the rotor blade length to regenerate wind and require certain distances from buildings and infrastructure) constraints into account. They found multiple areas suitable for wind turbines. In total the maximum amount of wind turbines possible is 388. Of these 388 turbines 355 are relatively big, placed in open environments, and 33 are '*dorpsmolens*'. Two types of turbines have been chosen to model these. The big turbine is modelled using the dimensions and power curve of the 4.2 MW '*Enercon E126 EP4*I' (Bauer & Matysik, 2016; Enercon, 2016). The power curve of this turbine type has been verified by data measured from a Dutch wind park *WP A15-Lingewaard* (SolidWinds, 2017). The *dorpsmolens* are modelled using the 3MW '*V126-3.0 MW Vestas*'(Bauer & Silvio Matysik, 2016). In total, these turbines together add up to a maximum of 1590MW installed capacity onshore wind.

Offshore

Wind offshore is more efficient in terms of energy generation. Not only is it possible to build enormous turbines, offshore winds are also much stronger and more consistent. This does not only increase the maximum power output, but also the CF. Some of today's biggest available models, which have already been installed in Belgium's offshore wind parks (Fruergaard, 2016) have been chosen as the 2030 standard, the 8 MW '*MHI Vestas Offshore V164-8.0 MW*' (Vestas, 2011) (Although 9MW versions already exist as well).

Spatially, offshore wind has a lot to offer. Where the spatial societal and technological maximum of the province is set on just 1590MW from 388 turbines, in PBL's study '*De toekomst van de Noordzee*' 60GW of offshore wind could be installed in 2050 (Jan Matthijsen, Ed Dammers, & Hans Elzenga, 2018), which would result in 7500 8MW turbines.

5.4.4. Batteries

Batteries are amongst the hottest topics in energy research. Costs are reducing rapidly, mainly due to the rapid growth of EVs. However, what started with EVs is already becoming profitable for load balancing (Lambert, 2018). In other words: "The lithium-ion snowball is rolling and picking up new sectors and applications along the way" (Liebreich, 2018).

IRENA, the international renewable energy agency, has gathered results from a number of technologies to predict their cost and lifetime (IRENA, 2017). Combining an average of these technologies with research from BNEF (Henze, 2018) and earlier work in the Spark City model (Linesh Sundrani, 2017) the average battery CAPEX is assumed to be 100 €/kWh, dividing this over an average of 5000 cycles makes a levelized cost of 0.2€/kWh stored. The roundtrip efficiency of lithium-ion batteries can go up to 94-98% (IRENA, 2017).

5.4.5. Hydrogen

Stationary hydrogen systems are composed of multiple components, the most important being an electrolyzer to produce hydrogen from electricity and a fuel cell to reverse this process. Furthermore, hydrogen storage is required, as well as some form of battery storage to balance the electricity in the system. Battery storage is already covered, so the next section will cover electrolyzers, fuel cells and hydrogen storage. Other components, such as a water purifier etc. are minor system components and therefor out of scope (Eubanks et al., 2017).

Electrolyzers can create hydrogen from electricity and water. In mid-century the CAPEX (investment costs) will drop to 250 €/kW with an efficiency of 80-85% (Jamie Speirs et al., 2017; Oldenbroek, Verhoef, & van Wijk, 2017). This cost value is amongst the lowest to be found in literature; however, it is used as the envisioned large-scale hydrogen storage is a radical system change, opening up a large new market for fuel cells. So, if this new potential of hydrogen starts to break ground, rapid technological advancements and cost reductions are expected. However, it remains an uncertain part of the system. Therefore, a scenario has been dedicated especially to see the effects of different storage costs.

Fuel cells, to reverse this process and get the energy out of the hydrogen to 30$ /kW ~ 27€/kW with an efficiency of 70% (Parra, Valverde, Pino, & Patel, 2019; Wilson, Marcinkoski, & Papageorgopoulos, 2016). Note that in fuel cell literature a large variation exists between stationary and mobile systems. The system used in the model is stationary. However, the bulk of the system costs in stationary systems is caused by balancing the plant and storage (Eubanks et al., 2017). This is not required in the setup described in the model as batteries and storage are already included separately. Only fuel cell pack costs are relevant. Total investment costs of electrolyzers and fuel cells add up to 277 €/kW. These investment costs seem high, but can be divided over a lifetime varying from 15-20 years (>20.000 cycles) (Jamie Speirs et al., 2017; Zakeri & Syri, 2015).

Hydrogen can be stored in tanks, salt caverns or depleted oil or gas reservoirs (see figure 15). In terms of large-scale seasonal storage, the caverns and reservoirs are by far the cheapest and most suitable. Storing and distributing hydrogen is actually comparable to current natural gas storage and distribution (Dodds & McDowall, 2013). The city of Leeds is already looking at transferring their gas network to a hydrogen network including storage in salt caverns in the "H21 Leeds City Gate" project, ultimately converting all of their households to hydrogen use before 2030, with about 70 GWh storage capacity in salt caverns (H21 Leeds City Gate, 2016; Hydrogen Council, 2017). By looking at lessons learned from the relatively recent (1960-1970) transition from town gas (containing up to 50% hydrogen) to natural gas (Dodds & Demoullin, 2013), and the similarities between hydrogen and natural gas, it is concluded that the transition is both technologically and economically feasible. Stating that the biggest challenge is not technical, but the social and spatial implementation, which is still better compared to other renewable alternatives. Claiming that within three years of construction (just in summer months in which demand is low) the entire city can be converted. Although the structure of these plans is different from the system proposed in this model (hydrogen used as direct heat solution from combustion), it shows hydrogen storage and distribution using the current gas grid are technologically and economically feasible. The technological feasibility in the Netherlands is underlined by a recent study from TNO, exploring underground gas storage scenarios (Gessel, Breunese, Larré, Huijskes, & Remmelts, 2018).

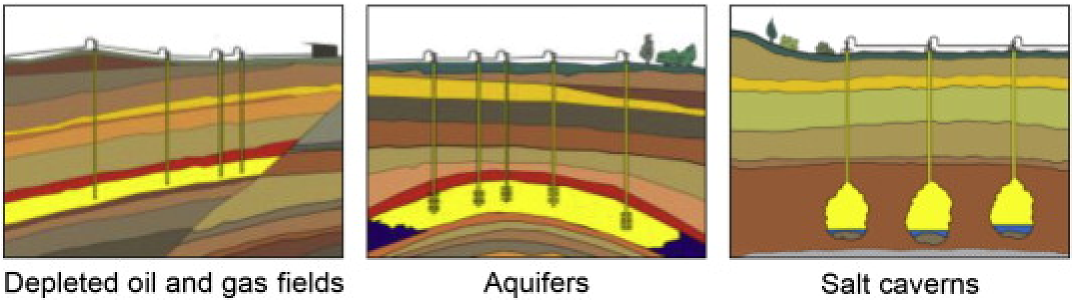


Figure 15: Underground hydrogen storage possibilities: Reprinted from (Schiebahn et al., 2015)

The predictions on price for the hydrogen storage in salt caverns or depleted gas or oil sites varies on local geological circumstances between values like 0.002 €/kWh and 0.41 €/kWh (Hydrogen Council, 2017; Steward, Saur, Penev, & Ramsden, 2009; Stolten & Grube, 2010; Wijk & Hellinga, 2018; Zakeri & Syri, 2015). Averaging out these values we assume a value of around 0.15 €/kWh. When adding up the budgeted CAPEX and fixed OPEX of hydrogen storage of the project in Leeds and dividing this by the total storage capacity the costs are 0.058 €/kWh storage capacity annually in 2030 decreasing to 0.032 €/kWh in 2050 as a result of an estimated 4% annual reduction in OPEX due to economies of scale and learning curves (H21 Leeds City Gate, 2016). Although these values are based on a wide range of research, there is still a lot unknown when deploying hydrogen on such large scales as proposed in this model. Also, most papers indicate current prices, so learning curves are not yet taken into account. As this technology and its system integration is still in an early phase of its development (with still a lot of competing technologies), accurate cost predictions are difficult to be made. However, the current assumption should lead to a clear direction of the effects of hydrogen storage to the system.

5.5. CO_2

The emissions generated per type of fuel, energy, or heat generation have been adapted from the organization '*CO_2-Emmissiefactoren*' ("Lijst emissiefactoren," 2017). This is a Dutch organization, backed by the most important stakeholders and government agencies responsible for calculating emissions per unit of energy. The emissions are calculated on an hourly basis and summed to annual aggregates. In the visual representation of the model, an annual total is displayed to immediately make sense out of the effects of certain settings.

Apart from calculating CO_2 emissions, there is also a cost attached to these. In the EU, the ETS CO_2-trading scheme is used. Current prices vary around 18-22 €/ton (September – October 2018) with a peak even above 25 €/ton in September ("Carbon Price Viewer," n.d.). However, the EU-ETS is a very politically influenced trading scheme. Trade prices will remain within an industry acceptable level as the trading cap is set by EU-politicians. Based on low levels of trust in EU regulation, PBL assumes prices varying from 15-40 €/ton in 2030 and 40-160 €/ton in 2050 (Matthijsen, Aalbers, & van den Wijngaart, 2016).

Another way of looking at CO_2 prices is calculating the required price to achieve climate goal. PBL has created two models, which result in a very broad range (Matthijsen et al., 2016). They result in a lower value of 100 €/ton in 2030 and 200 €/ton in 2050, and upper value of 500 €/ton in 2030 and 1000 €/ton 2050.

A last way to calculate to the value of CO_2 emissions is by calculating their costs. When including externalities of CO_2 emissions, the social costs of carbon (SCC) is calculated. A literature review to SCC calculations leads to range of costs with a lower bound of 125 \$/ton, medium 250 \$/ton and upper bound of 600 \$/ton. Extrapolating this towards 2050 values towards 282 \$/ton to 1,063 \$/ton in 2050. (Jacobson, Delucchi, Bauer, et al., 2017).

In other words: currently accounted costs (ETS); required prices to achieve emission reduction targets (PBL); and emission related costs (SCC) vary tremendously. Although required prices and SCC are within similar ranges. Politics and industry are not yet ready to enforce these, making the current ETS costs significantly lower. General assumptions used in the scenario analysis will include a CO_2-price of 50 €/ton, which is low when looking at large scale decarbonization (usually calculated at 2050 prices) and around the minimum value required to achieve EU wide 2030 goals (due to switching from coal to CCGT) (Lewis, 2018). Furthermore, CO_2 price has been varied amongst scenarios to investigate at what level a 100% RES could be cost competitive with the current system.

5.6. Costs

Cost have been considered for energy generation methods, storage and CO_2 emissions. To make adequate comparisons to non-100% renewable systems, transport and heating fuel costs are also considered. Making an honest comparison between all energy generation sources is difficult, as cost predictions often include different cost factors. Therefore, all cost assumptions are based on 2030 levelized costs of energy (LCOE) predictions. This excludes taxes and subsidies and CO_2 prices, and includes learning rates and discount rates. To reduce the uncertainty of these predictions, multiple sources have been combined. For the most uncertain assumptions (oil prices, CO_2 costs and hydrogen costs) scenarios comparing the expected range of costs are made. All major cost assumptions are summarized in table 7. Most of the assumptions are averages of multiple sources, further detailed in appendix D.

Learning curves, efficiency increases, and other future predictions are based on annual rates. Another often used way is calculating such curves based on installed capacity. However, the scale of Brabant is too small to have any effect on global installed capacity to really accelerate any of the learning curves or developments.

System costs exclude possible required grid improvements, increased investment costs of EV's and heat pumps (in comparison to internal combustion engine cars and gas boilers). These are outside the scope of the study, adequately researching the investment costs would mean an entire research to the transition paths, investigating when cars and gas boilers reach the end of their lifetime, when they would be replaced and what the additional costs would be.

Table 7: Cost assumptions

2030 Assumption	Cost	Unit	2030 Assumption	Cost	Unit
Natural Gas 2030	0.032	€/kWh	Batteries CAPEX	100	€/kWh
Transport All fuel average*	0.078	€/kWh	Batteries lifetime	5000	cycles
PV-utility scale	0.033	€/kWh	Electrolysis CAPEX	250	€/kW
PV-roof commercial	0.052	€/kWh	Electrolysis lifetime	15	years
Wind Onshore	0.054	€/kWh	Fuel Cell CAPEX	27	€/kW
Wind Offshore	0.059	€/kWh	Hydrogen storage (salt cavern)	0.058	€/kWh
CCGT CAPEX	925	€/kW	Heat pump CAPEX	474	€/kW
CCGT lifetime	30	Years	Heat pump lifetime	20	years
CCGT OPEX	38.5	€/kW	Gas boiler CAPEX	62	€/kW
Geothermal heat network	0.048	€/kWh	Gas boiler lifetime	15	years

5.7. Weather input

Heating demand and wind and solar power are all resultants of weather input. Extreme weather scenarios are an often-discussed topic in renewable energy systems, especially a long cold winter period (high energy demand) with low levels of wind and solar insulation. In Germany this is called a '*dunkelflaute*'. In the model KNMI data of 2017 is being used. 2017 weather patterns were not extreme but did have a relatively cold January. Even though no exact quantitive definition of *dunkelflaute* exists, Belgium has reportedly encountered 9 days of *dunkelflaute* in January 2017 (VRT NWS, 2017). An analysis about the required levels of storage in more extreme years is outside the scope of this study. However, different studies have focused on analyzing recent years on high discrepancies between energy consumption and renewable production due to weather patterns. A Dutch study found 2010 as extreme with most days of *dunkelflaute* (Pelka, 2018), while a German study found 2006 as longest consecutive period of *dunkelflaute* (Huneke, Perez Linkenheil, & Niggemeier, 2017). The difference between longest consecutive period and the greatest number of days is important for the type of storage. Longest consecutive period means that all energy in this period is required from seasonal storage, while inconsecutive days could mean inter-day storage could solve part of the deficit.

6. Verification and validation

In the ABM theory section, the method to verifying and validating agent-based methods was discussed. The first step is by explicitly describing the functionality, data and assumptions of the model as proposed by the ODD protocol (Grimm et al., 2010). This has been done in the past two chapters.

The main verification technique used is Indirect Calibration approach. Furthermore, the effect of uncertain storage assumptions is investigated. The results of this investigation are described in the storage assumptions scenario in the 'Results – Storage assumptions' section.

The Indirect Calibration approach focusses on verifying bottom-up modelled dynamics to measured aggregate statistics. Parts of the model verified by the Indirect Calibration approach are:

- Driving patterns leading to energy consumption.
- CO_2 emission calculations based on emission characteristics per technology.
- Energy generation based on weather data and technological characteristics leading to annual capacity factors.

The electricity consumption of EVs is based on driving patterns and trip distances. Each of the agents within the EV fleet has stochastically determined trip patterns. When aggregating the total annual aggregate of all trips of all EVs (in case of 100% EVs) this should align to the total amount of kilometers driven by personal transportation in the province. As these statistics are known it is an easy way to verify the stochastically determined trip patterns. The average outcome across scenarios varies between 13,366 km and 13,415 km annually. The 2016 statistics is 13,241 (CBS, 2017) resulting in a minor error margin (between 0.9% - 1.3%).

CO_2 calculations are verified by checking whether the annual aggregates of the emissions of all relevant technologies add up to current statistics. This has been further detailed by checking whether specific sector statistics such as electricity, transport or heat emissions align to the specific model outcomes, making sure these subparts of the model produce realistic results. Both these sectors align closely to the 2017 Klimaatmonitor statistics.

Similarly, the output of wind and solar energy is calculated from the basics, starting with hourly weather patterns combined with technical specifications of PV efficiency and wind turbine power curves. As a result, the capacity factors (CF) of these technologies is an output of these weather conditions and specifications. The CF can therefore be used as a measure to validate the assumptions on these specifications. Model results show a capacity factor of 36% for onshore wind and 56% for offshore wind. This is a steep increase in comparison to current capacity factors. The current average capacity factor for onshore wind in Brabant is around 19% (see table 8). This however includes old turbines and PV as well, while recent developments such as new IEC3A wind turbine models have strongly increased the average CF. Especially in relatively low wind areas which most of Brabant is. Capacity factors of new installed capacity do follow a steep learning curve. PBL for example, uses 29% for onshore wind and 48% for offshore wind in 2030 in its Climate and Energy studies (Matthijsen et al., 2016). Globally the CF for onshore wind increased by 45% between 1983 and 2017 to a current 29%. Offshore learning curves have been even more dramatic with a 56% increase between 1999 and 2017 to a current CF of 42% (IRENA, 2018). Continuing this linear trend line would result in a CF of 53%, showing that the model results are relatively high, but not out of bounds. See figure 16 as a reference for wind turbine capacity factor learning curves.

Table 8: Average capacity factors of onshore wind and PV in Brabant. Numbers deducted from annual production and installed capacity based on Klimaatmonitor (2018)

		2012	**2013**	**2014**	**2015**	**2016**
Capacity factor	Onshore wind	21%	18%	19%	18%	19%
	PV	8%	8%	8%	9%	9%

PV capacity factor learning curves have been smaller, mainly due to technical choices focusing on higher inverter load ratios which decrease LCOE but also negatively influence the CF. Also PBL is less optimistic about PV's learning curve, using a CF of 10% in 2030 (Matthijsen et al., 2016). Globally the learning curve has resulted in a 28% growth between 2010 and 2017, resulting in an average CF of 17.6%. However, as the CF of PV rises dramatically with more sun and a most of the annual increase in PV is done in very sunny regions, this does not compare to Brabant. The current average CF in Brabant of total installed capacity is 9% (table 8). The model shows a relatively modest increase towards an average CF 12% in 2030. This could easily be achieved by technical progress in PV technology itself (ITRPV, 2018), or system improvements like trackers (IRENA, 2018).

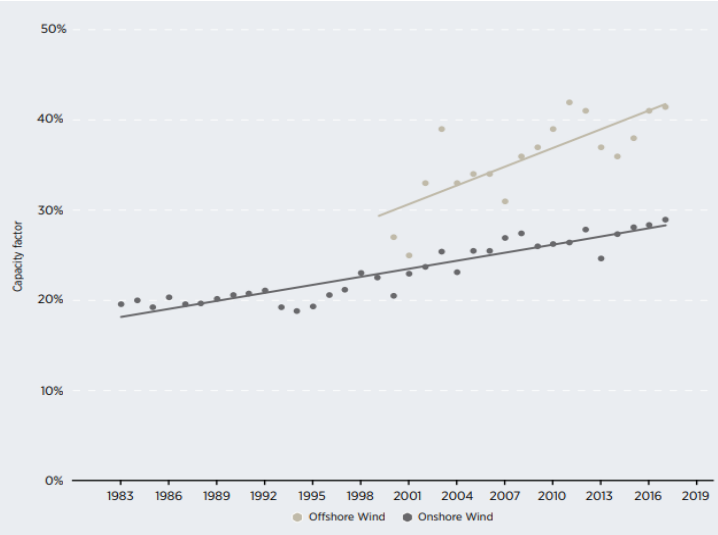


Figure 16: Global weighted average capacity factors for new onshore wind power capacity additions by year of commissioning, 1983-2017. Reprinted from '"Renewable power generation costs in 2017" (P102) (IRENA, 2018).

Capacity Factors (model results)

PV roof commercial	12%
PV utility plant	12%
Wind onshore	36%
Wind offshore	56%
CCGT	*48% - 66%

*Scenario dependent based on energy demand

7. Analysis

A structured way to analyze complex, multi-variable models is to create scenarios. This chapter describes a number of scenarios and on what grounds these where chosen. The main output factors are annual and per kWh system costs and CO_2 emissions. The scenarios are not just focused on optimizing these techno-economic factors, but also take social and political factors into account.

7.1. Scenarios

In this analysis multiple scenarios are simulated. Those scenarios function as hands on examples of different technologies and dynamics in the energy transition. The objective of this analysis is to show the effects of these technologies. This is done by starting with a 'current' scenario, followed by an increase in renewable energy sources and electrification technologies towards a 50% sustainable electricity and a 50% sustainable energy scenario. Furthermore, multiple designs of 100% renewable energy systems are analyzed, focusing on the differences between renewable energy technologies. These differences are exaggerated for illustrative purposes in scenarios in which all energy is generated by either gas turbines, wind or solar. Lastly, three optimized scenarios are analyzed. The first showing what would happen if the province was required to generate all its energy within its boundaries, serving as an autarchic province. This scenario connects to the provincial policy makers struggle to count on offshore wind, as this is outside their jurisdiction. The other optimized scenarios are a (manually) cost optimized scenario and a scenario showing the socio-economical potential when balancing between social and economic factors. The criteria of socio-economical optimization will be further explained in the dedicated section. The scenarios mentioned enable a detailed analysis of multiple energy generation sources. Parameters excluding electricity generation have been maintained constant (see table 9) to ensure a fair comparison between these sources.

Table 9: General baseline parameter settings used in all scenarios unless explicitly mentioned otherwise

Transport fuel price	0.076	€/kWh
Hydrogen storage costs	0.058	€/kWh
Battery storage costs	100	€/kWh
CO_2-prices	50	€/tonne
Smart charging	*selected*	n.a.
*District heating	10	PJ
*Heat pumps	79.1	% of total heat demand

* In case of 100% electrified scenarios

In the next scenarios the focus of analysis will shift from electricity generation methods to heating, smart charging, storage assumptions and CO_2-prices. First, heat pumps are compared to district (geothermal) heating. Second, the effect of smart charging in comparison to ordinary EVs is examined. Third, the assumptions regarding battery and hydrogen storage are investigated in a high, medium and low-cost configuration.

The last focus of analysis is the percentage of renewable energy generated. Comparing the 2030 and 2050 targets of 50% and 100% renewable energy to a forecast of renewable energy production. With the help of domain experts on PV and EV adoption, trend reports and policy plans of renewable energy diffusion, assumptions on the growth of renewable energy have been made. This ultimately shows the discrepancy between policy goals and current growth and deployment plans.

See table 10 for an exact description of the scenarios and appendix E for a list of input parameter settings per scenario.

Table 10: Scenario characteristics

Scenario	**Characteristics**
Current	Approximations of current renewable electricity generation. All non-renewable electricity is generated by CCGT. Cost and efficiency parameters are already set at 2030 levels.
50% Renewable electricity, 25% renewable energy	Renewable energy generation levels set on obtaining approximately 50% renewable electricity and 25% renewable energy. Storage is already required to bridge summer and winter gaps. All electricity is still generated within Brabant, so no offshore wind.
100% Renewable electricity, 50% renewable energy	Shows the effects of a 100% renewable electricity system with storage. However, electrification of other energy carriers is not yet complete, thus heat and transport still consume non-renewable energy.
100% Gas	To compare to other 100% renewable scenarios. What would hypothetically be the cost of gas in an all-electric, all-gas scenario.
100% Wind	What if all energy was generated by wind. What would be the required amount of offshore wind capacity taking the limited capacity within Brabant into account
100% Solar	What if all energy was generated by solar. This serves as an extreme to show the levels of storage required to bridge the intraday and inter-seasonal differences in PV production
100% Cost optimized	A manually cost optimized scenario. By running numerous simulations an approximately optimal mix has been determined. Solar is still relatively cheap as storage costs are not prominent yet.
100% Socio-economically optimized	Space is limited. Especially onshore wind is often faced with a political hurdle. Offshore wind is not ideal either for a landlocked province. However, costs should remain within acceptable limits. Is there an optimum taking all these points into account?
CO_2 pricing	What will be the cost differences if the social costs of carbon are considered? The current CO_2 price is still relatively low but future increases can be expected.
Renewable heat	An analysis of the differences between heat pumps and district heating.
Smart Charging	An analysis of the effects of smart charging, in comparison to the ordinary EV load.
Storage assumptions	Storage required at the proposed scale has never been done before. Especially developments around seasonal storage are still in an early phase, making price assumptions highly uncertain. Therefore, the effects of the current price range are investigated.
Projected growth	In these scenarios the projected growth trajectories of wind, PV, EVs and heat pumps are analyzed. Based on expert knowledge, government plans and forecast studies a prognosis of the future energy mix in 2023 and 2030 has been made. The main goal of this is to show the discrepancy between policy goals and forecasts.

7.2. Output

Once the energy system is modelled, a wide range of analysis and output variables is possible. Scenarios output is measured using 54 output variables, ranging from technology specific consumption, production, costs and emissions to general sector or overall system indicators (see Appendix F for all scenario outputs). The most important output measures are CO_2 emissions, total annual system cost and costs per kWh final energy demand. These last two vary from each other as the total energy consumption varies per system design (based on level of electrification and conversion losses). The cost output variables represent the costs of generating all the required energy to create a balanced system including, non-renewable sources and added investment costs for heat pumps and EVs on top of current heating and transport solutions. They exclude transmission costs and the added costs for increased energy efficiency such as improving built environment insulation and industry efficiency. It is important to note that all scenarios except for the last projected growth analysis are based on 2030 assumption regarding costs and energy efficiency. In other words, most of the scenarios are explicitly no future forecasts, they merely compare different system designs based on forecasted assumptions to analyze the effects of different system choices.

8. Results

In this chapter the results of the aforementioned scenarios will be analyzed. Furthermore, the research question regarding models as a tool for comprehensive yet engaging policy making is answered.

One key notion that is important to correctly compare scenarios is the difference between primary energy consumption and final energy consumption. Figure 17 displays the difference in energy consumptions amongst the scenarios. There are two main effects to explain the reduction in energy consumption across the scenario. The first is a reduction of primary energy consumption, the other of final energy consumption. Primary energy consumption measures the total energy demand of the province, including conversion losses by the energy sector itself. Final energy consumption includes just the amount of energy consumed by consumers.

The reduction of primary energy consumption across the scenarios is due to this definition. Generating electricity by fossil fuels always result in conversion losses. These conversion losses are the difference between primary and final energy consumption. As renewable sources like wind and solar directly generate electricity, they do not have conversion losses. This explains the reducing difference between primary and final energy consumption across the scenarios (except for the 100% gas scenario of course) in figure 17.

The reduction of final energy consumption is because of the efficiency gains that encompass the electrification of heat and transport. Both are several times more efficient than their fossil fueled alternatives. In energy designs with a lot of fossil fuel generated electricity this difference diminishes due to the increase in primary energy demand (see the 100% gas scenario). However, in case electrification is combined with renewable electricity sources the primary energy consumption is more than halved (52% reduction).

Final energy consumption is just shy of being halved (49% reduction) as the storage requirements of high levels of renewables result in conversion losses. Especially scenarios with high levels of PV (see the 100% Solar and In Brabant scenarios in figure 17) result in large amounts of storage, thus relatively large amounts of conversion losses, thus a higher primary energy consumption. Albeit less than the fossil fuel powered scenario of 100% gas.

The difference between primary and final energy consumption, and how they are affected by renewables and electrification of heat and transport is important as it explains the difference between total energy system costs (figure 18) and energy costs in €/kWh (figure 19). This might seem trivial but is often overlooked and has a highly important implication. Often energy scenarios are judged based on €/kWh costs based on dividing system costs by final energy demand. However, as highly electrified systems are more efficient, their final energy consumption is relatively low, making their €/kWh costs relatively high without realizing far less energy is required. This makes an unjust comparison to the actual system costs. Therefore, further cost comparisons are based on annual system costs.

The following pages show the most important graphs. The scenarios are compared on the basis of these graphs. For an easy comparison, first all graphs are displayed. The structure of the results is based on the scenarios. During the explanation of the scenario results the figures will be further referenced.

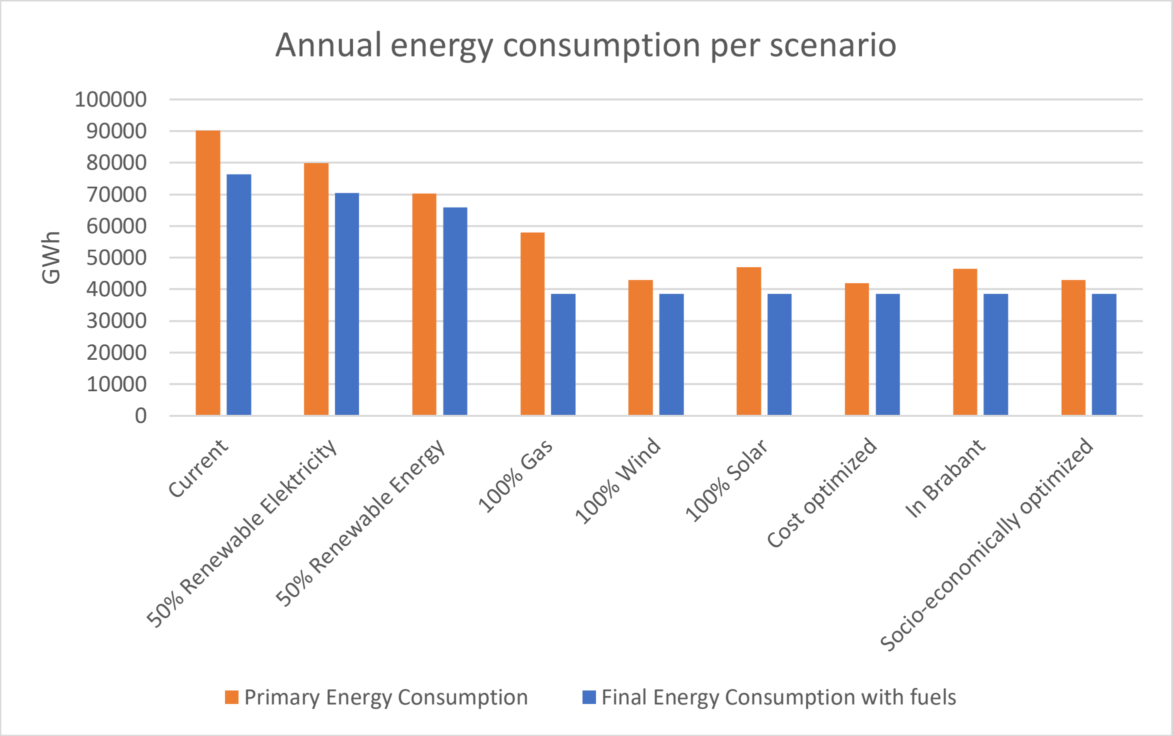


Figure 17: Annual Energy consumption in different scenarios in GWh. Showing the effects of electrification.

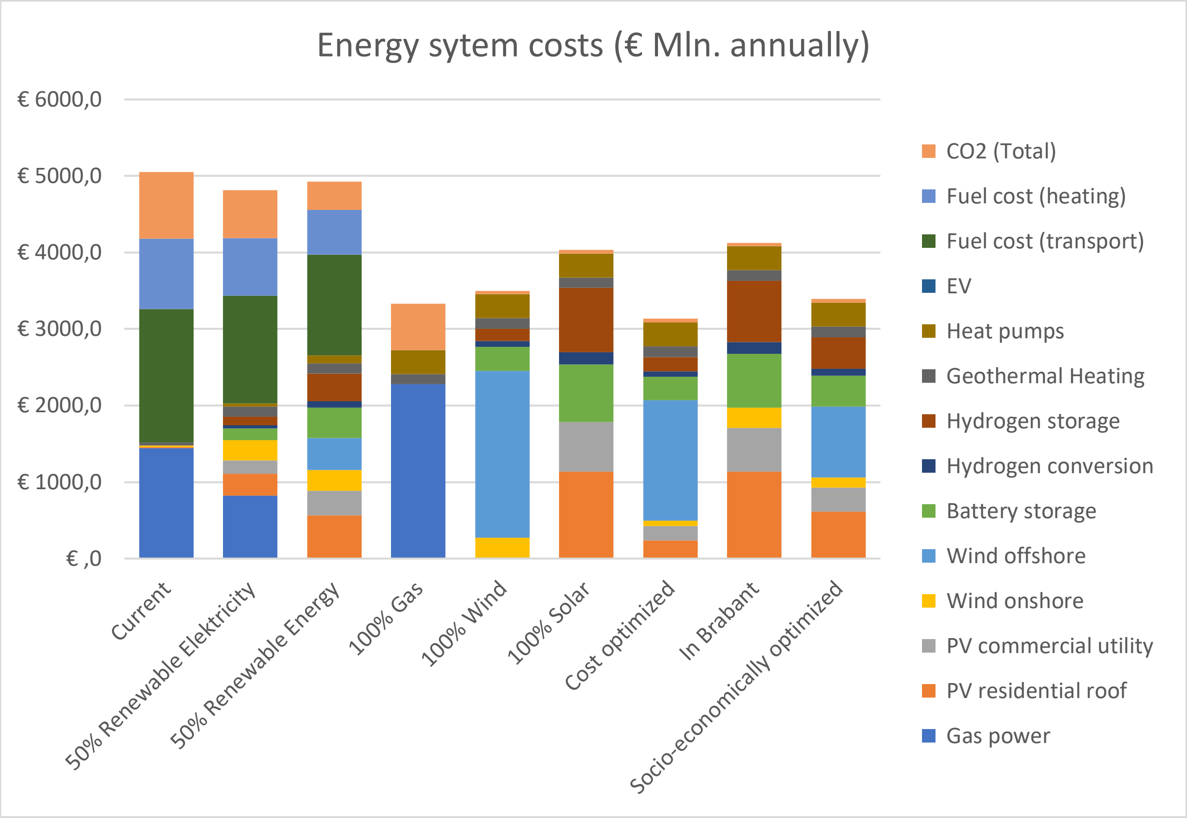


Figure 18: Energy costs of different scenarios (in Mln. € annually)

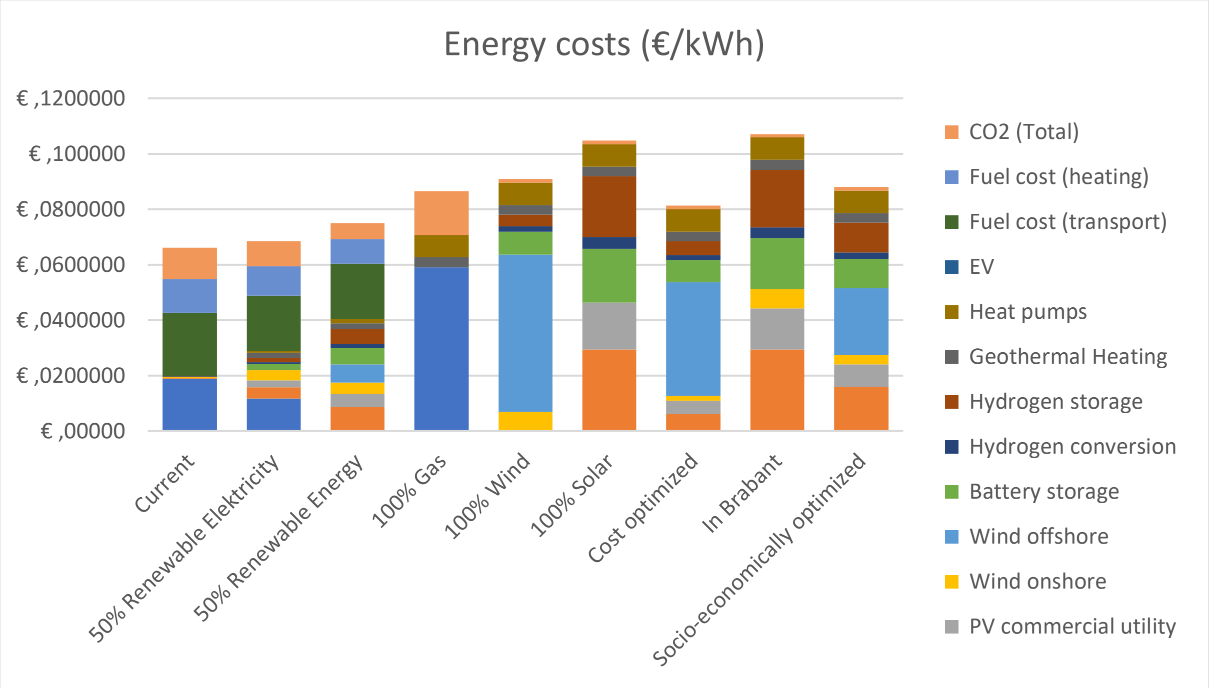


Figure 19: Energy costs of different scenarios (in €/kWh)

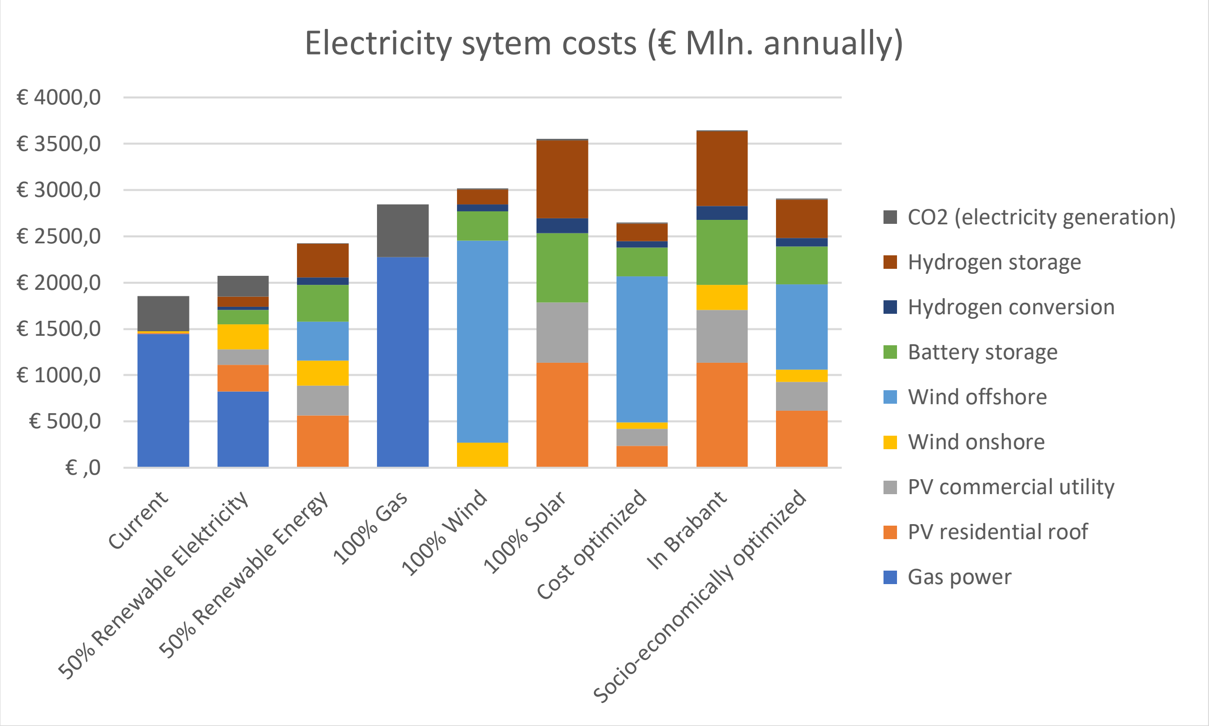


Figure 20: Electricity annual system costs (in Energy costs of different scenarios (in € Mln. annually)

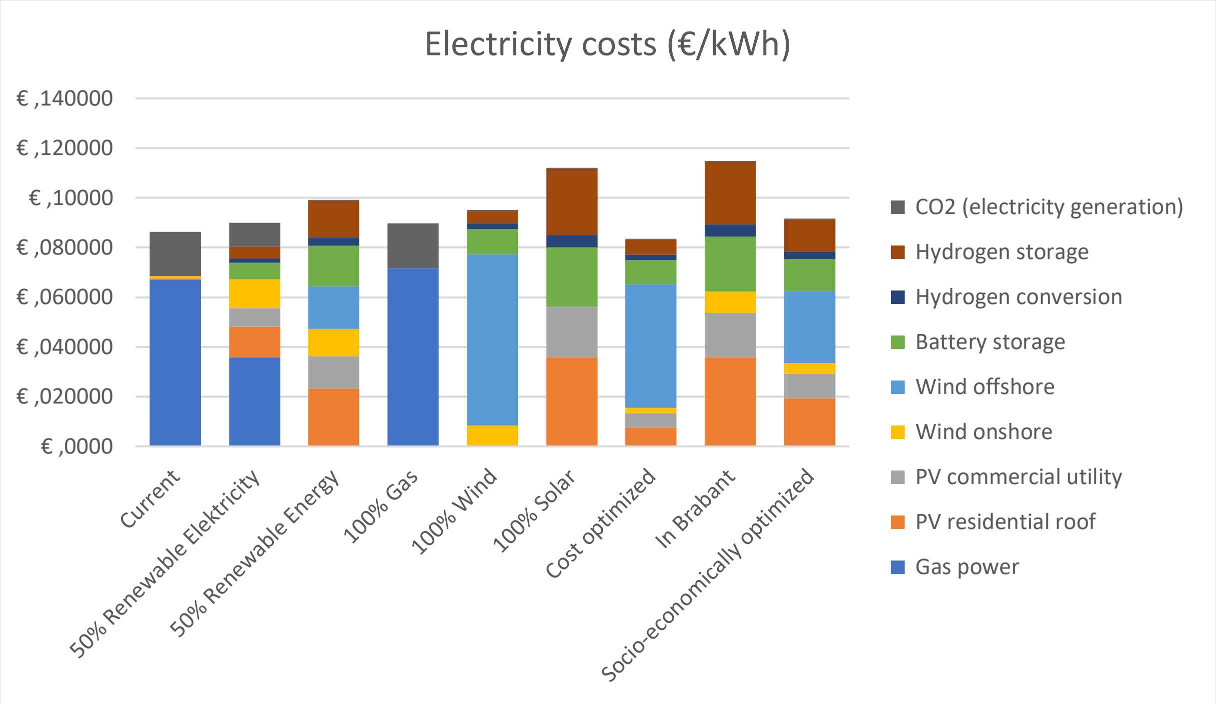


Figure 21: Electricity costs (in €/kWh)

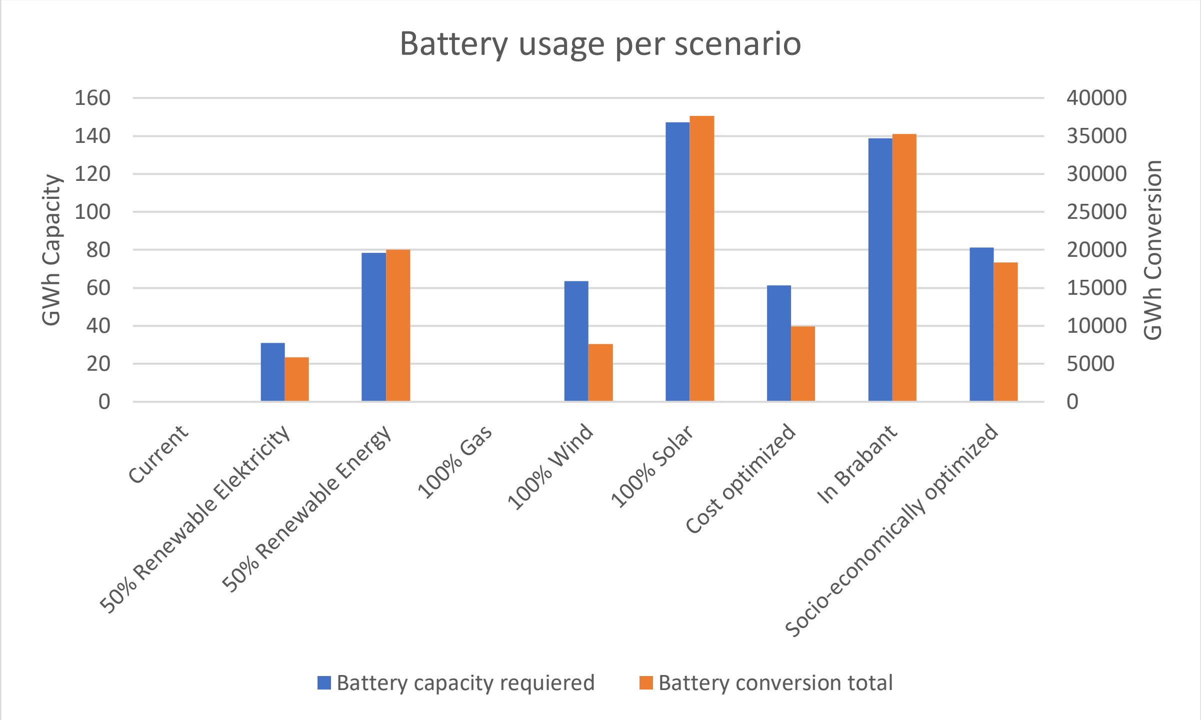


Figure 22: Battery required capacity and total conversion per scenario (MWh annually)

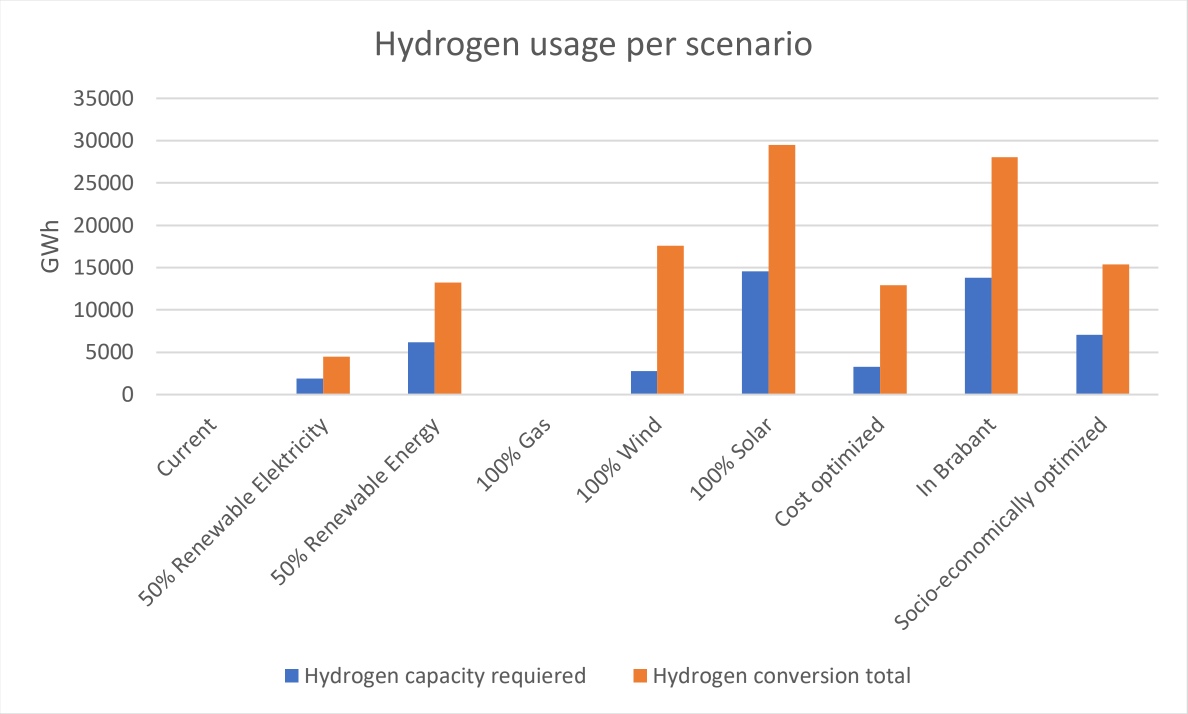


Figure 23: Hydrogen required capacity and total conversion (in MWh annually)

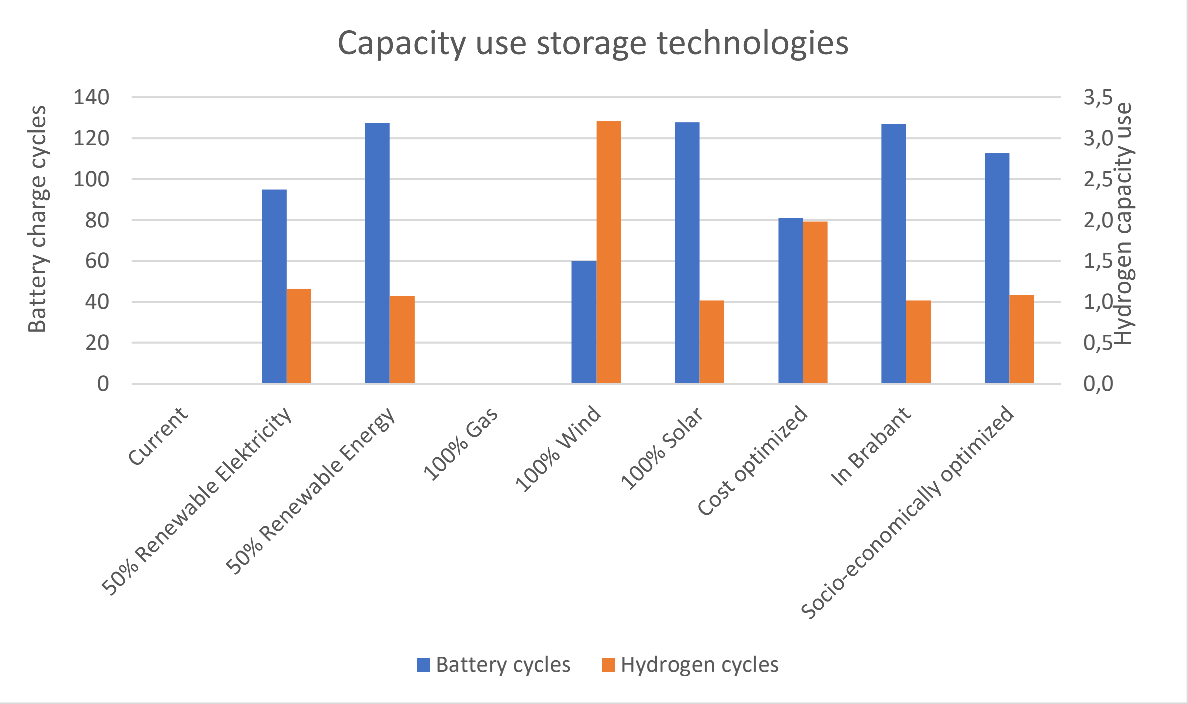


Figure 24: Capacity use of batteries and hydrogen. Batteries in the number of fuel charge cycles annually and hydrogen in the similar number of how capacity usage (Annual conversion divided by required capacity).

8.1. Current

The first three scenarios show the transition phases from current levels of renewables to a 100% renewable system. The ‘current’ scenario shows what happens with current amounts of renewable energy generation at 2030 price assumptions. Current renewable energy is still a small fraction of the final energy demand. Wind and solar contribute to about 2% of Noord-Brabant’s final electricity demand. Looking at final energy demand renewables make up around 7% due to a larger contribution of renewable heat from residual, geothermal or biomass sources. Storage is not yet required at these levels of renewable supply.

Looking at 2030, natural gas and transport fuels will increase in price, making the non-electrified scenarios in general more expensive. Furthermore, CO_2 prices at 50€/ton add another €868 million. The total costs add up to €4,981 million, which is (averaged out over fuel, gas and electricity) 0.065 €/kWh. This €/kWh price is somewhat misleading as fossil fuel transport and heating is inefficient, creating a higher energy demand, thus a lower price per kWh. In terms of electricity prices this scenario is the cheapest off all when CO_2 prices are excluded, at 0.069 €/kWh. When a carbon tax of 50€/ton is added, electricity prices reach up to 0.086 €/kWh.

The difference between electricity and energy prices and primary energy consumption is a notion with significant influence. Energy will be more expensive per unit which could cause resistance, however, multiplying this with the required energy results in a reduction of total system costs. Thus, lower costs per household can be expected.

Looking at CO_2 emissions this scenario results in 17.4 Mton of emissions. This already is a reduction of 18% in comparison to 2015 emissions. Because of the name of this scenario it is confusing that current emissions are reduced by 18% in the ‘Current’ scenario. This can be explained by the fact that in 2030 it is assumed all non-renewable electricity will be generated by gas, which is far cleaner than coal or the average of currently generated electricity. This significant reduction is an important implication for energy policy. When focusing on CO_2-reduction, which is the ultimate goal of the energy transition, pragmatically shifting to less polluting fossil fuels (in opposition to renewables) is already an important step. This can be a fast and relatively easy way to achieve climate goals.

Conclusion 1: The most important lesson from this scenario is the fact that just shifting from coal to gas leads to a significant reduction of CO_2 emissions.

8.2. 50% Renewable Electricity

The two main pillars of the energy transition in this research are; renewable electricity and electrification. In this scenario both attain significant amounts at 50% renewable electricity and 25% renewable energy. Although this is just halfway the 2030 goal, it is a huge step already as it requires 33 times the amount of renewable electricity currently generated. In other words, to achieve these goals the renewable energy technologies should be deployed at a tremendous pace.

Daily and seasonal storage are already required in substantial amounts, 31 GWh of battery storage and 1,919 GWh of hydrogen storage in this case. The results are slightly higher electricity prices in comparison to the ‘Current’ scenario at 0.090 €/kWh. This is important as it shows that renewables can compete with gas for electricity generation, even at levels including a substantial amount of storage. Due to the reduction in transport and heating costs, the total system cost excluding CO_2 prices is comparable to the ‘Current’ scenario (around €4,2 billion). Significant cost reductions occur when taking CO_2 prices into account. The reduced emissions result in a cost reduction of €238 million in comparison to the ‘Current’ scenario at 50€/ton.

Note that this scenario is not cost optimized, other parameter settings could result in lower costs for a 25% renewable energy, 50% renewable electricity scenario. Especially the configuration between renewables and gas turbines could be better optimized, potentially further reducing the electricity price to make it even more competitive.

Conclusion 2: Renewables can compete with gas on electricity prices in a 50% renewable electricity scenario, especially when taking a CO_2 price into account.

8.3. 50% Renewable Energy

This scenario would fulfill the renewable energy goal of 2030, showing high levels of renewables while acknowledging that electrification is not always evident, especially high-temperature heat or long and heavy transport require high energy density. Therefore, the scenario shows a full renewable electricity sector, whilst heat and transport are lagging in terms of renewable energy and electrification. Storage requirements grow exponentially. In other words: The last part is the hardest part in renewable electricity systems. Due to a steep increase in storage requirements to be able to supply energy at all times, this is according to the expectations. See figures 22 (battery) and 23 (hydrogen) for the rise in storage requirements comparing the 50% renewable electricity to the 50% renewable energy scenario.

The results show similar trends as the 50% renewable electricity scenario. Electricity prices rise up to 0.099 €/kWh, while total system costs are reduced in comparison to the ‘Current’ scenario. However, in comparison to the 50% renewable electricity scenario, total system costs rise. The added storage costs are higher than the reduction in CO_2-costs leading to a more expensive scenario. Total system costs are second highest of all scenarios at €4,928, only trailing the ‘Current’ scenario at high CO_2 prices.

Note that this scenario is not cost optimized. In other words, the share of solar and wind is not optimized with regard to reducing storage. Instead, the full potential of onshore wind, and large numbers of solar are complemented by a relatively small amount offshore wind to ensure a balanced, fully renewable electricity sector. Furthermore, this scenario shows the effects of a rapid growth in renewable electricity, while the electrification of renewable heat and transport lags. This is not the cheapest way to attain 50% renewable energy.

This scenario shows two implications for the climate goals. First, the scenario is focused on achieving the goal on renewable energy. However, achieving a 50% reduction of CO_2 emissions is much easier. At 50% renewable energy the CO_2 reduction is already 65%. Second, although 50% of the energy consumption in this scenario is generated by renewable sources, already all electricity is. The amount of sustainably generated energy is already at 84% of the amount required in the 100% sustainable cost optimized scenario. This can be explained by the efficiency gains of electrification, which are lagging in this scenario. The final energy demand will decrease sharply upon achieving a 100% RES. Thus, from this point on all focus of the energy transition should be put in electrification. In other words: When the share of renewables rises rapidly, electrification should follow closely.

Conclusion 3: When making policy towards the 50% renewable energy target, focus should be applied on both renewable energy sources and electrification of current demand.

8.4. 100% CCGT

This scenario is for comparison only. Where the previous scenario shows full focus on renewable electricity sources, this scenario fully focusses on electrification of transport and heat. The benefits of electrification are separated from renewable electricity generation. This hypothetical scenario is a 100% electrified energy system fully run on CCGTs. It is interesting as it results in the lowest system costs excluding CO_2 prices. With the lowest final energy demand due to the high levels of electrification and no storage thus no conversion losses. At just 38,537 GWh the final energy demand is reduced by 50% in comparison to the 'Current' scenario. This is caused by electrifying transport 100% and heating to 79.1%, while both are around 4 times more efficient as their fueled counterparts. These same electrification levels are being used in all the other 100% renewable energy scenarios except for the renewable heating analysis.

Looking at costs excluding CO_2, this scenario is the cheapest of all at €2.7 billion. When taking CO_2 emissions into account at a price of 50€/ton the cost rise to €3.3 billion, and 100% renewable scenarios can already be cheaper. It must be noted that even though electrification is very beneficial. It will be accompanied by external costs not considered in this model such as home insulation and adapting industrial processes. In certain sectors (e.g. new houses and new (2030) cars) this not a problem. However, more difficult sectors such as high-temperature heat and other large heating demands do pose large addition costs.

A last important result from this scenario is the CO_2 reduction at 43%. This shows that in reducing CO_2 priority should not only be given to renewable energy technologies. By reducing energy demand due to electrification, and using a relatively clean fossil fuel, the 2030 emission reduction goals come well into sight.

Conclusion 4a: Electrification in road transport and low-temperature heat is one of the most beneficial parts of the energy transition.

Looking at these conclusions from an analytical socio-economic point of view has interesting implications. Converting from a fuel based to an electricity-based system implies a shift in balance between incumbent companies. Electrification seems highly efficient; however, transition costs hinder the introduction of these technologies. Incumbent companies in non-electrified sectors will suffer big losses if they are unable to shift along. Electricity generation companies will for example substitute oil companies as EVs lift off. As electrification is a threat to these companies, they are less probable, even though electrification is highly beneficial to the society as a whole. Although they do require shift in government spending as large-scale electrification diminishes the income on fossil fuel and energy excise taxes.

Conclusion 4b: From a socio-economical point of view, electrification is difficult as it substitutes the powerful incumbent regimes of oil and gas companies.

8.5. 100% Wind

The first 100% RES of this analysis. All non-renewable heat and transport is electrified, and all energy is generated by renewables. This extreme 100% wind scenario shows the effects of wind power in a renewable energy system. For a balanced system Brabant would require 881 (7GW) offshore wind turbines, next to the social and spatial maximum of 388 onshore wind turbines. Although this sounds like a lot, it is spatially possible looking at the already envisioned 60GW of offshore wind capacity scenario by PBL (Jan Matthijsen et al., 2018).

In comparison to 100% CCGT the costs are higher. The base costs of wind per kWh are already higher, which is increased by the storage costs. When taking the CO_2 price into account this scenario costs €3.5 billion annually, €170 million more than the 100% CCGT scenario. Total storage costs add up to €552 million, 16% of the total energy costs.

Another interesting finding from this scenario can be deducted from the figures on required storage capacity and how efficient this is used (figures 22 and 23). This can best be done by looking at the annual number of charge cycles of storage technologies (figure 24). Cycles are the required capacity divided by total annual conversion. In this scenario batteries have 60, and hydrogen 3.2 full charge cycles annually. These figures are compared to the 100% solar scenario discussed in the next section.

In terms of CO_2 emissions one might expect that this scenario results in zero emissions. However, still 0.96 Mton is emitted, resulting in a reduction of just 95%. This is a result of the CO_2 emissions as a result of the fractions of biomass, bio-digestors and heat networks ("Lijst emissiefactoren," 2017) and the emissions related to constructing and installing wind turbines and PV-panels. In a fully renewable society these emissions will reduce due to a reduction in supply chain emissions. However, it is important to realize that achieving a fully carbon neutral environment would still be a challenge and probably require some compensation even within the energy sector.

All following scenarios except the renewable heat comparison have relatively similar CO_2 reductions (95.4%-95.5%). In terms of CO_2 emissions, the scenarios are interchangeable. Therefore, CO_2 reductions will not be further discussed in these scenarios.

Wind is a difficult subject from the province's perspective. It generally reduces storage requirements in comparison to solar and is therefore cheaper. However, onshore wind is accompanied by a lot of social and political opposition, while offshore wind is outside of the province's territory. This is a good example of where techno-economic and socio-economic analysis collide. Politicians should be given the tools to make informed decision between the techno-economic advantages and socio-economic disadvantages of wind.

Conclusion 5: Wind is techno-economically speaking most suited to generate large shares of renewable energy. However, onshore wind is hampered by socio-economic factors (spatial planning and social opposition).

8.6. 100% Solar

The other extreme is the 100% solar scenario. By analyzing these two extremes (wind and solar) we can compare the effects between both energy sources. 100% solar results in the most storage intensive scenario, due to the large day-night and seasonal differences in solar insolation. This scenario is not possible within the spatial and societal limits in Brabant. As explained at the PV assumptions and in '*Brabant op 100% wind, water en zon*' (Hoekstra, 2018), farmland is excluded from the spatial potential. If this is included, it would be possible. Daily storage capacity adds up to 147 GWh and seasonal storage capacity to 14534 GWh, respectively a 2.4 and 4.5 time increase in comparison to the cost optimized scenario. This is reflected in the energy demand and price. The roundtrip efficiency of hydrogen is assumed at around 58%, explaining the peaks in primary energy consumption (See figure 17). It is important to realize this when analyzing the cost structure (figure 18-21), as not only storage costs rise due to increased storage capacity, electricity generation costs rise as well due to increased required capacity because of conversion losses. All together this leads to a total cost of around €4 billion annually, which is over half a billion more than the 100% wind scenario and even €0.7 billion more than the 100% CCGT scenario. Storage costs more than triple in comparison to wind (€1,754 versus €552 million).

As PV requires most storage, this scenario is the most storage intensive. In comparison to 100% wind, battery storage is 2.4 times more expensive and hydrogen even 5.3 times. This difference relates to the earlier mentioned point about storage efficiency in annual number of charge cycles (figure 24). Where wind uses hydrogen capacity relatively efficient, PV uses battery capacity relatively efficient. This scenario has 127 charge cycles annually, which more than doubles the 60 of the 100% wind scenario. Hydrogen shows the opposite trend, with just 1.015 charge cycles in the 100% solar scenario in comparison to 3.2 in the 100% wind scenario. This is because almost all required seasonal storage is due to reduced solar radiation in winter, thus hydrogen capacity is completely filled in summer and used in winter. Even on sunny winter days PV production rarely covers or exceeds demand, as solar radiation decreases and (electric) heating demand increases. Making seasonal storage a back-up for the entire winter shortage. Wind has less seasonal differences, thus hydrogen is produced in windy periods and used in non-windy periods, which vary more widely throughout the year. This notion, combined with the ratio of production costs between PV and wind, creates the dynamic that a cost-optimum is a smart combination of these sources.

Conclusion 6: PV itself is relatively cheap, but results in high storage costs. As storage requirements for wind and solar oppose, mixing them is the optimal solution. The goal is to find the balance between the utilization of batteries and hydrogen.

8.7. 100% In Brabant

One of the requests of the province's policy makers was to find out if it was possible to produce all energy within the province's borders. As the province is landlocked, claiming offshore wind is politically sensitive. In this case Brabant is a completely autarchic province, generating, converting and storing all its energy locally. The research by '*HNS*' landscape architects on the province's spatial and social capacity of energy generation has set the limits on spatial availability. Combining this in the most efficient system to reach 100% renewable electricity has resulted in 388 onshore wind turbines, a maximum of 10,676 hectares (15 GWp) of PV-plants (based on a spatial optimum from the province perspective, so excluding retrofitted farmland) and 12,000 hectares (20 GWp) of PV on roofs (92% of the potentially available capacity).

Although this result might be politically desired, it is financially the worst. With a total annual energy cost of €4,.1 billion it is almost one billion more expensive than the cost optimized scenario and even €92 million more expensive than the 100% Solar scenario. Storage costs are slightly reduced but do not compensate the added costs of onshore wind. Note, that onshore wind is less efficient in reducing storage than offshore wind. The capacity factor is almost twice as high for offshore wind in comparison to onshore wind. Wind speeds lower than the turbine's cut-in speed (at which it can start working) occur less often offshore, making these turbines less intermittent. Thus, they have less storage requirements.

On top of the 100% In Brabant scenario a scenario is tested in which the entire spatial capacity is used by installing a total of 13,028 hectares (17 GWp) of PV on roofs. In this maximum case the province would be able to produce 107% of its energy use making it a net energy exporter, however, at the high costs (0.115 €/kWh electricity) this is highly unlikely. A more cost-efficient scenario is achieved by adding offshore wind, which is described in the following section.

Conclusion 7: A self-supporting 100% province is technically possible. However, it is economically and socially unfavorable in comparison to efficient, cheap and out-of-sight offshore wind.

8.8. Cost optimized

The cost optimized scenario is derived from manually adjusting parameter settings of renewable electricity generation methods. At low cost scenarios the optimum depends on when the added costs of storage as a resultant of additional PV, outweigh the initial costs difference between PV and wind. Focusing on wind, onshore is cheaper per kWh, however, requires more storage due to less stable winds, thus in high quantities of onshore wind becomes more expensive. As a result, 100 onshore and 637 offshore wind turbines are used. PV-types are not cost-optimized, as this would be highly unrealistic looking at current installed and planned capacity. In general, it would be cheapest to use big, commercial plants only, as installation costs (and therefor LCOE) are cheaper. Instead a compromise has been chosen at 2500 hectares (4.25 GWp) of roof-mounted PV and 3500 hectares (5GWp) of PV-plants. These numbers add up to around 62% of all energy being generated by wind (of which 95% by offshore wind) and 23% PV (the remaining 15% is made up of biomass, waste heat and geothermal heat). This shows that the most cost-efficient mix heavily depends on offshore wind.

The results of this scenario are promising in terms of 100% renewable energy systems. At €3.1 billion annually this is the cheapest of all scenarios, almost one billion cheaper than the 'in Brabant' scenario, and even close to €200 million cheaper than the 100% CCGT scenario. Although storage costs are €14 million higher than the 100% wind scenario, cheap solar makes up for it. Electricity costs are 0.084 €/kWh, showing that 100% RES does not have to be expensive. Of course, grid costs are not yet being considered. However, by placing the batteries and hydrogen storage and converters smartly while taking local consumption and generation patterns into account, current infrastructure utilization can be optimized and costs reduced. This makes a 100% RES eminently possible without having to integrate non-renewable baseload or ramping technologies such as gas peaker plants, biomass or nuclear (either big plants or small modular reactors (SMR)).

Note that in 2030 in general electricity will be a more expensive than currently. This holds for both, renewable and non-renewable scenarios. However, this scenario shows the potential rise is limited Current electricity prices (although volatile) lie between 0.04-0.06 €/kWh (day ahead market). However, add up the new renewable energy tax (*Opslag Duurzame Energie*) of around 0.02 €/kWh and the difference already reduces greatly (although it must be noted that industrial consumption has very different tax ratings). For consumers, electricity will be more expensive on a per kWh basis, but the difference is small. Furthermore, the efficiency gains more than make up for this.

Conclusion 8: A cost-optimized 100% renewable energy system would be the cheapest option for the province of Noord-Brabant. It is based on large scale electrification, high shares of wind (over 60% of all energy generation) followed by a big share of solar (23% of all energy generation).

8.9. Socio-economical potential

Cost optimization is the most often used criteria in assessing 100% RES models. However, the energy transition is of course shaped by far more inputs than just the financial ones. This model takes spatial, social and political limitations into account by having spatial maxima in wind and solar generation. Considering these factors in the analysis is difficult, as they are often subjective. This scenario relates to one of the original goals of the model as a tool for politicians. The goal of this scenario is to show the potential of stepping away from the cost-optimum, and taking political and societal stakeholders into account. The tradeoff is mainly between PV within the province or offshore wind. Furthermore, cost increase can remain limited as long as energy sources are sufficiently mixed, as this reduces required storage capacity.

Assumptions are set on using half of the societal and spatial maximum completed by offshore wind. Resulting in 6,514 hectares PV on roofs (11 GWp), 5841 hectares PV plants (8 GWp), 194 onshore wind turbines (0.8 GWp) and 372 offshore wind turbines (3 GWp). This way two-thirds of the primary energy demand is generated within the province without having to use every possible identified location, which would likely lead to social and political resistance. In terms of installed capacity, onshore wind is attainable, as current 2020 goals are already set on 0.47 GWp (RVO, 2018). Also, offshore wind is feasible, 3 GWp is slightly under the current total capacity (CBS, 2018c), however, big growth factors are targeted (Jan Matthijsen et al., 2018). PV requires a far higher growth rate. Currently just 2.8 GWp is installed in the Netherlands (CBS, 2018b), while a total of 19.5 GWp is required in this scenario.

Even though the scenario is not cost optimized, it is only €60 million more expensive than 100% CCGT (incl. CO_2 prices). In comparison to 100% In Brabant costs are reduced by €736 million annually (18%). It is €259 million more expensive than the cost optimal scenario, in which just 40% of all energy is generated within the province. Energy costs increase 8% in comparison to the cost optimized scenario, which is more significant in terms of electricity costs resulting in an almost 10% increase to 0.092 €/kWh. These values would form a good basis for a social cost-benefit analysis, adding the costs of societal and spatial effects of renewable energy. Furthermore, it begs the question: Who is going to pay for the 10% increase in comparison to the cost optimized scenario in electricity costs?

The goal of this scenario is to find a balanced mix, not only in terms of costs, but also politically. As seen from the discussion session in which the model was used, politicians all have their own norms and values. However, by showing spatial, societal, climatological and economic output in one model, political discussion can really be focused on these differences in norms and values. This focus enables politicians to get into a constructive dialogue, instead of debates on different assumptions, understandings and scenarios.

Conclusion 9: As long as there is a balanced mix of wind, PV and storage, costs do not rise dramatically compared to fossil fuel scenarios, when stepping away of the techno-economic optimum. This creates room for other criteria apart from economic effects. Models can show the costs and benefits of these criteria, enabling policy makers to make well-informed choices.

8.10. Renewable heat

TNO has calculated that, within certain criteria until 3km depth, there is approximately 85.000 PJ of potentially profitable recoverable heat om the Netherlands. Comparing this to the 115 PJ of assumed heat demand in Brabant in 2030, the potential is obvious (Kramers, Wees, Pluymaekers, Kronimus, & Boxem, 2012). Although heating is not the main focus of this model, a comparison between geothermal based heat networks and on heat pumps powered by renewable electricity is made. Heat generation from residual biomass and bio-digestion is capped at absolute waste stream values. The remaining part of the heat demand is covered by the variable heating sources: Heat networks (geothermal complemented with residual heat); heat pumps and non-renewable gas boilers. Two extremes of renewable heating have been simulated, one in which heat networks fulfill the entire resulting demand and another in which this demand is covered by heat pumps. See table 11 for a reminder on cost assumptions and figure 25 for the results.

An important reduction in energy costs for heat pumps in comparison to heat networks comes from the reduction in energy demand, due to the efficient SCOP of heat pumps. Energy consumption is reduced by one third, from 61,899 GWh to 41,106 GWh. Although the heat pump scenario requires a lot more electricity and even higher storage costs, the added investment costs of heat pumps outweigh the annual costs of subtracting and distributing geothermal heat. The annual cost difference is €486 million, a 16% reduction.

Table 11: 2030 Heat cost assumptions

2030 Heat cost assumptions	Costs	Unit
Heat network	0.048	€/kWh
Heat pump CAPEX	474	€/kW
Heat pump lifetime	20	years
Gas boiler CAPEX	62	€/kW
Gas boiler lifetime	15	years

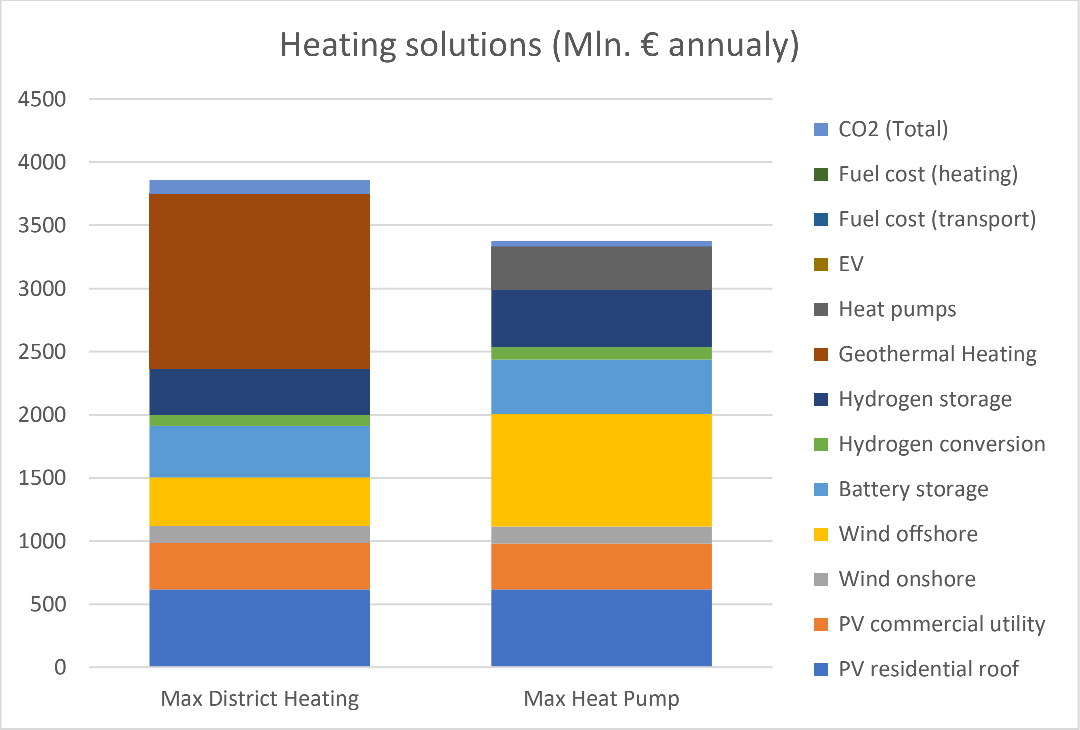


Figure 25: Comparing full heat supply by either heat networks or heat pumps (in Mln. € annualy)

Although heat pumps seem a lot cheaper, it cannot be concluded they are the most optimal source in all cases. For one, heat pumps require additional costs for insulation which can increase rapidly. Furthermore, specific spatial, temporal and temperature requirements of heat demand need to be investigated. Optimal solutions can be found in combing residual or geothermal heating with heat pumps, or even add other sources such CHP hydrogen fuel cells or thermal batteries (McDonald, 2018; TNO, n.d.). Further research is required focused on smart heating systems including a mix of all these technologies and factors.

Conclusion 10: Heat pumps are expected to be the cheaper than district heating for low temperature heat generation. However, more research is required to the costs of insulation requirements and smart heating solutions.

8.11. Smart charging

The effect of smart charging (SC) depends on the scenario. In this case the 100% solar and cost optimized scenarios will be compared because the first results in the highest peaks and required storage while the second has the lowest peaks and least storage. The results of SC are limited in this model, mainly due to the way of implementation. SC is only applied on personal EV transportation, without using vehicle to grid (V2G). This is a limited form of SC as the available load management capacity is just the capacity required for the EV's consumption. Average EV consumption is far less than the average battery size, therefor, V2G enables far more flexibility. V2G is amongst the future research recommendations to be implemented in this model.

Also, grid investment reductions are not considered. These can probably be reduced significantly by smart charging, especially when combined with V2G. This is recommended to implement in future models.

The current form of smart charging results in a cost reduction of 125 Mln. € annually in a maximum storage scenario and 67 Mln. € annually in a cost optimized scenario (2-3% of system costs). Of this cost reduction 79% in the least storage case and 86% in the maximum storage case is the result of less batteries required. Battery costs are reduced by 13-15%. This makes sense as batteries are used more efficiently. Without SC electricity would first have to be stored in a regular battery, transported to homes, and charge the EV whenever it arrives home. This middle step is now reduced whenever EV capacity is directly available.

The effect of smart charging varies across the scenarios. Higher shares of PV lead to better effects of smart charging (figure 26). Note that in this model 50% of the EV users have the ability to charge at work, thus are able to take full advantage of the PV peaks. This is important for policy making as it indicates two things. First, if PV development continuous its current path of rapid growth, smart charging becomes increasingly important. Second, when building this infrastructure, consider carefully where EVs will be during potential solar peaks in energy supply.

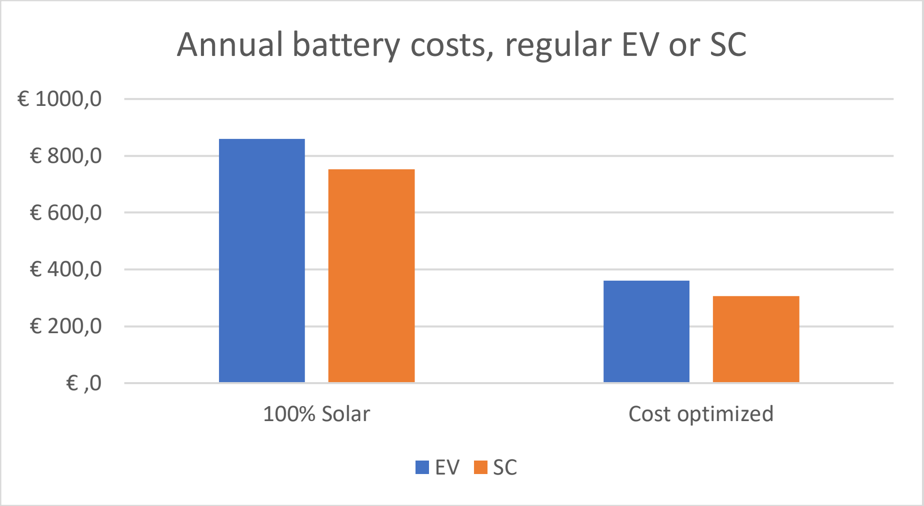


Figure 26: The annaul battery costs for a system with regular EVs versus Smart charging EVs. Due to the increased usefullness of EV batteries the totla battery cost decline

In terms of the viability of smart charging a cost reduction of 67-125 million is relatively modest. This is achieved with a total of 1.3 million cars, making the savings per car less than €100,- a year. This is a substantial amount for a relatively cheap (mostly software) solution. Also, it could be more beneficial for three reasons: Taking grid costs into account; adding V2G; and for specific people who drive a lot and have highly flexible charging schedules.

Conclusion 11: Smart charging is an easy yet beneficial way to save some of the storage costs. Important aspects in assessing the value of smart charging are: The development of PV versus wind; the number of chargers at work in case of PV peaks; the development of V2G; and the reduction on grid costs.

8.12. Storage assumptions

Storage is often mentioned as one of the key challenges of a 100% RES. Furthermore, large scale storage required for this system is unprecedented and relies on technologies which are still rapidly in development. Especially large-scale hydrogen conversion and storage is still in the early development phase. Prognosis are made on the learning curves, efficiency, costs and lifespan. However, all these prognoses incorporate high levels of uncertainty. On one hand storage is critical for the energy transition, on the other it is one of the most uncertain aspects. To map this uncertainty and investigate the effect of storage costs on 100% RES three scenarios have been made. These scenarios include minimal, medial and maximal values for storage assumptions (see table 12). These values have been implemented in the model for a minimal required storage (cost optimized) scenario and a maximal required storage (100% Solar).

Table 12: Range of cost assumptions for storage technologies in 2030

Storage	Minimum	Medium	Maximum	
Battery	75	100	150	€/kWh
Battery lifespan	5000	5000	5000	cycles
H2-storage	20	58	150	€/kWh
H2 electrolysis	250	500	1000	€/kW
Electrolysis lifespan	30	20	15	years
H2 Fuel cell	27	30	35	€/kW
FC lifespan	20	15	10	years

The results of the storage cost assumptions are visualized in figure27. Two main results can be deducted. First, cost reduction in storage is highly important. In the cost optimized scenario minimal storage costs are 3.7 times cheaper than maximal storage costs (1,125 versus 332 € Mln. annually) and even 4.2 times cheaper in the 100% solar scenario (938 versus 3911 € Mln. annually).

Second, creating an optimal mix of renewable resources is key for keeping the renewable energy system payable as long as storage is costly. This means wind (especially offshore) has a strong advantage over solar. From a spatial and political point of view this might be difficult, as wind has strong NIMBY resilience and offshore is not within Brabant's influence. However, when storage costs reduce to the currently expected minimal value, wind's advantage evaporates, making the spatial arguments stronger. In other words, if policy makers want to use the potential of PV to its full benefit, they should invest in storage and reduce the costs. Looking at cost development of other renewable energy technologies (e.g. batteries, PV and offshore wind) in recent years, achieving or even overachieving estimates is certainly possible (Hoekstra, 2017). When renewable energy rises, and the need for storage increases rapidly, cost reductions could be beyond expectation.

The model shows that storage costs are not an insurmountable hurdle in the way of large-scale PV adoption. This is best visualized when comparing the minimal storage cost 100% solar scenario to the 100% CCGT scenario. Both are extremes for illustrative purposes, 100% CCGT is originally the cheapest way of generating electricity, while 100% solar is the most expensive due to the storage costs. However, when looking at the minimal storage cost scenario and including a CO_2 price of €50 per ton, 100% solar is cheaper than 100% CCGT. Expressed in price per kWh of final electricity demand, 100% solar minimal storage is 0.086 €/kWh while 100% CCGT is 0.090 €/kWh. The absolute minimum electricity price in the minimal storage cost optimized scenario is 0.076 €/kWh. Although this is more expensive than current electricity prices, it is cheaper than any 2030 alternative, even when CO_2 prices would remain at their current level, which would result in an electricity price of 0.079 €/kWh.

Note that altering storage cost assumptions also has an effect on the optimal amount of wind versus PV generation. In this case, the cost optimized scenario is based on the medium storage assumption costs, if it would be based on the low range of storage assumption costs solar capacity would increase and wind decrease, if based on the high range of assumption it would be the other way around.

Conclusion 12: Storage cost assumptions have a large influence on scenario results. There are two possibilities. If storage technologies do not follow a rapid trend of efficiency gains and cost reductions, offshore wind is strongly favored over PV. However, if storage technologies develop rapidly, they can reduce the economic constraints between PV and wind. Enabling policy makers to make choices on non-economic criteria.

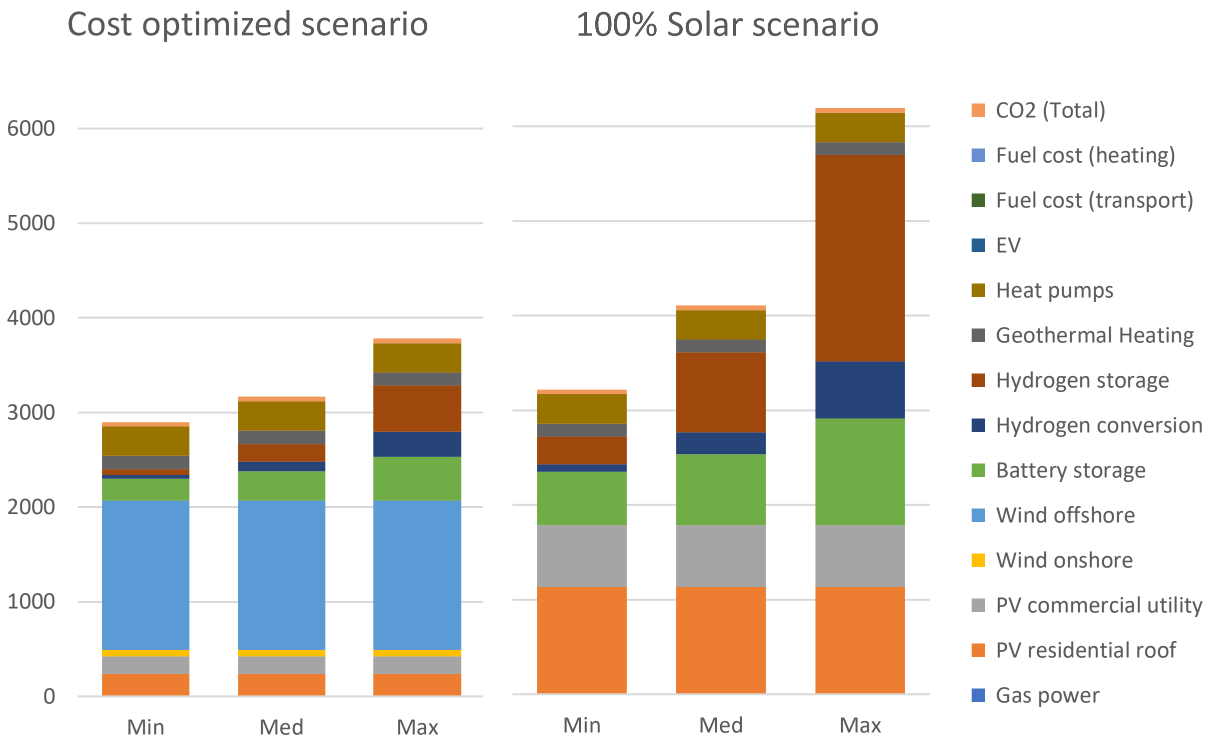


Figure 27: Storage costs (in € Mln. annually) assumptions on a minimal storage (cost optimized) scenario and a maximal storage (100% Solar) scenario.

8.13. CO_2 pricing

Multiple CO_2 pricing schemes exist today. A lot of (scientific) debate is held around what the accurate CO_2 prices should be, which vary widely from a climatological, innovational or economical perspective (see CO_2 section in the 'Data and Assumptions' chapter). In this case the analysis is based on when a 100% RES becomes cost comparative to a fossil fuel-based alternative. To compare this the total system costs of the 100% RES cost optimized scenario are compared to the similar 100% CCGT scenario, in which all electricity is generated by CCGT plants. This has been done on a CO_2-price range from €0 to €50 per ton (see figure 28). The two lines intersect at a CO_2 price of €32 per ton. In this case the total energy cost for both scenarios is €3.1 billion, of this €391 million is due to CO_2 costs in the 100% CCGT scenario and €31 million in the 100% renewable cost optimized scenario. In other words, 100% RES do require some form of CO_2 prices, but those are more in the range of current ETS prices than in the range mentioned by Jacobson and PBL (Jacobson, Delucchi, Bauer, et al., 2017; Matthijsen et al., 2016). This difference can be explained because of differences in the method for storage calculations, assumptions and learning curves, and the exclusion of grid impact and specific energy requirements (such as high temperature heat) in this study.

An important conclusion is that a tenfold or more increase of CO_2 prices is not a necessity to make 100% RES cost competitive. Even though not all transition costs are considered, the earlier mentioned prices required (€250-€500 per ton) or even higher are out of scope. The fact that CO_2 costs of €250/ton or more can very well be realistic from the perspective of externalities, make the impact of renewable energy systems on society even better.

Conclusion 13: CO_2 prices do make an important difference in making 100% renewable energy system competitive. However, the price range is well within sight, not even doubling of current ETS prices (in comparison the tenfold or more sometimes mentioned).

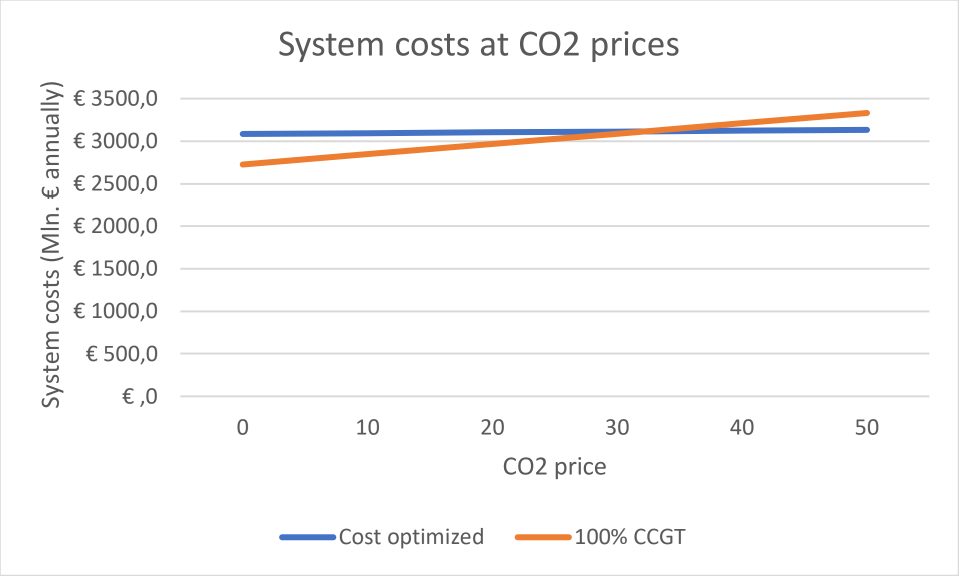


Figure 28: System costs for the cost optimized and 100% CCGT scenarios at certain levels of CO_2 prices. The point of intersection is at a CO_2 price of €32 per ton.

8.14. Renewable energy growth

The previous scenarios have shown the dynamics of 100% renewable energy systems and the effects of certain technological choices, answering the first research question to the effects of renewable energy technologies. This shows the sustainability goals are technologically, economically, spatially and socially viable. The next question is: Are they likely achieved within the time limits. The province is still set on achieving 50% renewable energy in 2030 and 100% in 2050 (Provincie Noord-Brabant, 2018). Looking at the current developments of sustainable energy sources a rapid acceleration is required to achieve this. These scenarios show the discrepancy between currently planned and forecasted growth, and the policy goals. To obtain RE growth forecasts, domain expert knowledge from Auke Hoekstra (EVs) and Gerard de Leede (PV) is combined with current policy plans to wind energy (NWEA, 2018; RVO, 2018) and trend reports on heat pumps (Dutch New Energy Research, 2018) into 2023 and 2030 forecasts. The assumptions are displayed in table 13. Note that these are not exact predictions, they are meant to investigate whether current developments lead to the required range of acceleration.

Table 13: Scenario setting forecasted growth

Assumptions	2019	2023	2030	Unit
Heat networks	3.1	6	10	PJ
Heat pumps	1	3	10	% of heat demand
CCGT	3846	3844	2700	MW
PV rooftop	110.5	600	2500	MW
PV plants	0	300	900	MW
Wind onshore	218	300	400	MW
Wind offshore	141	662	1691	MW
EVs	0.7%	2.4%	30%	% of electrified transport

The results of these scenarios are compared to the 2030 and 2050 goals in figure 29. The 2030 forecasted growth results in just 28% renewable energy. This is just over half of the goal, meaning that the diffusion of renewable energy technologies is far from the required pace. To achieve the goals, a radical regime change is required. However, the current pace and power of incumbent regime actors do not make this a realistic scenario. Unrealistic goals could result in hampering the actual developments, making these targets a difficult political point.

On a more positive note, CO_2 emission reduction (caused by the energy and transportation sector) is ahead of the percentage renewable energy. See figure 30 for the forecasted CO_2 emissions. The 2030 forecast is a 45% reduction, just 5% short of the goal.

Conclusion 14: The climate goals far exceed the forecast. Even though renewable energy has experienced some unprecedented growth, it is unlikely the provincial goals on renewable energy will be achieved.

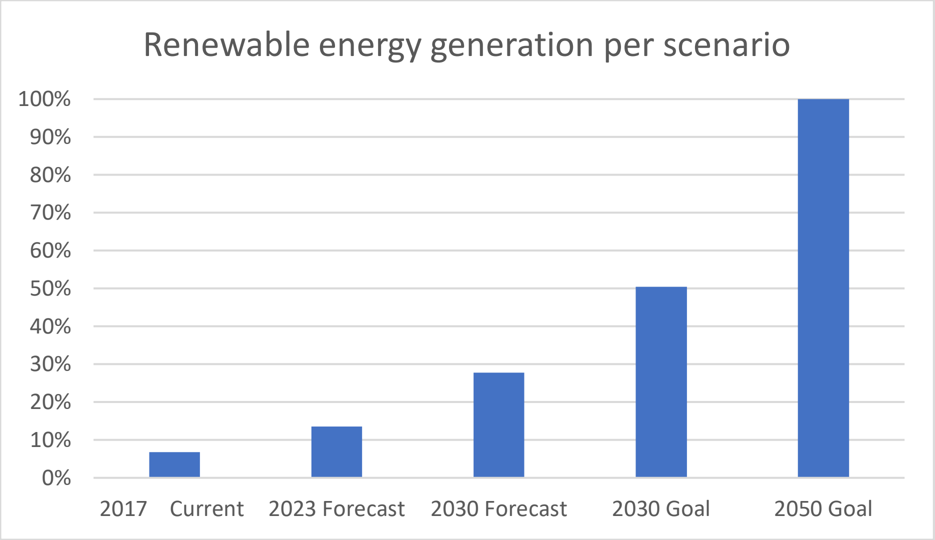


Figure 29: Percentage renewable energy in different scenarios. Spatial maximum is the theoretic maximum when onshore wind and PV are set at the spatially defined maxima from (Hoekstra, 2018) including conversion losses from storage.

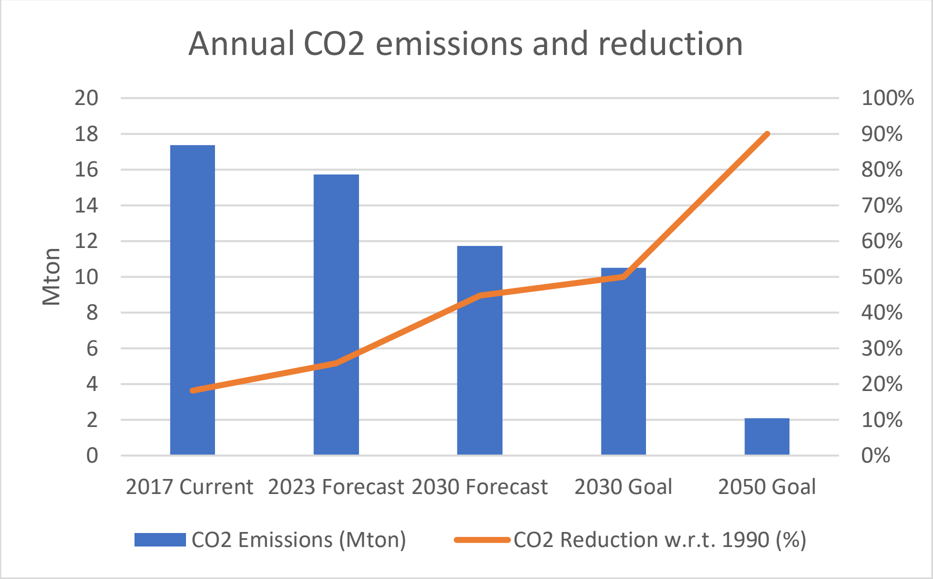


Figure 30: Annual CO_2 emission of projected and goal scenarios

8.15. Interactive discussion tool

The final part of this result section focusses on answering the second sub-question; *How can renewable energy models be used in a comprehensive yet engaging way in renewable energy policy making?* The spatial and temporal design of the model offer a perfect opportunity to show the interdependencies upon which a renewable energy system is based. In prior debates, too often the discussion was based on comparing alternative facts based on different concepts. With the numerous different concepts within energy and economics, this often leads to discussing the facts without the context. Presenting this model as the foundation of the discussion resulted in a coherent discussion, at least based on matching concepts. Furthermore, having the ability to interactively alter scenarios while explaining and discussing them gave immediate, clear inside in the subject matter. This creates the ability to dive much deeper into actual problems, creating the fundament for a constructive discussion. The model was presented to the members of the Provincial Council during a two-hour interactive brainstorm and discussion session. First a quick overview of the most important dynamics (similar to the scenarios and their conclusions) was interactively presented to increase renewable system understanding. The resulting common ground of system understanding led to a broad political discussion touching the whole spectrum of the energy transition debate. From a wide range of generation and storage methods to employment and education issues. Although no predefined research was done to the opinion of the involved politicians and policy maker, feedback was positive. They stated it was one of the most constructive RE debates they have had in the council. Two months later, three policy makers have been interviewed, amongst others about the value of the model. All three policy makers mentioned the importance of the visual and interactive characteristics of the model to increase knowledge and understanding on the subject as a basis for constructive debates.

Furthermore, involving policy makers (especially in the case of broad range of political views) also helps the researcher in increasing the validity of the model. By interactively discussing the model set-up, parameters and scenarios the researcher gets an improved insight in what matters most in social and political terms. In other words, the distinction between which parameters to include and which not from a social or political perspective can be verified. The policy makers perspective is also valuable in deciding which scenarios and which parameters within these scenarios to analyze. This resulted in a broad analysis of the entire energy system, as combining all individual technologies, trends and their effects in one coherent and calibrated system was most lacking and desired. Clearly showing these system effects of different technologies was the main reason to create the extreme scenarios. A technology’s effects are best visualized when these are isolated and exaggerated. In terms of results politicians are most interested in costs, spatial planning, transition paths and labor market. The first two are integrated and discussed extensively, the second two are amongst the areas included in the future research plans. In conclusion, instead of the researcher, now the policy maker (or any other model user) can decide upon possible scenarios, taking their personal motives into account. This broadens the discussion outside the academic debate, taking more and more social issues into account.

Conclusion 15: Comprehensive energy transition models can help policy makers in creating a common ground for a constructive debate. A cross sector, domain and scale overview is required to be able to show the system effects of renewable energy technologies. Due to the interactive scenarios and visualized effects, policy makers could grasp the full range of implications their choices have, ultimately making better informed decisions.

9. Conclusions

The of analysis focusses on three main aspects. First and foremost, investigating the system effects of renewable energy technologies in a renewable energy model of the province of Noord-Brabant. Second, the suitability of agent-based modelling to create comprehensive renewable energy models. And third, the usability of such an overview in political decision making.

The conclusion first answers these main questions. The conclusions derived from each of the scenario results extensively answer the main research question, showing an overview of the most important dynamics in renewable energy systems (they are reprinted in table 14). This table can be interpreted as an overview to renewable energy system dynamics.

The model is an extensive and inclusive representation of the energy system in the province of Noord-Brabant. The broad research question '*What are the economic, spatial, societal and climatological effects of choices in renewable energy, storage and conversion technologies towards reaching the climate goals?*' is answered by analyzing scenarios in an agent-based model of the energy system of Noord-Brabant. As a broad range of technologies and assumptions within multiple types of energy is included, the range of analysis is also very broad. This is a result of the chosen scale, a complete overview of the entire energy system and possible transition trajectories. One of the advantages of such a model is that once the energy system has been modeled, a very wide range of investigations is possible. Just reconfigure a number of input settings and the effects of a different scenario or subset of the system can be analyzed.

The 100% RES shows many economically and technologically feasible options. The remaining question is; What choices do we make apart from a techno-economic optimum, towards an inclusive socio-economically viable transition path?

The effects of renewable energy technologies are assessed to investigate these choices. The most important results are repeated in this paragraph. First, electrification of heat and transport is key. It means big savings in energy demand, and connects renewable electricity sources to fuel and heat demand. Second, in techno-economic terms, offshore wind is the best building block for a 100% RES. However, when further breakthroughs occur in the area of storage technologies and PV, this difference will diminish. In this case the economic argument declines, making PV relatively more attractive because of spatial, social and political arguments. Third, smart charging is a beneficial technology as it reduces required battery capacity. However, effects remain limited as long as charging at work and V2G are not implemented, as only fractions of the total available battery capacity are used. Fourth, heat pumps are relatively cheap but more research is required to demand specific solutions and additional costs and requirements. And fifth, in a cost optimized scenario a carbon tax of €32/ton is required to make a 100% RES economically beneficial. This is well within predictions of the current ETS system.

These results are obtained with current cost forecasts. Radically changing the energy system would likely reinforce cost reduction developments, potentially making it even a better deal.

Before overstating positive effects, it is important to realize that not all transition costs are included. Multiple areas of future research are required to improve these results, such as: Including transmission and distribution costs; a more thorough investigation to heating (e.g. insulation costs, high-temperature demand and smart heating systems); and more detailed smart combinations of renewable energy technologies. Furthermore, a lot of research and extensive governmental processes are required for a successful energy transition. However, once the system is developed and in place, it is certainly an improvement for society.

The ABM method has been essential to this model for a number of reasons. The multi-level structure of ABM is a natural fit to both the bottom-up structure of energy generation in renewable energy models and the multi-level perspective of socio-economic transitions. the structure of agents in a population is a natural way to determine components in a system and create a stepwise increase in scale, while still enabling heterogeneity within subcomponents and have them interact with other subcomponents. This structure enables a domain expert-based approach without losing grip on the system overview, which is relevant in the scattered domain of renewable energy technologies. Furthermore, this wide range of scales enables ABM to incorporate multiple modelling methods (DES and SD), resulting in a pick and choose multimethod but still agent-based design.

ABM provides the possibility to easily integrate spatial and temporal characteristics in dynamic interface. Enabling a simultaneous analysis of temporal balance and spatial issues (in terms of spatial planning and transport of energy) and tell this story in an engaging and interactive way. One downside of ABMs is the difficulty of statistically validating the model. This should be taken into account when deciding if ABM is the right method to answer the research question and when analyzing the results. To compensate the model structure and assumptions should be validated and explained thoroughly. Even when this is done, ABM is most fit to research possibilities, instead of prognosis. As in any future scenario study the range of uncertainty is high. Therefore, the analysis should be based on trends, dependencies and factors, instead of exact quantities. When introducing these results in public (or political) debate, researchers should always be careful to notify this uncertainty. This does not only hold for ABM, but for any future prognosis or scenario study like the '*Nationale Energieverkenning*' (K. Schoots et al., 2017), ´*World Energy Outlook'* (IEA, 2017, 2018) or '*New Energy Outlook*' (BNEF, 2017).

Lastly, the use of models as a tool to quantify and illustrate effects of the energy transition is discussed. The potential explanatory characteristics are important. The energy transition is not a technical transition. The most important question is based on social and political norms and values. Costs need to be restructured, who is going to pay for what? What are the costs and benefits of one choice over the other? To debate this, based on norms, values and ideas, a thorough understanding of the energy transition is necessary. However, this thorough understanding is also difficult in complex systems where one change might lead to many different, unforeseen, effects. Quantified narrative, based on model results and told in a clear, concessive manner are utterly important to get to these debates, enabling policy makers to discuss the issues they should discuss. More effort should be put in keeping the visual representation as intuitive as possible, however, the interactive visual design already had a positive influence on model users' understanding.

Table 14: List of main conclusions of the scenarios. Showing a large number of effects of choices in renewable energy technologies.

Scenario	Conclusion
Current	The most important lesson from this scenario is the fact that just shifting from coal to gas leads to a significant reduction of CO_2 emissions.
50% Renewable electricity, 25% renewable energy	Renewables can compete with gas on electricity prices in a 50% renewable electricity scenario, especially when taking a CO_2 price into account.
100% Renewable electricity, 50% renewable energy	When making policy towards the 50% renewable energy target, focus should be applied on both renewable energy sources and electrification of current demand.
100% Gas	Electrification in road transport and low-temperature heat is one of the most beneficial parts of the energy transition. From a socio-economical point of view, electrification is difficult as it substitutes the powerful incumbent regimes of oil and gas companies.
100% Wind	Wind is techno-economically speaking most suited to generate large shares of renewable energy. However, onshore wind is hampered by socio-economic factors (spatial planning and social opposition).
100% Solar	PV itself is relatively cheap, but results in high storage costs. As storage requirements for wind and solar oppose, mixing them is the optimal solution. The goal is to find the balance between the utilization of batteries and hydrogen.
100% Cost optimized	A cost-optimized 100% renewable energy system would be the cheapest option for the province of Noord-Brabant. It is based on large scale electrification, high shares of wind (over 60% of all energy generation) followed by a big share of solar (23% of all energy generation).
100% Socio-economically optimized	As long as there is a balanced mix of wind, PV and storage, costs do not rise dramatically compared to fossil fuel scenarios, when stepping away of the techno-economic optimum. This creates room for other criteria apart from economic effects. Models can show the costs and benefits of these criteria, enabling policy makers to make well-informed choices.
Renewable heat	Heat pumps are expected to be the cheaper than district heating for low temperature heat generation. However, more research is required to the costs of insulation requirements and smart heating solutions.
Smart Charging	Smart charging is an easy yet beneficial way to save some of the storage costs. Important aspects in assessing the value of smart charging are: The development of PV versus wind; the number of chargers at work in case of PV peaks; the development of V2G; and the reduction on grid costs.
Storage assumptions	Storage cost assumptions have a large influence on scenario results. There are two possibilities. If storage technologies do not follow a rapid trend of efficiency gains and cost reductions, offshore wind is strongly favored over PV. However, if storage technologies develop rapidly, they can reduce the economic

	constraints between PV and wind. Enabling policy makers to make choices on non-economic criteria.
CO_2 pricing	CO_2 prices do make an important difference in making 100% renewable energy system competitive. However, the price range is well within sight, not even doubling of current ETS prices (in comparison the tenfold or more sometimes mentioned).
Projected growth	The climate goals far exceed the forecast. Even though renewable energy has experienced some unprecedented growth, it is unlikely the provincial goals on renewable energy will be achieved.

10. Discussion

The scenario results and their conclusions have been covered extensively. In this chapter modelling renewable energy systems in general, and how these should be used is discussed.

Currently, 100% RES models are reviewed extremely critical in scientific debate, posing new solutions or more criteria to take into account. As the system is large and complex, there will always be less detailed domains. The discussion that results from this undermines the value of these models. There are numerous problems with even more solutions all having a wide range of often interlinked effects. To many people involved in the renewable energy transition this leads to a choice overload, losing a sense of control and understanding. This hampers the introduction of renewables, as each and every renewable solution is not only compared to incumbent systems, but also any other possible alternative which often result in an entirely different system. Instead, these models should reduce this choice overload by critically assessing the most important choices and dynamics and showing their effects. As policy is based on much more than economics, the effects should not only contain technological or economical optimization, but also include societal and spatial effects. Furthermore, the models should clarify the combination of learning curves, technological paradigms and trajectories, path dependency and societal acceptance resulting in non-linear trends. Focusing on theories of emergence and diffusion of innovation, together with policy measures and institutional transformation that could facilitate renewables or devaluate fossil fuels, is required to model the effects of the energy transition. In this, models do not display an 'optimal' solution, instead they clarify interlinking effects and dependencies resulting in a quantified and visualized narrative that can serve as a basis for political discussion and trade-offs.

Integrating the socio-economic concepts into the renewable energy model of Noord-Brabant has proven to be a challenge. It has been implemented by jointly investigating the model requirements with policy makers and social planners. Good examples of this are: The spatial planning of the maximal 355 relatively big onshore wind turbines in different geographical environments and smaller turbines connected to villages (*dorpsmolens*); The choice to use biomass and residual heat only in case of absolute waste without aiming at any increases as this creates lock-in effects for polluting industries; And the decision to exclude nuclear based on the lack of policy plans, costs and construction time. Furthermore, socio-economic concepts have been included in a part of the analysis. Showing that for example electrification could be hindered by incumbent market power of oil and gas companies, or onshore wind which is often opposed by local residents. Lastly, spatial factors are integrated in the model, directly visualizing the effects of wind turbines and PV plants on the map of Noord-Brabant.

Even though the previous paragraph states a number of ways in which socio-economic analysis is used, the model cannot be seen as a STET model. The essence is still a techno-economic renewable energy model focused on system balance and cost and CO_2 calculations. STET models are a promising method to investigate the energy transition. Although it in the second chapter that the transition cannot be separated from the final system, it has been to extensive to integrate these dynamic patterns. As said, the foremost goal was providing an overview of a balanced energy system in 2030. As the scope of the model was already large across multiple sectors, the transition paths had to be simplified to integrating technological trends.

The last point of discussion relates to this same point. Making assumptions of a renewable energy system in 2030 is a delicate process. The assumptions should be viable according to current standards. However, researchers should take into account they are modeling radically different energy system, including a unknown transition path in which technologies can have rapid developments. Such a radical transition will influence many aspects of society, and certainly the techno-economic components involved. Instead of assessing the viability of assumptions according to current forecasts, it would be better to switch the framing: Start at the desired goal and state the required assumptions in order to achieve this. For example, if the goal is a 100% WWS energy system by 2050 in Brabant, design a roadmap with possibilities to achieve this goal. One option could be international grid balancing resulting in dependencies of wind and water sources in other parts of Europe. Another pathway could resemble the system described in this thesis aimed at a smart combination of daily and seasonal storage. Investigating an autarkic 100% WWS energy system with social and spatial constrains capping biomass and onshore wind capacity. The result is a range of requirements of demand reduction, PV, offshore wind, battery, hydrogen and heat pump costs. From this a researcher could conclude such a system is either viable or not. However, it would be more useful to investigate what is required to reach this viability. Give policy makers grip on what kind of developments are required, as they are eager to incubate or accelerate technological (and thus economical) development in their region. By doing this they increase the viability of their desired energy system, creating a positive reinforcing feedback loop. For example, the province accelerates PV development (Solliance, n.d.) increasing both, their economy and the viability of their desired energy system. By identifying the critical assumptions and requirements to achieve the goals and explaining them to policy makers, these kind of reinforcing feedback loops can radically accelerate the energy transition.

In general, it is important to increase the usefulness of renewable energy models. As the energy transition is ultimately a political question of shaping the future. I believe renewable energy transition models should focus on increasing knowledge, showing trade-offs and system effects. Not to achieve the system design I think is best, but to achieve a well-grounded debate ultimately leading to a broad consensus towards a transition trajectory.

11. Limitations and recommendations for future research

As the system in scope in this research is huge, of course numerous simplifications have been made. Of course, not all system components have to be integrated to the smallest detail. However, a number of them certainly required some extension in future research. Smarter combinations between energy carriers could have been made to reduce the cost. Furthermore, socio-economic characteristics of STET models require attention. Quantifying and visualizing these effects is the next step in enhancing the value of models for policy advice.

The integration of energy grids and transportation is the most important direction of future research. Not only in terms of costs and losses (typically 10-15% of system costs (T. W. Brown et al., 2018), but also to create locally optimized solutions per energy carrier. For example, adjusting grid connections to the local demand, varying between energy carriers. Ultimately the spatial integration of grids and transportation could largely contribute to comprehensive regional spatial energy development strategies. This is important as government regulation says that all Dutch municipalities should develop a regional energy strategy. The province has indicated this to be an important area of future research as well. The optimal regional energy tool would be a highly detailed local map of all energy generation, demand, transportation and storage, with a connection to the national energy infrastructure. Detail is required up to the level of local neighborhood planning such as the age of houses to determine the potential for heat pumps versus district heating or hydrogen powered boilers, or the planning for road construction to reduce the amount of nuisance when constructing new energy infrastructure.

The focus of this is on showing the effects of scenarios in 2030, making a socio-economic analytical approach of the techno-economic results possible. Another area for future research is investigating the entire transition path, including the implications of policy measures and social change. Transition paths have interesting dynamics of feedback-loops or emergence. Within the energy sector a lot of social, technical and economic developments are going on with patterns that could be implemented in such a model. To give an example, PV plants currently strive due to technological and economic advancements in PVs, easier in social consent and spatial planning than wind, and favorable subsidies. This variety of social, technical and economic effects reinforce each other creating more and more cheap PV. Until the growth is hampered again by grid problems. Grid problems and cheap PV together result in a more positive business case for batteries, which in itself enhances the development of batteries. When putting this in a model, battery storage is a natural business case emerging from the combination of PV boosting factors and grid capacity problems.

This would create an even more valuable model for policy makers as certain policy measures with certain effects on the emergence of renewable energy could be implemented at specific times. This would show the system level results of specific actions affecting subsets of the system. Bridging the often-difficult gap between small development of for example subsidizing heat pumps for new houses on the system as a whole. By experimenting and exploring with a lot of policy measures the most effective ones can be determined and the most difficult parts of the transition identified. And as we know, modelling this is a lot cheaper than trying in real life and effectively investing is of critical importance to accelerating the energy transition.

Another direction is a smarter integration between different energy carriers. Converting hydrogen into combined heat and power is for example more efficient than just power. This is difficult as heat and power have very different demand profiles. Other options for smarter energy systems are the combination of solar heat collectors, residual heat or geothermal heat with (seasonal) thermal storage and heat pumps. Also, sectors that are difficult to electrify, such as heavy-duty transport or high-temperature heat need further specification. When all these options are integrated storage should become based on market prices to make realistic differentiations between batteries, hydrogen, thermal storage or curtailment.

We see the concept of STET models as the most promising direction of research for investigating the energy transition and helping policy makers. This model cannot be called a full STET model, as socio-economic aspects are limited. However, previous STET models have shown the potential and ABM gives the tools as agency possessing actors can be seen as smart agents. These agents will result in even more dynamics which are vital to understand when steering the energy transition towards its 100% renewable goal.

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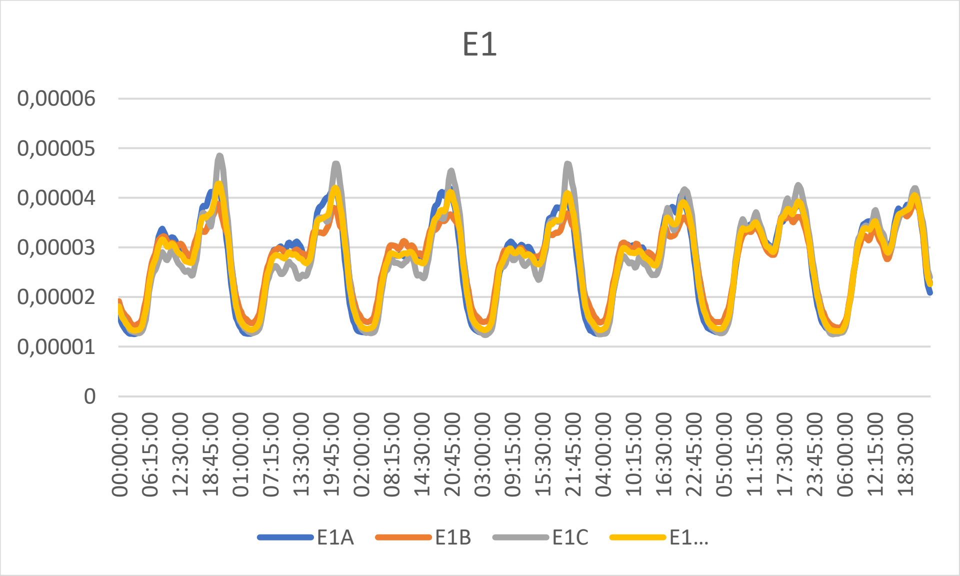
13. Appendix

A. ODD Elements

Elements of the updated ODD protocol. Adapted from (Grimm et al., 2010)

Overview	1. Purpose
	2. Entitites, state variables and scales
	3. Process overview and scheduling
Design Concepts	4. Design concepts
	• Basic Principles
	• Emergence
	• Adaptation
	• Objectives
	• Learning
	• Prediction
	• Sensing
	• Interaction
	• Stochasticity
	• Collectives
	• Observation
Detail	5. Initialization
	6. Input data
	7. Submodels

B. NEDU demand profile examples



NEDU demand profile Electricity E1, 10-16th of April

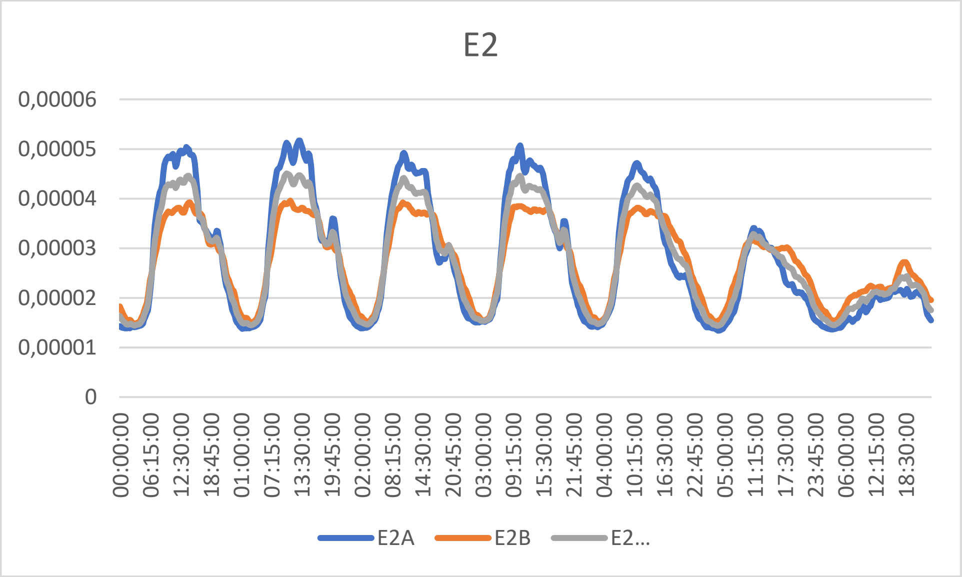


Figure 31: NEDU demand profile Electricity E2, 10-16th of April

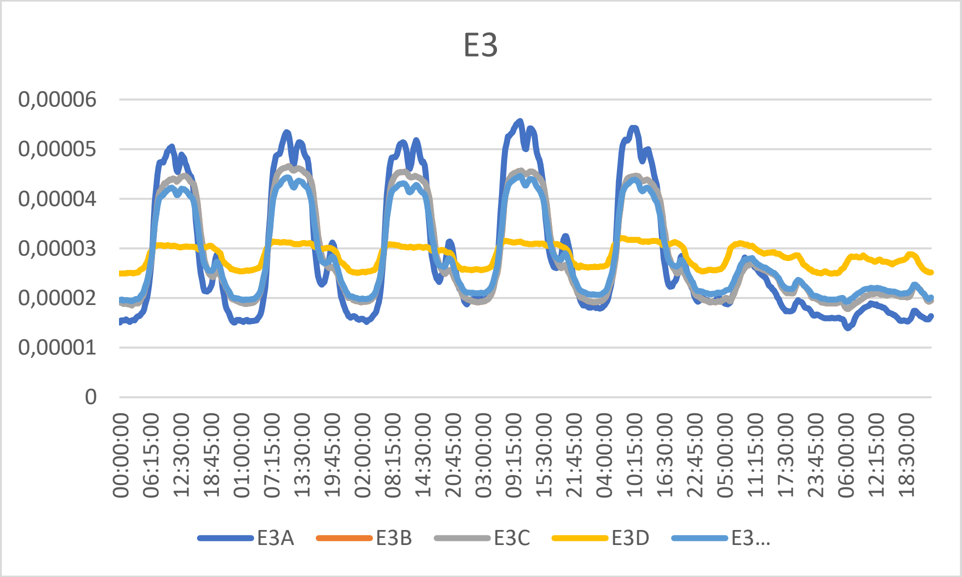


Figure 32: NEDU demand profile Electricity E3, 10-16th of April

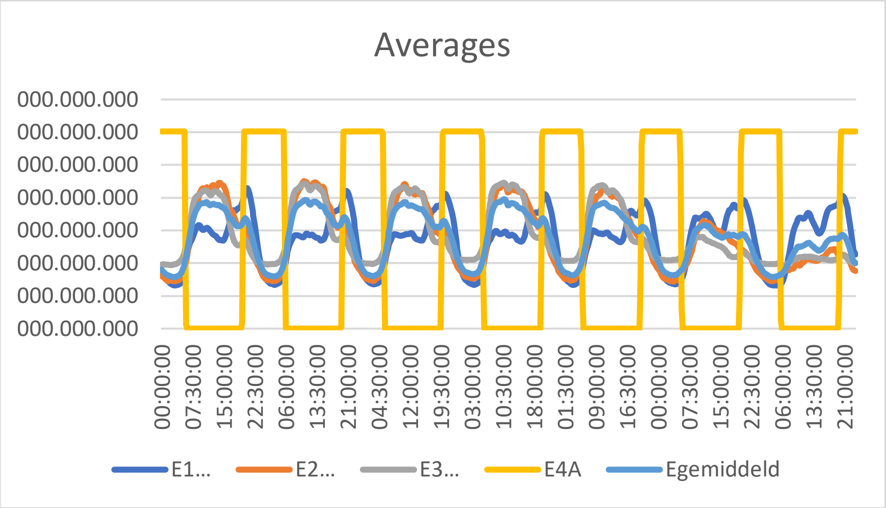


Figure 33: NEDU demand profile Electricity averages, 10-16th of April

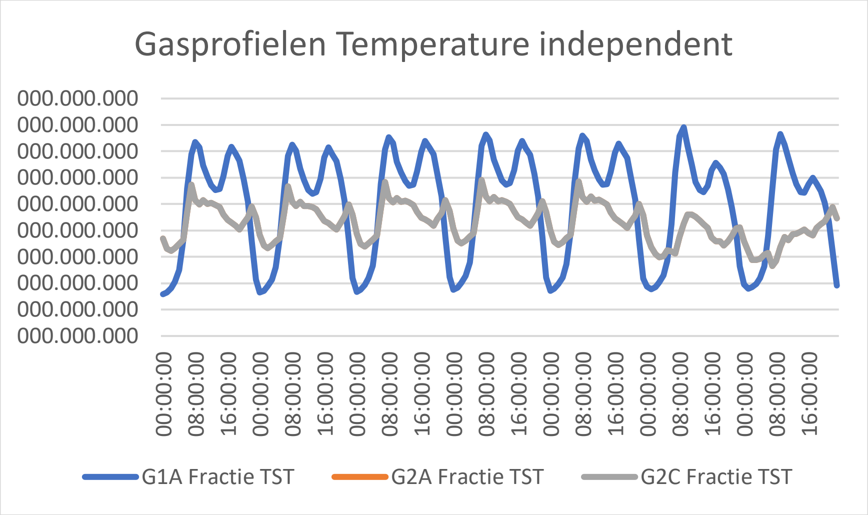


Figure 34: NEDU natural gas demand profile temperate independent, 10-16th of April

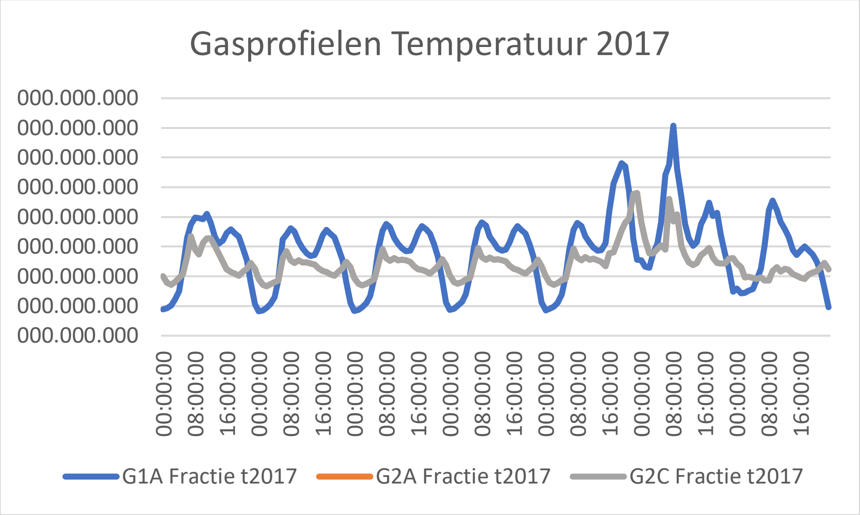


Figure 35: NEDU natural gas demand profile depended on 2017 temperatures, 10-16th of April

C. Schematic representation of model algorithm

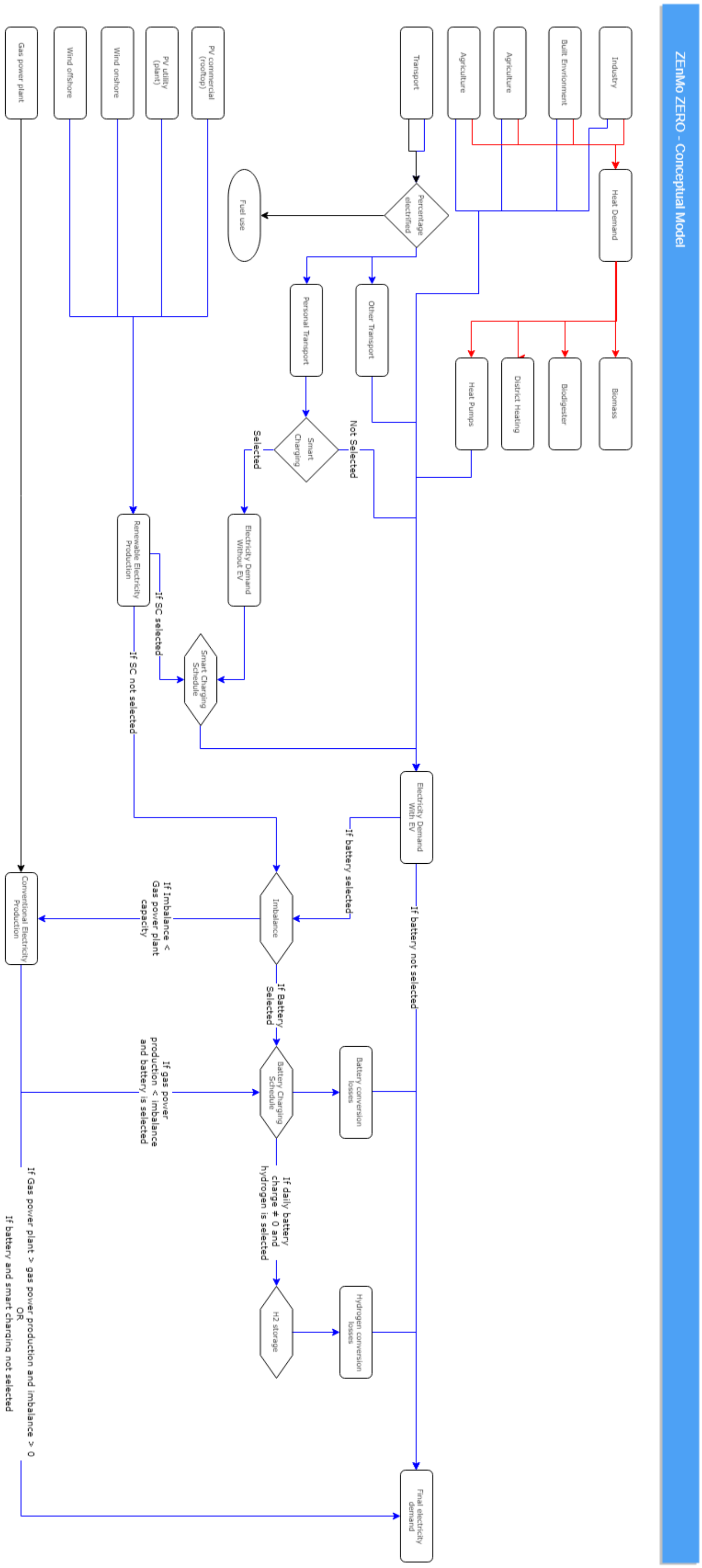


Figure 36: Schematic representation of the energy balancing algorithm amongst energy carriers. Red = heat, blue = electricity and black = fossil fuel.

D. List of cost assumption

Table 15: 2030 cost assumptions electricity generation and natural gas. The assumptions used are the averages of multiple sources. Sources are noted by numbers and explained in the under stated list

2030 Assumption	Cost	Unit	Sources
Natural Gas 2030	0.032	€/kWh	1, 3
Transport All fuel average*	0.078	€/kWh	2, 3, 4, 5
PV-utility scale	0.033	€/kWh	1, 6, 7
PV-roof commercial	0.052	€/kWh	1, 6, 7
Wind Onshore	0.054	€/kWh	1, 6
Wind Offshore	0.059	€/kWh	1, 6, 8
CCGT CAPEX	925	€/kW	1, 9
CCGT lifetime	30	Years	1, 9
CCGT OPEX	38.5	€/kW	1, 9
Geothermal heat networks	0.048	€/kWh	10, 11, 12
Batteries CAPEX	100	€/kWh	13, 14, 31
Batteries lifetime	5000	cycles	13, 14
Electrolysis CAPEX	250	€/kW	15, 16
Electrolysis lifetime	15	years	16, 17
Fuel cell CAPEX	27	€/kW	17, 18, 19
Fuel cell lifetime	20	years	17, 18, 19
Hydrogen storage (salt cavern)	0.058	€/kWh	17, 20, 21, 22, 23, 24
Heat pump CAPEX	474	€/kW	25, 26, 27
Heat pump lifetime	20	years	25
Gas boiler CAPEX	62	€/kW	28
Gas boiler lifetime	15	years	28
EV surplus in comparison to combustion engine car	0	€	25, 30, 31

* see Transport section for price structure

1. Fraunhofer ISE - Levelized cost of electricity renewable energy technologies (Kost et al., 2018).
2. European Environmental Agency – Transport fuel prices weighted average without taxes (EEA, 2017)
3. ECN - Nationale Energieverkenning 2017 (K. Schoots et al., 2017).
4. Commodities (oil) price forecast - (The World Bank, 2017).
5. IEA World energy outlook - Low Oil Price minimum scenario (IEA, 2017).
6. BNEF New Energy Outlookk 2017 (BNEF, 2017).
7. SunShot 2030 (U.S. Department of Energy, 2016).
8. Wind Europe – Unleashing Europe's offshore wind potential (Giles Hundleby & Kate Freeman, 2017).
9. Assumptions from '*Cost-optimal design of a simplified, highly renewable pan-European electricity system*' (Rodriguez et al., 2015)
10. LCOH deep geothermal in Groningen - (Daniilidis et al., 2017)
11. PBL – heat networks (Hoogervorst, 2017)
12. IEA Technology Roadmap Geothermal Heat and Power (International Energy Agency, 2011)
13. IRENA electricity storage costs – (IRENA, 2017)
14. BNEF battery price prediction - (Henze, 2018)
15. Sustainable gas institute - (Jamie Speirs et al., 2017)

16. Hydrogen in transportation systems (Oldenbroek et al., 2017)
17. Electrical energy storage systems: A comparative life cycle cost analysis - (Zakeri & Syri, 2015)
18. Review of hydrogen energy systems - (Parra et al., 2019)
19. Fuel cell system costs - (Wilson et al., 2016)
20. Leeds City Gate project - (H21 Leeds City Gate, 2016)
21. Life-cycle cost of hydrogen (Steward et al., 2009)
22. A sustainable pathway to scaling up hydrogen - (Hydrogen Council, 2017)
23. World hydrogen conference proceedings - (Stolten & Grube, 2010)
24. Waterstof – de sleutel voor de energietransitie - (Wijk & Hellinga, 2018)
25. NREL electrification future study - (Jadun et al., 2017)
26. ECN/TNO industrial heat pump – (ECN/TNO, n.d.)
27. CE Delft renewable heat - (Naber et al., 2016)
28. Retail prices excluding taxes.
29. Gas boiler life expectancy - ("The Average Boiler Life Expectancy | DoItYourself.com," n.d.)
30. SparkCity article - (Linesh Sundrani, 2017)
31. BNEF EV outlook - (Soulopoulos, 2017)

E. List of Input parameters

Energy Demand	**Value**	**Unit**	**Source**
Built Energy Consumption (2015)	92.2	PJ	Klimaatmonitor Database (Klimaatmonitor, 2017)
Built Environment Electricity share	47%	%	Brabant op 100% wind, water, zon (Hoekstra, 2018)
Built Environment Heat share	53%	%	Brabant op 100% wind, water, zon (Hoekstra, 2018)
Industry Energy Consumption (2015)	70.0	PJ	Klimaatmonitor Database (Klimaatmonitor, 2017)
Industry Electricity share	34%	%	Brabant op 100% wind, water, zon (Hoekstra, 2018)
Industry Heat share	66%	%	Brabant op 100% wind, water, zon (Hoekstra, 2018)
Agriculture Energy Consumption	22.0	PJ	Klimaatmonitor Database (Klimaatmonitor, 2017)
Agriculture Electricity share	15%	%	Brabant op 100% wind, water, zon (Hoekstra, 2018)
Agriculture heat share	85%	%	Brabant op 100% wind, water, zon (Hoekstra, 2018)
Transport Energy Consumption	81.0	PJ	Klimaatmonitor Database (Klimaatmonitor, 2017)
Electrification Conversion factor	0.3		Brabant op 100% wind, water, zon (Hoekstra, 2018);
Personal transportation share 2030	49%	%	PBL verkeer en vervoer, NEV 2016 (Geilenkirchen et al., 2016)
Energy Generation			
Wind			
Wind generation Brabant (2015)	0.99	PJ	Klimaatmonitor Database (Klimaatmonitor, 2017)

Wind Turbine Onshore	4.20	MW	Enercon E126 EP4 (Bauer & Matysik, 2016; Enercon, 2016)
Wind Turbine Onshore (village)	3.00	MW	Vestas V126-3.0 MW Power Curve
Wind Turbine Offshore	8.00	MW	Vestas V164-8.0 MW (Fruergaard, 2016)
Onshore turbine hub height	99	m	Enercon E126 EP4 (Bauer & Matysik, 2016; Enercon, 2016)
Offshore turbine hub height	105	m	Vestas V164-8.0 MW (Fruergaard, 2016)
Wind onshore (at 10m height)	0 - 14	m/s	KNMI hourly data 2017 Gilze-Rijen (KNMI, 2018a)
Wind offshore (at 10m height)	0 - 22	m/s	KNMI hourly data 2017 252-K13 (KNMI, 2018b)
Land roughness exponent	0.25		(Gipe, 2004).
Sea roughness exponent	0.08		(DNV, 2014)
Solar			
PV roof generation 2015	0.65	PJ	Klimaatmonitor Database (Klimaatmonitor, 2017)
PV system efficiency	17%		
Solar insulation	0 - 1000	w/m2	KNMI hourly data 2017 Gilze-Rijen (KNMI, 2018a)
Other			
Bio-digester (potential)	6.57	PJ	(Posad, 2016)
Biomass (potential)	7.4	PJ	(Posad, 2016)
District Heating 2015	3.2	PJ	Klimaatmonitor Database (Klimaatmonitor, 2017)
Heat pump COP	4		(Jacobson, Delucchi, Bauer, et al., 2017; Jadun et al., 2017)
Storage			
Battery efficiency	96%		* 13, 14
Electrolysis efficiency	83%		* 15, 17, 24, 25
Fuel cell efficiency	70%		* 16, 19, 21
Transport			
Number of cars	1309461	#	CBS
Average charging speed	5	kW	SparkCity
Average battery size	45	kWh	SparkCity
Average driving speed	50	km/h	SparkCity
Average daily distance	35.86	km	CBS
EV consumption	5000	km/MWh	SparkCity
EV consumption per km	0.2	kWh/km	SparkCity
Day trip probability	0.8		SparkCity
Evening trip probability	Uniform (0.3, 0.6)		SparkCity
Weekend trip probability	Uniform (0.5, 1)		SparkCity
Percentage working	70%		SparkCity
Charger at work	Uniform (0,1) < 0.5		SparkCity
CO_2 emissions			
PV	7	g/kWh	Lijst CO_2 emissiefactoren

Wind Onshore	5	g/kWh	Lijst CO_2 emissiefactoren
Wind Offshore	4	g/kWh	Lijst CO_2 emissiefactoren
Grey Electricity	649	g/kWh	Lijst CO_2 emissiefactoren
Heat (average)	130	g/kWh	Klimaatmonitor 2015
Biomass	90	g/kWh	Lijst CO_2 emissiefactoren
Bio-digester	190	g/kWh	Lijst CO_2 emissiefactoren
District Heating (Heat network)	54	g/kWh	Lijst CO_2 emissiefactoren
Combustion engine cars	180	g/km	Lijstemissiefactoren + spritmonitor
Total emission Brabant (2015)	21.2	Mton	Klimaatmonitor Database (Klimaatmonitor, 2017)
Transport Emissions (2015)	5.77	Mton	Klimaatmonitor Database (Klimaatmonitor, 2017)

* Reference to list of sources in appendix D.

F. Model output all scenarios

Please turn over:

Model Runs	Current	50% Renewable	50% Renewable	100% Gas	100% Wind	100% Solar	Cost optimized	In Brabant	Socio-economic	Spatial maximu
Energy Consumption (MWh)	76398773	71701591	69719220	38537702	43020659	46990373	41987996	46556470	42889488	46895227
Energy Generation (MWh)	26383514	31154526	35211204	38537940	43029568	46992017	41988657	46557469	42895299	49945272
Renewable Energy Generation (MWh)	5223360	18942789	35211204	6819801	43029568	46992017	41988657	46557469	42895299	49945272
Percentage Renewable Energy (%)	7%	26%	51%	18%	100%	100%	100%	100%	100%	107%
Energy Costs (Mln. € annually)	€ 5,052	€ 4,814	€ 4,928	€ 3,331	€ 3,501	€ 4,035	€ 3,133	€ 4,128	€ 3,391	€ 4,504
Energy Cost (€/kWh)	7%	7%	7%	10%	9%	9%	8%	10%	9%	10%
CO2 Emissions (Mton)	17.4	12.6	7.4	12.1	1.0	1.0	1.0	1.0	1.0	1.0
CO2 Reduction w.r.t. 1990 (%)	18%	41%	65%	43%	95%	95%	95%	95%	96%	95%
Electricity Consumption (MWh)	21526914	24335051	28372104	31718139	36201096	40170810	35168433	39736907	36069925	40075664
Electricity Generation (MWh)	21526860	24334725	28391403	31718139	36209767	40172216	35168856	39737668	36075498	43125471
Renewable Electricity Generation (MWh)	366706	12122989	28391403	0	36209767	40172216	35168856	39737668	36075498	43125471
Renewable Electricity (%)	2%	50%	100%	0%	100%	100%	100%	100%	100%	108%
					49%	73%	37%	71%	43%	
Electricity Costs (Mln. € annually)	1857.209888	2074.520721	2425.569739	2847.576783	3017.718736	3551.882918	2649.337568	3644.236653	2907.944412	4020.681195
Electricity Cost (€/kWh)	€ 0.086	€ 0.090	€ 0.099	€ 0.090	€ 0.095	€ 0.112	€ 0.084	€ 0.115	€ 0.092	€ 0.127
Electricity Generation										
Gas plant (MWh)	21160154	12211736	0	31718139	0	0	0	0	0	0
PV commercial rooftop (MWh)	234090	5402076	10804152	0	0	21608303	4501730	21608303	11729707	23459415
PV utility plant (MWh)	0	4883232	9156061	0	0	18563913	5341035	16291684	8913425	17828376
Wind onshore (MWh)	360898	4980240	4980240	0	4980240	0	1269834	4980240	2484226	4980240
Wind offshore (MWh)	0	0	6593510	0	34372087	0	24852462	0	14513526	0
Gas plant (GWp)	3.8	2.1	0.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0
PV commercial rooftop (GWp)	0.2	5.1	10.2	0.0	0.0	20.4	4.3	20.4	11.1	22.1
PV utility plant (GWp)	0.0	4.6	8.6	0.0	0.0	17.5	5.0	15.4	8.4	16.8
Wind onshore (GWp)	0.1	1.6	1.6	0.0	1.6	0.0	0.4	1.6	0.8	1.6
Wind offshore (GWp)	0.0	0.0	1.4	0.0	7.0	0.0	5.1	0.0	3.0	0.0
Storage										
Battery capacity requiered (MWh)	0	30954	78496	0	63462	147163	61421	138847	81337	151246
Battery conversion total (MWh)	0	5880321	20011873	0	7622925	37604494	9954964	35259195	18309860	38760610
Battery conversion losses (MWh)	0	231196	796278	0	300858	1499966	393918	1406171	728123	1546280
Battery Max charge speed (GW)	0.0	4.9	6.9	0.0	6.0	12.8	6.2	12.1	11.1	13.2
Hydrogen capacity requiered (MWh)	0	1918617	6197316	0	2745533	14534311	3262039	13814623	7082708	16196697
Hydrogen conversion total (MWh)	0	4455077	13236312	0	17604639	29523491	12912137	28071881	15375831	29724504
Hydrogen conversion losses (MWh)	0	1050158	3109354	0	4182099	6953700	3057031	6613592	3624658	6812240
Hydrogen max. conversion rate (GW)	0.0	2.0	4.4	0.0	4.1	8.6	3.8	8.2	5.1	9.0
Costs (Mln. € annually)										
Electricity Costs (€/kWh)	€ 0.09	€ 0.09	€ 0.10	€ 0.09	€ 0.10	€ 0.11	€ 0.08	€ 0.11	€ 0.09	€ 0.13
Electricity Cost	€ 1,857	€ 2,075	€ 2,426	€ 2,848	€ 3,018	€ 3,552	€ 2,649	€ 3,644	€ 2,908	€ 4,021
Gas power	€ 1,444	€ 826	€ -	€ 2,277	€ -	€ -	€ -	€ -	€ -	€ -
PV residential roof	€ 12	€ 284	€ 567	€ -	€ -	€ 1,134	€ 236	€ 1,134	€ 616	€ 1,232
PV commercial utility	€ -	€ 171	€ 320	€ -	€ -	€ 650	€ 187	€ 570	€ 312	€ 624
Wind onshore	€ 19	€ 269	€ 269	€ -	€ 269	€ -	€ 69	€ 269	€ 134	€ 269
Wind offshore	€ -	€ -	€ 419	€ -	€ 2,183	€ -	€ 1,578	€ -	€ 922	€ -
Battery storage	€ -	€ 155	€ 400	€ -	€ 317	€ 752	€ 307	€ 705	€ 407	€ 775
Hydrogen conversion	€ -	€ 36	€ 81	€ -	€ 76	€ 159	€ 70	€ 151	€ 94	€ 167
Hydrogen storage	€ -	€ 111	€ 359	€ -	€ 159	€ 843	€ 189	€ 801	€ 411	€ 939
CO2 (electricity generation)	€ 381	€ 223	€ 10	€ 571	€ 14	€ 14	€ 13	€ 13	€ 13	€ 14
Geothermal Heating	€ 43	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137
Heat pumps	€ 0	€ 39	€ 98	€ 311	€ 311	€ 311	€ 311	€ 311	€ 311	€ 311
EV	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Fuel cost (transport)	€ 1,744	€ 1,409	€ 1,321	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Fuel cost (heating)	€ 921	€ 748	€ 586	€ -	€ -	€ -	€ -	€ -	€ -	€ -
CO2 (Total)	€ 868	€ 629	€ 369	€ 606	€ 48	€ 49	€ 48	€ 48	€ 48	€ 49
Electricity consumption										
EV consumption	35043	708070	885088	3541346	3541346	3540350	3540690	3540350	3540350	3540350
Heat pump consumption	8157	815737	2039343	6452481	6452481	6452481	6452481	6452481	6452481	6452481
Heat Consumption (MWh)	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489
Renewable Heat Generation (MWh)	4889284	10082750	14977173	32629727	32629727	32629727	32629727	32629727	32629727	32629727
Percentage Renewable Heat (%)	15%	31%	46%	100%	100%	100%	100%	100%	100%	100%
Heat generation										
District Heating (MWh)	881993	2845140	2845140	2845140	2845140	2845140	2845140	2845140	2845140	2845140
Heat pumps (MWh)	32629	3262949	8157372	25809926	25809926	25809926	25809926	25809926	25809926	25809926
Biomass (MWh)	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661
Assumptions										
District Heating (PJ)	3.1	10	10	10	10	10	10	10	10	10
Heat pumps (%)	0.1	10	25	79.1	79.1	79.1	79.1	79.1	79.1	79.1
Gas power plant	3836	2126	0	6993	0	0	0	0	0	0
Windturbines onshore (#)	28	388	388	0	388	0	100	388	194	388
Windturbines offshore (#)	0	0	169	0	881	0	637	0	372	0
PV rooftop commercial (acres)	130	3000	6000	0	0	12000	2500	12000	6514	13028
PV utility plant (acres)	0	3200	6000	0	0	12165	3500	10676	5841	11683
Electrified transport (%)	1	20	25	100	100	100	100	100	100	100
Smart Charging	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Battery Storage	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Hydrogen Storage	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Cost assumptions										
CO2 (€/tonne) effects on electricity price	50	50	50	50	50	50	50	50	50	50
Gas power (€/MWh)	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2
PV rooftop commercial (€/MWh)	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5
PV utility plant (€/MWh)	35	35	35	35	35	35	35	35	35	35
Wind onshore (€/MWh)	54	54	54	54	54	54	54	54	54	54
Wind offshore (€/MWh)	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5
Battery storage (€/kWh)	100	100	100	100	100	100	100	100	100	100
Battery lifetime (cycles)	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
Hydrogen elektrolyser (€/kW)	250	250	250	250	250	250	250	250	250	250
Hydrogen elektrolyser lifespan (year)	15	15	15	15	15	15	15	15	15	15
Hydrogen fuel cell (€/kW)	27	27	27	27	27	27	27	27	27	27
Hydrogen fuel cell lifespan (year)	15	15	15	15	15	15	15	15	15	15
Hydrogen storage (€/MWh)	58	58	58	58	58	58	58	58	58	58
Transport fuel costs (€/MWh)	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28
CCGT (CAPEX) (€/MW)	900000	900000	900000	900000	900000	900000	900000	900000	900000	900000
Heat Network (€/MWh)	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3
Heat Pump added CAPEX (€/kW)	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6

Model Runs	solar EV	solar SC	cost optimized E	cost optimized S	Max District Hea	Max Heat Pump	Min cost optimi	Med cost optimi	Max cost optimi	Min 100% solar
Energy Consumption (MWh)	47178472	46990373	42140375	41987996	61898711	41106383	41987996	41987996	41987996	46990373
Energy Generation (MWh)	47179716	46992017	42144717	41988657	61896114	41105519	41988657	41988657	41988657	46992017
Renewable Energy Generation (MWh)	47179716	46992017	42144717	41988657	61896114	41105519	41988657	41988657	41988657	46992017
Percentage Renewable Energy (%)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Energy Costs (Mln. € annually)	€ 4,160	€ 4,035	€ 3,200	€ 3,133	€ 3,861	€ 3,375	€ 2,899	€ 3,165	€ 3,782	€ 3,220
Energy Cost (€/kWh)	10%	9%	8%	8%	7%	9%	8%	8%	10%	7%
CO2 Emissions (Mton)	1.0	1.0	1.0	1.0	2.3	0.8	1.0	1.0	1.0	1.0
CO2 Reduction w.r.t. 1990 (%)	95%	95%	95%	95%	89%	96%	95%	95%	95%	95%
Electricity Consumption (MWh)	40358909	40170810	35320811	35168433	29269222	37132112	35168433	35168433	35168433	40170810
Electricity Generation (MWh)	40359916	40172216	35324916	35168856	29268048	37130858	35168856	35168856	35168856	40172216
Renewable Electricity Generation (MWh)	40359916	40172216	35324916	35168856	29268048	37130858	35168856	35168856	35168856	40172216
Renewable Electricity (%)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Electricity Costs (Mln. € annually)	3676.952271	3551.882918	2716.105204	2649.337568	2372.97787	3002.360536	2415.446753	2681.550901	3298.165156	2736.134147
Electricity Cost (€/kWh)	€ 0.116	€ 0.112	€ 0.086	€ 0.084	€ 0.094	€ 0.093	€ 0.076	€ 0.085	€ 0.104	€ 0.086
Electricity Generation										
Gas plant (MWh)	0	0	0	0	0	0	0	0	0	0
PV commercial rooftop (MWh)	21608303	21608303	4501730	4501730	11729707	11713501	4501730	4501730	4501730	21608303
PV utility plant (MWh)	18751612	18563913	5341035	5341035	10572198	10453169	5341035	5341035	5341035	18563913
Wind onshore (MWh)	0	0	1269834	1269834	2484226	2484226	1269834	1269834	1269834	0
Wind offshore (MWh)	0	0	25008522	24852462	6047302	14045348	24852462	24852462	24852462	0
Gas plant (GWp)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PV commercial rooftop (GWp)	20.4	20.4	4.3	4.3	11.1	11.1	4.3	4.3	4.3	20.4
PV utility plant (GWp)	17.7	17.5	5.0	5.0	10.0	9.9	5.0	5.0	5.0	17.5
Wind onshore (GWp)	0.0	0.0	0.4	0.4	0.8	0.8	0.4	0.4	0.4	0.0
Wind offshore (GWp)	0.0	0.0	5.1	5.1	1.2	2.9	5.1	5.1	5.1	0.0
Storage										
Battery capacity requiered (MWh)	155590	147163	71980	61421	81983	85998	61421	61421	61421	147163
Battery conversion total (MWh)	42966884	37604494	14209584	9954964	19586144	19756886	9954964	9954964	9954964	37604494
Battery conversion losses (MWh)	1714435	1499966	564189	393918	779212	786145	393918	393918	393918	1499966
Battery Max charge speed (GW)	26.8	12.8	9.1	6.2	7.4	11.9	6.2	6.2	6.2	12.8
Hydrogen capacity requiered (MWh)	14668596	14534311	3338021	3262039	6281405	7809814	3262039	3262039	3262039	14534311
Hydrogen conversion total (MWh)	29618290	29523491	12996421	12912137	13712082	16615585	12912137	12912137	12912137	29523491
Hydrogen conversion losses (MWh)	6963443	6953700	3066423	3057031	3225348	3917500	3057031	3057031	3057031	6953700
Hydrogen max. conversion rate (GW)	8.8	8.6	3.8	3.8	4.6	5.4	3.8	3.8	3.8	8.6
Costs (Mln. € annually)										
Electricity Costs (€/kWh)	€ 0.12	€ 0.11	€ 0.09	€ 0.08	€ 0.09	€ 0.09	€ 0.08	€ 0.08	€ 0.10	€ 0.09
Electricity Cost	€ 3,677	€ 3,552	€ 2,716	€ 2,649	€ 2,373	€ 3,002	€ 2,415	€ 2,682	€ 3,298	€ 2,736
Gas power	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
PV residential roof	€ 1,134	€ 1,134	€ 236	€ 236	€ 616	€ 615	€ 236	€ 236	€ 236	€ 1,134
PV commercial utility	€ 656	€ 650	€ 187	€ 187	€ 370	€ 366	€ 187	€ 187	€ 187	€ 650
Wind onshore	€ -	€ -	€ 69	€ 69	€ 134	€ 134	€ 69	€ 69	€ 69	€ -
Wind offshore	€ -	€ -	€ 1,588	€ 1,578	€ 384	€ 892	€ 1,578	€ 1,578	€ 1,578	€ -
Battery storage	€ 859	€ 752	€ 360	€ 307	€ 410	€ 430	€ 230	€ 307	€ 461	€ 564
Hydrogen conversion	€ 162	€ 159	€ 69	€ 70	€ 85	€ 99	€ 37	€ 102	€ 265	€ 83
Hydrogen storage	€ 851	€ 843	€ 194	€ 189	€ 364	€ 453	€ 65	€ 189	€ 489	€ 291
CO2 (electricity generation)	€ 14	€ 14	€ 13	€ 13	€ 10	€ 13				
Geothermal Heating	€ 137	€ 137	€ 137	€ 137	€ 1,384	€ -	€ 137	€ 137	€ 137	€ 137
Heat pumps	€ 311	€ 311	€ 311	€ 311	€ -	€ 346	€ 311	€ 311	€ 311	€ 311
EV	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Fuel cost (transport)	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Fuel cost (heating)	€ -	€ -	€ -	€ -	€ 0	€ -	€ -	€ -	€ -	€ -
CO2 (Total)	€ 49	€ 49	€ 48	€ 48	€ 114	€ 40	€ 48	€ 48	€ 48	€ 49
Electricity consumption										
EV consumption	3504238	3540350	3513406	3540690	3540350	3540350	3540690	3540690	3540690	3540350
Heat pump consumption	6452481	6452481	6452481	6452481	0	7163804	6452481	6452481	6452481	6452481
Heat Consumption (MWh)	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489
Renewable Heat Generation (MWh)	32629727	32629727	32629727	32629727	32628066	32629878	32629727	32629727	32629727	32629727
Percentage Renewable Heat (%)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Heat generation										
District Heating (MWh)	2845140	2845140	2845140	2845140	28653406	0	2845140	2845140	2845140	2845140
Heat pumps (MWh)	25809926	25809926	25809926	25809926	0	28655217	25809926	25809926	25809926	25809926
Biomass (MWh)	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661
Assumptions										
District Heating (PJ)	10	10	10	10	100.71	0	10	10	10	10
Heat pumps (%)	79.1	79.1	79.1	79.1	0	87.82	79.1	79.1	79.1	79.1
Gas power plant	0	0	0	0	0	0	0	0	0	0
Windturbines onshore (#)	0	0	100	100	194	194	100	100	100	0
Windturbines offshore (#)	0	0	641	637	155	360	637	637	637	0
PV rooftop commercial (acres)	12000	12000	2500	2500	6514	6505	2500	2500	2500	12000
PV utility plant (acres)	12288	12165	3500	3500	6928	6850	3500	3500	3500	12165
Electrified transport (%)	100	100	100	100	100	100	100	100	100	100
Smart Charging	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Battery Storage	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Hydrogen Storage	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Cost assumptions										
CO2 (€/tonne) effects on electricity price c	50	50	50	50	50	50	50	50	50	50
Gas power (€/MWh)	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2
PV rooftop commercial (€/MWh)	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5
PV utility plant (€/MWh)	35	35	35	35	35	35	35	35	35	35
Wind onshore (€/MWh)	54	54	54	54	54	54	54	54	54	54
Wind offshore (€/MWh)	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5
Battery storage (€/kWh)	100	100	100	100	100	100	75	100	150	75
Battery lifetime (cycles)	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
Hydrogen elektrolyser (€/kW)	250	250	250	250	250	250	250	500	1000	250
Hydrogen elektrolyser lifespan (year)	15	15	15	15	15	15	30	20	15	30
Hydrogen fuel cell (€/kW)	27	27	27	27	27	27	27	30	35	27
Hydrogen fuel cell lifespan (year)	15	15	15	15	15	15	20	15	10	20
Hydrogen storage (€/MWh)	58	58	58	58	58	58	20	58	150	20
Transport fuel costs (€/MWh)	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28
CCGT (CAPEX) (€/MW)	900000	900000	900000	900000	900000	900000	900000	900000	900000	900000
Heat Network (€/MWh)	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3
Heat Pump added CAPEX (€/kW)	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6

Model Runs	Med 100% solar	Max 100% solar	100% CCGT CO2	cost optimized (	cost optimized (	cost optimized (	cost optimized (	cost optimized (	100% CCGT CO2	100% CCGT CO2
Energy Consumption (MWh)	46990373	46990373	38537702	41987996	41987996	41987996	41987996	41987996	38537702	38537702
Energy Generation (MWh)	46992017	46992017	38537940	41988657	41988657	41988657	41988657	41988657	38537940	38537940
Renewable Energy Generation (MWh)	46992017	46992017	6819801	41988657	41988657	41988657	41988657	41988657	6819801	6819801
Percentage Renewable Energy (%)	100%	100%	18%	100%	100%	100%	100%	100%	18%	18%
Energy Costs (Mln. € annually)	€ 4,109	€ 6,192	€ 2,968	€ 3,094	€ 3,104	€ 3,114	€ 3,123	€ 3,133	€ 2,725	€ 2,847
Energy Cost (€/kWh)	10%	14%	9%	8%	8%	8%	8%	8%	8%	8%
CO2 Emissions (Mton)	1.0	1.0	12.1	1.0	1.0	1.0	1.0	1.0	12.1	12.1
CO2 Reduction w.r.t. 1990 (%)	95%	95%	43%	95%	95%	95%	95%	95%	43%	43%
Electricity Consumption (MWh)	40170810	40170810	31718139	35168433	35168433	35168433	35168433	35168433	31718139	31718139
Electricity Generation (MWh)	40172216	40172216	31718139	35168856	35168856	35168856	35168856	35168856	31718139	31718139
Renewable Electricity Generation (MWh)	40172216	40172216	0	35168856	35168856	35168856	35168856	35168856	0	0
Renewable Electricity (%)	100%	100%	0%	100%	100%	100%	100%	100%	0%	0%
Electricity Costs (Mln. € annually)	3625.158651	5709.03237	2505.017793	2638.663028	2641.331663	2644.000298	2646.668933	2649.337568	2276.645133	2390.831463
Electricity Cost (€/kWh)	€ 0.114	€ 0.180	€ 0.079	€ 0.083	€ 0.083	€ 0.083	€ 0.083	€ 0.084	€ 0.072	€ 0.075
Electricity Generation										
Gas plant (MWh)	0	0	31718139	0	0	0	0	0	31718139	31718139
PV commercial rooftop (MWh)	21608303	21608303	0	4501730	4501730	4501730	4501730	4501730	0	0
PV utility plant (MWh)	18563913	18563913	0	5341035	5341035	5341035	5341035	5341035	0	0
Wind onshore (MWh)	0	0	0	1269834	1269834	1269834	1269834	1269834	0	0
Wind offshore (MWh)	0	0	0	24852462	24852462	24852462	24852462	24852462	0	0
Gas plant (GWp)	0.0	0.0	7.0	0.0	0.0	0.0	0.0	0.0	7.0	7.0
PV commercial rooftop (GWp)	20.4	20.4	0.0	4.3	4.3	4.3	4.3	4.3	0.0	0.0
PV utility plant (GWp)	17.5	17.5	0.0	5.0	5.0	5.0	5.0	5.0	0.0	0.0
Wind onshore (GWp)	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.4	0.0	0.0
Wind offshore (GWp)	0.0	0.0	0.0	5.1	5.1	5.1	5.1	5.1	0.0	0.0
Storage										
Battery capacity requiered (MWh)	147163	147163	0	61421	61421	61421	61421	61421	0	0
Battery conversion total (MWh)	37604494	37604494	0	9954964	9954964	9954964	9954964	9954964	0	0
Battery conversion losses (MWh)	1499966	1499966	0	393918	393918	393918	393918	393918	0	0
Battery Max charge speed (GW)	12.8	12.8	0.0	6.2	6.2	6.2	6.2	6.2	0.0	0.0
Hydrogen capacity requiered (MWh)	14534311	14534311	0	3262039	3262039	3262039	3262039	3262039	0	0
Hydrogen conversion total (MWh)	29523491	29523491	0	12912137	12912137	12912137	12912137	12912137	0	0
Hydrogen conversion losses (MWh)	6953700	6953700	0	3057031	3057031	3057031	3057031	3057031	0	0
Hydrogen max. conversion rate (GW)	8.6	8.6	0.0	3.8	3.8	3.8	3.8	3.8	0.0	0.0
Costs (Mln. € annually)										
Electricity Costs (€/kWh)	€ 0.11	€ 0.18	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.07	€ 0.08
Electricity Cost	€ 3,625	€ 5,709	€ 2,505	€ 2,639	€ 2,641	€ 2,644	€ 2,647	€ 2,649	€ 2,277	€ 2,391
Gas power	€ -	€ -	€ 2,277	€ -	€ -	€ -	€ -	€ -	€ 2,277	€ 2,277
PV residential roof	€ 1,134	€ 1,134	€ -	€ 236	€ 236	€ 236	€ 236	€ 236	€ -	€ -
PV commercial utility	€ 650	€ 650	€ -	€ 187	€ 187	€ 187	€ 187	€ 187	€ -	€ -
Wind onshore	€ -	€ -	€ -	€ 69	€ 69	€ 69	€ 69	€ 69	€ -	€ -
Wind offshore	€ -	€ -	€ -	€ 1,578	€ 1,578	€ 1,578	€ 1,578	€ 1,578	€ -	€ -
Battery storage	€ 752	€ 1,128	€ -	€ 307	€ 307	€ 307	€ 307	€ 307	€ -	€ -
Hydrogen conversion	€ 232	€ 603	€ -	€ 70	€ 70	€ 70	€ 70	€ 70	€ -	€ -
Hydrogen storage	€ 843	€ 2,180	€ -	€ 189	€ 189	€ 189	€ 189	€ 189	€ -	€ -
CO2 (electricity generation)			€ 228	€ 3	€ 5	€ 8	€ 11	€ 13	€ -	€ 114
Geothermal Heating	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137	€ 137
Heat pumps	€ 311	€ 311	€ 311	€ 311	€ 311	€ 311	€ 311	€ 311	€ 311	€ 311
EV	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Fuel cost (transport)	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Fuel cost (heating)	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
CO2 (Total)	€ 49	€ 49	€ 242	€ 10	€ 19	€ 29	€ 38	€ 48	€ -	€ 121
Electricity consumption										
EV consumption	3540350	3540350	3541346	3540690	3540690	3540690	3540690	3540690	3541346	3541346
Heat pump consumption	6452481	6452481	6452481	6452481	6452481	6452481	6452481	6452481	6452481	6452481
Heat Consumption (MWh)	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489
Renewable Heat Generation (MWh)	32629727	32629727	32629727	32629727	32629727	32629727	32629727	32629727	32629727	32629727
Percentage Renewable Heat (%)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Heat generation										
District Heating (MWh)	2845140	2845140	2845140	2845140	2845140	2845140	2845140	2845140	2845140	2845140
Heat pumps (MWh)	25809926	25809926	25809926	25809926	25809926	25809926	25809926	25809926	25809926	25809926
Biomass (MWh)	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661
Assumptions										
District Heating (PJ)	10	10	10	10	10	10	10	10	10	10
Heat pumps (%)	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.1	79.1
Gas power plant	0	0	6993	0	0	0	0	0	6993	6993
Windturbines onshore (#)	0	0	0	100	100	100	100	100	0	0
Windturbines offshore (#)	0	0	0	637	637	637	637	637	0	0
PV rooftop commercial (acres)	12000	12000	0	2500	2500	2500	2500	2500	0	0
PV utility plant (acres)	12165	12165	0	3500	3500	3500	3500	3500	0	0
Electrified transport (%)	100	100	100	100	100	100	100	100	100	100
Smart Charging	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Battery Storage	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Hydrogen Storage	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Cost assumptions										
CO2 (€/tonne) effects on electricity price c	50	50	20	10	20	30	40	50	0	10
Gas power (€/MWh)	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2
PV rooftop commercial (€/MWh)	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5	52.5
PV utility plant (€/MWh)	35	35	35	35	35	35	35	35	35	35
Wind onshore (€/MWh)	54	54	54	54	54	54	54	54	54	54
Wind offshore (€/MWh)	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5	63.5
Battery storage (€/kWh)	100	150	150	100	100	100	100	100	100	100
Battery lifetime (cycles)	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
Hydrogen elektrolyser (€/kW)	500	1000	1000	250	250	250	250	250	250	250
Hydrogen elektrolyser lifespan (year)	20	15	15	15	15	15	15	15	15	15
Hydrogen fuel cell (€/kW)	30	35	35	27	27	27	27	27	27	27
Hydrogen fuel cell lifespan (year)	15	10	10	15	15	15	15	15	15	15
Hydrogen storage (€/MWh)	58	150	150	58	58	58	58	58	58	58
Transport fuel costs (€/MWh)	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28
CCGT (CAPEX) (€/MW)	900000	900000	900000	900000	900000	900000	900000	900000	900000	900000
Heat Network (€/MWh)	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3
Heat Pump added CAPEX (€/kW)	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6

Model Runs	100% CCGT CO2	100% CCGT CO2	100% CCGT CO2	100% CCGT CO2	2019	2023	2030 verwachtte	2030 50% wind	2030 50% zon	100% duurzaam
Energy Consumption (MWh)	38537702	38537702	38537702	38537702	76235081	75427542	68753175	63393504	64039939	41977587
Energy Generation (MWh)	38537940	38537940	38537940	38537940	26446041	27498611	30450057	34551582	35160366	41990235
Renewable Energy Generation (MWh)	6819801	6819801	6819801	6819801	5223360	10228254	19128138	31964025	31853872	41990235
Percentage Renewable Energy (%)	18%	18%	18%	18%	7%	14%	28%	50%	50%	100%
Energy Costs (Mln. € annually)	€ 2,968	€ 3,089	€ 3,210	€ 3,331	€ 4,519	€ 4,707	€ 4,142	€ 3,444	€ 3,746	€ 2,114
Energy Cost (€/kWh)	9%	9%	9%	10%	6%	7%	6%	6%	6%	6%
CO2 Emissions (Mton)	12.1	12.1	12.1	12.1	17.4	15.7	11.7	6.9	7.2	1.0
CO2 Reduction w.r.t. 1990 (%)	43%	43%	43%	43%	0.181711741	0.258642763	0.447983406	0.674301521	0.662840691	0.954717935
Electricity Consumption (MWh)	31718139	31718139	31718139	31718139	21589387	21816938	23636636	27671388	28317822	35158024
Electricity Generation (MWh)	31718139	31718139	31718139	31718139	21589387	21816866	23630256	27731782	28340565	35170434
Renewable Electricity Generation (MWh)	0	0	0	0	366706	4546509	12308337	25144224	25034072	35170434
Renewable Electricity (%)	0%	0%	0%	0%	2%	21%	52%	91%	88%	100%
Electricity Costs (Mln. € annually)	2505.017793	€ 2,619	€ 2,733	€ 2,848	€ 1,637	€ 1,700	€ 1,607	€ 1,365	€ 1,667	€ 1,620
Electricity Cost (€/kWh)	€ 0.079	€ 0.083	€ 0.086	€ 0.090	€ 0.076	€ 0.078	€ 0.069	€ 0.054	€ 0.066	€ 0.051
Electricity Generation										
Gas plant (MWh)	31718139	31718139	31718139	31718139	21222681	17270357	11321918	2587557	3306494	0
PV commercial rooftop (MWh)	0	0	0	0	234090	635644	2648818	2648818	9003460	6302422
PV utility plant (MWh)	0	0	0	0	0	317410	953756	953756	7324849	3815025
Wind onshore (MWh)	0	0	0	0	360898	956305	1269834	1269834	1269834	1269834
Wind offshore (MWh)	0	0	0	0	0	3238233	8232134	21068021	8232134	24579358
Gas plant (GWp)	7.0	7.0	7.0	7.0	3.8	3.8	2.7	0.7	0.6	0.0
PV commercial rooftop (GWp)	0.0	0.0	0.0	0.0	0.2	0.6	2.5	2.5	8.5	6.0
PV utility plant (GWp)	0.0	0.0	0.0	0.0	0.0	0.3	0.9	0.9	6.9	3.6
Wind onshore (GWp)	0.0	0.0	0.0	0.0	0.1	0.3	0.4	0.4	0.4	0.4
Wind offshore (GWp)	0.0	0.0	0.0	0.0	0.0	0.7	1.7	4.3	1.7	5.0
Storage										
Battery capacity requiered (MWh)	0	0	0	0	0	0	10405	42051	60142	61363
Battery conversion total (MWh)	0	0	0	0	0	0	760157	5208218	13957231	10110389
Battery conversion losses (MWh)	0	0	0	0	0	0	28101	204158	554075	400259
Battery Max charge speed (GW)	0.0	0.0	0.0	0.0	0.0	0.0	1.7	3.2	9.0	6.3
Hydrogen capacity requiered (MWh)	0	0	0	0	0	1	207044	1040229	4464691	3355410
Hydrogen conversion total (MWh)	0	0	0	0	0	0	741258	8677388	10000067	12846070
Hydrogen conversion losses (MWh)	0	0	0	0	0	72	176475	2054670	2351431	3040267
Hydrogen max. conversion rate (GW)	0.0	0.0	0.0	0.0	0.0	0.0	0.7	2.5	3.6	3.8
Costs (Mln. € annually)										
Electricity Costs (€/kWh)	€ 0.08	€ 0.08	€ 0.09	€ 0.09	€ 0.08	€ 0.08	€ 0.07	€ 0.05	€ 0.07	€ 0.05
Electricity Cost	€ 2,505	€ 2,619	€ 2,733	€ 2,848	€ 1,637	€ 1,700	€ 1,607	€ 1,365	€ 1,667	€ 1,620
Gas power	€ 2,277	€ 2,277	€ 2,277	€ 2,277	€ 1,448	€ 1,243	€ 831	€ 197	€ 226	€ -
PV residential roof	€ -	€ -	€ -	€ -	€ 15	€ 19	€ 66	€ 53	€ 180	€ 126
PV commercial utility	€ -	€ -	€ -	€ -	€ -	€ 13	€ 33	€ 31	€ 242	€ 126
Wind onshore	€ -	€ -	€ -	€ -	€ 36	€ 77	€ 76	€ 69	€ 69	€ 69
Wind offshore	€ -	€ -	€ -	€ -	€ -	€ 130	€ 288	€ 632	€ 247	€ 737
Battery storage	€ -	€ -	€ -	€ -	€ -	€ -	€ 78	€ 210	€ 301	€ 307
Hydrogen conversion	€ -	€ -	€ -	€ -	€ -	€ -	€ 13	€ 39	€ 56	€ 44
Hydrogen storage	€ -	€ -	€ -	€ -	€ -	€ 0	€ 12	€ 60	€ 259	€ 195
CO2 (electricity generation)	€ 228	€ 343	€ 457	€ 571	€ 138	€ 219	€ 209	€ 73	€ 89	€ 17
Geothermal Heating	€ 137	€ 137	€ 137	€ 137	€ 43	€ 82	€ 137	€ 137	€ 137	€ 137
Heat pumps	€ 311	€ 311	€ 311	€ 311	€ 4	€ 12	€ 39	€ 98	€ 98	€ 311
EV	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Fuel cost (transport)	€ -	€ -	€ -	€ -	€ 1,749	€ 1,719	€ 1,233	€ 881	€ 881	€ -
Fuel cost (heating)	€ -	€ -	€ -	€ -	€ 911	€ 862	€ 748	€ 586	€ 586	€ -
CO2 (Total)	€ 242	€ 363	€ 485	€ 606	€ 313	€ 551	€ 586	€ 449	€ 465	€ 62
Electricity consumption										
EV consumption	3541346	3541346	3541346	3541346	24828	85028	1062130	1770419	1770175	3540704
Heat pump consumption	6452481	6452481	6452481	6452481	81574	244721	815737	2039343	2039343	6452481
Heat Consumption (MWh)	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489	32629489
Renewable Heat Generation (MWh)	32629727	32629727	32629727	32629727	5182949	6660629	10082750	14977173	14977173	32629727
Percentage Renewable Heat (%)	100%	100%	100%	100%	16%	20%	31%	46%	46%	100%
Heat generation										
District Heating (MWh)	2845140	2845140	2845140	2845140	881993	1707084	2845140	2845140	2845140	2845140
Heat pumps (MWh)	25809926	25809926	25809926	25809926	326295	978885	3262949	8157372	8157372	25809926
Biomass (MWh)	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661	3974661
Assumptions										
District Heating (PJ)	10	10	10	10	3.1	6	10	10	10	10
Heat pumps (%)	79.1	79.1	79.1	79.1	1	3	10	25	25	79.1
Gas power plant	6993	6993	6993	6993	3846	3844	2700	700	600	0
Windturbines onshore (#)	0	0	0	0	28	75	100	100	100	100
Windturbines offshore (#)	0	0	0	0	0	83	211	540	211	630
PV rooftop commercial (acres)	0	0	0	0	130	353	1471	1471	5000	3500
PV utility plant (acres)	0	0	0	0	0	208	625	625	4800	2500
Electrified transport (%)	100	100	100	100	0.7	2.4	30	50	50	100
Smart Charging	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Battery Storage	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Hydrogen Storage	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Cost assumptions										
CO2 (€/tonne) effects on electricity price c	20	30	40	50	18	35	50	65	65	65
Gas power (€/MWh)	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2
PV rooftop commercial (€/MWh)	52.5	52.5	52.5	52.5	65	30	25	20	20	20
PV utility plant (€/MWh)	35	35	35	35	65	40	35	33	33	33
Wind onshore (€/MWh)	54	54	54	54	100	80	60	54	54	54
Wind offshore (€/MWh)	63.5	63.5	63.5	63.5	54	40	35	30	30	30
Battery storage (€/kWh)	100	100	100	100	500	400	150	100	100	100
Battery lifetime (cycles)	5000	5000	5000	5000	8000	10000	12000	12000	12000	12000
Hydrogen elektrolyser (€/kW)	250	250	250	250	750	550	440	350	350	250
Hydrogen elektrolyser lifespan (year)	15	15	15	15	20	20	25	25	25	25
Hydrogen fuel cell (€/kW)	27	27	27	27	50	40	30	30	30	30
Hydrogen fuel cell lifespan (year)	15	15	15	15	15	15	20	20	20	20
Hydrogen storage (€/MWh)	58	58	58	58	58	58	58	58	58	58
Transport fuel costs (€/MWh)	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28	78.28
CCGT (CAPEX) (€/MW)	900000	900000	900000	900000	900000	900000	900000	900000	900000	900000
Heat Network (€/MWh)	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3	48.3
Heat Pump added CAPEX (€/kW)	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6	19.6