From Complexity to Clarity

Generating Near-Optimal Scenarios for the Dutch Electricity Network using MGA

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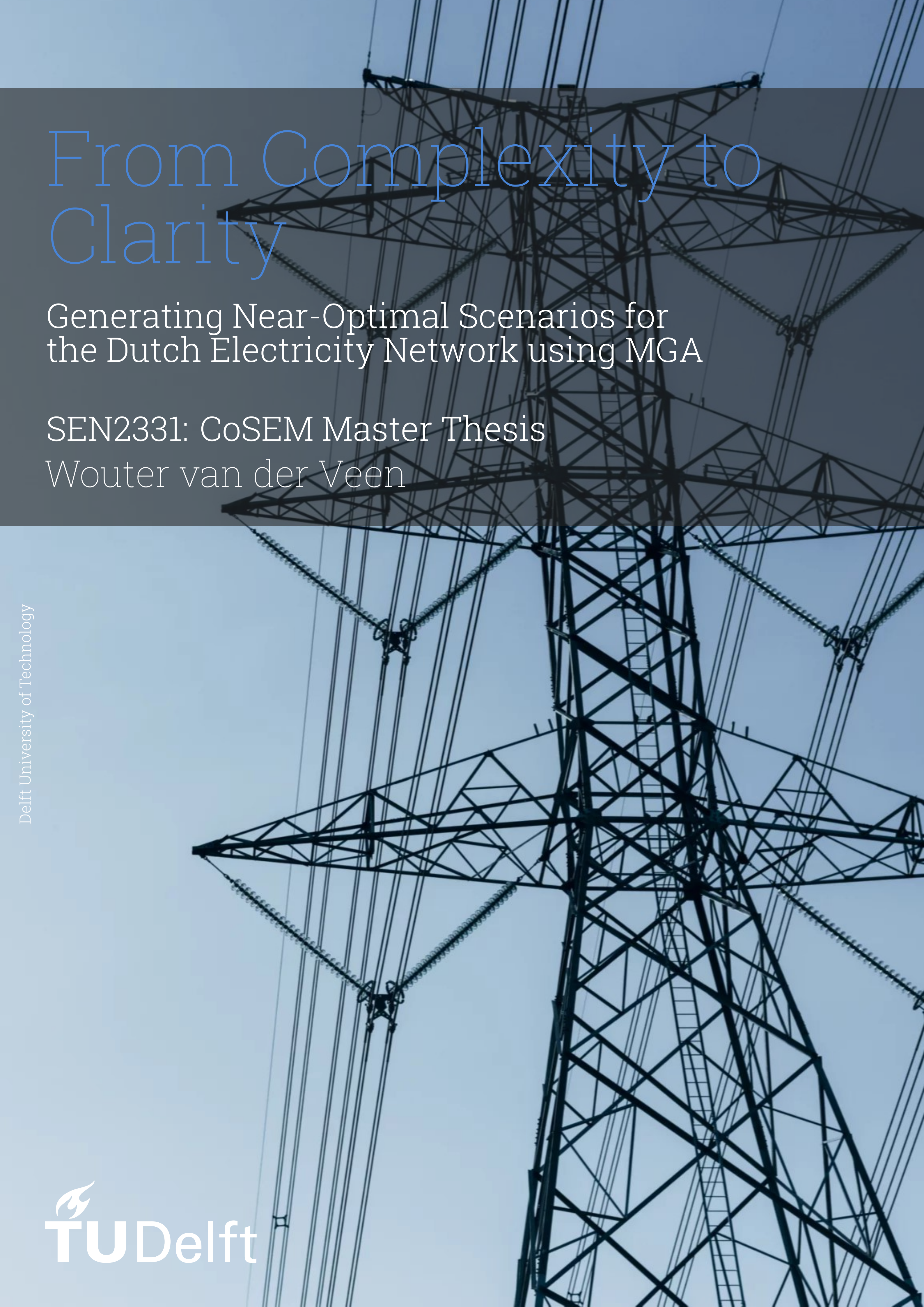

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by

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Preface

Writing this thesis has been a challenging but rewarding journey, and I would like to take a moment to thank the people who made it possible.

First, I want to sincerely thank my academic supervisors at TU Delft. Francesco Lombardi, thank you for your thoughtful guidance throughout the process. Your help with the model setup was of inestimable value. I was always able to send you an email with questions and I could then also expect a response the same day. Jafar Rezaei, thank you for answering even quicker to my emails. Although these were mostly practical matters, it was still very much appreciated. Your questions during our meetings helped me avoid tunnel vision and stay open to alternative perspectives.

I am also very grateful to Balthasar Klimbie, my supervisor at TenneT, for your support and encouragement during moments when I felt stuck. Through our “puzzling” sessions and your ability to ask the right questions, I was able to make progress after every meeting. I would also like to thank Viktor Beelen, you were my go-to person at TenneT for model-specific questions and played a key role in shaping the foundation of the model as it stands today.

Thanks also to the experts who participated in the interviews. Your willingness to share your time and knowledge added valuable depth to this research and helped connect the model to the real-world uncertainties that shape energy system planning.

Finally, I want to thank my friends and family for their encouragement and above all patience.

Wouter van der Veen
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Summary

Exactly predicting what the future energy system in the Netherlands will look like in 25 years is impossible, but there are ways to epxlore possible scenarios. A widely used tool to help give an idea of how such a system will look is energy system optimisation modelling (ESOM). TenneT, the Dutch TSO, also uses optimisation modelling to explore possible cost-effective plans for this future network. A challenge they face is not the ability to run intensive models but the need for a model that can rapidly generate a wide range of alternatives of interest. While highly detailed results with high resolution are necessary, in many cases a model is more useful when it can produce results quickly and efficiently without the need for long computation times.

This research aims to develop a flexible and exploratory energy system model for the Netherlands in 2050. This enables analysing a large set of alternatives without the high resolution of a detailed model that causes long running times. Additionally, with the modelling approach Modelling to Generate Alternatives (MGA), specifically the SPORES method, we can uncover a range of near-optimal solutions to provide insight into the technical composition of the model. With a large number of alternatives, different technology choices, technology trade-offs and spatial capacities can be examined. To create this model, the energy system modelling framework Calliope was used. The literature provides research gaps and opportunities in the current methods of using MGA. The focus for this research is aimed at developing a method to be able to create large sets of solutions without the need for long modelling times. Desk research and secondary data analysis gave insights on the current state of the Dutch energy system, and conducted interviews ensured the model was a good fit for the company and their vision of the model. The interviews resulted in a set of six questions that could be answered using MGA.

The model consists of a twelve-node Dutch energy system with both electricity and hydrogen carriers included. It also has connections to the neighbouring countries to represent the import and export of energy. The model results project a high reliance on renewable energy technologies like offshore wind and solar PV. The model also uses several types of energy storage, namely salt caverns for hydrogen storage and Li-ion batteries for electricity storage. Especially hydrogen storage is used as the main flexibility technology of the system. In comparison with the II3050 modelled energy system, the model outputs show lower use of offshore wind and more use of hydrogen. The results also show a promising possibility for Small Modular Reactors (SMR). The transmission network will need to be expanded to handle large amounts of energy from Groningen to Noord-Holland and from Zuid-Holland to Limburg. The SPORES results demonstrate that not all technologies are mandatory for the energy system. Some technologies are interchangeable within a small cost margin. BECCS-rebuilt and SMRs frequently replace hydrogen technologies or renewables in alternative configurations. This change in technique compositions also has an impact on the transmission system. Although certain reinforcements appear consistently. Directed SPORES runs show that assumptions about affordability, nuclear expansion, decentralisation, or BECCS-rebuilt availability significantly affect system architecture. Limitations of the model include fixed electricity import/export prices, costless and lossless hydrogen transport, and GDP-based spatial demand allocation. Despite these simplifications, the model allows rapid exploration of structural differences across scenarios.

This thesis advances the field of energy system optimisation modelling by integrating qualitative knowledge from expert interviews with quantitative scenario generation. The study shows how system planning questions can be addressed more quickly by using MGA to generate rapid results. It demonstrates how the MGA method SPORES can be used to generate insight into system design flexibility, infrastructure needs, and guided searching. Methodologically, the research highlights the accessibility and adaptability of open-source tools like Calliope for exploratory analysis. Future research could build on this model by incorporating varying electricity and hydrogen prices, simplified foreign demand profiles, or expanding the nearly optimal solution alternatives with a new post-processing tool, Modelling to Generate Continuous Alternatives.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating Current
BECCS	Bioenergy with Carbon Capture and Storage
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
COSEM	Complex Systems Engineering and Management
DC	Direct current
ESOM	Energy System Optimisation Modelling
GDP	Gross Domestic Product
HSJ	Hop Skip Jump (method)
II3050	Integrale energiesystemen verkenning 2030 en 2050
LDES	Long Duration Energy Storage
MAA	Modelling All Alternatives
MGA	Modelling to Generate Alternative
MGCA	Modelling to Generate Continuous Alternatives
MGPA	Modelling to generate near-Pareto-optimal alternatives
MOO	Multi Objective Optimisation
OAT	One At a Time
OCGT	Open Cycle Gas Turbine
PII	Personal Identifiable Information
PIRD	Personally Identifiable Research Data
PSA	Parametric Senesitivity Analysis
PV	Photo voltaic
SMR	Small Modular Reactor
SPORES	Spatially Explicit Practically Optimal Alternatives
TSO	Transmission System Operator

1 Introduction

1.1. Problem introduction

After the Paris Agreement in 2015, it was clear all energy-consuming sectors needed to reduce their emissions [75]. This means that from now on, there are roughly 2 decades to work towards a climate-neutral society. The electrification needs to be supported by a resilient and robust electricity network that is being developed and sustained by a transmission system operator (TSO). In the Netherlands, this operator is TenneT [74]. The expected electricity demand compared to total energy demand in 2050 is between 40-70% [3]. Currently, the electricity demand is around 20% of the total energy demand. Because the electricity demand will be significantly higher than its current demand, the electricity network needs to be expanded and improved to be ready in 2050. The network expansion and layout are dependent on a series of different factors, including location impact, technology development, and spatial optimisation [73]. In order to make this transition as smooth as possible, a network map can be made with various scenario data that provide insight into the investments required to keep up with the electrification of the grid.

Such a map has been created by TenneT in 2023. They have come up with their vision to be prepared for the time to come. This vision is translated into TenneT's 'Target Grid'. Target Grid is a visual map that strategically guides the development of infrastructure by anticipating the future now. It focuses on long-term planning, timely planning, building futureproof, and standardisation [72]. Although this vision is a great representation of what plans need to be executed before 2050, it has not yet been substantiated by actual numbers. The results are based on backcasting the goals of 2050 and are largely expert-based. A great way to improve this map is by using Energy System Optimisation Modelling (ESOM). ESOM can help create more precise scenario data by representing the physical and technical constraints of the distribution network and by benchmarking the effectiveness of different options [11].

Optimisation models allocate and coordinate system components efficiently by solving well-defined mathematical problems that include an objective function, decision variables, and system constraints. In electricity systems, they support decisions on investment, operation, and control, particularly as systems become more complex due to decentralised generation and demand-side flexibility. These models help minimise total system costs while meeting technical and regulatory constraints, such as locational restrictions or satisfying demand. ESOM is especially powerful for modelling distribution networks, where operational limits like transmission capacity and generator dispatch need to be respected under increasing stress from new technologies. By applying ESOM, planners can identify least-cost solutions that comply with climate agreements and decarbonisation targets, such as those of the Dutch government for 2050.

Optimisation modelling presents one optimal solution of the system you are modelling. In order to explore different feasible pathways instead of relying on one optimal solution, there are different methods to find a diverse set of near-optimal solutions. These methods include Modelling to Generate Alternatives (MGA), Parametric Sensitivity Analysis (PSA), and Multi-Objective Optimisation.

MGA makes it possible to go beyond only finding the optimal solution. It can enlarge the decision space to give the stakeholder different possibilities to discuss and identify a solution that best suits them [41].

Parametric sensitivity analysis, like robust optimisation, varies its inputs to represent numerical uncertainty ranges for a subset of important parameters, which creates a set of scenarios with different assumption sets with the goal of testing how the model responds to parameter changes [81]. Robust optimisation is more often used to ensure solutions are robust against uncertainty. This takes away the flexibility inside the solution space [26].

MOO can be used when you would want to understand the tradeoffs between conflicting objectives [9]. MOO extends the least-cost objective by incorporating additional alternative objectives, resulting in a set of non-dominated solutions known as the Pareto frontier. Within this frontier, no objective can be improved without diminishing the performance of another, a condition referred to as Pareto optimality or Pareto efficiency [32]. The limitation for this method is that it can only deal with 2 or, at maximum, 3 objectives. In a complex planning problem, like an energy system, there are more, many of which are initially unknown. MOO would be used when you would want to understand the tradeoffs between conflicting objectives [9].

This study chooses to use MGA over PSA and MOO because it finds a range of structurally distinct, near-optimal solutions inside a single objective framework. Unlike MOO, it does not require defining competing objectives in advance, and unlike PSA, it does not focus solely on input parameter uncertainties. MGA, on the contrary, expands the solution space by finding several viable solutions that are close to the cost-optimal solution. This gives stakeholders realistic choices that take into account practical, contextual, or political factors.

Additionally, MGA is a good way to look for different solutions in large, complex models because it is computationally efficient. It makes a lot of meaningful alternatives without the need for exhaustive enumeration [16]. Compared to MOO, which becomes increasingly computationally demanding as the number of objectives grows and is limited to 3 objectives, MGA maintains focus on a single objective while revealing structural differences between solutions. On the other hand, PSA tests how well a single solution can handle changes in parameters but does not come up with other options.

1.2. Literature review

As mentioned in the previous segment, this research aims to use MGA to find a variety of solutions that can provide a climate-neutral network for the Netherlands in 2050. However, while MGA is widely used, it is not always clear which method is most suitable for a specific modelling purpose, especially when considering computational cost and solution diversity. Furthermore, existing MGA methods have limitations, such as high computational demands, difficulty in covering all spatial or technological options, or lack of integration with uncertainty analysis. Therefore, before selecting an MGA approach, it is essential to analyse the existing literature to identify what methods have been developed, understand their limitations and research gaps, and justify why this research uses a specific MGA method rather than regular MGA approaches. The following literature reviews the development of MGA methods, their applications in energy system modelling, and recent advancements aimed at overcoming these challenges.

The literature study is based on searching for literature in two different academic databases: Scopus and Google Scholar. We found the literature by searching with 4 different key concepts. These include modelling to generate alternatives, energy systems, optimisation modelling, and near-optimal solutions. These concepts were searched in both the title and abstract. The number of sources was scoped down because of language and date. All sources are in English, and no source has been selected before 2021. Lastly, a few sources were found by looking at the literature section of the articles found in the databases or sources recommended by the supervisor. An overview of the sources used for the literature study can be found below in table 1.1 or in appendix A

Table 1.1: Overview of the sources

Source	Title	About
Lombardi et al. (2023) [42]	What is redundant and what is not? Computational trade-offs in modelling to generate alternatives for energy infrastructure deployment	Minimise redundant computation with the SPORES method.
Dubois et al. (2023) [19]	Multi-objective near-optimal necessary conditions for multi-sectoral planning	MGA with multiple objectives.
Pedersen et al. (2021) [58]	Modeling all alternative solutions for highly renewable energy systems	Unlike traditional MGA methods that generate a few alternatives, this approach seeks to determine the entire continuum of near-optimal solutions.
Neumann et al. (2021) [56]	The near-optimal feasible space of a renewable power system model	Valuable MGA for policymakers because it reveals investment flexibility and essential infrastructure choices in a cost-efficient renewable energy system.
Lau et al. (2024) [38]	Measuring exploration: evaluation of Modelling to Generate Alternatives methods in capacity expansion models	Tests four different MGA methodologies and proposes a new combination vector approach.
Schwaeppe et al. (2024) [68]	Finding better alternatives: Shadow prices of near-optimal solutions in energy system optimization modeling	The near-optimal solutions space is further explored by looking at the shadow prices of the alternatives.
Vågerö et al. (2025) [77]	Exploring near-optimal energy systems with stakeholders: a novel approach for participatory modelling	MGA with the input of stakeholders. Allows stakeholders to use the MGA alternatives to make informed decisions.
Van Greevenbroek et al. (2023) [30]	Enabling agency: trade-offs between regional and integrated energy systems design flexibility	Illuminates trade-offs and interactions between national and continental energy transitions under uncertainty with MGA.
Grochowicz et al. (2023) [31]	Intersecting near-optimal spaces: European power systems with more resilience to weather variability	MGA method that uses a geometric approach to identify robust solutions.
Zhang et al. (2025) [83]	Exploring resilient alternatives in community energy systems planning to address parameter and structural hybrid uncertainties	Modelling to Generate Resilience: With this method, the resilience of the results stays higher than with traditional MGA.
Finke et al. (2024) [24]	Modelling to generate near-Pareto-optimal alternatives (MGPA) for the municipal energy transition	This approach tackles explicit, easy-to-formulate objectives first before exploring a spectrum of alternatives within a region of interest in a second step.
Lau et al. (2024) [39]	Modelling to Generate Continuous Alternatives: Enabling Real-Time Feasible Portfolio Generation on Convex Planning Models	Post-processing algorithm that lets you explore and generate MGA results in a matter of seconds.

1.2.1. Modelling to Generate Alternatives

There are lots of different types of MGAs to explore near-optimal solutions. After the first article about Modelling to Generate Alternatives by Brill et al. [6], the Hop, Skip, Jump (HSJ) method was introduced. This showed that within energy system optimisation, it is possible to explore diverse near-optimal solutions. This was the beginning of many more researchers looking at the possibilities of MGA.

Variable Min/Max

Different studies apply MGA to assess alternative investment strategies in the European energy system. Lombardi et al. [44] were the first to use MGA to explore near-optimal designs for a fully renewable electricity system in Europe. Neumann and Brown [56] also use this technique in combination with the One At the Time (OAT) approach, where the objective is chosen to minimise and maximise the capacity of every technology in the solution, one at the time. This ensures identifying the most extreme points in the solution space. Their findings suggest that many cost-efficient paths exist, but some investments, such as offshore and onshore wind, are consistently necessary to keep costs within an acceptable range.
MGA accounts for structural uncertainties in energy system modelling. Many uncertainties, such as future technology costs, energy demand shifts, or political developments, cannot be easily captured by a single optimal solution. By exploring a range of near-optimal alternatives, MGA helps create more resilient and adaptable energy strategies. Schwaeppe et al. use the variable min/max MGA method to look at the shadow prices of the found alternatives to better determine which alternative is superior to the other [68].

MAA

A report by Pedersen et al. [58] uses MGA to examine how alternative solutions perform under different land-use constraints, levels of self-sufficiency, and transmission network configurations. Their research highlights the importance of considering a continuous range of solutions rather than focusing on isolated scenarios. This is done with a novel numerical method called Modelling All Alternatives (MAA).
Grochowicz et al. (2023) build on both MGA and MAA and introduce a geometric approach to identify robust solutions. An advantage of this method is that it uses multiple years of weather data to improve the robustness of the model. A disadvantage is the computational complexity and potential loss of spatial detail [31].
MGA supports stakeholder engagement in energy planning. Traditional optimisation models tend to be highly technical, making it difficult for policymakers and the public to engage with their findings. Studies such as Vågerö et al. (2025) [77] show that MGA can be used in participatory modelling, allowing stakeholders to explore different options and make informed decisions. To get as many options to choose from, MAA was used for this research as well.
Finally, when energy system optimisation modelling and MGA are done, it is important to take into account the whole system. Van Greevenbroek et al. (2023) [30] found, by using MAA, that energy decisions in one country have a great impact on neighbouring countries.

Other MGA's

Other studies combine MGA with multi-objective optimisation [19][38]. These reports analyse trade-offs between different priorities. Dubois et al. (2023) extend MGA by incorporating multiple objectives, such as cost and energy self-sufficiency, to provide a more balanced assessment of different strategies. They use the random vector method to generate the most diverse set of optimisation factors possible. Lau et al. (2024) evaluate various MGA methods and find that some approaches are better suited for broad exploration (random vector), while others are more efficient in identifying extreme alternatives (variable Min/Max).

One of the key benefits of MGA is its ability to highlight different pathways to decarbonisation. It helps the decision-maker understand the flexibility of investment choices while maintaining economic feasibility [56][58]. This is particularly valuable when considering infrastructure projects that may face public resistance, such as expanding the electricity grid or developing large-scale wind farms.

A downside of MGA is that the number of alternatives to generate is virtually endless. A paper by Lombardi et al. (2023) introduces a new method of MGA called SPORES to deal with this problem. It is a highly customisable, spatially explicit advancement of MGA [44]. The high customisability of the SPORES workflow makes it possible to tweak the search towards either spatial or technological dissimilarity. This allows for exploring trade-offs between the two. There is a clear trade-off between leveraging available computational power to explore technological options and accounting for spatial differences across alternative system configurations.

Lau et al. [39] introduce an MGA post-processing method that can rapidly create new solutions with associated outcome metrics from both the interior and the exterior regions of the feasible region identified via any MGA. This method can also impose a new objective and constraints and rapidly calculate the impact of the optimal solution for this new objective or constraint. Lastly, it can quickly approximate Pareto frontiers between a wide range of outcomes and retrieve capacity solutions for any point within the near-optimal feasible region to recreate more detailed feasible outcomes. This method is called Modelling to Generate Continuous Alternatives (MGCA).

Lastly, Finke et al. (2024) [24], extend MGA by incorporating multi-objective trade-offs, particularly between cost and emissions. This method is called Modelling to Generate near-Pareto-optimal Alternatives (MGPA). MGPA offers a way to systematically explore alternative solutions while maintaining Pareto efficiency, ensuring that selected pathways are not only diverse but also optimal under different priorities.

1.2.2. Challenges MGA

Despite its advantages, MGA also presents several challenges. One major issue is computational complexity. Large-scale models covering Europe require significant computing power to analyse thousands of near-optimal solutions. Defining appropriate constraints for MGA without making the process too slow or data-intensive is an ongoing challenge [68].

Apart from the deviation from the cost-optimal solution, there is also the problem of a virtually infinite number of alternatives. The MGA method 'SPORES' could be a solution to this problem. SPORES aims to minimise the redundant computations. A paper by Lombardi et al. (2023) proposes to initially search for options in a way that balances spatial and technological dissimilarity [42].
The potential for resilience degradation in the near-optimal solution is also a challenge with traditional MGA. This means that traditional MGA does not evaluate whether alternatives remain reliable under renewable generation fluctuations. As a result, some solutions may appear attractive from a cost perspective but fail to ensure system resilience in practical operation [83]. A new method, 'Modelling to Generate Resilience (MGR), is addressed by Zhang et al. (2025), which ensures robustness against renewable intermittency.

Finally, a challenge for MGA is determining how much deviation from the cost-optimal solution is acceptable. While many studies use a fixed slack threshold, for example, 10 or 20%, some approaches, such as the repeated optimisation sampling used by Vågerö et al. (2025) [77], employ a maximum slack of 125% to broaden the diversity options and present these to participants to let them decide on what slack level the system should end. There is no universally accepted approach, which can lead to different interpretations of what qualifies as a near-optimal solution.

1.2.3. Knowledge gap and research objective

While traditional optimisation models typically focus on identifying a single optimal solution, this often conceals the broader range of viable system designs within a small cost margin. Modelling to Generate Alternatives (MGA) is used to uncover multiple, near-optimal solutions. This approach makes the analysis more robust by revealing sensitivity to assumptions and allows a deeper understanding of different 'flavours' of solutions, each with its own trade-offs in spatial layout, technology mix, or system characteristics. By comparing a diverse set of alternatives, it supports more informed decision-making, especially in complex and uncertain transition pathways [41].

Although optimisation models for complex systems produce one objective solution, incorporating MGA broadens the range of potential outcomes, enabling a more thorough exploration of system uncertainties. In general, this method has worked well to deal with the uncertainties that come with changing sociotechnical systems. While MGA methods generate valuable solution diversity, they also create large volumes of data, posing challenges for processing and interpretation.

Many MGA applications rely on iterative methods such as Hop-Skip-Jump (HSJ) to explore near-optimal solutions. However, these methods often fail to fully map the near-optimal space due to computational limits. This is particularly in large-scale energy system models like those for Europe [68]. Finke et al. (2024) propose an enhanced multi-objective method (MGPA) that expands solution diversity; however, while it improves decision space exploration, its computational efficiency and completeness in covering all feasible alternatives are not fully evaluated [24]. Another post-processing method, Modelling to Generate Continuous Alternatives [39] provides a way to explore the solution space without large computational difficulties.

While existing MGA methods can generate diverse near-optimal solutions, they often lack guidance on which differences are most relevant to decision-makers. Traditional approaches such as Hop-Skip-Jump (HSJ) focus on maximising generic solution diversity without prioritising specific technological or spatial dimensions. Recent methods like SPORES enable guided exploration, directing searches towards specific differences such as technological configurations or spatial allocations, making the alternatives more meaningful for planning [41]. It allows stakeholders to design alternatives based on their preferences and knowledge about the system.

Meanwhile, MGCA allows systematic investigation of all alternatives within the solution space, providing a full mapping of feasible near-optimal options. However, this has not been done on a large energy system yet and does not inherently prioritise solutions based on stakeholder-relevant differences.

Furthermore, current MGA applications do not consider explicitly which preferences the policy-maker wants to have mapped out. There is limited research on identifying and integrating these preferences systematically within MGA frameworks.

Additionally, decision-makers struggle to interpret results effectively [77]. There is no clear framework for clustering near-optimal solutions into a manageable set of macro-options that retain essential system diversity while simplifying trade-off analysis. Finke et al. (2024) highlight the need for explicit and implicit optimisation methods to improve decision support but do not provide structured methods for clustering solutions [24]. Techniques such as Modelling to Generate Pareto Optimum Alternatives and Modelling to Generate Continuous Alternatives improve solution diversity coverage or computational performance but do not fully resolve the need for guided, decision-relevant exploration of the near-optimal space.

In summary, although methods like SPORES improve targeted exploration and MGCA enables comprehensive mapping, there is no standardised, widely adopted approach that systematically identifies and integrates stakeholder preferences into MGA searches while ensuring computational feasibility and planning relevance.

1.3. Research question and Sub-questions

There are still significant knowledge gaps in the field of Modelling to Generate Alternatives (MGA) that require further research.

One particularly relevant challenge for TenneT is developing a method to be able to generate large sets of solutions of interest without the need for long modelling run times while also integrating stakeholder preference in the model. Ideally, they would be able to run a model with certain thresholds and be able to find several near-optimal solutions without having to wait for a long time. When an interesting solution surfaces, another model can explore this in detail.

The most pressing knowledge gap for TenneT lies in quickly exploring modelling results of the near-optimal feasible space without large computational challenges. This knowledge gap will actually be used in the real world, so for the sake of priority, this research will focus on this gap. The knowledge gap leads to the following research question:

"How can MGA be used to create and explore near-optimal solutions for the future Dutch electricity network without large computational modelling challenges?"

In order to determine how we can use MGA to create and explore near-optimal energy transition pathways, we first have to divide the main research question into different sub-questions. These questions are listed below, and for each sub-question, we will also look into the data requirements, the data sources needed, and the data analysis tool to apply the model approach. The table below gives an overview of both the sub-questions and the methods that will be used.

#	Sub-question	Method(s)
1	What are relevant preferences to map out with Energy System Optimisation Modelling?	Interviews & desk research
2	How to align TenneT data with the optimisation modelling program Calliope?	Modelling & Secondary data analysis
3	What type of MGA is appropriate for the preferences for modelling the Dutch energy system?	Literature review & Interviews
4	How do we explore the alternatives without large computational difficulties?	Modelling to Generate Alternatives
5	How do we make usable results from MGA alternatives?	Data processing & Modelling

Table 1.2: Method(s) and sub-questions

1.4. Research approach and methods

As discussed in the introduction, this research will use energy system optimisation modelling (ESOM) as its main method. There are several reasons why ESOM is useful for researching the future energy network of the Netherlands. First, we are dealing with a complex system, and this type of modelling can help understand such a system. Also, ESOM is a critical tool for policy analysis [15]. Secondly, it can give an idea of what our future network will look like. Before we start modelling, we will first want to know how to shape our model and see what interesting technologies, questions and interconnection capacities are to be used for or in the model. The model needs to be in the correct resolution in line with its purpose. We will then take these insights and decide on what MGA method to use. With this method the solution space will then be explored, also to give an answer to some of the questions that might arise.
To reach this goal, a main research approach is needed that best fits this research. The research approach can be derived from the knowledge gap, defined to be generating a large diversity of model solutions without large computational difficulties; the main research question sets out to find an MGA method implemented on an optimisation model to explore the future electricity network of the Netherlands. Given this research involves modelling the Dutch energy system and finding out what type of future grid the Dutch TSO modelled, the modelling approach is used.

The modelling approach derives from the knowledge gap. The approach is usually considered when you want to understand the functioning of a sociotechnical system. The objective is often trying to visualise the impact of system interventions or optimise a sociotechnical system [22].

In order to find out the needed inputs for the model, what way to steer and what inputs to look for, desk research is done. Before we can start with modelling, we first need to explore what an interesting scenario is for the Dutch TSO TenneT to be explored. We build the model based on insights from previous reports and ensure its real-world relevance by comparing it with existing models. This is done by both looking at the interest of TenneT and the scenario analysis performed by the Dutch government [52]. After the fitting scenario has been selected, the model setup can be started. When this is done, the cost-optimal solution can be selected. From this point, the solution space can be explored using MGA. Modelling a future network requires making assumptions. These assumptions will be discussed in the fourth chapter.

1.4.1. Research methods

This section explores the methods, tools, and data requirements for answering the sub-questions. Firstly, the research methods are discussed per sub-question. Secondly, we look at the data source needed for the subquestions. Finally, tools and strategies for assessing the model results are discussed.

Research methods and implementation

To address the first sub-question, various methods can be used to identify which preferences are most relevant to map using ESOM. This part of the research involves both desk research and interviews. We begin by exploring the energy systems and current technologies of the Netherlands and its neighbouring countries. While surveys are a common way to gather public opinions, it may be more valuable to examine existing data on preferences or likely scenarios, such as those provided by Netbeheer Nederland [52]. This forms the basis for our first research method: desk research.

To gain more detailed insights from professionals, we will also conduct interviews. These offer a unique, in-depth perspective that often cannot be obtained through desk research alone [62]. Since the interviews will be conducted with colleagues within TenneT, no ethical dilemmas or concerns are anticipated.

To answer the second sub-question, we will perform a secondary data analysis using data provided by TenneT. This involves examining outcomes from previous energy system models. The first step is to determine what types of data are available from TenneT. Once identified, the data can be cleaned and processed to serve as input for building the base model. Relevant data includes the technologies identified in the first sub-question and demand projections, particularly those aligned with the II3050 framework. If certain datasets are not available through TenneT, we will consider using open-source alternatives such as those provided by ENTSO-E [21]. Additionally, model results will be compared with those from other energy system models that share similar objectives and methodologies. To ensure accuracy, several iterations will be conducted to align model outputs with the input data. Once this validation is complete, we can proceed to the next phase of the research.

This validation process, which ensures the model accurately reflects the real-world system under study, will follow a two-step approach. First, a benchmark will be created using a literature review, including official national energy transition plans for the Netherlands. The model's outcomes will then be compared against this benchmark. In the second step, the results will be discussed with experts to confirm the validity of the model in relation to its intended application.

The third sub-question is very much connected to the first sub-question. In the literature review, several different types of MGA have been discussed with both their advantages and drawbacks. This subquestion is answered by taking the knowledge from the literature review and combining this with the outcomes of subquestion one. This means that for this question, desk research, literature review, and interviewing all come together as research methods.

Now, the fourth subquestion. This can also only be answered when the previous questions have already been resolved. For this question, we will be Modelling to Generate Alternatives. Here we will implement the selected MGA methodology from question three. We will perform modelling benchmarking and parameter tuning in order to obtain the best results. We will use a certain MGA algorithm to be able to explore the alternatives in a way that is fast and useful for policymakers.

The last sub-question is mostly about finding a good way to process the found data. It is a very important step because this will be the way of sharing the results. The results will be represented using Python, and based on the input from sub-question one, we will know what interesting plots are to represent the results.

1.4.2. Data analysis tools

Once the research methods have been defined, it is necessary to determine the data analysis tools for each of these methods. For the first selected research method, desk research, we will use scientific document search tools, such as Scopus and Google Scholar. All non-scientific research will be done through the search engine Google [29]. Cross-referencing will be used to complement each tool. Finally, Mendeley will be used as a referencing tool.

For the second selected research method, interviews, data will be collected through in-person conversations with participants. Interviews will be recorded using the Teams application to ensure accurate documentation. Prior to each interview, participants will be asked to sign an informed consent form outlining the purpose of the research, their rights, and how their data will be used. The specifics of this informed consent, along with the interview questions, can be viewed in appendix B.

In addition to the desk research methods previously mentioned, the first two study sub-questions require the gathering of key parameters and their related values to make a realistic and detailed foundation model of the Dutch energy system. This includes technical specifications, such as capacity, efficiency, and lifetime, of key components like energy storage systems (e.g., batteries, electrolysers), generation technologies (e.g., solar, wind, nuclear), and transmission infrastructure. Financial parameters, including capital and operational expenditures, are also necessary. Furthermore, demand profiles will be integrated into the model, reflecting the consumption patterns of various sectors such as industry, households, services, and transport in 2050.

The data will be sourced from reliable public institutions, including ENTSO-E [21], the Danish Energy Agency [1], the Dutch transmission system operator TenneT [74], and the II3050 framework [53]. The Energy Transition Model [55] will also be used as a key reference tool. Where specific Dutch data is unavailable, selected data from comparable international contexts may be used, supported by reasoned assumptions and, where applicable, complementary calculations.

The second part of the second subquestion is designing the initial model and expanding the model. For making the model and optimising the Dutch energy system, the Calliope modelling framework is selected. Calliope is an open source tool that makes it easy to build energy system models at scales

ranging from urban districts to entire continents [59]
The chosen optimisation tool for the model is the Gurobi Solver [2].

For the last subquestion, we want to make useful results out of our analysis. We will make use of tables and graphs created with Python or Excel as data analysis tools.

1.4.3. Research flow diagram
A research flow diagram was built to give an overview of the layout of the report. In this diagram you will find the research questions and feedback loops of the different stages of the research. The diagram is shown in figure 1.1

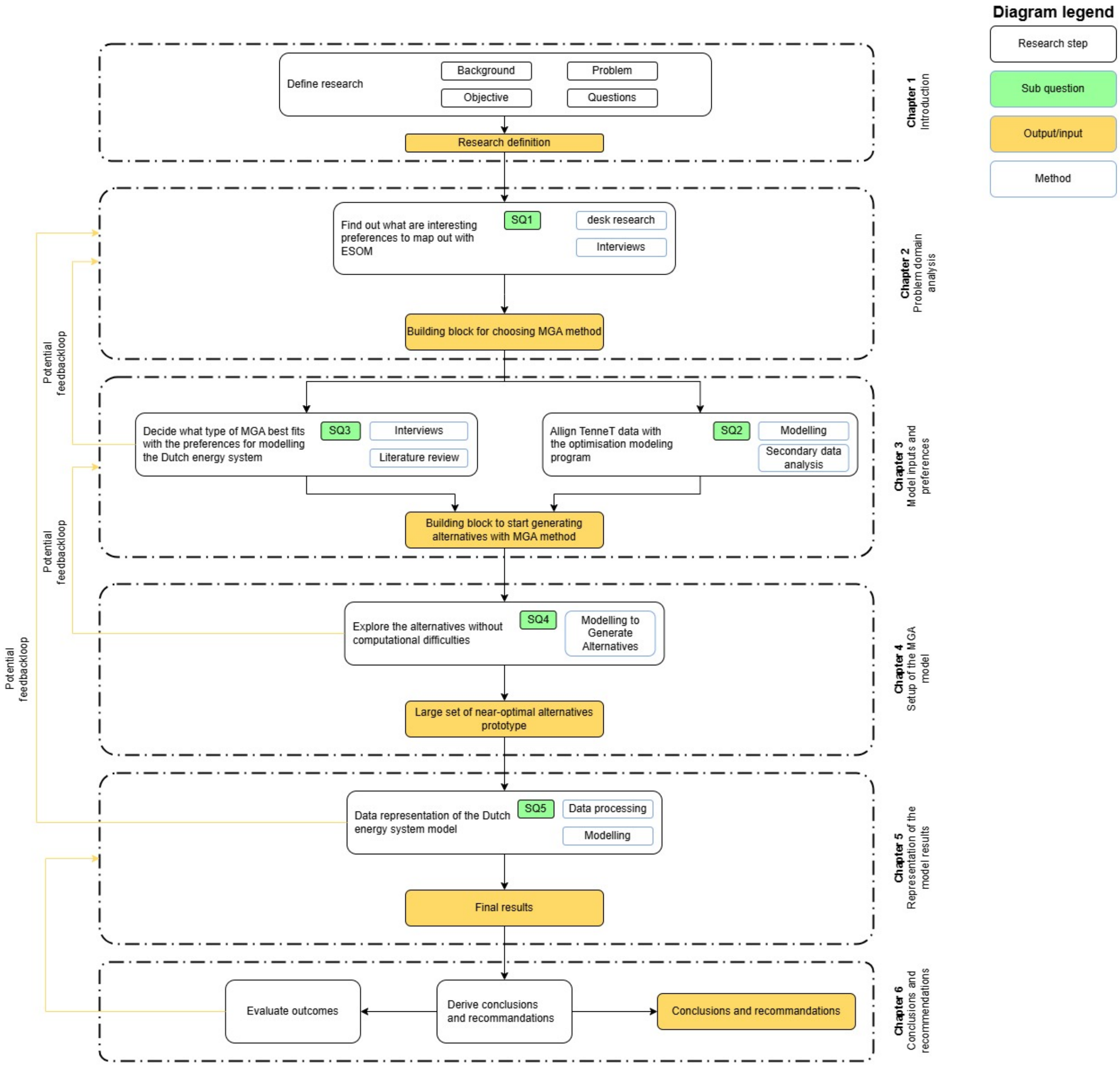


Figure 1.1: Research flow diagram

1.5. Link to CoSEM program
This research is related to the Complex System Engineering and Management program, because it fits the complex system that is the electricity network of the Netherlands. By looking at a new way to find the structure of the future network of the Netherlands, we are designing in a clear technological field. By also implementing scenarios that are preferred either by the government, TSO, or public preference, there is also a public and societal relevance.

1.6. Research structure
This thesis report consists of 6 more chapters apart from this one. The next chapter, chapter 2, presents research context with the findings from the desk research done to explore the energy system of the

Netherlands and the technologies that might be used in the future. Chapter 3 discusses the methodology used in this report. Here the research approach, the design of the energy system, information about the Calliope framework, the setup of the interviews and the choice for MGA type are discussed. Chapter 4 will talk about the model setup and its assumptions, and chapter 5 will present the results of the research. Chapter 5 discussed the interview results first and then the model results with a conclusion. Chapter 6 presents the conclusion of the thesis, answering the main research question. And finally, chapter 7 is the discussion chapter, discussing the limitations, implications and recommendations.

2
Research context

This chapter reviews multiple papers related to energy modelling and the future of the electricity grid through desk research. Several promising technologies are discussed, which will likely contribute to the electricity grid of 2050. Finally a conclusion is given on these articles. The literature is sourced using specific keywords detailed in the table below. The search engines used for this review are Google Scholar and Scopus. Backward and forward snowballing helped find the right articles.

Subject	**Used keywords**
Role of hydrogen	”Electricity grid” AND Hydrogen
Storage technologies	(”Storage technologies” OR ”electricity storage”) AND (Netherlands OR Europe)
Small Nuclear Reactors	”Small modular reactor” AND (Netherlands OR Europe)
Energy demand 2050	”Dutch electricity network” OR ”Dutch energy transition”

Table 2.1: Subjects and search-terms

2.1. Role of hydrogen

In order to become climate neutral in 2050, a deep transformation of the energy sector is needed. The energy sector accounts for nearly three quarters of the GHG emissions in Europe [69]. To decarbonise the Dutch energy system, the energy system will face large amounts of electrification. The electricity use could grow worldwide from today's 20% to a final energy demand close to 70% by 2050 [47]. Renewable energy and clean electricity will have a major role in replacing the fossil fuels. Also, energy efficiency and behavioural changes are important to reduce energy consumption. But with only electrification and behavioural changes, we will not succeed. There are also hard-to-abate sectors that will need other forms of energy to become net-zero [27]. In many of these sectors hydrogen can play a major role in decarbonisation, either directly or in another form of derived fuels like ammonia or synthetic fuels. Hydrogen will also remain indispensable for the production of plastics or steel. The global hydrogen demand could therefore grow 5-7 fold compared to 2021, where hydrogen will account for 15-20% of the final energy demand [48][18]. All this hydrogen must be produced in a net-zero way, via electrolysis using green electricity (”green hydrogen”) or using low-carbon technologies in combination with CCS (”blue hydrogen”). Whilst today the green hydrogen price is currently higher than both blue and grey hydrogen, these prices are expected to drop and become the more affordable option by 2040 [69]. Although new research suggests that the expected green hydrogen price will remain high for the years to come [4]. This means we can expect a green product premium for green hydrogen. For example, near-zero CO2 steel production will likely get a premium of 40% per tonne. Hydrogen used for electrification comes with significant production losses (20-40%), but is most competitive in processes that involve high-temperature heat. With the Dutch goals to install 72 GW of offshore wind capacity by 2050, offshore hydrogen production can be a potential solution for transporting and storing hydrogen to limit the electricity network [78]. Storing hydrogen also comes with large energy losses, with an efficiency of less than 40%. But with the advantage of hydrogen that it can be safely stored without energy losses, it will be used for long-duration storage.

These insights confirm the importance of including hydrogen infrastructure and electrolysers in the model. Due to its versatility in decarbonising hard-to-abate sectors and its potential as long-duration storage, hydrogen is modelled as both a carrier and a storage option in the system.

2.2. Storage technologies

Since the energy grid of 2050 will involve a much larger amount of intermittent technologies, the demand for storage technologies will also increase. While electricity storage has been technologically feasible for some time, the associated costs compared to dispatchable fossil fuels have hindered its deployment [49]. There are several types of energy storage. There is electrochemical storage (batteries), mechanical storage, thermal storage and chemical storage. The electrochemical storage is currently the most used storage, mainly because of the wide use of Li-ion batteries in electric cars. It is mostly useful for short-term storage [10] [67]. Mechanical storage, like pumped hydro-storage, is used for longer-term storage, from daily to weekly. But in this category, compressed air energy storage (CAES) can be used for long-term storage. Thermal storage is not yet used extensively in the Netherlands. Thermal storage is mainly used as seasonal storage to complement other technologies. Power-to-gas storage (hydrogen) will have a big impact on the future energy grid, as discussed above.

Currently, lithium-ion batteries account for most of the newly installed energy storage capacity since they are already relatively mature, and through their use in electric vehicles, they experienced a large price drop. A downside of this technology is its fire hazard and the scarcity of lithium, increasing the price over the years. Another, more long-term battery is the vanadium flow battery. The advantage of flow batteries is that capacity and storage volume can be easily separated.

Given the expected variability of renewable supply in 2050, multiple storage technologies are included in the model. Short-term flexibility is handled via Li-ion and flow batteries, while long-term balancing is enabled through compressed air energy storage (CAES) and hydrogen caverns. These technologies are explicitly modelled to assess how different storage mixes impact system reliability and cost under various scenarios

2.3. Small Nuclear Reactors

The European nuclear power is expected to double between 2020 and 2050. New nuclear reactors, called small modular reactors, are designed to generate up to 300 MW of electricity. Small Modular Reactors (SMRs) offer a potential solution for Europe's low-carbon energy transition, especially to complement intermittent renewables by providing reliable baseload power. SMRs are defined as nuclear reactors generating up to 300 MW and offer benefits such as modularisation, shorter construction times, co-siting economics, and design simplification. These characteristics could lower costs and financial risks compared to large reactors, particularly through factory fabrication, standardisation, and learning effects when deployed in multiple units.

A study done by TNO and NRG-Pallas stated that SMRs also have a potential in the Dutch electricity system. The Dutch government wants to keep the existing Borssele nuclear plant and, in addition to this, expand its nuclear power by making efforts to realise more plants. SMRs could also be a part of this nuclear expansion [82]. Constructing larger nuclear reactors reduces the cost per megawatt due to economies of scale, but it also extends the construction period. In contrast, serial production lowers costs per megawatt through standardisation and shorter construction times, benefiting from economies of numbers. This can be an advantage for the SMRs [28]. Their smaller absolute investment cost also means lower financial exposure and easier financing.

Based on the growing interest in SMRs, especially for space-constrained, dispatchable baseload power, the model includes SMRs as an optional generation technology. Their relatively small footprint and flexibility make them suitable candidates for exploring centralised low-carbon generation in MGA variants.

2.4. Energy demand 2050

As mentioned before, the Netherlands wants to comply with the Paris Agreement and have a net-zero energy network by 2050. This is defined more precisely in the Dutch climate agreement in 2019 [50]. All the electricity consumption is generated with renewable sources, and fossil energy and associated greenhouse gases will be reduced. These new technologies will also have an impact on the electricity network, where the transmission system operator TenneT has to prepare for a higher demand increase and a fluctuating supply [63]. One of the main issues for the future is the investment uncertainty. Because of the long lead time of the project, the investments need to be made in advance.
An essential area of research is finding out what the different technologies are that will be part of the 2050 electricity grid in the Netherlands. There are several reports that talk about the future of the Dutch grid and its composition [52][54][66]. The reports outline how the Dutch energy system is evolving and what technologies are expected to remain, emerge, or decline by 2050.

Currently, the Netherlands is rapidly expanding its use of renewable electricity sources. Solar PV and wind, both onshore and offshore, are central technologies that will continue to grow. By 2035, solar PV capacity is projected to reach 22–30 GW and wind energy, especially offshore, will also increase significantly. These technologies are expected to remain essential up to and beyond 2050.

To maintain balance in the electricity grid, flexibility technologies will become increasingly important. Battery storage, demand-side management, and Power-to-X systems (which convert electricity into heat, hydrogen, or other usable forms) will play a vital role. Electrolysis for green hydrogen production is scaling up, with up to 4 GW of capacity expected by 2035. Hydrogen will be used both domestically and as an imported energy carrier, especially for industry and dispatchable power generation.

Some existing technologies will transition. Natural gas-fired power plants are still part of the system today but are expected to be phased out or repurposed to run on hydrogen. Green gas (biogas) will have a limited but stable role, with around 2 bcm projected by 2030. The nuclear plant in Borssele will remain in operation and is included in all future scenarios. Coal power has already been largely phased out and will not return.

In addition to electricity, heat networks, geothermal energy, and bio-based heating solutions are expected to expand, especially in urban and industrial areas. However, their future role will depend on regional implementation and societal acceptance.

The report also highlights the increasing tension between long-term goals and short-term capacity limitations. Permit delays, public opposition to infrastructure, and material shortages are significant risks. While national policy often assumes a plan-based, linear transition, the report emphasises the need for adaptive planning and attention to uncertainties.

In summary, the technologies expected to stay or grow in the Netherlands toward 2050 are solar PV, wind, battery storage, hydrogen infrastructure, and smart grid systems. Fossil gas and coal will decline, while technologies like green gas, Power-to-X, and district heating will evolve based on local conditions.

The projected increase in electricity demand, driven by electrification in all sectors, justifies the use of the II3050 “National Leadership” scenario as the model’s demand baseline. The model excludes heat demand explicitly but retains power-to-heat as a form of electricity demand. This helps maintain realistic system load patterns without modelling heat flows directly.

2.5. Discussion literature review

With this literature, we have identified key hurdles, focus points, and considerations that must be incorporated when modelling the Dutch energy system for 2050. First, the system will face high electrification levels, requiring a robust grid and sufficient flexibility through storage and demand management.

Hydrogen is expected to play a central role in decarbonising industry and enabling long-duration storage. This justifies its inclusion as both a carrier and conversion option. The increasing dependency on intermittent renewables reinforces the importance of incorporating a diverse set of storage technologies with different time scales, from batteries to hydrogen caverns.

The inclusion of Small Modular Reactors (SMRs) is motivated by their potential to provide flexible, low-carbon baseload power with spatial and siting advantages. Because the future electricity demand is projected to grow sharply due to electrification, supporting the use of the II3050 "National Leadership" scenario as a realistic demand baseline.

Altogether, the reviewed literature supports a model setup that balances technical innovation with usability. It also underlines the need for exploring multiple future pathways. This desk research serves as a great input for setting up the interviews. The findings in this literature can be directly used in forming the interview questions.

3 Methodology

This chapter discusses the approach of this research, and then it discusses how the Dutch energy system will be designed. Following this, the modelling framework Calliope is discussed. Thereafter, the interview setup is presented. The chapter ends with the selection of the MGA type that is used for this report.

3.1. Research approach

In chapter 1 the literature analysis brought forward the knowledge gap, resulting in a main research question and subquestions. As discussed, the model-based approach will be done for this research in combination with interviews.

The model-based approach involves Energy System Optimisation Modelling (ESOM) and the alternative generation approach Modelling to Generate Alternatives (MGA).

3.2. Design Dutch energy system

The model-based approach is used to model the Dutch electricity grid of 2050. As with all models, this model is a simplified version of the reality. The model setup was based on four main sources of input. These sources include the model's resolution [40], the model's demand [52], the model's technologies and available space [8], and the required input data [1].

The energy system is based on the 12-node NL model of F. Lombardi [40], but was further developed to increase the model's level of detail. The model is divided into 12 different nodes, each representing a different province of the Netherlands. The system has two energy carriers, electricity and hydrogen. The electricity carrier has its own demand, while the demand of hydrogen is unknown, leaving this up to the model. The system has production, conversion, storage and transmission methods for both carriers. All provinces are connected with transmission lines for both hydrogen and electricity. The nodes are also connected with the surrounding countries in the form of a link with the closest province. These countries include Belgium, Germany, Norway, Denmark and Great Britain.

The electricity demand is taken from the II3050 [52]. This is a report made by Netbeheer Nederland that forecasts the future demand of the Netherlands. In order to do so, it creates different scenarios as to how the future might look. For this system the national leadership scenario was chosen for the demand. This scenario has a strong focus on self-sufficiency and is nationally orientated. It is also the same scenario that Target Grid uses for its network map for 2050. The model has storage and hydrogen technologies, so these are included in the model. Heat has been left out of the system and is therefore included as demand in the model. The demand file can be found on the Energy Transition Model website [55].

For every province there is a different demand. The national demand for 2050 is known from the II3050 scenario. In order to make the demand fit for the different provinces, the total demand is multiplied by the percentage of the GDP of the province. This is a known method also used in the EU's POLES model [37]. A more extended explanation is discussed in chapter 4.

Since the demand for hydrogen is unknown, the amount of hydrogen used in the model is completely dependent on the amount of hydrogen produced by the technologies in the system and the amount of green hydrogen imported from the other countries. This means that this system will only have green hydrogen produced by an electrolyser. This hydrogen, in its turn, can then be turned into electricity by OCGT or CCGT hydrogen-to-power plants or by a hydrogen fuel cell. Hydrogen demand is dependent on the use of other energy carriers.

In figure 3.1 there is an overview of all the different technologies implemented in the model. It needs to be mentioned that we are dealing with a model that represents the 2050 network. Because this network is climate neutral, there will be no carbon-emitting technologies, and therefore, there is no need for carbon pricing since there is none in the system. The selected technologies are similar to the technologies used in an earlier report that models the Dutch electricity grid of 2035 [8]. This model has also phased out all fossil fuel technologies and can be used as a base for technology selection and space restrictions.

The available space in the provinces was important for the number of renewable plants that could be installed. These technologies include wind onshore, wind offshore and solar PV. For the amount of available space in the provinces, the same method used in a report from CE Delft is applied [8]. Their approach limits the available space based on the area outside of the Natura 2000 areas. The calculation for these numbers is discussed in chapter 4. For the offshore potential we followed the North Sea Wind Power Hub map [23].

The transmission line capacity is based on the current 380 kV and 220 kV lines already installed in the Netherlands. From there the model is free to expand the capacity to 3 times its original capacity at max. This maximum is chosen because more than 3 times would be impossible, either financially or physically [35].

Both energy carriers, hydrogen and electricity, can be stored in the system. For the electricity, there are batteries and compressed air energy storage (CAES). For the hydrogen, there is storage in salt caverns. These technologies are in the system to store all potential surplus.

The figure below gives an overview of the energy system. As previously mentioned, there is no hydrogen demand in the model, and this means that hydrogen is only made in the hours that the demand is lower than the renewable production. Otherwise, the hydrogen is imported. The system can also store its power in batteries or with CAES. Then hydrogen is not needed. The hydrogen is still included in the model because eventually the demand for hydrogen will increase, and it can be imported from the surrounding countries.

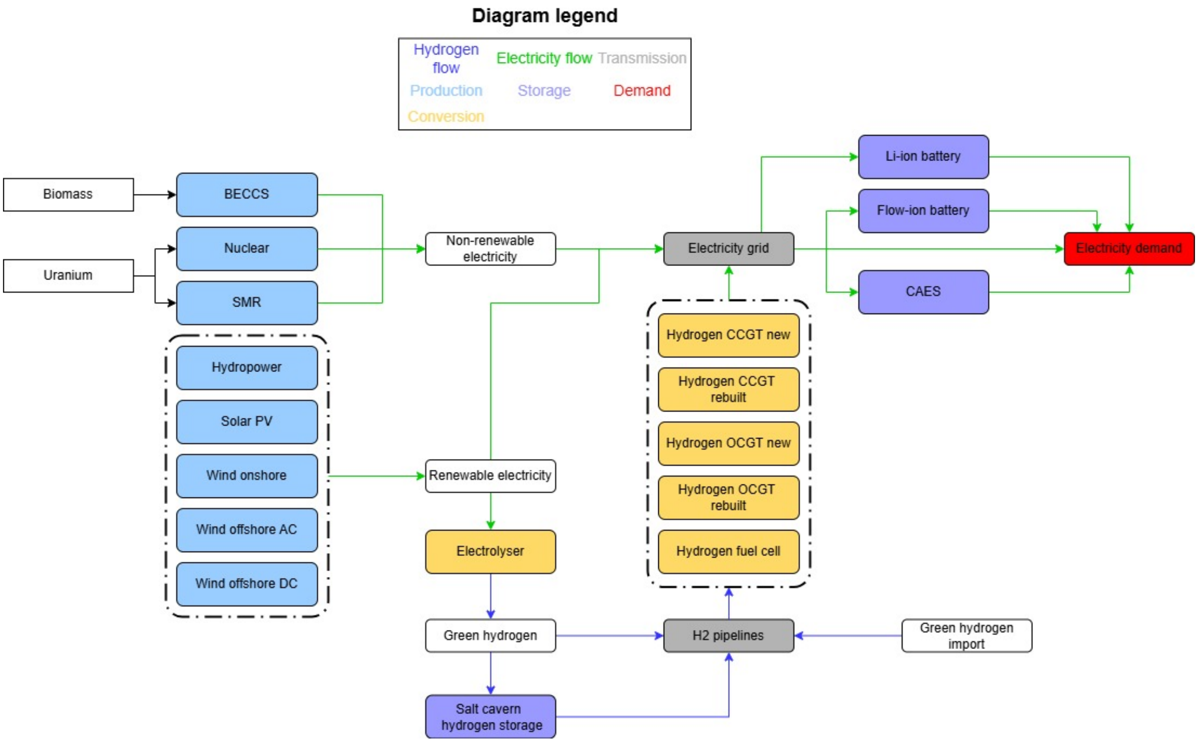


Figure 3.1: Dutch energy system overview

3.3. Calliope

The research tool that is used for this report is Calliope. Calliope was developed by Stefan Pfeninger and Bryn Pickering in 2018 [59].

It is a powerful, open-source modelling framework designed to construct energy system models that are flexible in scope and resolution. The framework was made to allow energy models to adapt to a wide range of planning contexts, from urban districts to national and continental systems. By providing a flexible mathematical formulation, Calliope enables modellers to explore how energy is produced, transported, stored, and consumed across multiple time and spatial scales. It is particularly well suited for analysing the impacts of constraints, such as limited land availability, fossil fuel phase-outs, or storage costs, on the design and cost of decarbonised energy systems.

A significant strength of Calliope is its flexibility in handling high spatial and temporal resolution. Furthermore, Calliope has been generalised to model a wide variety of energy carriers, including heat, hydrogen, and biofuels. This makes it a versatile tool for integrated energy system modelling, like the Dutch energy system.

Despite these advantages, Calliope also has some drawbacks. It is currently limited to linear and mixed-integer linear optimisation problems. Although this is sufficient for a wide range of applications, including this research, it may restrict its use in cases where nonlinear modelling of technology behaviour is required. While nonlinear components could theoretically be added, this would require further development effort and a more advanced modelling setup. Additionally, as with many powerful modelling tools, effective use of Calliope may require a learning curve, particularly for users unfamiliar with energy modelling or optimisation.

There are similar research tools used for optimisation modelling, like PyPSA and PLEXOS. Compared to these tools, Calliope offers a streamlined YAML-based framework for defining multi-energy system models at different scales, from local to national. PyPSA is also an open-source Python-based tool but is primarily focused on detailed power system analyses, including operational dispatch and DC load flow calculations, which are less central to the aims of this research [7]. PLEXOS, in contrast, is a commercial software platform widely used in the energy industry for market simulations, unit commitment, and capacity expansion planning. While it offers extensive detail and built-in market modules, its commercial, closed-source nature limits transparency and adaptability for novel academic methods development [60].

Overall, Calliope offers a robust and flexible platform for constructing energy system models at various scales and complexities. Its open-source nature, strong documentation, and separation of data and code make it particularly suitable for academic research. While it does have some limitations in modelling nonlinear behaviour, its strengths in flexibility, clarity, and computational performance make it a valuable tool in the context of the energy transition.

3.3.1. Calliope setup

The Calliope framework is built in such a way that the input data is separate from the model data. This is achieved through the use of plain text input files in YAML and CSV format, which define the technologies, locations, links, constraints, and resource potentials in the system being modelled. Once a model is defined, Calliope translates it into an optimisation problem, solves it using Pyomo, and returns results in the form of xarray datasets. These results can be saved in NetCDF format for further analysis and visualised using built-in tools based on Plotly [59].

A Calliope model is a collection of interconnected nodes, technologies and carriers that describe a real-world system of energy flows [13]. The carriers are the commodities whose flow we track, and for the case of our model, these are hydrogen and electricity. The technologies supply, consume, convert, store or transmit carriers. Finally, the nodes contain groups of technologies and are usually geographic. For this model the nodes are the Dutch provinces and the 5 surrounding countries. All constraint types that need to be used for the Calliope model are presented in Appendix F.

Modelling with Calliope consists of three large steps: creating the model, running the model and analysing the model. The

Creating the model

The model can be created completely from scratch, or an existing model can be expanded. We will do the latter by expanding the Calliope-NL model. This model consists of three different YAML files, namely Techs, Nodes, and Transmission. The Techs file contains all the technologies that the model can implement in the 2050 energy system. These different technologies are based on a previous study that also created a net-zero model for the Netherlands. Only this model was for the year 2035 and created with a PyPSA model [8]. The nodes are the same as the Calliope-NL model. Transmission is based on the existing hi-voltage transmission network in the Netherlands. [8][40][35]. All the constraints of the model in both the Techs file and the Nodes file will be discussed in the next chapter.

In addition to the YAML files, the model also has CSV files, which contain the necessary data needed for the model. This is the demand data and the weather data. The data is obtained from various sources, and this will be explained in detail in the next chapter.

Running the model

When the model is built, the model simulation starts where it constructs an optimisation problem, solves it and then presents the results in the form of xarray datasets that can be saved as a NetCDF file. For solving the problem, it uses the Gurobi optimiser [2].

Analysing the model

Finally, the model needs to be analysed. This was done by doing a comprehensive analysis to see the overall outcomes of the energy flows and the installed capacity of the model. This is also to check if the outcomes are in the right order of magnitude you would expect. After this, a more thorough examination of the model is done to analyse the model per node or per technology to get an understanding of what the future energy system looks like according to the model. These tests also came with some form of iteration to improve the overall quality of the model. By implementing certain targets or limits per province or technology, it results in a more realistic model. The outputs of this analysis are presented in tables and figures that simplify the interpretation of the results.

3.4. Interviews

To gain insight into how professionals in the energy sector envision the future electricity grid and to explore how they perceive potential uses for the model, interviews will be conducted.

The interviews were used when setting up both the basic model configuration and scenario assumptions, as well as in shaping the MGA component of this research. Experts offered views on alternative solutions relevant to them, including spatially varied generation layouts and flexibility alternatives, which guided the aspects of the system to diversify with MGA modelling. Furthermore, interview discussions emphasised the importance of reflecting not only cost-optimal alternatives but also near-optimal configurations that correspond with practical feasibility, regional planning factors, and stakeholder preferences. These viewpoints guided the choice of MGA algorithms and the analysis of the produced alternative solutions within the framework of robust decision-making for the future Dutch power system.

The interviews are conducted with employees and key stakeholders involved in designing the future electricity grid at TenneT. These individuals provide insights into their experiences with future scenarios and discuss potential applications for the energy model. The interviews take place on-site at the TenneT office, following the guidelines outlined by Hancock [33]. Key participants are first identified by directly approaching relevant employees within the organisation.

Each interview is conducted individually in the office environment to ensure the interviewees feel comfortable and to improve the quality of the information gathered. The face-to-face setting also enables the interviewer to observe and interpret non-verbal cues, which can enrich the understanding of responses. A semi-structured interview guide is used, focusing primarily on identifying questions that could be addressed through energy modelling.

All interviews are audio recorded and fully transcribed, with additional notes taken during the conversation. This approach allows the interviewer to remain actively engaged without the need for continuous manual documentation. In instances where an interviewee declines to be recorded, only handwritten notes are used. Finally, informed consent is obtained from each participant. Respondents are clearly informed about the purpose of the research, the potential for information to be published, and the fact that their data will be used confidentially and anonymously.

The questions of the interview are formed after the desk research from chapter two and involve questions about the future energy scenarios and novel technologies that might be used. The questions also ask the interviewee about their perspective on how this future would look.

3.5. MGA selection and explanation

As discussed in Chapter 1, various approaches to Modelling to Generate Alternatives (MGA) have been developed to explore the near-optimal space of energy system optimisation models.

Among the more recent developments, the SPORES (Spatially Practically Optimal REnewable Systems) method presents a highly customisable framework for MGA. Unlike earlier methods that may explore the solution space more randomly or uniformly, SPORES allows the modeller to guide the search toward either spatial or technological dissimilarity. This level of control makes it especially useful in the context of this research, where specific questions derived from expert interviews require focused exploration of system configurations. SPORES can be adjusted dynamically to reflect these evolving questions, enabling a responsive and iterative modelling process.

Given these benefits, SPORES has been selected as the primary MGA strategy for this study. It aligns with the core research objective of generating a diverse set of network designs for 2050, without having excessive computational costs. Moreover, it provides the flexibility needed to tailor model explorations to stakeholder-relevant questions, thus improving the practical applicability and decision-support value of the results. In order for us to understand how SPORES is used and how it works, the equations used for SPORES are presented in the next section.

3.6. Mathematical approach SPORES

The SPORES approach can be seen as a spatially explicit extension of the conventional MGA method. It allows us to look further than a mode representing a region or country with just one node and lets you explore capacity expansions in different locations. The approach is specifically meant for energy system models with high spatial resolution, like the model that is used for this research. All equations are extracted from several reports on SPORES from Lombardi et al. [43][44].

3.6.1. Cost optimisation

In order to start with SPORES, we first have to find the global optimum of the optimisation problem that is made in Calliope. Finding this optimum is presented in equation 3.1.

$$\begin{aligned} \min: \ cost = \textstyle\sum_j \sum_i \left(c_{fix,ij} x_{ij}^{cap} + \sum_t c_{var,ij} x_{t,ij}^{prod} \right) \\ \text{s.t.} \quad \mathrm{Ax} \leq \mathrm{b} \\ \mathrm{x} \geq 0 \end{aligned} \tag{3.1}$$

The Calliope model optimises by minimising the total system costs. In this formulation, i and j represent the technology and location indices, respectively. The variable x_{ij}^{cap} denotes the installed capacity of technology i at location j, while $x_{ij,t}^{prod}$ is the power production of technology i at location j and time t. The parameter $c_{fix,ij}$ represents the discounted financial fixed costs per technology-location combination, and variable $c_{var,ij}$ denotes the discounted variable cost per unit of production for each technology-location combination. A is the matrix of coefficients and b is the vector of coefficients used to formulate all physical constraints in the model, which are applied to the vector x of decision variables.

In simpler terms this equation calculates:

- How much capacity to install for each technology at each location
- How much to produce from each technology at each location and time

In such a way that:

- Total cost (fixed + variable) is minimised
- All physical and technical constraints (e.g. demand must be met, capacity limits, balance equations) are satisfied

3.6.2. Weighting

Although this next equation is not used for this model, it is what makes assigning SPORES weights different from the original MGA. A strictly positive weight (w_n^{ij}) is assigned to decision variables that take non-zero values in the cost-optimal solution, specifically to location-technology combinations where a non-zero capacity is installed. By scoring capacity decision variables rather than production variables, an ad-hoc scoring logic is defined that assigns to each location-technology a weight equal to the ratio between its installed capacity and its maximum theoretically installable capacity. For iterations beyond the initial one, this score is then combined with the weight obtained in the previous iteration (w_{ij}^{n-1}), as shown in Equation 3.2. This approach differs from the original MGA formulation, which uses an integer weighting logic (+1 for each non-zero decision variable).

$$w_{ij}^{n} = w_{ij}^{n-1} + \frac{x_{ij}^{cap,n}}{x_{ij,\max}^{cap}} \tag{3.2}$$

Equation 3.2 adds the ratio of installed capacity to maximum capacity to the previous weight each iteration. This ensures weights increase over iterations based on how much capacity has been installed relative to the tech-location's maximum potential. This is done to ensure location-technology combinations that are already fully used in the previous iteration are penalised more. This way, poorly utilised locations will be used faster in new iterations. For example, if onshore wind capacity is installed in the cost-optimal solution, SPORES assigns a penalty to the onshore wind in each location, instead of penalising the wind in general. This equation also allows for us to customise the weights even more, which will be discussed later in the next section. In that section the weight equation used for this model is presented.

3.6.3. Customised search strategy

Equation 3.2 can be customised in several ways to push the search either more on technology or versus spatial dissimilarity, or vice versa. In this research the 'random' scoring method is used. In this approach, the weights have no underlying rationale and are instead assigned as random integer values, as shown in Equation (3.5). This method approximates the random MGA search proposed by previous studies ([5][64]. The only difference is the random weights are applied specifically to spatially explicit decision variables.

$$w_{ij}^{n} = w_{ij}^{n-1} + r_{ij}, \text{ with } r_{ij} = U(0, 100) \tag{3.3}$$

Here $U(0, 100)$ is a random uniform distribution. We use this equation in the report instead of equation 3.2. Using the random weighting method (3.3) instead of the default relative deployment method (3.2) can be advantageous when the objective is to maximise the diversity of explored solutions without introducing systematic biases towards or against specific technologies or locations. Additionally, the random method assigns weights drawn from a uniform distribution, ensuring each SPORES iteration explores the near-optimal solution space along entirely different and uncorrelated search directions. This enhances the exploratory power of SPORES.

3.6.4. SPORES Generation

SPORES are derived by minimising the sum of location-specific weighted capacity decision variables across all location-technology combinations while constraining the cost of the current model run ($cost_n$) to remain within the accepted neighbourhood of the optimal cost ($cost_t$). This is shown in equation 3.4.

$$\begin{aligned} & \min Y = \textstyle\sum_j \sum_i w_{ij} x_{ij}^{cap} \\ \text{s.t.} \quad & \operatorname{cost} t_n \leq (1+s) \cdot \cos t_0 \\ & Ax \leq b \\ & x \geq 0, \end{aligned} \tag{3.4}$$

In this equation s is the allowed cost relaxation (slack) in the model. This can be chosen however preferred, but in this report, in general, a slack of 20% is chosen. Previous research [76] shows that added costs up to 30% are accepted.

The primary objective of equation 3.4 is to minimise already explored decision variables and to find diverse solutions. The secondary objective is to keep the total cost within an acceptable range (slack) of the optimal cost.

3.6.5. SPORES with secondary objectives

As mentioned in the weighting section, this can also be used to explore further systematic exploration of the design space, where technology diversity is handled explicitly. This is done by adding a second explicit objective to the objective function. This objective is minimising or maximising the capacity of a specific technology. This equation (3.5) is presented below.

$$\begin{aligned} & \min(\text{ or } \max) Y_{2,\bar{i}} = a \cdot \textstyle\sum_j x_{\bar{i}j}^{cap} + b \cdot \sum_j \sum_i w_{ij} x_{ij}^{cap} \\ \text{s.t.} \quad & \text{cost}_n \leq (1+s) \cdot \text{cost}_0 \\ & \mathbf{Ax} \leq \mathbf{b} \\ & \mathbf{x} \geq 0, \end{aligned} \tag{3.5}$$

In this equation x_{ij} is the capacity decision variable for technology i at location j that is being minimised or maximised in the objective function. a and b are weights (coefficients) assigned to different components of the objective function. They determine how much each objective is prioritised and can be customised as needed.

4 Model setup and assumptions

This chapter describes how Dutch and European climate goals are translated into model assumptions. It begins with an overview of policy ambitions (4.1), then explains how these are operationalised in the model (4.2), followed by details on spatial node design (4.3), data sources and processing (4.4–4.5), and technology constraints (4.6–4.7).

4.1. Dutch future network

In the Netherlands it is widely recognised that there are too many fossil fuels being used in the energy sector. In order to change, a larger part of energy production needs to be made with renewable energy. This switch demands behavioural change and choices by consumers, companies and governments. In order to make this switch as smooth as possible, clear and efficient policy is needed that gives a long-term goal to work towards. All these goals have been written down in the Dutch climate agreement (Klimaarakkoord) [50] from 2019. These goals have been adjusted in 2022 to match economic growth and new policy goals. A year later, in 2023, there was a new reason to sharpen the goals again because of the EU's "Fit for 55", the Dutch climate act and REPowerEU [61][80][25]. The European Union wants to reduce 55% of its greenhouse gas emissions before 2030 compared to 1990. Fit for 55 also reforms the EU emission trading system. This is the EU's key tool for reducing greenhouse gas emissions. It covers different sectors, namely electricity and heat generation, energy-intensive industry sectors, commercial aviation, maritime transport emissions and buildings and road transport. The Dutch Climate Act stipulates that the Netherlands must reduce its greenhouse gas emissions by 95% in 2050 compared to 1990. In addition, it adds another goal of 100% CO2-neutral electricity supply by 2050. Energy savings and renewable energy are considered the means at the Netherlands' disposal for the energy transition[45].

With REPowerEU the European Union sets out to phase out Russian fossil fuel imports and create a new stream to power the EU. Its three main goals are saving energy, diversifying the energy supply and producing clean energy. Since this plan was adopted in 2022, the energy imports from Russia have significantly dropped. The EU Energy Platform, which has been in place since April 2022, plays a crucial role in helping to diversify our energy supply. The platform helps coordinate infrastructure investments and external gas suppliers to prevent EU countries from outbidding each other.

These frameworks can help reduce regulatory uncertainty and create favourable conditions for investment. It encourages the involvement of end energy consumers in the supply chain by enabling self-production of energy and setting clear targets to be achieved by 2030 and 2050 at both national and European levels.

All the plans and objectives mentioned above are presented in the Dutch long-term strategy on climate mitigation from 2019 [46]. The Dutch objectives for climate mitigation include:

- The CO2 emissions should be reduced by 49% in 2030 compared to 1990
- The greenhouse gasses should be reduced by 95% by 2050

- No use of fossil fuels for electricity generation in 2050
- Achieve 100% CO2 neutral electricity supply by 2050

The Dutch government introduces their national plan for energy systems in 2023, NPE [34]. This paper underlines that the Dutch energy policy is in line with the European guidelines and is aimed at reaching the EU goals. An addition to this goal is that the goals should also reach their wanted developments for the long term. This combination has led to the following choices:

- Possible generation of 70 GW of wind energy at sea
- 3.5-7 GW of nuclear energy
- 15-20 GW of electrolyser capacity
- Large expansion of renewable energy plants on land

These numbers already give a direction of where boundaries of the model should be, but a more structured direction can be derived from the II3050 in combination with another scenario study executed by CE Delft [8].

4.2. Integration of Dutch energy transition plans in the model

With all these European and national plans in place, there are several parties that have drawn up scenario studies to present a possible layout of the future network. The scenario that is used as a departure point for this model is the II3050 scenario "National leadership". This scenario was published in 2023 by Netbeheer Nederland in collaboration with all TSO's and DSO's of the Netherlands, including TenneT. Specifically, the national leadership scenario is chosen because this is also used in TenneT's Target Grid and prepares for a maximisation of self-sufficiency and electrification. To better understand what this scenario entails, the assumptions of this scenario will be discussed below.

Starting off, the total expected energy demand will reduce from 7-39% compared to 2023. This is because of technical improvements, energy savings and increased efficiency. This does not mean the electricity demand will also go down. On the contrary, the electricity demand will rise between 180-250% compared to 2019. Also, the hydrogen demand will increase drastically. This will be used for fuel, raw material for industry and partially for heavy transport. The use of biofuels will rise as well and will be used for heavy transport and later on aviation fuel. Oil, coal and natural gas demand will decline when the shift to batteries or hydrogen is made. Heat demand will decrease because of better isolation in the built environment. Heat demand will be met by electric heat pumps, heating networks and hydrogen or biogas.

The largest renewable power supply in 2050 is from wind. The generation capacity will be between 48-92 GW, delivering 25-60% of the total renewable energy. Solar will have the largest amount of installed capacity with 100-183 GW, good for 10-20% of the renewable electricity generation. Because of large overdimensioning of renewable energy, these generators can deliver enough energy for most of the year.

Initially, hydrogen supply is largely imported from other countries or leftover gases from industry, but in 2050 the green hydrogen production will grow between 16-45 GW. With the rise of import facilities, the Netherlands will develop to be a transit country of hydrogen, with an expected throughput of 50-150 TWh in 2050. This will mainly go to Germany. To be able to comply with national and European goals, no natural gas will be used in 2050, and green hydrogen and nuclear energy will generate the missing energy that is not already covered by wind and solar energy. The transition period before 2050, natural gas will play an important role because of its security of supply. Green gas is the partial substitution for natural gas in 2050, used for the heat demand of a small part of the built environment and industry, where alternatives are not possible.

Another large transformation for the 2050 network is its infrastructure. There will be a huge rise in electricity production, but in order to bring this to the client, there is a need for infrastructure expansion. Replacing current infrastructure and building new infrastructure takes time, and this is why the system operators are already planning infrastructure expansion. The II3050 scenarios underline that anticipating is not enough and it is vital to increase the plannability of these developments in order to make the grand restructuring possible.

The figure below gives an overview of the expected required amount of renewable power for different scenarios in different years. The scenario we are focusing on is the 2050 NAT scenario.

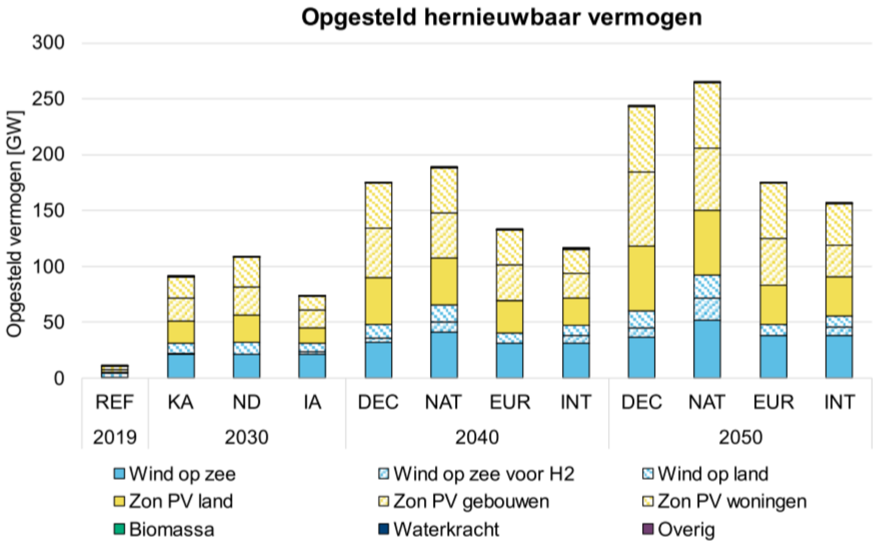


Figure 4.1: Renewable power for different II3050 scenarios

National leadership

In the national leadership scenario, total electricity demand reaches approximately 430 TWh, an increase of more than 250% compared to 2019. A significant portion of this demand, 110 TWh, is driven by the growing use of electrolysers. Renewable electricity production rises sharply, with solar and wind playing dominant roles. Offshore wind is fully utilised for electricity generation, with 52 GW installed capacity expected to produce 234 TWh. An additional 20 GW of offshore wind is allocated for hydrogen production. Onshore wind contributes an estimated 66 TWh, while solar PV is projected to generate nearly 135 TWh by 2050. Two other notable sources in this scenario are nuclear power and hydrogen-to-power plants, contributing 20 TWh and 14.3 TWh, respectively. The table below summarises the key figures for this scenario.

Production type	NAT 2050	Unit
National electricity demand	292.5	TWh
National hydrogen demand	122	TWh
Wind on land	20	GW
Wind on sea	72	GW
Solar PV	135	TWh
Batteries	59.7	GW
Electrolysers	25	GW
Biogas	13.9	TWh
Green hydrogen	136.5	TWh
Blue hydrogen	33.1	TWh
Hydrogen storage	13.6	TWh

Table 4.1: Key figures of the II3050 National leadership scenario

To efficiently utilise these large amounts of energy, flexibility is essential due to the high intermittency of power sources. This scenario includes six different types of flexibility to manage electricity production effectively. These options include:

- Interconnection
- Curtailment
- Storage (batteries, power-to-gas)
- Demand response
- Conversion (power-to-gas, power-to-heat)
- Back up plants (Fossil power plants, biomass, nuclear, hydrogen)

For each flexibility option, the II3050 has The amount of flexibility used per option is discussed in the table below.

Flexibility type	NAT 2050	Unit
Import	40-60	TWh
Export	60-90	TWh
Interconnection	18.8	GW
Curtailment	5-13	TWh
Large-scale batteries out	13-21	TWh
Large-scale batteries in	17-28	TWh
Gas-to-power	9-18	TWh
Demand response	2-4 TWh	TWh
Power-to-gas	40-110	TWh
Power-to-heat	0.9-2.6	TWh
Nuclear	3	GW
Hydrogen-to-power plants	15	GW

Table 4.2: Flexibility options of the II3050 National leadership scenario

4.3. Technology selection

In the methodology, we discussed the technologies used for this model. These technologies are in line with the goals of the Dutch government. This means that by 2050 the electricity network needs to be CO2 neutral, and no fossil fuels are used for electricity generation. The selected technologies are copied from a prior report, written by CE Delft, describing a similar CO2 neutral model, but then for 2035 [8].

4.3.1. Node selection

One of the key recommendations from the II3050 report was to determine which energy carriers should be deployed where and when across the country. To address this question effectively, while maintaining a model that is both fast and user-friendly, the decision was made to divide the Netherlands into 12 nodes, each corresponding to a province. This model is a spatial and structural expansion of the original Calliope-NL model. While the geographic locations of the nodes are retained from the original, all input parameters have been updated or replaced to reflect the latest technological and infrastructural data.

Each province-level node has its own portfolio of technologies and is connected to other provinces and neighbouring countries through interconnections, facilitating the flow of electricity and hydrogen. Neighbouring countries are modelled as simplified nodes that support only the import and export of electricity and hydrogen, without internal generation or storage technologies.

Importantly, offshore energy technologies (offshore wind) are assigned to the province where the cable reaches ashore, meaning they are considered part of that province's technology portfolio and infrastructure. This method ensures that offshore production is integrated into the regional planning logic while maintaining geographic realism.

This provincial node-based approach provides a broader view of the energy system, extending beyond the internal Dutch network to include cross-border dynamics and offshore integration. It enables fast iteration and analysis at a national scale.

4.3.2. Electricity grid

The electricity grid used in the model is based on the current high-voltage infrastructure of the Netherlands, including its interconnections with neighbouring countries. Specifically, all existing 220 kV and 380 kV transmission lines have been incorporated to reflect the present-day backbone of the national electricity system. The lines correspond to the green and red lines in figure 4.2. This ensures that the model starts from a realistic and operationally grounded network.

However, in order to assess future scenarios and explore how the grid might adapt to increasing demand and changing energy flows, the model allows for expansion of transmission capacity. To keep this expansion both realistic and manageable, a constraint was introduced: each transmission line can be scaled up to a maximum of three times its currently installed capacity. This threshold reflects the physical and economic limitations of the Dutch landscape. Building more than three times the existing capacity is generally considered financially prohibitive or spatially infeasible due to land use constraints, permitting issues, and societal acceptance challenges.

By allowing this controlled degree of grid expansion, the model provides valuable insight into which parts of the network are likely to become congested and where targeted reinforcements may be most effective. It strikes a balance between flexibility for future planning and practical implementation limits, ensuring that the model outputs remain relevant for both strategic decision-making and policy development.

Figure 4.2: Dutch 220-380 kV electricity network

4.3.3. Hydrogen network

For the hydrogen network, the decision was made to align the hydrogen transmission infrastructure with the existing electricity transmission network. This co-location ensures that hydrogen can be efficiently transported between different nodes in the model, facilitating regional supply and demand balancing.

Unlike the electricity grid, however, hydrogen transmission is modelled with unlimited capacity between nodes. Also, there is no price and no transport loss when using the grid, effectively assuming free transmission. This simplification was made intentionally, as the primary focus of the model is the electricity system, not the detailed planning or optimisation of the hydrogen network. Nevertheless, the transmission lines for hydrogen make it possible to meet the hydrogen demand needed for the technologies that are using hydrogen as fuel.

4.4. Required data

Based on the system overview shown in figure 3.1 and the necessary variables shown in F.1, F.2, F.3, and F.4, the required data for the different technologies is shown in table 4.3. This table shows all the information a technology needs to be implemented in the model.

Technology	Information needed
Electricity demand	Hourly demand per node
Export hydrogen, Export electricity	Selling cost, Max use
Import hydrogen, Import electricity, Lost load	Cost
Curtailment	Max use
BECCS rebuilt, Nuclear, SMR	Capacity, Location, Capacity, Efficiency, Capex, Opex, Lifetime, Fuel cost, Ramping time, Fixed annual O&M costs
Hydrogen CCGT &OCGT, Hydro plant	Capacity, Location, Capacity, Efficiency, Capex, Opex, Lifetime, Ramping time, Fixed annual O&M costs
Solar PV, Onshore wind, Offshore wind	Capacity, Lifetime, Capex, Opex, Fixed annual O&M costs
Li-ion batteries, Flow-ion batteries, CAES, Hydrogen storage (salt cavern)	Capacity, Efficiency, Storage discharge depth, Lifetime, Discharge time, Storage loss, Capex, Opex, Fixex annual O&M costs
Electrolyser, Hydrogen fuel cell	Capacity, Conversion efficiencies, Lifetime, Capex, Opex, Fixed annuel O&M costs
Transmission lines	Efficiency per distance, Lifetime, Capex, Capacity

Table 4.3: Required data to model the Dutch 2050 electricity grid

The capacity is not yet known for all technologies; that is why there is an optimisation run for the model. All technologies can optimise within reasonable boundaries of the system. These boundaries are determined by either space restrictions or Dutch policies and will be presented and elaborated on in the next paragraph.

4.5. Data-gathering process

In this paragraph the different data used for the model are presented and discussed. First the demand data is discussed and then the specific technology data. Lastly, the data concerning location restrictions are discussed.

4.5.1. Demand data

The Calliope model uses tabular data in the form of CSV files for its demand data. Since we are modelling the electricity model for a full year, this file has an hourly demand value, totalling 8760 datapoints.

4.5.2. Electricity demand

The electricity demand used in this model is based on the same demand file as the II3050 National Leadership scenario. This file is available through the Energy Transition Model [55], but several modifications were necessary before it could be used here.

First, the original file included both input and output demand. Since this model optimises generation capacity based on national electricity consumption, only the input demand was retained. In addition, demand associated with technologies already modelled internally, namely storage (P2P) and hydrogen production (P2G), was excluded to avoid double counting. After these adjustments, the total annual electricity demand amounts to 449 TWh.

To regionalise this national demand across Dutch provinces, an additional step was needed. As described earlier, the demand was distributed proportionally based on each province's contribution to national GDP. This approach is commonly used in energy system modelling and is also applied in the EU's POLES model [37]. For this purpose, the most recent GDP figures from 2022 were obtained from Statline [71].

The calculation was performed for every hour of the year and for each province using the following formula:

$$\frac{GDP_{Province}}{GDP_{National}} * Hourly\ demand$$

The result is a fully regionalised hourly electricity demand file tailored for this model.

4.5.3. Hydrogen demand

The model does not have a specific hydrogen demand, but it does have hydrogen-to-power plants. The demand for hydrogen arises from these plants. When the demand for electricity is larger than the other plants can produce, and there is no stored electricity left, the hydrogen-to-power plants need to produce electricity. In order for them to work, it is possible to get hydrogen from the hydrogen caverns or import hydrogen from neighbouring countries.

4.5.4. Weather data

The weather data used for this model is also added to the model with a CSV file. This model has two, one for the wind and one for solar. The weather profile chosen for this model is data from 2019. The 2019 weather profile is a strong choice for modelling the 2050 Dutch electricity network because it provides recent, high-quality data from a year unaffected by the COVID-19 pandemic or energy crisis, making it a stable and neutral baseline. It represents a climatologically average year for the Netherlands, offering typical wind and solar conditions ideal for base case modelling.

4.6. Technologies

This paragraph discusses the specific data values per technology presented in table 4.3. The techno-economic data that is needed for this model is largely taken from the technology catalogue of the Danish Energy Agency [1]. The data is specifically forecasted for 2050. The missing data was gathered from Scenariostude kernenergie [65]. The table below, table 4.4, shows all cost assumptions made for the model. These cost assumptions include the capital cost (CAPEX), the operational costs (OPEX), the fixed annual operation and maintenance costs (Fixed annual O&M costs), and the fuel price. Since we are modelling far ahead in the future, no distinction is made between new and existing plants in terms of efficiency. There are some locational restrictions based on the location of existing plants, but this will be discussed in the next paragraph.

Category	Capex	Opex	Fixed annual O&M cost	Fuelprice	Source
Production					
Hydro_ccgt_new	877 kEUR/MW	4.24 EUR/MWh	3.25 kEUR/MW peryear	231 EUR/MWh	[1], [65]
Hydro_ccgt_rebuilt	182 kEUR/MW	4.2 EUR/MWh	3.25 kEUR/MW peryear	231 EUR/MWh	[1], [65]
Hydro_ocgt_new	860 kEUR/MW	4.79 EUR/MWh	1.794 kEUR/MW peryear	231 EUR/MWh	[1], [65]
Hydro_ocgt_rebuilt	182 kEUR/MW	4.79 EUR/MWh	1.794 kEUR/MW peryear	231 EUR/MWh	[1], [65]
BECCS_rebuilt	2758 kEUR/MW	4.22 EUR/MWh	6 kEUR/MW peryear	60 EUR/MWh (Biomass)	[65]
Nuclear	8400 kEUR/MW	4 EUR/MWh	2.195 kEUR/MW peryear	8 EUR/MWh	[65]
SMR	2700 kEUR/MW	4 EUR/MWh	4.44 kEUR/MW peryear	8 EUR/MWh	[65]
Hydro	2.437 kEUR/MW	0.00 EUR/MWh	2.2 kEUR/MW peryear	-	[65]
Solar_PV	410 kEUR/MW	0.01 EUR/MWh	1.828 kEUR/MW peryear	-	[1]
Wind_onshore	1090 kEUR/MW	1.85 EUR/MWh	1.431 kEUR/MW peryear	-	[1]
Wind_offshore_DC	2867 kEUR/MWh	2.78 EUR/MWh	0.976 kEUR/MW peryear	-	[1]
Wind_offshore_AC	1986 kEUR/MWh	2.78 EUR/MWh	1.407 kEUR/MW peryear	-	[1]
Conversion					
Hydrogen_fuel_cell	850 kEUR/MW	0.00 EUR/MWh	5.00 kEUR/MW peryear	-	[1]
Electrolyser	395 kEUR/MW	0.00 EUR/MWh	1.5 kEUR/MW peryear	-	[65]
Storage					
Li_ion_battery	270 kEUR/MWh	1.7 EUR/MWh	0.211 kEUR/MW peryear	-	[1]
Flow_ion_battery	350 kEUR/MWh	0.96 EUR/MWh	1.5 kEUR/MW peryear	-	[1]
CAES	851 kEUR/MWh	2.6 EUR/MWh	0.307 kEUR/MW peryear	-	[1]
Hydrogen_cavern	1.28 kEUR/MW	0.00 EUR/MWh	0.0021 kEUR/MW peryear	-	[1]

Table 4.4: Overview cost assumptions

4.7. Capacity restrictions

The model will optimise the rollout of power plants in the Netherlands based on demand, costs and location restrictions. This paragraph will discuss the latter. First the hydrogen-to-power plants will be discussed, then the wind turbines, both on land and in the water. Lastly, the solar PV panels are discussed.

Hydrogen power plants and BECCS rebuilt

There are two types of hydrogen power plants in this system; these are the Open Cycle Combined Gas Turbine (OCGT) and the Closed Cycle Gas Turbine (CCGT). Because natural gas is excluded from the system, the model has the option to choose between refitting existing natural gas plants to work with hydrogen or to build a new plant using hydrogen. There are no capacity restrictions for these new plants, and the installed capacity is selected entirely by the optimisation. This is different for the plants that are refitted. The amount of installed capacity per province is capped based on the current amount of installed natural gas OCGT and CCGT plants. This data was collected from the data platform Open Power System Data [14].
The Bioenergy Carbon Capture and Storage (BECCS) plant is a rebuilt plant from existing coal plants or chp plants. To find this data, the same source was used.

Wind

The wind turbines are divided into three different technologies. There are two offshore wind turbines and the onshore wind turbines. Offshore turbines are either DC (direct current) or AC (alternating current) connected. For the offshore wind, the possible capacity was taken from a report from the Dutch government [57]. This report discussed all existing wind parks in the North Sea and where they are connected to the Dutch shore. The wind parks planned in the future up until 2032 are discussed here as well. This brings us to a total of 21 GW of offshore wind energy. We have seen in II3050 that the total amount of wind is expected to be 72 GW of offshore wind. This was first presented in the North Sea Energy Outlook report [12] and further developed by the North Sea Wind Power Hub [23]. This extra capacity is also added to the model, but because the locations of this extra capacity are not known exactly, the capacity is divided between Groningen and North Holland, which will likely be the landing spot for the electricity. The division between DC connection and AC connection to shore is based on distance. A visualisation of this division is shown in the figure below.

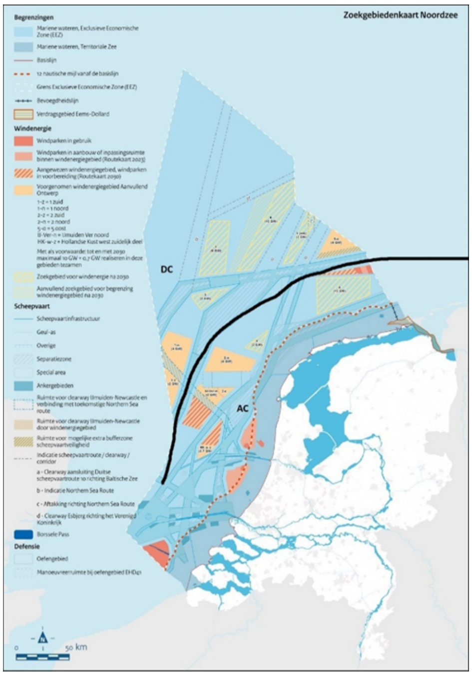


Figure 4.3: Windparks Northsea [20]

For the wind turbines on land, a different approach was used, similar to the one used in a report modelling the 2035 network [8]. All areas within the Natura 2000 regions are excluded, and the maximum density of installed capacity is 10 MW/km2 and the maximal area use is set to 10% to prevent unrealistic amounts of installed wind capacity. The areas of each province designated as Natura 2000 were identified using the Natura 2000 map [51], while the total land area per province was obtained from Statline [70]. The total amount of wind on land was 21.8, which is in line with the 20 GW from II3050.

Solar PV
The amount of available solar capacity was determined in a similar manner as for onshore wind turbines. In the 2035 Dutch network, a maximum solar PV density of 5.1 MW/km² was assumed, and all Natura 2000 areas were excluded. This results in a total capacity of 161 GW. This includes solar parks on land and water, as well as rooftop installations on houses and buildings. In order to match the amount of possible capacity used for the II3050 scenario (135 TWh), the calculations are interpolated to match a total of 118 GW.

Hydrogen cavern
The hydrogen caverns are mostly located in the northeastern part of the Netherlands, in the provinces Groningen, Friesland and Drenthe. Here we can find a combined storage capacity of 33 MW. A report by Larre et al. [36] shows the amount of available capacity for these provinces and also the offshore possibilities. The amount of offshore storage is equal to 179 TWh, and this amount is equally distributed between North Holland and South Holland.

Nuclear plants
There is one existing plant in Borssele. This plant has a capacity of 500 MW and is also included in the model. The model allows for a maximal nuclear capacity of 7 GW. This is in line with nuclear potential in 2050, according to NPE [34]. The model also allows for Small Modular Reactors to be installed. According to TNO research, there is a potential for installing ten of these reactors by 2050 [82]. This would allow for a total capacity of 3 GW.

Import and export
The model allows for import and export for both electricity and hydrogen. This is done to be able to simulate the highly interconnected network, which is the Netherlands. Because we are basing this model on the 'National leadership" scenario of II3050, we want this model to produce most of its electricity by itself. Therefore, the model is only allowed to import 20% of the total energy needed to meet electricity demand. 80% is thus generated within the Netherlands. The same goes for the export of electricity. Although the system can sell electricity to neighbouring countries, the limit for export is also set at 20%. A similar limit is set for the import of hydrogen. Here the maximum is set to 50%. This means that 50% of the hydrogen used by the system must be produced by the system's electrolysers.

4.8. setting up the SPORES

To guide the model toward system configurations that reflect the priorities identified in our interviews, we assign SPORES scores to selected technologies. These scores function as directional incentives, promoting or discouraging the deployment of certain technologies without overriding the core optimisation logic. This equation can be found in the methods chapter (3.5). After testing a range of values, a score of 1000 was chosen, as it provides a clear signal to the model while still allowing trade-offs across technologies. It is high enough to influence deployment decisions in line with our analytical goals, yet moderate enough to avoid overwhelming cost-optimal outcomes. If the results do come out too extreme, this score can always be reduced for that case. Importantly, the SPORES score interacts with the model's constraints in a subordinate way: hard constraints always take precedence. This ensures that prioritising a technology via its SPORES score cannot violate physical or economic system boundaries, preserving the integrity of the solution space.

5 Results

With the model calibrated to Dutch policy targets, spatial constraints, and techno-economic assumptions, we now move to the results.
The chapter opens with a discussion of the interviews in section 5.1. This is followed by a presentation of the base model's outcomes and its validation in section 5.2. Subsequently, in section 5.3, the results of the SPORES model are examined. Based on the interview findings, the directed SPORES results are then presented. The chapter ends with a conclusion summarising the key insights.

5.1. Interviews

As mentioned in the methodology, several questions will be extracted from the interview, based on the answers of the professionals. The next segment will give a summary of these interviews, and after that the questions will be presented. The questions asked during the interview can be reviewed in the appendix B.

5.1.1. Conducted interviews

This section presents the key insights from six interviews conducted with experts from TenneT, each involved in different aspects of electricity system planning. The interviews provide a grounded understanding of the assumptions, critiques, and priorities shaping future scenario development. These findings form the foundation for the modelling choices and ultimately guide the twelve questions addressed in the next section.

Relevance and limitations of scenarios

All interviewees agree that the II3050 scenarios are a vital starting point for long-term grid planning. The "National Leadership" scenario in particular is central, as it underpins the Target Grid strategy. However, there is also criticism: the scenarios are often viewed as static, overly extreme, or insufficiently grounded in political and societal feasibility. Several experts emphasised that these scenarios lack transitional logic, how to get from today's system to a desired future. As a result, there is strong support for more dynamic and incremental modelling approaches that allow for periodic reassessment every five to ten years. Moreover, several relevant dimensions are underdeveloped or missing in the current scenarios. These include circular economy objectives, the impact of AI and data centres, and more nuanced representations of industrial demand or sector-specific trade-offs.

Offshore wind

All current scenarios lean on the fact that offshore wind will be expanded up to 70 GW, but most experts do not even see 50 GW of installed offshore by 2050 happening. One of the concerns is the feasibility of expanding in such a short time period. Also, the public support has a big say in the matter, and not everybody wants to have such a large amount of wind at sea. Another problem is the transmission of all this excess power that will be generated. Who will pay for this, and is the network even ready for such an expansion? An alternative mentioned by one of the interviewees was generating less offshore wind power and focusing on interconnection, increasing nuclear power or investing in biogas plants. The overall conclusion would be that they would like to see scenarios that are different from the runs we know; even if this is not in line with the government's policy, models are there to explore options.

Centralised versus Decentralised

Perspectives on decentralisation vary significantly. Some experts point to growing regional production, the emergence of local energy hubs, and flexibility needs as signs that a more decentralised grid is already developing. Others are more sceptical, citing technical and financial barriers like the lack of scalable storage and reduced policy incentives for solar PV. While opinions differ, there is consensus that the future system will be hybrid: semi-autonomous regional systems interconnected through a national and international backbone. This shift also implies a changing role for TSOs, who will increasingly act as coordinators between decentralised systems and central infrastructure.

Industrial electrification and system demand

A recurring theme in the interviews is the future of Dutch industry. While the II3050 scenarios assume strong industrial demand, several experts question this assumption. Some sectors are already downsizing or relocating due to energy prices, and geopolitical tensions may accelerate this trend. Rather than assuming continued industrial growth, several interviewees argue for more strategic planning: prioritising resilient sectors such as housing, healthcare, and high-value industry, and only scaling up where capacity allows. This calls for scenarios that reflect deliberate choices about sector prioritisation instead of uniform electrification.

Sector coupling and flexibility

There is strong consensus on the need for sector coupling and flexible system design. Technologies like electrolysis and battery storage are mentioned as key enablers, but concerns remain about their scalability and commercial readiness. Medium-duration storage (from 24 hours to two weeks) is especially under-represented in current models, despite being seen as essential for managing longer-term renewable variability. Experts emphasise that coupling with the heat and hydrogen systems is not optional but foundational, and that flexibility must be embedded in both market mechanisms and physical infrastructure.

Affordability

Many interviewees highlight the financial challenges facing the energy transition over the next 10 to 15 years. Infrastructure investments, supply chain disruptions, and labour shortages are expected to drive up costs significantly. These pressures could impact both public support and industrial competitiveness unless temporary subsidies or fair cost-sharing mechanisms are introduced. The broader message is that scenario development must be guided not only by technical feasibility but also by political realism. Without this balance, even the most well-designed technical scenarios may fail to gain the necessary legitimacy or traction.

Ideal future

Several technologies are consistently mentioned by TenneT experts as promising components of the future energy system. Small Modular Reactors (SMRs) are seen as a potential alternative to large-scale wind infrastructure, offering decentralised, space-efficient, and dispatchable generation, though doubts remain about cost and public support. Blue hydrogen and gas plants with carbon capture (CCS) are viewed as transitional solutions to ensure reliability and affordability, especially if electrification or green hydrogen rollout falls short. Long-duration energy storage (LDES), including electrolysis, compressed air storage and heat storage, is widely seen as essential for balancing weather-dependent generation, particularly over 24-hour to multi-week timescales. Together, these technologies reflect a need for flexibility, resilience, and phased system development.

5.1.2. Strategic questions

Based on the interviews conducted with experts from TenneT, twelve strategic questions were identified that reflect current uncertainties, ambitions, and trade-offs in the development of the Dutch electricity network. These questions capture a range of concerns, from technological feasibility and system affordability to political realism and societal acceptance.

Rather than prescribing a single vision for the future, part of these questions serve as entry points for exploration using the Modelling to Generate Alternatives (MGA) approach. These questions are listed below. Each question can be interpreted as a hypothesis or scenario dimension that affects system design.

1. Is there a future for implementing small modular reactors in the energy network of 2050?
2. Are bioenergy plants with CCS (BECCS) a viable option in the 2050 network?
3. How can financial constraints be taken into account when modelling the 2050 network?
4. How would a network look with a lot of nuclear power and a restriction on wind?
5. What role can LDES (long-duration energy storage) play in the future electricity network of the Netherlands?
6. What will be the ratio for import and export in the 2050 Dutch electricity grid?

While MGA is a powerful tool for exploring design options and testing different locational or technical constraints, not all questions derived from the interview can be answered with MGA. The questions selected for an MGA approach are presented above. The other questions are discussed in appendix B. These questions focus more on social acceptance or political direction. Although these are highly relevant topics, they fall outside the scope of this research and will not be explored further. The questions that can be addressed through system modelling and the MGA approach, questions 1-6, are discussed in the sections below after the results of the base case have been discussed.

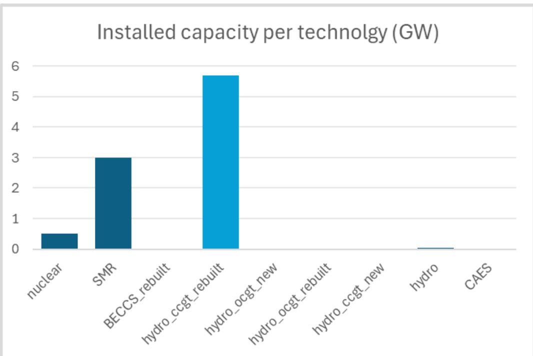
5.2. Base model

The coming segment will discuss the base model described in the previous chapter. These results will be used as a base to analyse the effect of the scenarios created with MGA on the system. We will first look at the installed capacities of the model and the energy flows. After this, the network layout and dispatch are discussed. These numbers will then be compared against the II3050 outcomes. The base model concludes with a sensitivity analysis to see how the model reacts to different input variables.

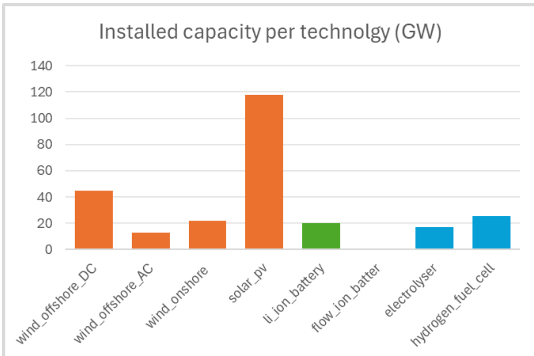
5.2.1. Installed electricity capacities

The base model, as well as the other model runs, has a total energy demand of 448 TWh in the year 2050. A total of 197.58 GW of renewable energy is installed, producing 337.34 TWh of that demand. The baseload capacity, comprising nuclear, SMR, and the BECCS_rebuilt, is a total of 3.50 GW, generating 30.65 TWh. The installed amount of electricity conversion and storage capacity, the hydrogen-to-power plants, the batteries, CAES, and the electrolyser is 68.69 GW. The combined utilisation of these technologies pumped 75.79 TWh of electricity into the system. The reason this is relatively low is because of the hydrogen fuel cell. This technology acts as a backup plant and only runs about 10% of the time. The model sees this as a cheaper option than installing nuclear or BECCS-rebuilt plants. Without these plants, the installed capacity would be 43.01, producing 54.9 TWh. Energy is lost here because of conversion. Apart from the electrolyser, the hydrogen-to-power plants also have access to hydrogen that is stored in hydrogen caverns. The yearly energy output of these caverns is equal to 111.359 TWh of hydrogen contributing to the electricity output described above. The difference between import and export is 95.49 TWh. Therefore, the total amount of electricity produced and imported by the system is 539.27 TWh, meeting the demand earlier locked in at 448 TWh. The mismatch between demand and production of the system is because of storage energy still left in the different storage technologies and because of efficiency losses due to conversions.

The two diagrams below give an overview of the installed capacity. The circle diagram below shows the energy produced with it. All technologies producing less than 0.01 TWh are excluded from the circle diagram to keep the figure readable.



(a) Installed capacity basecase.



(b) Installed capacity renewables basecase.

Figure 5.1: Installed capacity of basecase run.

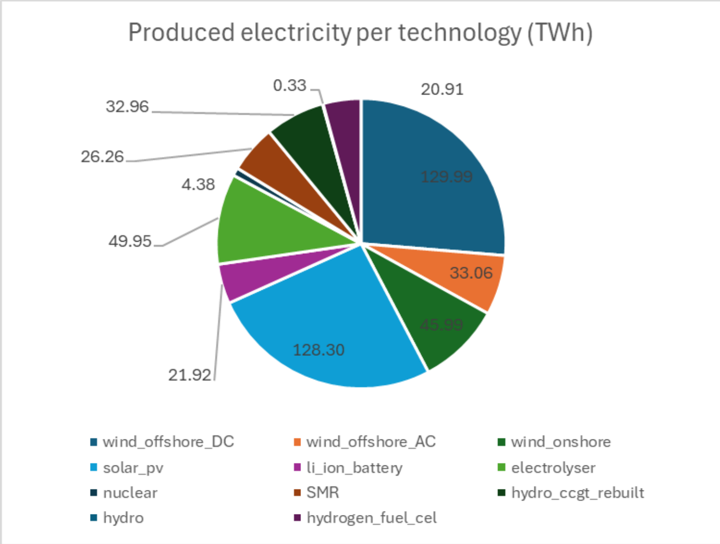


Figure 5.2: Produced electricity per technology

5.2.2. Installed hydrogen capacities

The hydrogen carriers also installed capacity in the model, as mentioned in the previous paragraph. The total installed hydrogen production is 17.32 MW, producing 49.95 TWh of hydrogen energy. The hydrogen production comprises solely of the electrolyser. These electrolysers are responsible for the green hydrogen produced in the network. The model can also import green hydrogen from neighbouring countries. The plants using this hydrogen are the hydrogen-to-power plants and the hydrogen fuel cell. The bar plot in figure 5.3 shows the division of hydrogen import versus the electrolyser. This is exactly equal, meaning it works on the limit of the import share of hydrogen of 50%. Because the import price and export price of the hydrogen are the same in the model, there is no incentive to buy or sell more hydrogen than needed for the demand. It can, however, buy hydrogen to store when there is no need for it to later be able to use 'free' hydrogen when the prices are high.

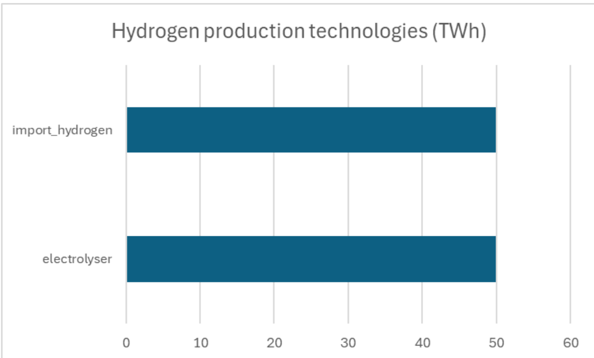
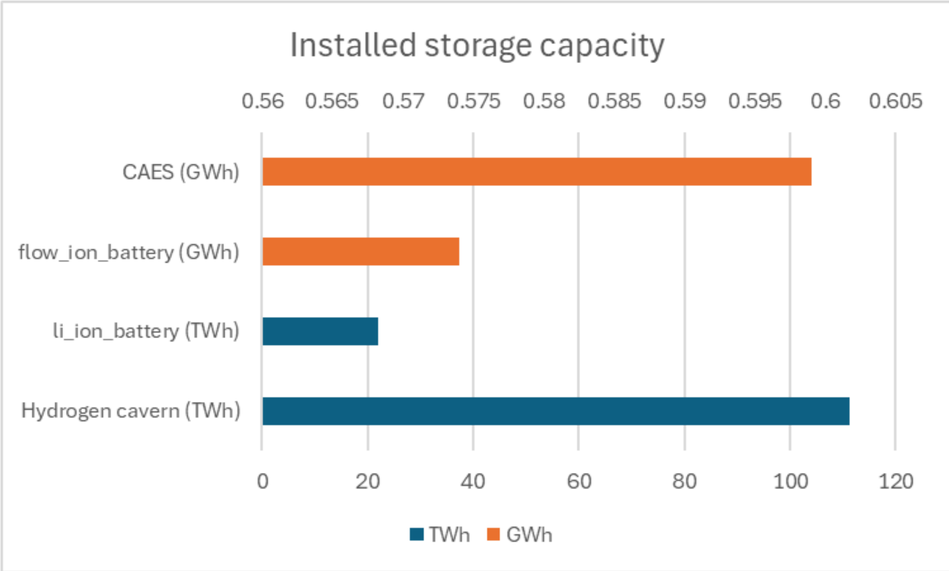


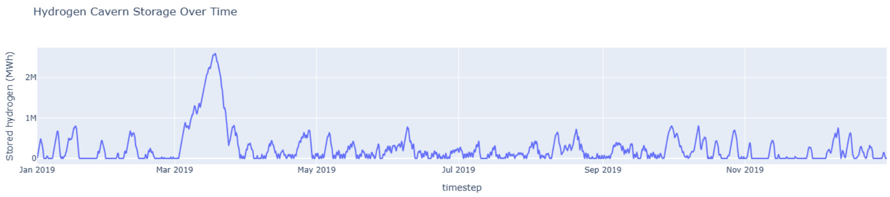
Figure 5.3: Total system-produced hydrogen

5.2.3. Storage technologies

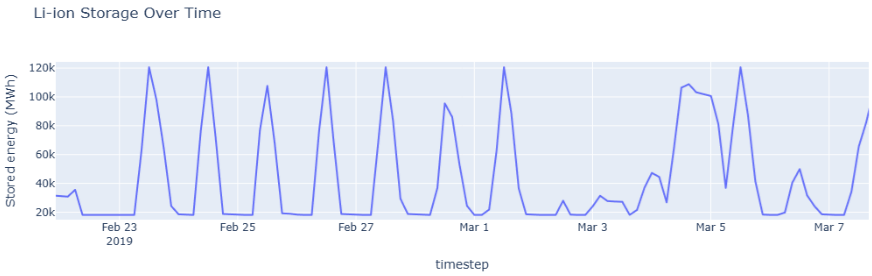
The model has several ways to store its energy during the year. Having storage in the model is essential to support renewable electricity and hydrogen generation. There is both hydrogen storage, being stored in salt caverns, and battery storage (Li-ion batteries). The model also allows flow-ion batteries and compressed air energy storage (CAES), but these technologies remain almost unused in this model run. This is because these two technologies's properties are too similar for the model to cost-efficiently install this power compared to Flow-ion batteries and salt caverns for hydrogen storage.
We can see that the model installs large amounts of storage in salt caverns. These caverns are regularly filled and depleted, and we see the model storing more often during the summer compared to the winter. An interesting time period is the month of March. The first half of this month the salt caverns fill up a lot and are emptied again by the end of the month. This is because during this month there is an exceptional amount of wind power being generated, giving the model a lot of extra electricity to generate hydrogen with. Some more detailed plots explaining this can be found in appendix G. Because there is a lot of hydrogen and the demand is already satisfied, the model stores the hydrogen in the caverns. The technology is modelled in such a way that at the start and finish of the model run, the cavern should be close to zero. The short-term storage of the Li-ion battery is also depicted in the figure for two weeks at the end of February and the beginning of March.



(a) Total installed storage capacity



(b) Hydrogen cavern storage over time



(c) Li-ion battery state of charge during 2 weeks

Figure 5.4: Storage technologies capacity and flows

5.2.4. Transmission lines

The next part we will look at is the transmission infrastructure of the model. The interconnections are already set. But it is interesting to look at the expansion of the lines. Since hydrogen is modelled as free transmission, this network will not be discussed. Comparing this result with the existing network shown in Chapter 4, we can see that the network has increased its capacity in several locations. Figure 5.5 shows the lines with their nodes. The thicker the line, the higher the installed capacity for that line. The lines going out of the figure boundaries are the connections to neighbouring countries (Belgium, Germany, Great Britain, Denmark, and Norway). Table 5.1 below the figure shows both the original transmission of today's network capacity as well as the new capacity.

A few connections stand out. First, we have to remember that the lines are only allowed to be increased three times their current capacity. This is because more than this is either spatially or financially infeasible. The lines that have expanded the most are the lines from Zuid-Holland to Noord-Brabant and the line from Overijssel to Gelderland. These two lines both maximised its capacity within the limits of the system. Then there was also expansion in lines: Friesland to Flevoland, Flevoland to Noord-Holland,

Zeeland to Noord-Brabant and Noord-Brabant to Limburg. These limits are strongly dependent on the installed capacities per province, which we will talk about in the next paragraph.
Although cross-border interconnections are modelled in a simplified way, they are still worth examining in more detail. The only permitted expansion was between Limburg and Germany, and this connection was utilised to its full capacity to enable increased power imports from neighbouring countries. If we take a look at the map in its entirety, we can see large amounts of energy being transported from Groningen to the south following the German border, across to Noord-Holland, and we see a large energy stream from Zuid-Holland to Noord-Brabant/Limburg. These two streams were also seen in the first Target Grid map [72].

Figure 5.5: Transmission network of the 2050 electricity grid

Transmission line	Current capacity (MW)	2050 network capacity (MW)
Groningen_to_Friesland	1905	1905.37
Groningen_to_Drenthe	7171	7171.18
Friesland_to_Flevoland	1905	**2683.68**
Drenthe_to_Overijssel	7171	7171.02
Overijssel_to_Gelderland	1900	**4304.82**
Overijssel_to_Flevoland	5196	5196.00
Gelderland_to_N-Brabant	3291	3291.84
Flevoland_to_N-Holland	3949	**7200.02**
Utrecht_to_N-Holland	3290	3290.00
Utrecht_to_Z-Holland	3291	3291.11
N-Holland_to_Z-Holland	7240	7240.29
Z-Holland_to_N-Brabant	3720	**11159.96**
Zeeland_to_N-Brabant	3720	**5747.01**
N-Brabant_to_Limburg	7011	**8327.53**
Zeeland_to_BEL	3500	3500
Limburg_to_DEU	6000	8500
Friesland_to_DNK	700	700
ZHolland_to_GBR	1000	1000
Groningen_to_NOR	700	700

Table 5.1: Transmission line expansion

5.2.5. Installed technologies per province

Because this model has a node installed for every province, we can take a look into the installed capacities per province of the model. The offshore wind turbines are part of the provinces where their cables reach shore; thus, we expect high amounts of installed production capacities at these locations. The installed capacities are presented in figure 5.6 and the specific numbers can be found in appendix C.

This bar chart in figure 5.6 shows the installed capacities (in MW) across various nodes, with each bar broken down by technology. There is a clear deviation in technology distribution across the regions: coastal nodes such as Groningen (NL11), Noord-Holland (NL32), and Zuid-Holland (NL33) exhibit significantly higher total capacities, primarily driven by offshore wind installations (both AC and DC). This aligns with their geographic location near the North Sea, making them suitable for offshore wind development. Other inland regions, like Overijssel (NL21) or Drenthe (NL13), show a more balanced or modest mix, dominated by technologies such as electrolysers, solar PV, and Li-ion batteries.
There are also some technologies that are not installed at all. These technologies include CAES, hydro_ocgt_new, hydro_ocgt_rebuilt, lost_load and nuclear. Based on the model inputs, these technologies are generally more expensive than similar alternatives, such as hydrogen-to-power CCGT plants instead of hydrogen-to-power OCGT plants or SMR plants instead of nuclear. However, it is important to note that the model also installs some technologies up to their maximum defined potential. This indicates that the resulting technology distribution is shaped not only by cost competitiveness but also by the spatial availability constraints in the model. If additional potential were available in other regions, the model's allocation decisions might have been different, potentially leading to a more geographically distributed deployment.

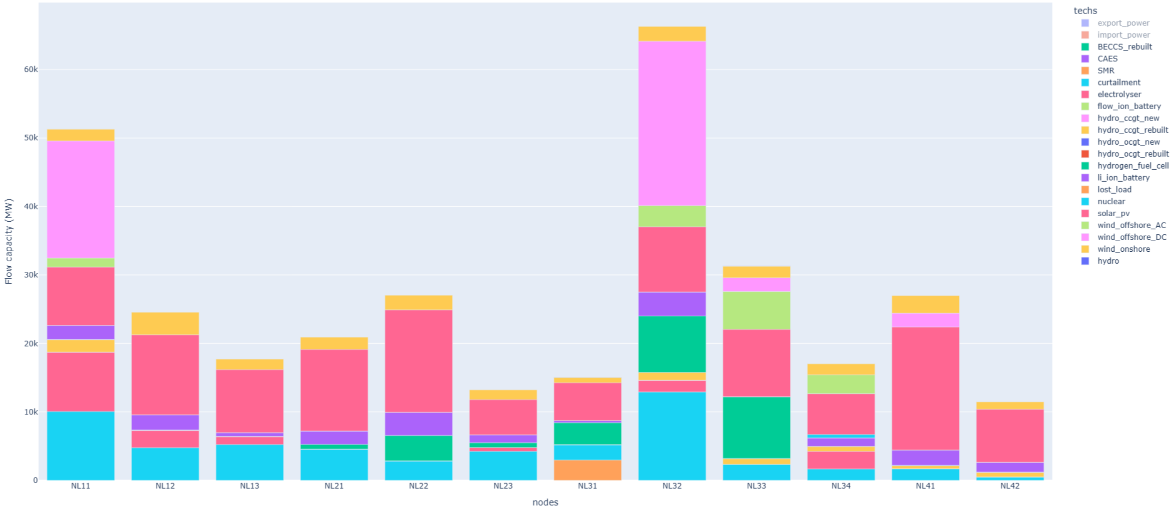


Figure 5.6: Total installed capacity per province

The spatial distribution of installed technologies reveals important insights about the functional role of different nodes in the future energy system. NL32 (Noord-Holland) exhibits the highest total installed capacity, including large amounts of hydrogen electrolysers, fuel cells, and Li-ion batteries. This aligns with expectations, given the province's high population density, central location, and large renewable generation potential, particularly from offshore wind. NL22 (Gelderland) also emerges as a notable node, especially in terms of fuel cell and battery capacity. While its local electricity demand is average, the province has high solar PV output and is centrally positioned within the transmission network. As shown in figure 5.5, NL22 connects to multiple neighbouring nodes, including the German interconnector via Limburg, making it well-suited for hydrogen reconversion and grid balancing. The model assumes hydrogen transport is lossless and costless, allowing for spatial separation between hydrogen production and reconversion. As a result, reconversion capacity is not necessarily installed in high-demand regions but rather in locations that are well interconnected and less congested. Although this assumption simplifies real-world infrastructure constraints, it illustrates how network topology can be used to distribute system flexibility more efficiently. The full system chart confirms that coastal provinces (e.g., NL32, NL11) concentrate more on renewable production and electrolysis, while inland nodes (e.g., NL22, NL31) take on balancing and reconversion roles.

MW	NL11	NL12	NL22	NL31	NL32	NL34
electrolyser	**8669.70**	**2551.43**	2.33	3.14	**1712.19**	**2579.31**
hydro_ccgt_rebuilt	**1834.24**	0	0	0	**1150.47**	715.04
hydrogen_fuel_cell	17.52	32.50	**3705.30**	**3204.46**	**8233.33**	18.82
li_ion_battery	2041.51	2209.54	**3389.14**	312.03	**3513.61**	1221.73

Table 5.2: Summary of outcomes for deployment of hydrogen-to-poewr plants, batteries and electrolysers

5.2.6. System behaviour

To gain deeper insight into how the system behaves under specific conditions, we examine the week of 21 to 28 July 2050, a period characterised by high solar irradiance and low wind generation, offering a useful window into the dynamics of supply and system flexibility.

The dispatch plot shows that solar PV makes most of the electricity during the day. It produces a lot of power that follows a clear daily cycle. Two technologies, SMR (in dark red) and rebuilt hydro CCGT (in pink), provide a stable baseload throughout the week. These technologies make sure that there is always electricity available, no matter what the weather is like.

During the middle of the day, especially on sunny days like July 24 and 26, there is more electricity than there is demand. This is shown by the space between the stacked bars and the black demand line. This makes the system turn on several flexibility options, such as electrolysers that turn extra electricity into hydrogen, Li-ion batteries (purple) that store extra energy, and curtailment when renewable energy can't be used or stored effectively.

Later in the day, especially in the evening and at night when solar production drops, the system uses energy from discharging Li-ion batteries, hydrogen fuel cells, and imported electricity to meet the remaining demand. This shows how dispatchable and flexible technologies can work together.

On July 22, the day starts with no solar energy coming in. To make up for the lack of energy in the morning, the system uses SMR, hydrogen fuel cells, discharging batteries, and power imports. This shows how it keeps things in balance when there isn't much renewable energy coming in.

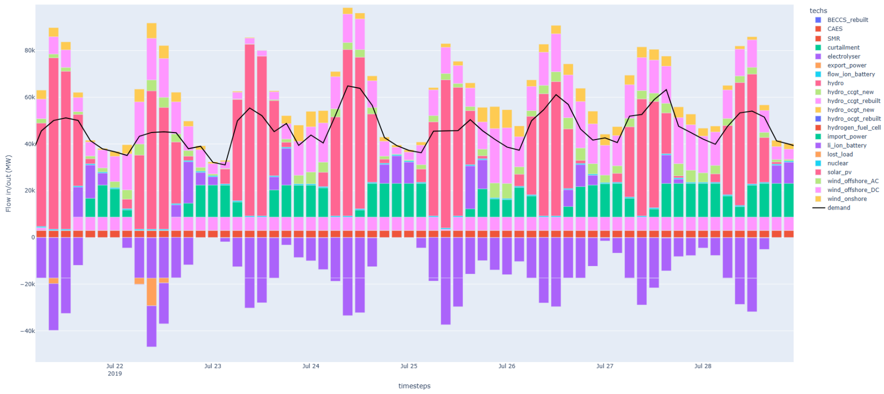


Figure 5.7: Model dispatch for the week 21-28 July

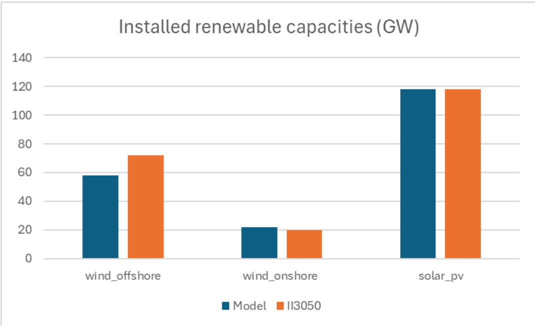
5.2.7. Comparison to other modelling study

When comparing the installed renewable capacities in this model to those in the II3050 "National Leadership" scenario, we see that wind onshore and solar PV reach their maximum allowable capacity in both cases. However, there is a notable difference in offshore wind: the model installs 57.8 GW, whereas II3050 targets 72 GW. This gap is mainly due to the higher cost of offshore wind DC technology, which makes it less attractive in a cost-optimised setting compared to cheaper alternatives. Another reason is the choice of weather year. The II3050 scenarios all use an adapted version of the 2012 weather year. For their scenarios, the full load hours of the wind were increased for wind onshore and offshore to 3200 and 4750 hours, respectively. Whereas the wind in this model is based on real data from 2019 with full load hours for onshore and offshore wind of 2110 and 2740 hours, respectively. These numbers might be possible to achieve, but then we would assume not only the most optimistic growth in wind turbines, it would also mean the old turbines would all have been replaced. The model in this paper chooses a more conservative approach.

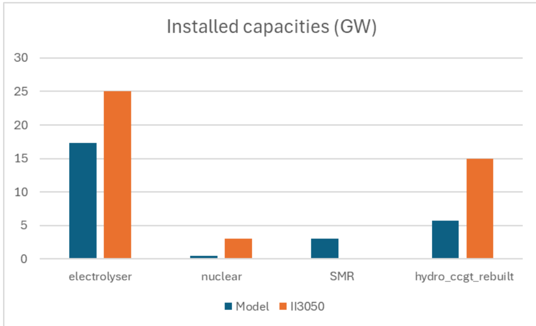
Looking at other key technologies, this model installs fewer electrolysers and hydrogen-to-power plants than II3050. However, it compensates by installing 25 GW of hydrogen fuel cell capacity, which helps to close the demand gap. For nuclear energy, total capacity is similar, but the model chooses to invest in Small Modular Reactors (SMRs) rather than conventional nuclear power. This choice is again driven by cost-effectiveness.

In terms of storage, both models show similar battery storage flows (around 20 TWh), but the hydrogen storage capacity is much higher in this model. This is because hydrogen scarcity is not a strong constraint: hydrogen can be produced domestically using electrolysers or imported, with a 50% import limit. Hydrogen can also transport freely, and this means the location of the hydrogen caverns is of little impact to the amount it wants to store. The model balances between these sources to minimise costs, resulting in high hydrogen storage use.

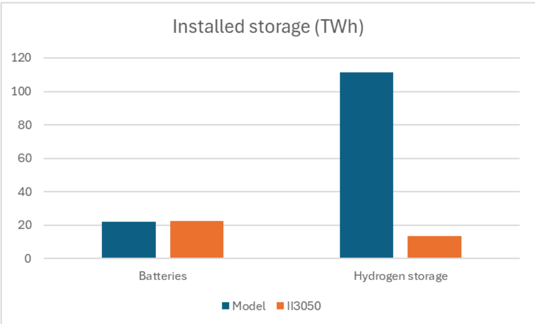
Finally, regarding production flows, the model installs fewer hydrogen-to-power plants and generates less green hydrogen compared to II3050. Instead, it relies more heavily on electricity imports. It also exports significantly less energy. The flows from BECCS (bioenergy with carbon capture), curtailment, and hydrogen-related technologies reflect this trade-off, showing how the model prioritises least-cost system design within the given constraints.



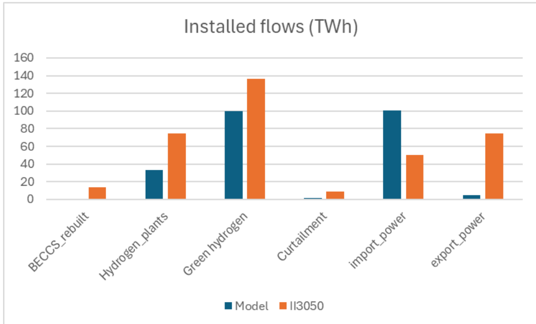
(a) Installed capacity renewables.



(b) Installed capacities.



(c) Installed storage



(d) Installed flows proction plants

Figure 5.8: Installed capacities and flows of model run versus II3050 numbers.

5.3. Sensitivity analysis

In order to test the sensitivity of the model, two other scenario runs were executed apart from the base case (BC). The first scenario is running the model for a different weather year. This year is 2015 (WY2015). Running the model with 2015 weather data is valuable because it was a year with higher wind yields, compared to 2019. This makes it ideal for testing how well the system performs under prolonged high-wind conditions. In contrast, 2015 also had a slightly lower solar irradiance with some prolonged low-solar periods during winter, which challenges the system's ability to manage the demand.

The second scenario is running the model with a much higher price for hydrogen (HHP). This high price is set at 308 euros per MWh. The current price is set at 231 euros per MWh. This is the same value used for the high hydrogen price in the 2035 model of CE Delft [8]. This will allow us to see if hydrogen-to-power plants are still favoured as base technology.

To get an idea of how the model changes based on these different inputs, we will go over several key datapoints of these runs and compare them with the original cost-optimal solution.

Installed renewable capacity per scenario

In the base case, the total installed renewable capacity was 197.58 GW. In the scenario using weather year 2015, this increased slightly to 201.67 GW, likely due to higher wind availability that year. It is, however, important to mention that the maximum allowed offshore wind capacity with direct current for this model is 57 GW. This means this technology has some room left for capacity installation. The other technologies have already installed their maximum allowed capacity, and therefore we do not see large variations in the outcomes. For the HHP scenario, the capacity was 198.07 GW, very close to the base case. This suggests that the hydrogen price has minimal impact on the total renewable capacity installed in the model.

Technology	BC	WY2015	HHP
Wind offshore DC	45.11	50.29	45.60
Wind offshore AC	12.67	12.67	12.67
Wind onshore	21.80	20.71	21.80
Solar PV	118	118	118

Table 5.3: Installed renewable capacities scenarios

Renewable production per scenario

In figure 5.9 below we can see a clear increase in renewable energy production in the 2015 scenario. This was expected, since in this weather scenario, we also see more installed capacity of offshore wind. For the increased hydrogen price scenario, we also see little difference in comparison with the base scenario. This means that from the flows we draw the same conclusion as with the installed capacity; more wind availability results in more renewable production, and hydrogen pricing has little impact on produced renewable energy.

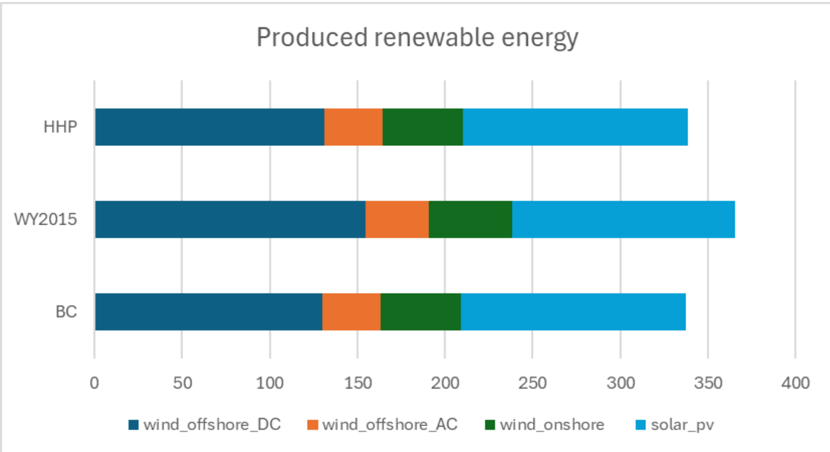


Figure 5.9: Renewable energy production per scenario

Non-renewable produced energy

The electricity-producing plants outside of the renewable wind and solar plants all behave very similarly. There is no significant difference in the installed capacities, except for the small modular reactor. In the WY2015 scenario, we see that no SMR is installed and the model seems to have enough capacity installed to maintain a baseload, given that import power can be used.

Technology	BC	WY2015	HHP
Hydrogen fuel cell	25.68	25.95	25.10
Hydrogen ccgt rebuilt	5.69	5.69	5.69
SMR	3	0	3
Nuclear	49.95	56.27	0.5

Table 5.4: Installed non-renewable production capacities scenarios

Hydrogen production

When looking at the two ways the system can obtain hydrogen, import or electrolysis, we see no surprises in the BC or WY2015 scenario. In the year 2015, we see more installed renewable capacity, and this will mean more excess energy. The model compensated by installing more electrolysers. The installed capacity is 56.27 GW compared to 49.95 in the BC scenario. This is done to make storable hydrogen for later usage. When looking at the HHP scenario, we can see the amount of produced hydrogen going down. This is expected in the case of the import of hydrogen because this is more expensive, but the electrolysers are also going down, suggesting the model starts to lean more towards dispatchable technologies, like nuclear and SMR or BECCS-rebuilt.

Technology	**BC**	**WY2015**	**HHP**
Electrolyser	49.95	56.27	45.36
Hydrogen import	49.95	56.27	45.36

Table 5.5: Installed hydrogen production capacities scenarios

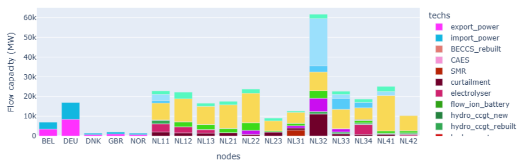
5.4. SPORES

In the next paragraphs, the results of different runs of SPORES will be discussed. First, SPORES runs of the base model are discussed to see what technologies, locations and interconnections are important for the Dutch electricity system. Then we will use Spores to actively assign weights to certain technologies, each answering a different question derived from the interviews. By answering the formed questions, we can answer the research questions as well.

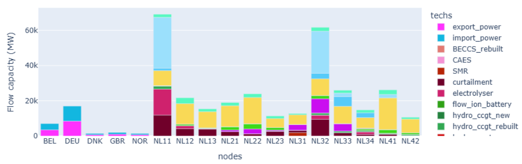
5.4.1. SPORES base model

While some aspects of the results may be undesirable due to policy constraints or lack of societal support, this paragraph identifies the essential technologies and the locations where they should be implemented. It also examines which technologies could potentially be substituted. This is done by running a range of different results with SPORES.
We ran 10 different runs for the base model with an accepted cost increase (slack) of 20% each. In order to keep the model computationally fast, the SPORES were not run for a year. Even when reducing the resolution to 12h, the model was not able to run on a regular laptop. There are alternatives to solve this problem, such as using a more powerful PC or running the code on an external, high-performance computing system, like the DelftBlue supercomputer [17]. But for the sake of easy implementation, we decided to divide the year into two time periods to represent the full year. The first period is the months April till June, representing a period with a lot of sun but little wind. The second period, from September till November, represents a period with higher demand and less solar power. This period does have more wind power.

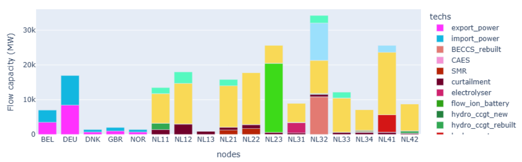
The four images below give a good view of how the SPORES actually change the outcome of the model's installed capacity per technology. The plots of the other SPORES can be found in appendix E



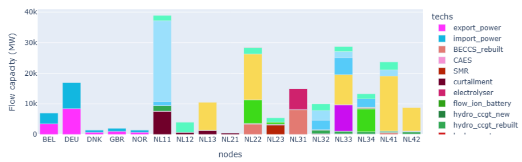
(a) April - June Spore baseline



(b) September - November Spore baseline



(c) April - June Spore 3



(d) September - November Spore 5

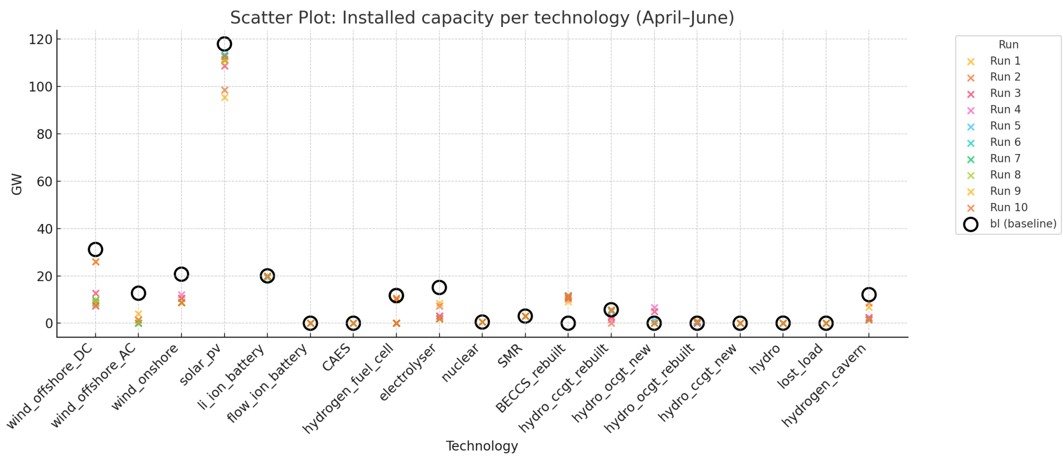
Figure 5.10: Example of Spore for installed capacities per province.

In order to get a better look at the differences in the model runs, the image below shows a scatterplot of the different SPORES. With these two plots we can easily see per technology what is a must-have and what technologies are interchangeable. The crosses are the installed capacity per technology for each spore, and the circle is the installed capacity for the cost optimisation plot.
This scatterplot gives us the possibility to see what technologies are indispensable for the energy grid and which ones are not. Let's first look at the scatter from the spring.

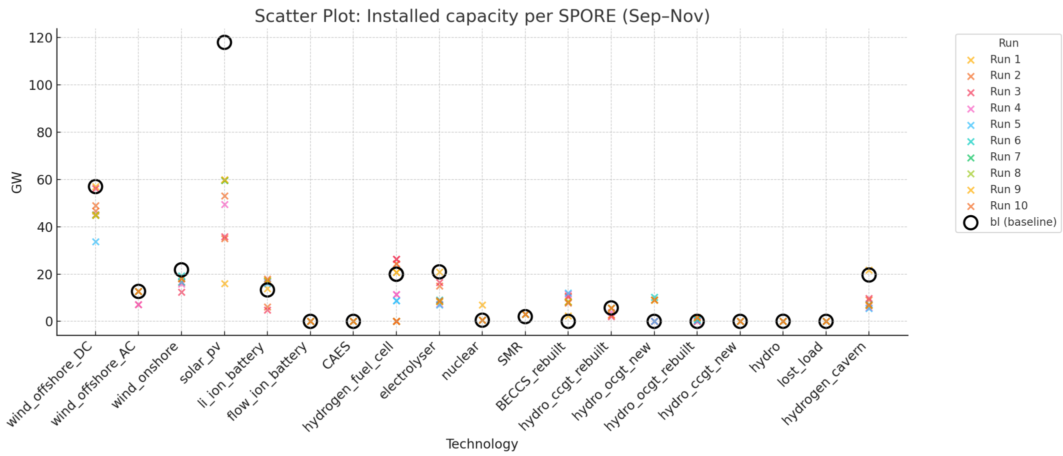
In the April–June runs, most technologies are installed at or below the capacity levels of the cost-optimal solution run for these months (baseline run). A notable deviation is observed in wind technologies: the capacity of wind_offshore_DC drops from 31.16 GW in the optimal solution to as low as 7.4 GW in some SPORES, while wind_offshore_AC is entirely absent in several runs. This suggests that when a 20% cost slack is permitted, the model tends to avoid higher-cost offshore wind in favour of other technologies. One such substitute is BECCS_rebuilt, which sees substantial deployment, rising from 0

GW in the optimal run to up to 11.65 GW in several SPORES, indicating a shift towards dispatchable, low-carbon capacity. In contrast, nuclear and SMR capacities remain fixed across all scenarios at 0.501 GW and 3 GW, respectively. This is because SMR is not allowed to install more than 3 GW of power, and nuclear has the existing plant Borssele built in every scenario. Battery storage also shows minimal variation, and hydrogen-related technologies (hydrogen_fuel_cell and hydrogen_cavern) are consistently installed at lower levels than in the cost-optimal configuration, possibly reflecting their relatively high capital cost or limited value within the flexible budget space.

In the September–November runs, we observe a different set of deviations from the cost-optimal solution (baseline run). Wind_offshore_DC, which is installed at 56.99 GW in the baseline, is consistently reduced across all SPORE runs, with values dropping to as low as 33.64 GW. In contrast to the spring period, solar_pv shows a significant reduction, falling from 118 GW to between 15.93 and 59.94 GW depending on the run. As in the earlier runs, BECCS_rebuilt emerges as a key substitute: while absent in the baseline, it is deployed at levels up to 11.99 GW under cost-flexible scenarios. Interestingly, electrolyser capacity also decreases substantially from 20.94 GW (bl) to values as low as 6.91 GW, indicating less emphasis on hydrogen production. Hydrogen_fuel_cell capacity is reduced dramatically, with several runs eliminating it entirely. Nuclear capacity remains almost constant around 0.5 GW, suggesting the extra cost for the model is still no incentive to invest in more nuclear capacity. SMR, however, is consistently increased from 1.998 GW in the baseline to 3 GW across all runs, suggesting its role as a cost-effective, dispatchable low-carbon option when more budget flexibility is allowed. The drop in solar PV capacity is because of the few sun hours the model has in this period.



(a) April - June Spores scatterplot

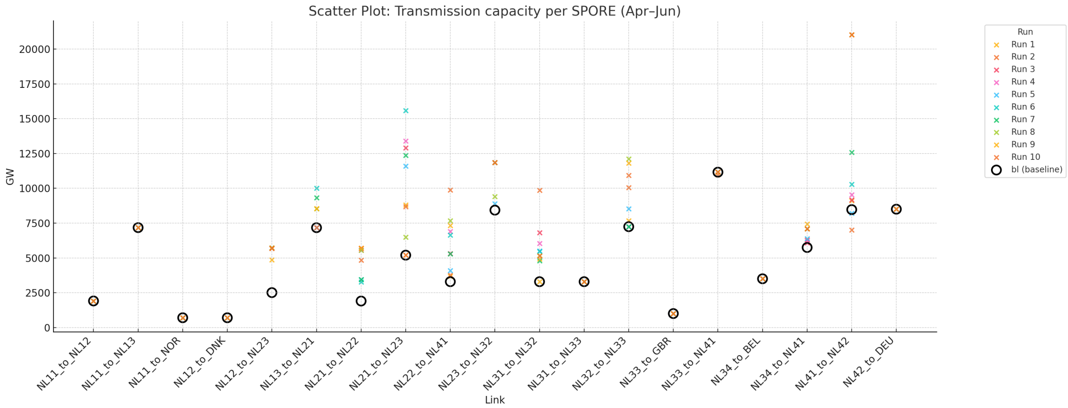


(b) September - November Spores scatterplot

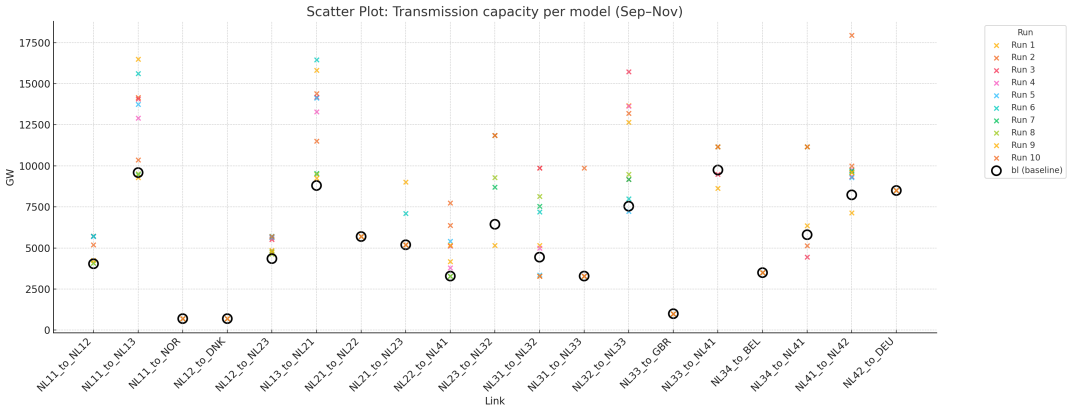
Figure 5.11: Scatterplots for installed capacities for different base case spores.

The results suggest that certain technologies are highly exchangeable, while others remain consistently important regardless of the cost constraints. Wind capacity, particularly offshore, appears flexible and is often substituted when more cost-effective options become available. In both seasons, BECCS_rebuilt emerges as a key alternative, frequently replacing wind in higher-budget SPORES due to its dispatchability and negative emissions. Similarly, electrolyser and hydrogen-related capacities (hydrogen_fuel_cell and hydrogen_cavern) fluctuate considerably, indicating that their deployment is sensitive to scenario-specific trade-offs. In contrast, nuclear capacity remains stable at 0.5 GW across all runs, and SMR consistently increases to 3 GW, highlighting their perceived robustness or essential role in the system. Battery storage (li_ion) also shows little variation, suggesting it is a foundational technology for grid flexibility that is consistently needed, regardless of broader system changes.

We did the same for the transmission lines in the system. From the cost-optimal solution, there were some lines not expanded at all (Groningen to Friesland), and some lines were maximally expanded (Zuid-Holland to Noord-Brabant). The scatterplot below shows capacity expansion in almost all transmission lines. Focusing on the internal transmission lines within the Netherlands, the scatter plots for both April–June and September–November reveal that most provincial connections remain relatively stable across the SPORE runs and stay within the 20% slack margin. Links such as Groningen to Friesland (NL11_to_NL12), Groningen to Denthe (NL11_to_NL13), and Utrecht to Zuid-Holland (NL31_to_NL33) show little variation from the baseline, suggesting that these parts of the grid are robust and not likely to become internal bottlenecks under a wide range of future conditions. However, a number of links display substantial variation, most notably Overijssel to Gelderland (NL21_to_NL22), Overijssel to Flevoland (NL21_to_NL23), Gelderland to Noord-Brabant (NL22_to_NL41), and Noord-Brabant to Limburg (NL41_to_NL42). These lines exhibit clear upward deviations in many runs, especially in the September–November period, which may be driven by higher wind production or seasonal shifts in load. Their behaviour suggests these connections could become critical transmission corridors in future system configurations. The consistent pattern across multiple SPORE variants indicates that these links are sensitive to scenario assumptions and may be key to maintaining system flexibility.



(a) April - June transmission capacities scatterplot



(b) September - November transmission capacities scatterplot

Figure 5.12: Scatterplots for transmission line capacities for different base case SPORES.

5.4.2. SPORES based on interview questions

This last section of the results will present the outcomes of the SPORES that specifically search for alternatives within the solution space, based on the direction of interest taken from the questions. When examining specific technologies, we will discuss locations and capacities of these techs. When looking at financial or import/export constraints, we will take a more global look at the system. All the SPORES made in this section use the same timeframes used for the SPORES base model to represent a full year. This is April-June and September-October.

Is there a future for Small Modular Reactors?

One of the interview topics that came forward was the opportunity and uncertainty of Small Modular Reactors in the electricity system. This technology is widely discussed, but there are no fully operational plants installed yet in Europe. This causes some scepticism by some interviewees. In order to find out what the electricity net would look like when SMR is being pushed into the system, we ran 5 SPORES for the two time frames we are researching. Before discussing these results, it has to be mentioned that the price for SMR in the system (2700 euros per kW) is seen as optimistic by some. From our cost optimisation results we can already see that SMR is fully utilised. So in order to see how far the model takes this expansion, the SMR limit is lifted. In order to keep the comparison fair, the SMR restriction is also lifted for the baseline. In the spring months, the installed SMR capacity is now 12.28 GW and in the autumn months this capacity is 2. Looking at the table below, we see a massive increase in installed SMR capacity. Because initially the increase in SMR was too large to see a difference in installed SMR capacities for all scenarios, the SPORES score was reduced. First from 1000 to 500; after doing this, SMR was still maxed out in every scenario. After reducing the SPORES score to 100, we finally saw a more diverse set of results. These are the ones presented in the table below. This means SMR is still being incentivised to build capacity, but less extreme. The alteration results in a more varied technology setup for the months April-June. During the Autumn months the SMR plants are still installed in large capacities. A large part of the renewables are being replaced by SMRs. In Spring the Solar PV is still installed, but in Autumn almost no renewables are left.

Installed SMR capacity (spores score 100)

Apr-Jun			Sep-Nov			
SPORE	bl	20%	SPORE	bl	20%	
1	12.28	21.64	**1**	2	38.36	GW
2	12.28	21.12	**2**	2	38.14	GW
3	12.28	15.63	**3**	2	37.76	GW
4	12.28	14.82	**4**	2	37.74	GW
5	12.28	14.94	**5**	2	37.55	GW

Table 5.6: Total installed capacity of SMR

The results in Table 5.6 are consistent with expectations. When the 3 GW capacity cap on SMRs is lifted and a preference score is applied in the SPORES model, we observe a dramatic increase in SMR deployment. In the April–June period, capacity rises to approximately 21.64 GW, and in the autumn months, it reaches as high as 38 GW. This 38 GW is extremely high and not only dependent on the SPORES incentive. We have already seen in the base case that the autumn months install fewer renewables because there is less sun during this period. The alternative is then to install more baseload technologies, like SMR. When this technology is then also incentivised by a positive sporesscore, we end up with a very high amount of installed SMR capacity. Another reason for the 'takeover' of SMR in these results could be in the model costs. This is further discussed in appendix G, where we zoom in on shadow prices and marginal costs in the model.

This expansion of SMRs comes at the expense of other technologies (figure 5.13). Most notably, renewable generation sees a sharp decline: solar PV drops to zero capacity in the autumn runs, and offshore wind is reduced to just 2 GW. The decline in renewable electricity generation also affects the hydrogen system. With less excess renewable energy available for electrolysis, both hydrogen production and storage are significantly reduced.

Despite the dominance of SMRs (in red), the model still requires short-term flexibility. This is reflected in the continued deployment of around 20 GW of lithium-ion battery capacity (in green). There is more battery storage used during Autumn compared to Spring.

These outcomes highlight the model's strong preference for SMRs under current cost assumptions (2700 €/kW) but also underscore the sensitivity of the system design to these assumptions. While SMRs appear highly cost-effective in this configuration, it is important to recognise that this reflects optimistic projections for a technology that has not yet been commercially deployed in Europe. These findings suggest that caution is needed when modelling emerging technologies, particularly those with significant cost and scalability uncertainties.

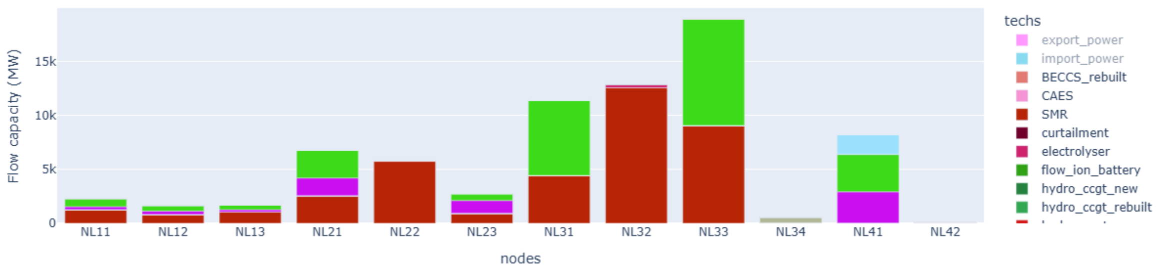


Figure 5.13: Installed capacities with SMR preference (Sep-Nov)

Are rebuilt bioenergy plants with CCS an option for 2050?

The question we want answered in this paragraph is whether or not refitting existing coal and CHP plants to bioenergy plants in combination with carbon capture storage will have a chance in the future electricity grid of the Netherlands. We have seen in our cost-optimal run that there was no BECCS rebuilt installed at all. This is because of the high CAPEX cost of 2758 kEUR per MW, but mostly because of the high annual operation and management costs (6%). During the SPORES runs of the cost-optimal model, we could already see some deployment of BECCS_rebuilt in the system, with some runs even using this technology almost at full capacity. To reinforce this argument, 5 SPORES were run with a slack of 10% and 5 with a slack of 20% for the two periods we are analysing. In these SPORES the BECCS technology has a strong preference in the system. In these results we can see an increase in installed BECCS_rebuilt capacity in almost every run.

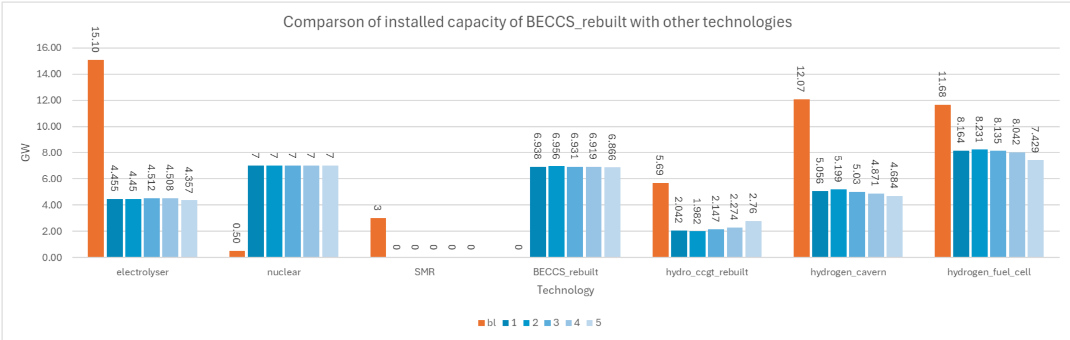
Installed BECCS rebuilt capacity

Apr-Jun				**Sep-Nov**			
SPORE	bl	10%	20%	SPORE	bl	10%	20%
1	0	6.64	7	**1**	0	6.73	12
2	0	6.63	7	**2**	0	6.70	12
3	0	6.61	6.95	**3**	0	6.70	12
4	0	6.58	6.93	**4**	0	6.68	12
5	0	6.59	6.95	**5**	0	6.71	12

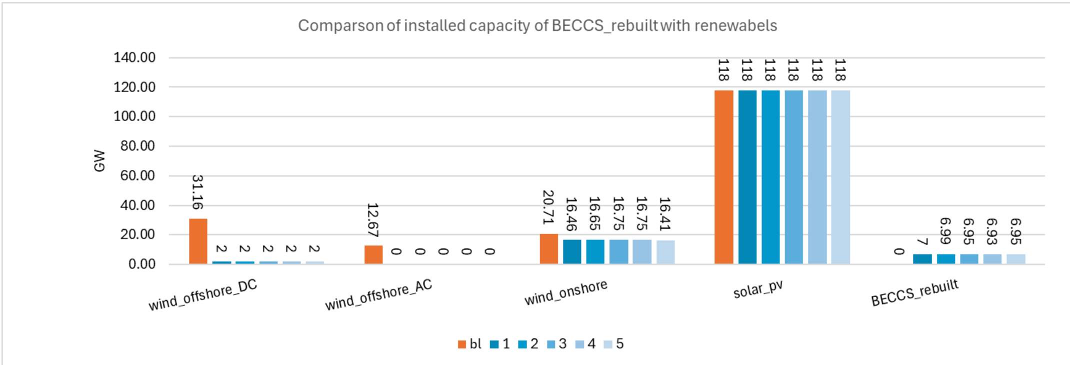
Table 5.7: Total installed capacity for BECCS_rebuilt

The table above shows that the model starts to use the BECCS plants at every run for all seasons. This means that BECCS is certainly an alternative to other technologies when looking at the electricity system of the Netherlands. Since BECCS is a constant energy source, we will compare the results with other similar electricity plants to see how their capacity changes when more BECCS is used in the system. We can see this in the two figures below. For both seasons, all other plants except nuclear go down in capacity. The right three technologies in the first graph all use hydrogen as a resource, and with the current hydrogen development being slower than first predicted, this is a valuable insight. This means BECCS can also be used as an energy source.

The final figure compares the installed renewable energy capacities in scenarios where BECCS is included in the model. A pattern emerges that mirrors the behaviour observed with hydrogen technologies: the deployment of BECCS appears to reduce the need for offshore wind capacity. Given that the original offshore wind projections were already highly ambitious, the availability of an alternative pathway is noteworthy. However, this substitution comes with an important side note. Unlike offshore wind, which generates electricity without requiring fuel, BECCS relies on a continuous supply of biofuels. As a result, offshore wind is expected to remain a cornerstone of the future energy system. Not only as a direct source of electricity but also as a key enabler of hydrogen production via electrolysis.



(a) April - June BECCS-rebuilt vs othter plants

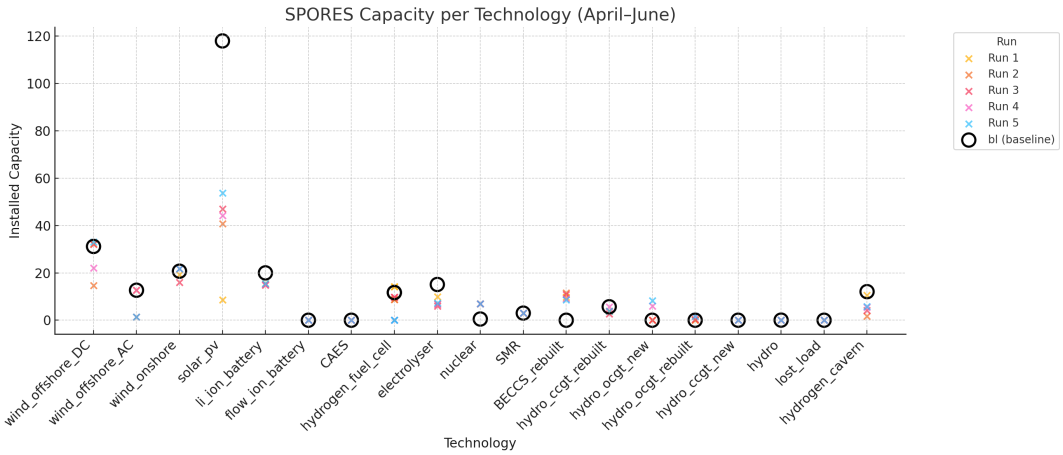


(b) November - September BECCS-rebuilt vs. renewable plants

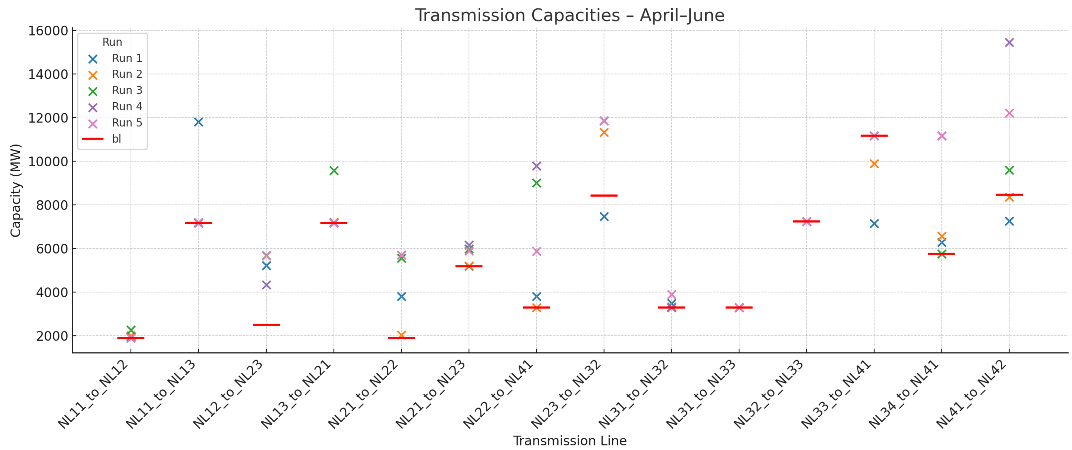
Figure 5.14: Installed capacity BECCS-rebuilt versus Renewables (10% slack).

What would the network look like when nuclear energy is preferred?

A more established technology similar to the SMR is the conventional nuclear plant. This technology is already widely used in other countries, and the Dutch government is also planning on installing more nuclear plants in the future with a capacity of 7 GW at most. To see what our model would look like with more nuclear power plants, we ran 5 SPORES with an incentive of installing nuclear power plants. All results had the same amount of installed nuclear capacity, namely its limit of 7 GW, but the other technologies had a variation in their installed capacities, as can be seen in the scatter plot below.



(a) April - June nuclear capacity vs other plants



(b) September - November nuclear capacity vs. renewable plants

Figure 5.15: Installed (transmission) capacities: nuclear plants versus other technologies (20% slack).

When nuclear power is favoured and a 20% cost slack is allowed, the model shifts away from the cost-optimal baseline and adopts a different mix of technologies. While solar PV and offshore wind remain present, their capacities are notably reduced in most SPORES runs, especially offshore wind in autumn. This reduction in variable renewable generation leads to less excess electricity available for hydrogen production, resulting in consistently lower capacities for electrolysers and hydrogen cavern storage. Hydrogen fuel cell capacity also decreases in most runs, though it remains present, while hydrogen-fuelled plants (hydro_ocgt_new/rebuilt) do not show a consistent decline and may still be used to meet peak demand. Additionally, BECCS-rebuilt appears in multiple SPORES solutions, suggesting it becomes more attractive as a dispatchable, low-carbon alternative under nuclear-preferred scenarios. Overall, favouring nuclear leads to a system that relies less on variable renewables and associated hydrogen infrastructure and instead leans more heavily on firm, dispatchable capacity such as nuclear and BECCS-rebuilt.

With the installation of more nuclear plants, it becomes particularly relevant to examine changes in the transmission network. The results show that in nearly every SPORES run, interconnection capacities increase substantially. This reflects a shift toward greater reliance on large, centralised power generation rather than distributed renewable sources. For example, the transmission line from Gelderland to Noord-Brabant nearly triples in capacity, highlighting the need to transport electricity from central production zones to demand areas. Similarly, the link from Noord-Brabant to Limburg is reinforced in three SPORES runs, with one scenario requiring almost 15.5 GW of transmission capacity. These upgrades illustrate how favouring nuclear power reshapes the spatial dynamics of the energy system.

What role can long-duration energy storage technologies play in the future energy grid?
Long-duration energy storage is something which will be needed in the future electricity grid. This model provides this option in two ways. The first one is hydrogen storage, which can be seen used a lot in the cost-optimal solution. The other form of long-term storage is Compressed Air Energy Storage. This technology is currently not used at all, while this might be a very useful storage technology because it does not need conversion to hydrogen. In order to find out what the system would look like if CAES and hydrogen storage had a policy preference in the Netherlands, 5 SPORES were run. The results are shown in the table below, and we can immediately see that the model maxes out both storage options to the set limits of the model. In order to create some more diversity in the results, the spores score is adapted for these runs and is reduced to 100. As with the SMR SPORES, the model still incentivises the use of more storage, but it is less extreme. These changes in spores score do not alter the results of installed capacity, and both the CAES and hydrogen caverns are still maximally utilised, see table 5.8. This tells us that even with a relatively low incentive (from 1000 to 100), we still end up with the mode choosing to maximally expand the storage options.

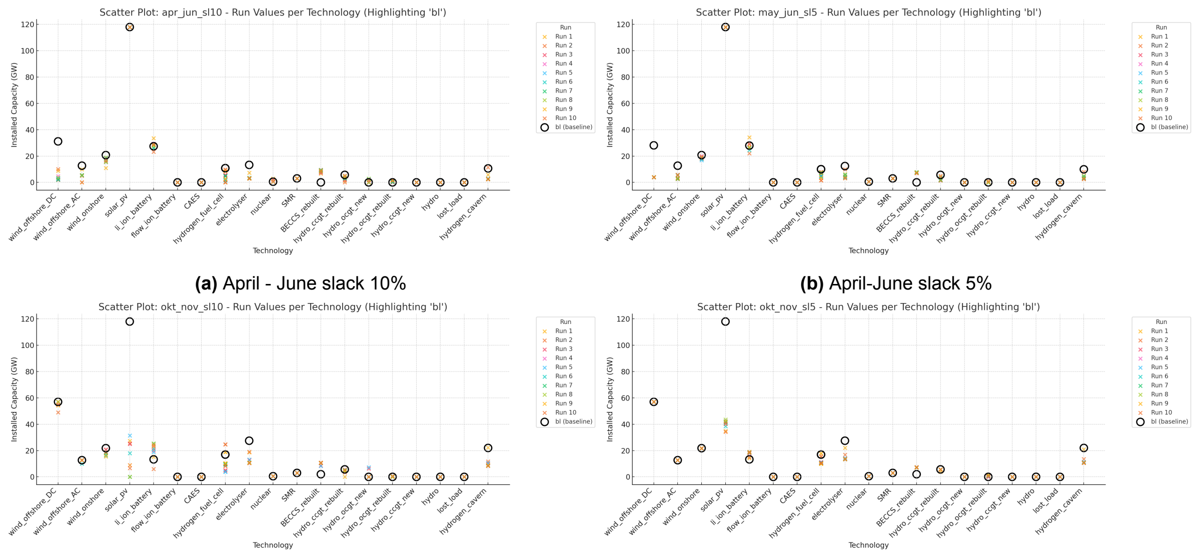
The results of larger local storage also result in a vast expansion of the transmission lines transporting this energy. Both wind and solar are reduced a lot, and the nuclear plants are expanded to their maximum capacities. When leaning towards this much storage, the model needs a more stable flow of energy input and therefore chooses nuclear plants over intermittent renewables.

Installed LDES capacity

	Apr-Jun		**Sep-Nov**		
SPORE	hydrogen cavern	CAES	hydrogen cavern	CAES	
bl	12.07	0	19.93	0	GW
1	58.4	3.17	58.4	3.17	GW
2	58.4	3.17	58.4	3.17	GW
3	58.4	3.17	58.4	3.17	GW
4	58.4	3.17	58.4	3.17	GW
5	58.4	3.17	58.4	3.17	GW

Table 5.8: Total installed capacity of LDES

How can financial constraints be taken into account when modelling the 2050 network?
In recent years, the focus of the renewable electricity grid has increasingly included the affordability of the network. This was also a recurring mention during the interviews. The system must not only be sustainable; affordability is just as important. In order to put this in an MGA perspective, we ran several SPORES, not only with 20% slack but also with 10% and 5% slack. This gives the model a smaller solution space to find alternative solutions, but it also limits the price increase of the model. To see the differences of these runs, we combined the results into scatter plots. To view the differences, we will look at the installed technologies and their capacities. Also, we will look at the total renewable capacity of solar and wind.



(a) April - June slack 10%

(b) April-June slack 5%

(c) Okt-Nov slack 10%

(d) Okt-Nov slack 5%

Figure 5.16: Different SPORES with varying slack percentages.

A comparison between the baseline scenario and the SL5 and SL10 SPORES reveals that most core elements of the energy system remain stable, particularly the large-scale renewable technologies. Installed capacities of offshore wind (both AC and DC) and onshore wind show minimal variation across all three scenarios. These technologies appear to be already cost-effective in the baseline solution, and further cost relaxation does not significantly alter their deployment levels.

Nonetheless, some technologies exhibit a clear sensitivity to the imposed cost constraint. In the SL10 scenario, the installed capacity of BECCS-rebuilt increases by more than 40% relative to the baseline. This suggests that BECCS is not selected under strict cost-optimality but becomes more attractive when limited budget flexibility is allowed. Its ability to provide firm capacity and negative emissions likely contributes to this shift. Similarly, Li-ion battery storage capacity increases by approximately 13% in SL10. This points to an under-representation of short-term storage in the baseline configuration and indicates that additional flexibility becomes favourable in slightly more expensive system configurations.

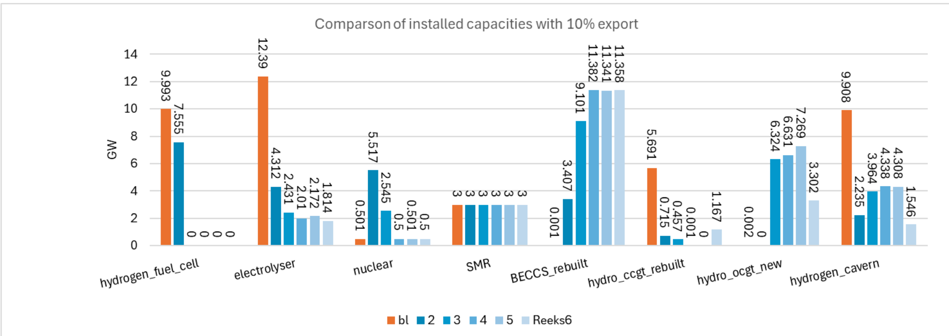
In contrast, hydrogen fuel cell capacity decreases marginally in SL10. This may indicate a substitution effect, where the model favours alternative flexibility options under less restrictive cost conditions. While the overall structure of the system remains largely unchanged, these adjustments contribute to a more flexible and robust energy system design.

What will be the ratio for import and export in the 2050 Dutch electricity grid?

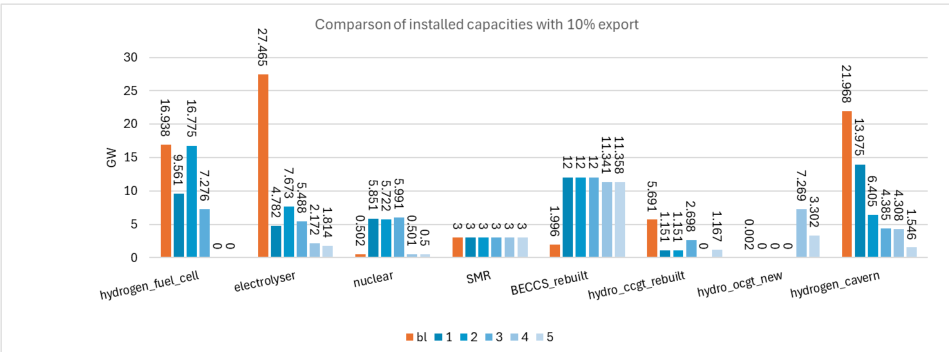
To see what the import-export ratio would change to in the system. The allowed import of this system varied from the current 20%. 5 SPORES were run with 10% of total production that may be imported, and 5 SPORES where only 5% of the total produced energy could come from imports. In the figure below you will find an overview of the installed capacities of technologies.

We will only look at the 10% export max in this paragraph, since we can already see changes in this part, these effects will only be larger when only 5% of energy is allowed to be imported over the year. Looking at the installed capacities, we can clearly see a change in composition of technologies in the system. Before going into detail, let's discuss the amounts of energy that were imported for the baserun, which had the full 20% of import capacity. In that case the total import for April till June was 25.18 TWh, and for September till October this was 24.76 TWh. With these restricted cases, we see 16.6 TWh and 17.22 TWh for the import during these time periods.

Knowing that the import of power has reduced severely, we would expect to see a rise in the dispatchable technologies in the system. This is exactly what we see in the capacity plots in figures 5.17a and 5.17b. SMR was already fully built, and in almost all other scenarios, BECCS rebuild is built to its max capacity as well. Also, we see an increase in nuclear power in some cases, although not in every. For the renewables, we see no big differences other than the lower dispatch of wind during the spring period and solar during the autumn period. These findings have been discussed in the first SPORES that were done. It was mentioned before that because it was so easy for the base model to import power, it uses this import as a baseload power supply, while in reality this can never be possible. With these SPORES, we can see that the model can also generate sufficient energy when more of the demand needs to be produced domestically.



(a) April - June 10% export



(b) Oktober - November slack 10% export

Figure 5.17: Different SPORES with varying slack percentages.

5.5. Conclusion results

This section will conclude the results from all model runs discussed above. The conclusion is split up in the same way the results were presented.

5.5.1. Baseline model

The baseline model demonstrates an energy system that is highly structured and spatially differentiated and that balances the production of renewable energy, the conversion of hydrogen, and the strengthening of the network. Hydrogen fuel cells are set up to work at a high level, but they are rarely used, which shows that they are backup plants. The model needs 9.18 GW of alternative dispatchable technologies besides these. The model puts a 50% limit on hydrogen imports, which is in line with II3050 rules. This makes it even more important to produce and store hydrogen locally. Hydrogen storage is very important for balancing the seasons. In March, for example, when there is too much electricity from renewables, it is utilised to fill the caverns. Coastal provinces are used for renewable power since they have good offshore wind potential, while inland provinces are used for balance. This distribution is possible because we assume that hydrogen may be transported without losing energy or paying transmission fees. The main areas where transmission growth is happening are along two major routes: one from Zuid-Holland to Noord-Brabant and the other from Groningen through Overijssel and Flevoland to Noord-Holland. This suggests that these areas play a critical role in coordinating the national system.

5.5.2. SPORES on baseline model

The SPORE runs derived from the baseline configuration explore whether alternative configurations emerge when limited financial slack is introduced. Across both spring (April–June) and autumn (September–November) SPORES, the core system structure remains stable, but certain technologies display higher sensitivity. BECCS_rebuilt stands out as a technology that consistently increases in capacity across nearly all SPORE runs, indicating its value as a flexible, dispatchable, and low-carbon energy source when the model is allowed to deviate slightly from strict cost-optimality. Conversely, the capacities of offshore wind DC, electrolysers, and hydrogen fuel cells fluctuate significantly, suggesting they are more expendable and may be substituted by other technologies depending on system conditions. Li-ion battery capacity remains relatively robust, though slightly lower in the autumn variants. Transmission expansion patterns are largely consistent, with the same key areas reinforced across scenarios. This suggests that these lines are structurally important and sensitive to a wide range of plausible configurations.

5.5.3. Interview-based SPORES

The final set of SPORES introduces targeted assumptions based on interview insights and stakeholder preferences. These runs evaluate the system's response to the incorporation or prioritisation of technologies that may become politically or socially relevant in the coming decades. Small Modular Reactors (SMRs) are readily integrated into the system when cost constraints are relaxed, further reinforcing their economic attractiveness already visible in the baseline model. However, concerns remain regarding their real-world feasibility and optimistic cost assumptions. BECCS-rebuilt also continues to show up as a consistent addition, further underlining its role as a promising controllable low-carbon source. The inclusion of nuclear power leads to a marked decrease in renewable capacity, indicating that dispatchable nuclear generation can substitute for intermittent renewables within a 20% cost margin. This substitution also results in increased investment in interconnection capacity, as nuclear centralises electricity production. Despite the technical potential, nuclear technologies face societal resistance, with concerns around safety, waste management, and public acceptance. In terms of long-duration energy storage, hydrogen storage remains dominant. Even when explicitly incentivised, CAES fails to enter the solution, indicating it is not economically viable under the current assumptions. Looking at the impact on financial constraints showed that two technologies increase, even with a 5% cost increase. These technologies are Li-ion batteries and BECCS-rebuilt. Finally, the SPORES limiting the import power of the system showed an expected increase in the installed capacity over the system but also proved that the system was able to sustain itself without this extra amount of power from import. Overall, these results confirm that moderate cost flexibility can enable strategic shifts in technology choice, especially in the realm of dispatchable and flexible generation.

6 Discussion

This chapter presents the discussion of the report. First, the limitations of the model are discussed. Next, the implications of the research are elaborated, and finally, recommendations for future research and implementations are discussed.

6.1. Limitations

As with any model-based analysis, this research comes with several limitations that should be considered when interpreting the results. The model was built in Python using the Calliope framework, which provides a flexible and transparent structure for energy system optimisation. However, Calliope relies on linear programming, which restricts the model to linear relationships between variables. In reality, many aspects of the energy system, such as technological learning curves, policy support, and economies of scale, are inherently non-linear and cannot be fully captured in this setup. For instance, the cost dynamics of electrolysers under widespread deployment are likely to be more complex than what this model can represent.

The weather data used to simulate renewable generation is based on 2019 hourly values. While 2019 represents a relatively average weather year, we do see a large increase in wind energy in the month of March, which makes it less representative. Also, it does not capture future climatic variability or extreme conditions that could impact the reliability and resilience of the energy system. Similarly, the energy demand input is based on projections from the II3050 “National Leadership” scenario. While this remains a widely used reference point in Dutch infrastructure planning, newer forecasts are already available and could yield different modelling outcomes.

Another important limitation concerns electricity imports. In the model, imports are always available at a fixed price and can be used at any moment, up to a maximum of 20% of the annual produced electricity. This simplification ignores temporal variability and market dynamics. In reality, import availability depends on external supply, weather conditions, geopolitical factors, and trading arrangements. As a result, the model may overestimate the reliability and flexibility of electricity imports in meeting Dutch energy needs.

The spatial allocation of electricity demand across the twelve Dutch provinces was done using each province’s share of national GDP in 2022, the most recent year with complete data at the time of modelling. Although this method is commonly used in energy modelling, it simplifies real-world energy demand patterns, which depend on a wider set of regional characteristics, including population density, industrial activity, and infrastructure developments. Another simplification concerning imported data is the offshore wind timeseries. Currently, this is the same for every location. Onshore wind and solar PV are specific to each location.

Another key simplification lies in infrastructure modelling. Transmission lines are allowed to expand up to three times their current capacity. While this provides the model with realistic flexibility in many areas, such expansion may be infeasible in densely populated or spatially constrained regions. Additionally, the hydrogen network is modelled as entirely costless and lossless. This strongly favours hydrogen technologies in the optimisation process, whereas in practice, hydrogen transport involves infrastructure costs, conversion inefficiencies, and regulatory hurdles that were not captured here.

Finally, due to the significant computational cost of running the full annual model with SPORES, the modelling period was reduced to two representative time windows: one from April to June (high solar, low wind) and one from September to November (higher demand, more wind). While this approach captures seasonal dynamics to some extent, it does not fully represent the variability of a complete year. Running the full 8760-hour simulation would have provided more accurate results but was deemed impractical within the available computing resources and timeframe.

These limitations mean the model should be interpreted as a simplified representation of the Dutch energy system in 2050. It highlights key trade-offs, system dynamics, and structural dependencies but does not offer exact forecasts. As such, its value lies in informing strategic discussions or as a starting point for more detailed modelling rather than prescribing definitive infrastructure blueprints.

6.2. Model implications

Based on the conclusions extracted from the model and the gained knowledge from both the interviews and the reference scenario from II3050, we can discuss this model's implications. The section is divided into technical implications, financial implications, regulatory implications and social implications.

6.2.1. Technical implications

The technical implications reflect the limitations and assumptions of the model when compared to real-world system behaviour. One of the most prominent issues is the simplified representation of the hydrogen network. In the model, hydrogen transport is costless and lossless, which lowers the barriers for its widespread use significantly. As a result, hydrogen technologies, including electrolysers, fuel cells, and storage caverns, are favoured in many scenarios. In reality, developing a national hydrogen infrastructure involves substantial technical challenges, including transmission losses, spatial constraints, and compression needs. The ease with which hydrogen is used in the model should therefore be interpreted with caution.

Another technical concern lies in the use of emerging technologies such as Small Modular Reactors (SMRs) and rebuilt Bioenergy with Carbon Capture and Storage (BECCS). While SMRs are consistently selected over conventional nuclear power in the SPORES runs due to their assumed cost, these reactors have yet to be implemented at a commercial scale. Their cost and performance characteristics remain speculative, meaning their dominance in the model may not reflect realistic feasibility. BECCS, although not selected in cost-optimal runs, appears regularly in near-optimal SPORES outcomes as a promising technology. Its competitiveness could improve if the model were to include negative emissions accounting, which would allow BECCS plants to generate revenue through carbon removal.

The last important technical limitation is the structure of the solution space in which the model operates. Because the model optimises strictly for cost, and the available technology options are predefined, technologies with slightly higher costs but otherwise comparable characteristics are typically excluded from the results. For example, flow-ion batteries or OCGT hydrogen turbines are rarely selected, despite offering potential advantages in terms of system resilience or operational flexibility. In principle, this is a valid consequence of cost-based optimisation. However, in practice, other factors, such as spatial integration, redundancy, or risk diversification, may justify the inclusion of such technologies in the system design.

6.2.2. Financial implications

The financial implications of the model highlight several challenges related to cost representation and economic feasibility. One of the most significant issues is the overall cost magnitude. The model estimates system-wide energy costs that are roughly ten times higher than those of the current Dutch electricity system, which operates in the range of tens of billions of euros annually. Similarly, the shadow prices generated by the model are consistently overestimated, often by a factor of ten. While these prices function as relative signals within the optimisation process and thus do not affect internal consistency, they complicate any comparison with other model runs or real-world cost estimates. For this reason, economic analyses were intentionally excluded from the results section because these values would misrepresent the economic viability of the proposed system.

It should also be noted that even if cost outputs were more accurate, drawing firm economic conclusions would remain difficult due to the long time horizon of the model. Projecting costs for 2050 necessarily involves major uncertainty in technology prices, market structures, and policy frameworks.

A further financial simplification concerns energy import and export for hydrogen and electricity. In the model, hydrogen can be imported and exported at a fixed price, while national hydrogen transport is assumed to be entirely costless and lossless. This significantly lowers the economic barrier for hydrogen deployment. Additionally, equal import and export prices do not reflect real-world trade asymmetries, such as supply constraints or market volatility.

The same applies to electricity: imports and exports occur at a constant, equal price. This removes the incentive for the model to export electricity strategically, leading to a system that prioritises self-sufficiency even when exporting surplus might be economically desirable. In reality, electricity prices are dynamic and dependent on location. This model does not take that into account.

6.2.3. Regulatory implications

The model assumes that grid and generation capacity can expand where needed, but it does not account for the real-world regulatory processes required to enable this growth. In practice, large-scale grid expansion demands early planning, long permitting procedures, and major upfront investments. TenneT is already anticipating these challenges by purchasing land for future substations and corridors, acknowledging that physical and legal preparations must begin well before infrastructure is built.

Similarly, the assumed expansion of onshore wind and solar PV capacity overlooks the complex reality of permitting, land-use competition, and ecological constraints. Reaching the modelled maximums for these technologies will require not only space but also regulatory approvals and local support. For example, ecological regulations increasingly restrict wind turbine development due to impacts on bird migration and habitat, while solar PV competes with agriculture and open landscape preservation.

In short, even if the modelled system is technically achievable by 2050, its realisation depends on immediate regulatory action, from spatial reservations and ecological assessments to long-term permitting frameworks, to ensure the necessary infrastructure can actually be built in time.

6.2.4. Social implications

While the model explores technically and economically feasible system configurations, it does not fully capture the social dynamics that influence real-world implementation. A key challenge is the public acceptance of energy infrastructure, especially the expansion of onshore wind and solar PV. These technologies often face resistance due to perceived impacts on landscape, noise, or space use, particularly when developments are planned near residential areas. This “not-in-my-backyard” sentiment can delay or block projects, regardless of their system-level benefits.

Similarly, the inclusion of Small Modular Reactors (SMRs) as a frequently selected option in the model brings up questions of societal acceptance. Although SMRs are more compact than traditional nuclear plants, nuclear energy in general remains a politically sensitive topic in the Netherlands. Safety concerns and waste storage still shape public opinion and could affect the speed or scale of deployment.

6.3. Recommendations

Based on this research, certain recommendations can be addressed. These recommendations are about the future use of this model and its usability for TenneT.

Based on the outcomes of this research, the developed model presents clear value as a strategic tool for future system planning. Its ability to quickly generate plausible 2050 electricity system configurations makes it well-suited for early-stage exploration of technology choices, policy-driven scenarios, and investment strategies. The model can be used as a first-step modelling instrument, allowing TenneT to rapidly assess the impact of including or excluding specific technologies, evaluating the importance of current infrastructure, or testing assumptions under cost or policy constraints. These exploratory results can then inform more detailed modelling tools used later in the planning process.

Given its fast runtime and transparent structure, the model can be used for scenario development to pre-screen promising directions. This helps reduce the computational modelling difficulties which are present on more complex tools. Output formats such as dispatch graphs, capacity maps, and network flows are straightforward to interpret, making the results accessible to both technical and non-technical stakeholders.

The use of human-readable YAML files further supports a steep learning curve for new users. Once the base model is set up, it is relatively simple to adapt input data, update parameters, or add and remove technologies. This allows TenneT to tailor the model to its own datasets and assumptions. This adaptability makes it particularly valuable in a policy and technology environment that is constantly evolving.

In short, this model should be seen as a lightweight but powerful tool to guide scenario thinking, support internal discussions, and direct attention to system-level trade-offs.

6.4. Future research

This research has shown that using the MGA method, and specifically SPORES, provides a powerful way to explore future energy system configurations. It allows for the identification of promising technologies, transmission bottlenecks, and their spatial implications within a near-optimal solution space. However, there are still important areas for future research that could refine the outcomes or address uncertainties not yet fully captured in this model.

An important opportunity for future research is the hydrogen network. The hydrogen network is simplified: transport is costless and lossless, and import prices for green hydrogen are static. Adding realistic hydrogen transmission costs and varying import prices, based on global supply, would offer a more accurate picture of the role hydrogen can play in the system. This could also affect the current high utilisation of hydrogen storage in salt caverns, which may become less attractive under more realistic assumptions.

To further explore uncertainties and alternative futures, future research could expand the number of scenarios generated through SPORES or adopt the more recent MGCA (Modelling to Generate Continuous Alternatives) method. MGCA is a post-processing technique that enables the fast creation of new, diverse system configurations based on an existing set of MGA outputs. This would allow for even deeper exploration of system trade-offs without increasing model runtime.

Additionally, adding simplified electricity demand profiles for neighbouring countries could make the international dimension of the model more realistic. While full representation would be computationally intensive, even a basic approximation could capture the influence of cross-border demand on Dutch system design, import behaviour, and regional balancing strategies.

Finally, not all questions raised during the expert interviews were addressed in the SPORES modelling. These include important topics such as the role of blue hydrogen in the 2050 network, cost-sharing for offshore infrastructure, regional grid structures, public acceptance pathways, incremental planning approaches, and the role of circularity in system design. These questions, listed in full in appendix B, offer valuable directions for future research and scenario development.

6.4.1. Practice

To ensure this research can be used effectively within the company, several process recommendations should be made when continuing with this model or working with similar models in the future. In this paragraph, recommendations are given based on the process of this thesis.

Run time

The runtime for the base model results is approximately 15–20 minutes on a regular laptop, though this varies depending on the computational power of the device used. While it is difficult to provide a precise estimate applicable to all computers, there are ways to improve model efficiency.

Firstly, the model imports timestamps from multiple datasets, such as wind or solar generation profiles. These datasets often include several years of data combined into a single file. While this is valuable for testing the model against different weather years, it increases runtime when only a single year is required. To improve efficiency, consider preprocessing these datasets to include only the necessary year before running the model. For SPORES runs, most computational time is spent generating multiple alternative solutions. This runtime can be reduced by selecting shorter time horizons. If the model needs to be run for initial testing, this can be done with lower temporal resolution if high-resolution outputs are not required.

Import and Export pricing

One key limitation is the simplification of import and export behaviour. In the current model, import and export prices for electricity are fixed and equal, meaning there is no price signal to use international trade strategically. As a result, the model treats electricity imports more as a baseload solution during low-renewable periods, rather than leveraging imports and exports for system balancing. If time-varying import/export prices were introduced, the real-world market behaviour would be better reflected and highlight the economic value of cross-border flexibility.

Documentation

Maintaining clear and accessible documentation is essential when working with models like SPORES. Since SPORES generates a large number of different scenarios, clear documentation is needed to keep track of all results. This involves systematically mapping and naming each scenario and its corresponding output, ensuring that both the modeller and anyone who works with the results later can easily understand and interpret them. The mapping for this model is explained in the next sections.

6.5. Implementation

Implementing this model enables the company to run a first set of results in order to explore the solution space of the 2050 energy network. By using the weighted SPORES method to explore specific issues, questions concerning the feasibility of certain technologies can be answered quickly. The model is well suited for creating and exploring a first version of a scenario that is interesting to be researched in depth.

This section provides a practical guideline for implementing the model developed in this research. It is intended to support future users in running, adapting, and extending the model to evaluate different scenarios and near-optimal solutions for the Dutch electricity network.

Purpose

The developed model determines spatial configurations of generation and storage capacities that are feasible within defined policy and technical constraints. It combines a Calliope-based optimisation with SPORES post-processing to explore flexibility in spatial planning.

Prerequisites

To run the model, the following software and resources are required:

- **Python** version $\geq$ 3.12
- **Calliope** version $\geq$ 0.7.0dev6
- **Gurobi Optimizer** with an active license
- Input data files (YAML and CSV) structured in the `model_files/`folder
- Sufficient computing resources for scenario runs

Step 1 - Set up the environment

The first step is to clone the repository to the desired directory. The repository contains all files needed to run the model. It also contains the results of the model runs and the code to plot all techs. All dependencies that need to be downloaded can be found in the ”environment.yml” file and are installed by running the following code in the same directory:

```
conda env create -f environment.yml
```

Step 2 - Prepare input data

If needed, the technology data can be altered based on the company's own datasets or newer data. The input data can be changed in the yaml-files found in the `tech_and_locs` folder. The time datasets can be found in the `timeseries` folder. Custom mathematical constraints are found in the `custom_math` folder. In here are the restrictions on nuclear, SMR, import/export, and SPORES slack setup. The setup for the model run itself (model resolution, time subset, weather data, demand profiles) can be altered in the "model-2050.yaml" file in the `model_files` folder.

Step 3 - Run the base optimisation

To run the base model, the jupyter notebook model_run_year.ipynb can be used, which is found in the main folder Calliope-nl-2050. This file contains everything needed to run the model for a year and shows some typical uses for the model with installed capacity and generation of technologies as well as visual results of the outcomes. The visual representations are imported from the plotting_utilities.py file.

Step 4 - Scenario definitions for SPORES

The scenarios you want to run as well as the preferred slack for the SPORES can be selected and altered in the spores.yaml file, found in the `scenarios` folder. This file specifies the overrides needed for SPORES mode and intensified (min or max) SPORES-runs. You can select all the techs you want to include in the SPORES runs.

Step 5 - Run SPORES or intensified SPORES

In order to run the regular SPORES, a Jupyter Notebook is presented in which the model can be run. This notebook is called "exploring_design_options.ipynb". This file is found in the main folder Calliope-nl-2050.

For all intensified SPORES, separate notebooks were made. These are also in the main folder under the name SPORES_... plus the intensified technology added. For example, with SMR this file name is "SPORES_SMR.ipynb". Running these Jupyter Notebooks will give you a results file, where you can extract all the information you want with your own python code, but the file also has capacity plots for all SPORES that are run.

Step 6 - Analyse results

All outputs from the model runs can be found in the `results` folder. This folder has a separate map for the SPORES results. The SPORES are structured by timestamp and intensified technology. You can import the results in a .ipynb file with:

```
results = calliope.read_netcdf("model_files/results/....nc")
```

As is done in the "model_results.ipynb" file. You can also create your own file to examine the results or create your own plots. The abovementioned file contains the code for making the scatterplot and code to export the data to .csv files. A large Excel file contains the results of all runs done for this research and contains all graphs used for the research that were not made in python.

Confidentiality note

This model and its implementation scripts are proprietary to TenneT and may include sensitive assumptions or input data. They are not publicly available. Future users should ensure compliance with internal data governance policies when adapting or extending the model.

7
Conclusion

With the model results presented in the previous chapter, the research questions outlined in the introduction can now be addressed. This chapter provides answers to those questions, forming the basis for the main conclusions of the study. The subsequent chapter will reflect on the project by discussing its limitations, implications, and recommendations for future research.

7.0.1. Main research question

This research aims to model and explore the future energy network of the Netherlands in 2050 by using Modelling to Generate Alternatives. To answer this question, the modelling approach was used in combination with a set of interviews. The research tries to achieve this goal by answering the following research question:

"How can MGA be used to create and explore near-optimal solutions for the future Dutch electricity network without large computational modelling challenges?"

In order to answer this main research question, several sub-questions were developed. In the following paragraphs we will answer these subquestions and eventually answer the main research question.

What are relevant preferences to map out wiht Energy System Optimisation Modelling?

This question was answered using two research methods: desk research and interviews. Desk research was done to get a deeper understanding of what the system should look like, what technologies are currently being used and what technologies might be used in the future. In order to get more detailed information on the current status of these technologies, the feasibility of government plans and the key aspects this research should focus on, interviews were conducted with professionals from the energy sector. The outcomes of the desk research show that hydrogen is expected to play a key role in decarbonising the industry sector and enabling long-term storage for the future energy grid. The energy transition will be accomplished with high electrification of the grid, which emphasises the importance of flexibility in the system through storage technologies and demand management. A relatively new technology which has potential for future implementation is the Small Modular Reactor, which is motivated by its flexible baseload of power and spatial advantages. The energy demand of 2050 is expected to decrease over the years due to increasing efficiencies, but the total electricity demand will rise up, calling for a robust electricity network.
From the interview we have gotten similar results, except more scepticism was found in their answers. All professionals believe in a highly interconnected electricity network for western Europe. A challenge for the future network lies in the industry. Some experts conclude that a selection of important industries should be made. Another interviewee suggested a Europe-wide industry plan, where the high-energy-consuming industries would be relocated to countries or locations within Europe with a higher sustainable energy supply. Sector coupling will be of high importance in the future network, and

although decentralised technologies are increasing, there will always be a demand for central dispatchable power. We found out that the planned amount of offshore wind is very optimistic and might not be the most cost-effective route. Also, there are mixed opinions about the SMR technology. In theory this is a cheaper, easier method to create dispatchable power compared to conventional nuclear plants. But, because SMRs are not yet built on a large scale, it is difficult to prove the theoretical advantages.

”How to align TenneT data with the optimisation modelling program Calliope?”

This question was answered by gathering data provided by TenneT. This data consisted of previous energy system models that were created by TenneT and data from the II3050. We know from subquestion one what type of data we want to collect, and with information from TenneT, the right datasets were selected. To ensure relevance for TenneT’s Target Grid project, this model adopts the same starting point: the National Leadership scenario from the II3050 framework. This gives us the same demand data for the model, where the optimisation will be based. Specific technology data was gathered from the Danish Energy Agency [1], as well as a study from the government [65], which are the same sources used in the report on the 2035 climate-neutral model that was co-created by a TenneT employee [8]. The other inputs, like transmission network and line expansions, were discussed within TenneT to create a well-aligned model. Throughout the model development, bi-weekly meetings were held to ensure alignment with TenneT’s requirements

This data was then implemented in the Calliope model, and the model results were compared with the II3050 numbers. The specifics on model results were already discussed in the previous chapter.

”What type of MGA is appropriate for the preferences for modelling the Dutch energy system?”

One of the main requests for this model was to keep the model computationally easy to run. The combination of the literature review and the interviews with the professionals revealed that the MGA method SPORES was best suited for this type of research. The literature showed that SPORES is very useful when you want to explore alternatives to our cost-optimal solution without having to deal with an endless amount of alternatives. The spores method allows for both searching for alternatives with cost relaxation as well as aimed searches to answer specific questions for the model. With the random scoring method to assign weights, the diversity of explored solutions is maximised without introducing systematic biases towards or against specific technologies or locations. The high customisability by applying secondary objectives allows tweaking the search towards either spatial or technological dissimilarity. In this report SPORES was used for the latter. SPORES also limits the amount of redundant computation by guided searching. After the interview, we were left with a collection of questions we want answered using MGA. These questions were mainly focused on the feasibility of certain technologies. SPORES is the fitting method to test this. By adding sporesscores to the technologies of interest, we could see what impact this technology would have on the system while staying within a 20% surplus cost margin of the total system costs.

”How do we explore the alternatives without large computational difficulties?”

We have already established that the SPORES method is used for exploring alternatives in the last paragraph. This question will be answered by explaining exactly how the SPORES method is used to explore our model and answer the questions that arose from the interview.
We start with the exploration of the cost-optimal solution. Based on our model we found a working composition of several technologies dispatched to several locations in the Netherlands. Since the model is based on cost optimisation, it initially produces a single optimal solution. However, as discussed in the literature, allowing for additional solution space enables the model to reveal alternative configurations that would otherwise remain excluded. By adding a so-called slack of 20% to the model, it allows for the model to optimise again with a total cost of 120% of the original optimisation. Of course, running several alternatives at once demands extra run power, increasing the computational stress on the model. In order to keep these difficulties at a minimum, the SPORE runs for the year 2050 were strategically split into two timesets representing the full year run. These these timeset were periods of three months, during April-June and September-October. The period represents both a period with a lot of solar and little wind as well as the other way around. It also represents a period with relatively low

demand and a period with relatively high demand. If we look at the result from these SPORES, we can give an estimate on how the network will look as if you were modelling for the whole year. For the two time periods, 10 SPORES were generated each. This resulted in a total of 20 SPORES for the base model, which gave enough result variation to be able to draw conclusions on the system.
As previously mentioned, SPORES was also applied to explore the questions that emerged from the interviews. In order to do guided searches to answer our question on the model, SPORES were used in a different way. For this case not only were alternatives run with a slack of 20% (or lower in some cases), but for these SPORES an additional weight was added to specific technologies of interest. For example, when looking at nuclear plants. When these SPORES were made, an additional spores score of 1000 was added to this technology, favouring it above the other technologies. This can be seen as an incentive for the model to install more capacity of nuclear while still keeping within the 120% total cost limit of the cost-optimal solution. Although the initial value of the spores score was set at 1000, this value was reduced when the answers of SPORES were not diverse enough, which was done for SMR. For the SPORES runs based on the interview questions, the same two time periods were used as in the base case SPORES runs. The difference for these runs is that per season, 5 different SPORES were run. This is because the high incentive pushes one technology, resulting in a smaller solution space for the other technologies. With 5 SPORE runs, enough results were collected to form a conclusion. Also, fewer runs mean a shorter running time, reducing computational difficulties.

"How do we make usable results from MGA alternatives?"

In order to present the result as well as possible, we have to look at the model runs we described while answering the previous subquestion. Also, these results depend on the focus points of interest for this model. Starting with the base model, we want to see the locations and compositions of the installed capacity of different technologies. This can best be presented with tables showing the amount of installed capacities per node. In order to see the transmission lines and their corresponding capacities, a map was plotted where the thickness of the line corresponds to the installed capacity. Focussing more on the large amount of alternatives created with MGA, these results were presented in the form of scatter plots. This allows for comparison of different runs in one figure. These scatter plots were mostly made for technology capacity comparison, but in some cases they were also used for comparison of transmission capacities.

Combining the answers to all these sub-questions allows us to answer the main research question.

How can MGA be used to create and explore near-optimal solutions for the Dutch electricity network without large computational modelling challenges?

This research successfully used energy system optimisation modelling in combination with the energy system modelling framework Calliope to create an energy system model of the Netherlands with several nodes, connecting the Dutch provinces and neighbouring countries with each other. It provides not only a result for the amount of capacity needed for the energy system but also the locations where these capacities should be installed. Furthermore, it gives a possible cost-effective plan on the expansion locations of the powerlines in the Netherlands.

The cost-optimal solution in combination with the MGA tool SPORES enabled us to create a variety of near-optimal solutions of what the future carbon-neutral energy system will look like. The model integrates policy goals with professional opinions and uses both as an input to the model, creating a critical view on the current plants and their feasibility.

The findings highlight the importance of certain technologies and also show the potential of others. This model allows for structured and guided searches within a cost-optimal solution without having to deal with large computational difficulties.

Overall, this study provides a solid model that can be used for exploratory research of the future electricity grid of the Netherlands in 2050.

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A

Literature overview

The table below gives an overview of the sources used for the literature review.

Table A.1: Overview of the sources

Source	Title	About
Lombardi et al. (2023) [42]	What is redundant and what is not? Computational trade-offs in modelling to generate alternatives for energy infrastructure deployment	Minimise redundant computation with the SPORES method.
Dubois et al. (2023) [19]	Multi-objective near-optimal necessary conditions for multi-sectoral planning	MGA with multiple objectives.
Pedersen et al. (2021) [58]	Modeling all alternative solutions for highly renewable energy systems	Unlike traditional MGA methods that generate a few alternatives, this approach seeks to determine the entire continuum of near-optimal solutions.
Neumann et al. (2021) [56]	The near-optimal feasible space of a renewable power system model	valuable MGA for policymakers because it reveals investment flexibility and essential infrastructure choices in a cost-efficient renewable energy system.
Lau et al. (2024) [38]	Measuring exploration: evaluation of Modelling to Generate Alternatives methods in capacity expansion models	Tests four different MGA methodologies and proposes a new combination vector approach.
Schwaeppe et al. (2024) [68]	Finding better alternatives: Shadow prices of near-optimal solutions in energy system optimization modeling	The near-optimal solutions space is further explored by looking at the shadow prices of the alternatives.
Vågerö et al. (2025) [77]	Exploring near-optimal energy systems with stakeholders: a novel approach for participatory modelling	MGA with the input of stakeholders. Allows stakeholders to use the MGA alternatives to make informed decisions.

Continued on next page

Table A.1 – continued from previous page		
Source	**Title**	**About**
Van Greevenbroek et al. (2023) [30]	Enabling agency: trade-offs between regional and integrated energy systems design flexibility	Illuminates trade-offs and interactions between national and continental energy transitions under uncertainty with MGA.
Grochowicz et al. (2023) [31]	Intersecting near-optimal spaces: European power systems with more resilience to weather variability	MGA method that uses a geometric approach to identify robust solutions.
Zhang et al. (2025) [83]	Exploring resilient alternatives in community energy systems planning to address parameter and structural hybrid uncertainties	Modelling to Generate Resilience: With this method, the resilience of the results stays higher than with traditional MGA.
Finke et al. (2024) [24]	Modelling to generate near-Pareto-optimal alternatives (MGPA) for the municipal energy transition	This approach tackles explicit, easy-to-formulate objectives first before exploring a spectrum of alternatives within a region of interest in a second step.
Lau et al. (2024) [39]	Modelling to Generate Continuous Alternatives: Enabling Real-Time Feasible Portfolio Generation on Convex Planning Models	Post-processing algorithm that lets you explore and generate MGA results in a matter of seconds.

B
Interview guide

In this appendix, first the interview questions will be presented. The second paragraph shows the informed consent form, and lastly, the resulting questions not used in the report are discussed.

B.1. Interview questions

Introduction

In the coming 60 minutes I will be conducting an interview with you. During this time, I will try to find out interesting scenarios that need to be considered when looking at the future electricity network of the Netherlands in 2050. Although the questions will be asked one after the other, there are two main departure points. The first one is the II3050 scenario, and the second one is the Target Grid scenario. The goal is not to only find out what your opinion is about these scenarios but more to get creative answers that provide a new insight into the scenarios. Eventually this input will be the base of one or more scenarios that will be modelled in an energy system optimisation model of the Netherlands.

General information

- Date
- Time
- Location
- Function
- Purpose of interview
- Topic

Introductory questions

1. Can I audio record this interview?
2. What is your function within TenneT?
3. How are you involved in the future energy scenarios of the Dutch electricity grid?

II3050 scenarios for the future energy grid

1. Are you familiar with the II3050 scenarios? (If not, explain briefly)
   (a) How realistic do you think the current II3050 scenarios are?
   (b) What scenario do you see as most viable for 2050?
   (c) What scenario do you see as least viable for 2050?
2. Are there any blind spots in the current scenario discussions that should be explored further?

   (a) What if we would want to go for minimal generation of energy instead of the national targets?
   (b) What if we would want a maximal preservation of Dutch industries?
3. In terms of these scenarios, what do you see as the most important focus point for the selection of the scenarios? (e.g., national vs. European, (De)central, Import/export, market vs government, etc.)
   (a) What role will sector coupling (e.g., electricity–hydrogen–industry–heat) play in future scenarios?
   (b) How should we balance centralized vs. decentralized energy generation in future models?
   (c) How critical is flexibility and storage, and what technologies should we prioritize in scenario design?
   (d) What is the order of importance when looking at these criteria?

Target grid scenarios for the future energy grid

4. What do you think of the current scenario for Target Grid?
   (a) What is possible when diverting from maximal electrification?
5. How do you see the future electricity network take form for 2050?
   (a) Focusing on industries?
   (b) Focusing on reliability?
   (c) Focusing on self-sufficiency?
6. What do you see as the biggest challenges and opportunities in achieving a climate-neutral electricity network by 2050?
   (a) What do you see as the biggest infrastructure bottlenecks that need to be addressed to support a climate-neutral electricity system?
7. What are the most important drivers of change to be included in the future scenarios? (e.g., technology, policy, economics, social behavior)
8. How should the role of TSOs evolve to accommodate increasing decentralization (e.g., prosumers, microgrids)?

Free scenario building outside of existing scenarios

9. What do you see as an interesting part of a scenario to be taken into account when doing optimization modelling?
10. If you had to choose one or two priority scenarios for detailed modeling, which ones would you pick and why?

B.2. Informed consent

You are being invited to participate in a research study titled *From Complexity to Clarity: Generating Near-Optimal Scenarios for the Dutch Electricity Network using MGA*. This study is being done by Wouter van der Veen as part of his graduation thesis for the master's in Complex System Engineering and Management from TU Delft in collaboration with TenneT NL as the internship provider.

The purpose of this research study is to find what are interesting future scenarios to implement in a cost optimal model that models the future energy grid of the Netherlands in 2050. This interview aims to go beyond the four scenarios discussed in II3050 and asks for a professional opinion on the topic. The interview will take you approximately 60 minutes to complete. The data will be used for creating new or other scenarios interesting for TenneT to be included in the optimisation modelling. Part of the data will thus also be published in the final thesis paper. We will be asking you to answer a few questions about your background in the field of energy scenarios, your vision on the scenarios from II3050, and your input for drawing up new scenarios that you might think are relevant.

Taking part in this study also involves collecting specific personally identifiable information (PII), e.g. name and email address, and associated personally identifiable research data (PIRD) e.g. job function, with the potential risk of your identity being revealed. Although these are anonymised, there is always a possibility of reidentification. Data that is considered sensitive data within GDPR legislation, e.g., religion or political views, will be left out of the documentation.

As with any data-collecting activity, the risk of a breach is always possible. To the best of my ability, your answers in this study will remain confidential. We will minimise any risks by only storing the data on the TU Delft institutional storage platform. The data will only be accessed by the TU Delft research team. All personal data gathered from this interview will be deleted after one month after completion of this thesis.

Furthermore, the interview discussion will be summarised, anonymised, and shared with you. If you have any comments, you can share them, and adjustments can be made. After this, the summarised file will be shared with TenneT and used for the thesis report. The de-identified interview summaries will be archived in the TU Delft repository so they can be used for future research and learning.

For the sake of both our health, the interview will be postponed or held online if either of us is feeling unwell.

Your participation in this study is entirely voluntary, and you can withdraw at any time. You are free to omit any questions. If you wish to remove any data after the interview, this can be done within 2 weeks after an interview summary has been shared with you. The interview will be recorded and transcribed.

My contact details are:

- Name: Wouter van der Veen

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
1. Despite our best efforts, your answers might be identified by your colleagues, do you agree with that?	☐	☐
RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
2. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐

I have read and understood the study information above, and I consent to participate in the study and to the data processing described above.

Signatures

Name of participant | Signature | Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher name | Signature | Date

[redacted]

B.3. results from the interview questions

As was mentioned in the results chapter, not all questions that were derived from the interview were used for this research. This section lists the questions that professionals from the field would like to be answered.

- Is incremental modelling an option? (steps of 5 years)
- How to divide the costs between European countries for laying out the network for wind at sea?
- What if the future network involves a lot more locally generated energy? (regional grid with interconnecting lines between these 'hubs')
- What will the network look like when we choose the route with the least public resistance?
- In what way can circularity be a part of the 2050 network (reuse, life extension)?
- Will the 2050 network still rely on blue hydrogen?

C
Results output table base model

Technology	Carrier	NL11	NL12	NL13	NL21	NL22	NL23	NL31	NL32	NL33	NL34	NL41	NL42
CAES	Power	0	0	0	0	0	0	0	0	0	0	0	0
SMR	Power	0.001	0.001	0.001	0.002	0.005	0.002	2.965	0.006	0.012	0.001	0.002	0.001
electrolyser	Power	8.123	2.708	1.625	0.075	0.003	0.633	0.003	1.43	0.003	2.797	0.005	0.046
flow_ion_battery	Power	0	0	0	0	0	0	0	0	0	0	0	0
hydro	Power	0	0	0	0	0.01	0	0.002	0	0.014	0	0	0.011
hydro_ccgt_new	Power	0	0	0	0	0	0	0	0	0	0	0	0
hydro_ccgt_rebuilt	Power	1.834	0	0	0	0	0	0	1.15	0.853	0.715	0.457	0.681
hydrogen_fuel_cell	Power	0.032	0.098	0.055	1.302	3.728	0.932	2.998	8.579	10.432	0.032	0.066	0.03
li_ion_battery	Power	1.933	1.919	0.255	1.91	3.894	0.632	0.174	5.362	0.103	0.899	0.709	1.123
solar_pv	Power	8.538	11.684	9.197	11.911	14.949	5.152	5.525	9.528	9.822	5.95	17.988	7.756
wind_offshore_AC	Power	1.3	0	0	0	0	0	0	3.078	5.54	2.752	0	0
wind_offshore_DC	Power	17.026	0	0	0	0	0	0	24	2	0	2	0
wind_onshore	Power	1.699	3.292	1.547	1.798	2.163	1.406	0.766	2.162	1.69	1.613	2.573	1.09
hydrogen_cavern	hydrogen	7.268	3.828	4.735	0	0	0	0	8.33	3.68	0	0	0
hydro_ocgt_new	Power	0	0	0	0	0	0	0	0	0	0	0	0
hydro_ocgt_rebuilt	Power	0	0	0	0	0	0	0	0	0	0	0	0
lost_load	Power	0	0	0	0	0	0	0	0	0	0	0	0
nuclear	Power	0	0	0	0	0	0	0	0	0	0.5	0	0
Total installed cap		**47.75**	**23.53**	**17.42**	**17.00**	**24.75**	**8.76**	**12.43**	**63.63**	**34.15**	**15.26**	**23.80**	**10.74**

Table C.1: Installed capacities per province

D

Input calculations energy model

In this appendix the calculation done in order to find the capacity boundaries for several technologies is presented. Starting with the solar and wind plants, afterwards, the province division of demand.

D.1. Wind on land and Solar PV

First, the preconditions of the calculations are presented

solar pv
natura 2000 area excluded
density = 5.1MW/km2
70-30% AC/DC ratio
max potential = 110 GW
wind_land
natura 2000 area excluded
density = 10MW/km2
max 10% areal use
max potential = 21.8 GW
not in built environment

(a) Preconditions for calculations of available space

	total area	water	land	natura 2000 total	natura 2000 land
Groningen	2960	644	2316	23	23
Drenthe	2680	-	2680	210	210
Friesland	5753	2413	3340	5502	202
Overijssel	3421	-	3421	222	222
Noord-Brabant	5081	-	5081	350	250
Limburg	2209	-	2209	126	126
Utrecht	1560	-	1560	76	76
Flevoland	2412	1000	1412	828.33	28.33
Noord-Holland	4092	1429	2663	104	104
Zuid-Holland	3404	703	2700	452	62
Zeeland	2934	1154	1780	219	182
Gelderland	5137	-	5137	1122	1122

(b) Available area per province

Figure D.1: Overview of spatial assumptions for solar and wind siting

For the amount of solar PV on land the calculation were based on the preconditions described above. The Natura 2000 areas per province were substracted from the total land area of this province. This total area was then multiplied by the preconditions of 5.1 MW/km2. Since the results of this calculation were a bit overestimated, the results were corrected to have a combined max capacity of 118 MW, which is within the range of the projections of Netbeheer Nederland.

For the wind capacity on land, we did a similar thing. We multiplied the available area on land with the the precondition of 10 MW/km2 . This resulted in a total of available wind turbine capacity per province. For wind on land we experienced an overestimation as well and we corrected the outcomed to match the 21.8 GW, which is the theoretical maximum according to a study from CE Delft [8].

Solar pv on land		
solarpv.max per provinc	original MW	corrected for 110max MW
Groningen	11694.3	8537.700916
Drenthe	12597	9196.738449
Friesland	16003.8	11683.95354
Overijssel	16314.9	11911.07947
Noord-Brabant	24638.1	17987.62893
Limburg	10623.3	7755.791979
Utrecht	7568.4	5525.489821
Flevoland	7056.717	5151.923518
Noord-Holland	13050.9	9528.118903
Zuid-Holland	13453.8	9822.265598
Zeeland	8149.8	5949.954673
Gelderland	20476.5	14949.3542
sum	161627.517	118000

Figure D.2: Total allowed installed capacity solar PV

wind.max per province	original MW	corrected for 21.8max MW
Groningen	2770	1698.90
Drenthe	2522.87	1547.33
Friesland	5366.77	3291.55
Overijssel	2932.01	1798.26
Noord-Brabant	4194.72	2572.71
Limburg	1777.45	1090.15
Utrecht	1249.35	766.25
Flevoland	2293	1406.34
Noord-Holland	3524.78	2161.82
Zuid-Holland	2755.46	1689.98
Zeeland	2630.35	1613.25
Gelderland	3527.5	2163.49
sum	35544.26	21800

Figure D.3: Allowed installed capacity wind on land

Describe all data drawn from the excel you made, weather/ccgt/space/demand per province

D.2. Wind offshore

The wind offshore has two different technology types for this model. The first one being wind offshore AC and the other one being wind offshore DC. The data of current and planned parks in the North Sea were taken from the site of the Dutch government [57]. The parks can be seen in the image below. There is a rough estimated line between DC turbines and AC turbines. This division was checked by a professional is detailed enough for the goals of this research.

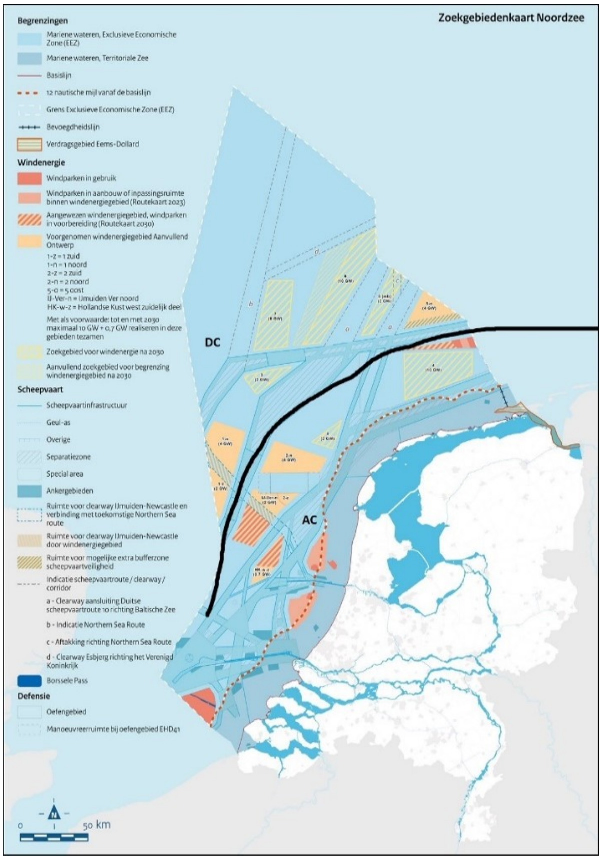


Figure D.4: Division between AC windparks and DC windparks

D.3. Demand 2050

In the methodology, it was already explained that the demand was based on the GDP of 2023, since this was the most recent accurate dataset to be found. In order to show how this was done, two figures have been added below. The first one shows the shares per province translated into percentages. the second image shows the multiplication of these percentages with the total demand. This will give you the demand per node of the Dutch energy system.

Province	GDP (€ million)	Percentage of National GDP
Groningen	32,566	3.40%
Fryslân	25,490	2.70%
Drenthe	18,434	1.90%
Overijssel	53,172	5.50%
Flevoland	17,303	1.80%
Gelderland	95,416	9.90%
Utrecht	88,660	9.30%
Noord-Holland	203,766	21.30%
Zuid-Holland	200,451	20.90%
Zeeland	17,839	1.90%
Noord-Brabant	143,315	14.90%
Limburg	54,104	5.60%
Total	**950,516**	**100%**

Figure D.5: Total GDP divided over 12 Dutch provinces

	Demand	**percentage**
Groningen (PV)	32,566	0.034261
Fryslân (PV)	25,490	0.026817
Drenthe (PV)	18,434	0.019394
Overijssel (PV)	53,172	0.055940
Flevoland (PV)	17,303	0.018204
Gelderland (PV)	95,416	0.100383
Utrecht (PV)	88,660	0.093276
Noord-Holland (PV)	203,766	0.214374
Zuid-Holland (PV)	200,451	0.210887
Zeeland (PV)	17,839	0.018768
Noord-Brabant (PV)	143,315	0.150776
Limburg	54,104	0.056921
The Netherlands	958,549	

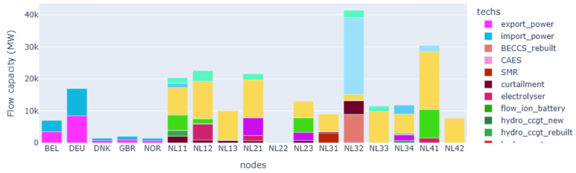
Figure D.6: Total demand per province based on percentual share

E

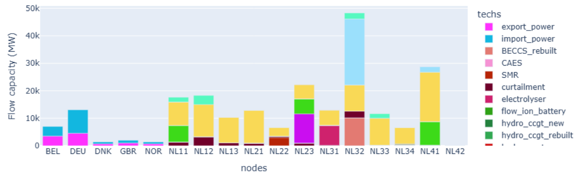
Output plots basecase SPORES model

In this appendix all plots from the basecase SPORES not used in the main text are shown to view as additional results.

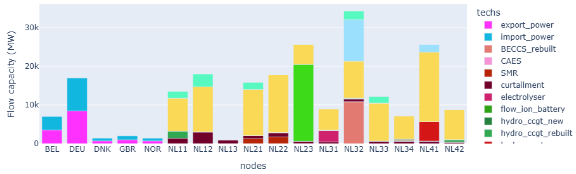
E.1. Base case capacity plots



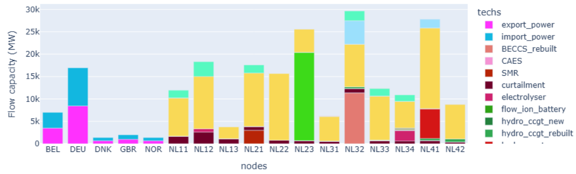
(a) April - June spore 1



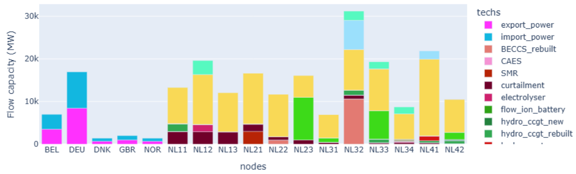
(b) April-June spore 2



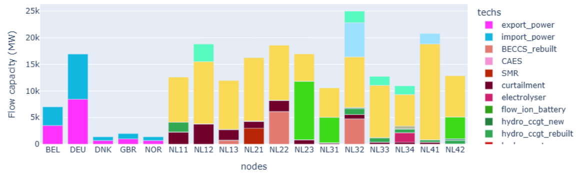
(c) April-June spore 3



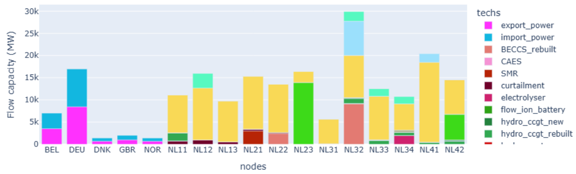
(d) April-June spore 4



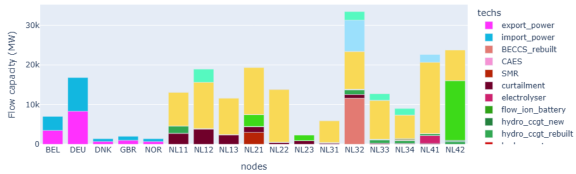
(e) April-June spore 5



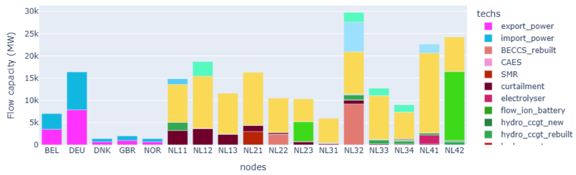
(f) April-June spore 6



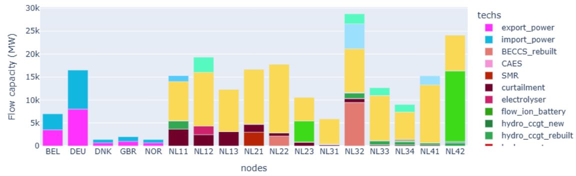
(g) April-June spore 7



(h) April-June spore 8

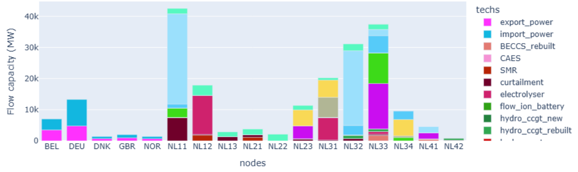


(i) April-June spore 9

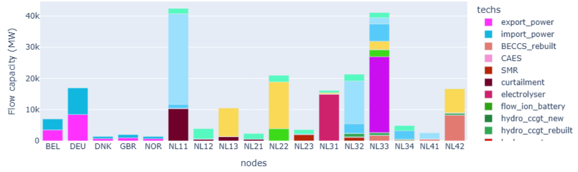


(j) April-June spore 10

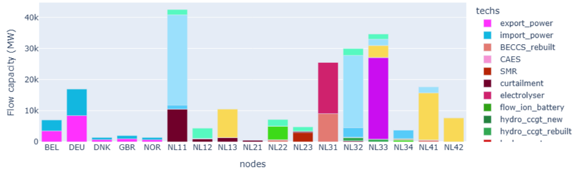
Figure E.1: Different SPORES with of the base case in April-June



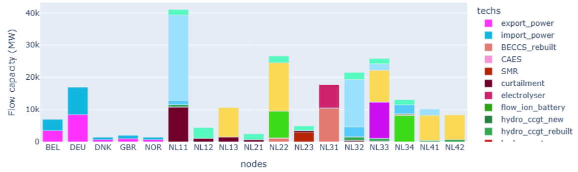
(a) September - November spore 1



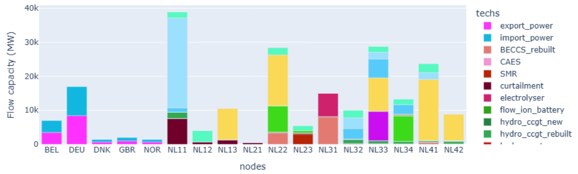
(b) September - November spore 2



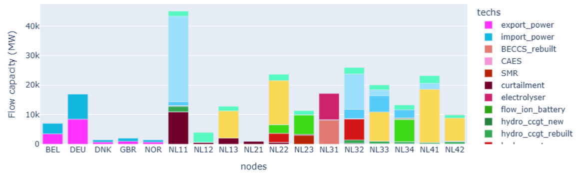
(c) September - November spore 3



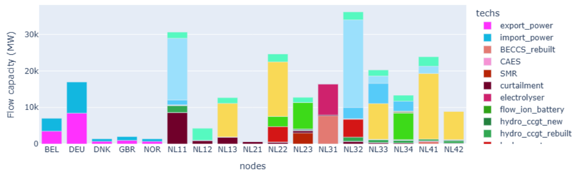
(d) September - November spore 4



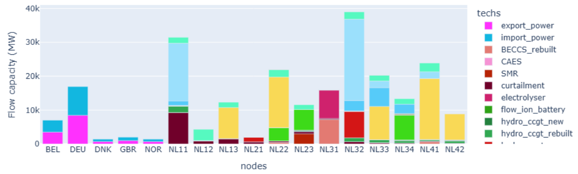
(e) September - November spore 5



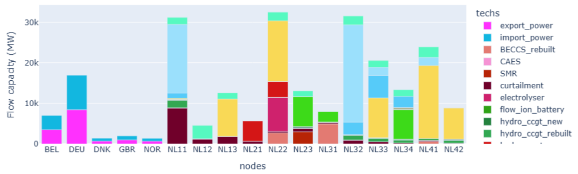
(f) September - November spore 6



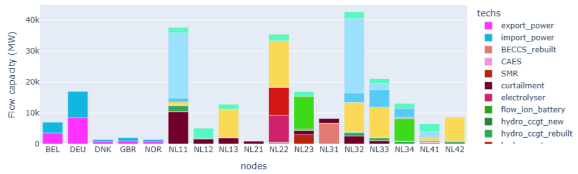
(g) September - November spore 7



(h) September - November spore 8



(i) September - November spore 9



(j) September - November spore 10

Figure E.2: Different SPORES with of the base case in September - November

F

Technology types for Calliope model

F.1. Technology types

This section gives an overview of the different types of technologies used in the model and how they are represented within the Calliope modelling framework. The model includes supply, storage, conversion, demand, and transmission technologies, each with their own functional role and specific constraints.

In Calliope, technologies are described using structured YAML configurations. Each technology must include key attributes such as carrier flows, lifetimes, and cost or efficiency parameters. Some constraints are common to all technologies (e.g., lifetime), while others are specific to the technology type, such as flow_ramping for flexible generation or storage_loss for batteries.

The tables below present a general overview of the constraint types associated with different technologies:

- Table F.1: Basic constraints for all technologies
- Table F.2: Additional constraints for supply and conversion
- Table F.3: Constraints for transmission links
- Table F.4: Constraints for storage technologies

These structural definitions are essential for how the model simulates the functioning of the Dutch electricity network in 2050. The actual constraint values and cost assumptions used in this model are discussed in detail in Chapter 4.

Constraint	**Description**
name	Name of technology
color	Color of technology for representation
base_tech	Supply, storage or conversion
lifetime	Lifetime of technology
carrier_in	Energy carrier going in the technology
carrier_out	Energy carrier going out of the technology

Table F.1: Essential constraints

Table F.1 shows all the criteria that are required in every type of technology. The only thing that is not needed for demand is *carrier_out* and for supply, it is *carrier_in*. These constraints form the base of all types of technologies. Table F.2 shows all constraints that are needed for setting up either the supply or the conversion constraint. An important thing to notice is the difference between MW (limits) and MWh (flows). Next, table F.3 does the same but for the transmission lines. Finally, the last table, table F.4, shows all the needed constraints for the storage technologies included in the model. In all tables the constraint, unit, and description are given.

Constraint	**Unit**	**Description**
flow_out_eff	[%]	The efficiency of the energy plant
flow_ramping	[%]	The ramping efficiency of the plant. When this is 1, it can immediately produce extra power when needed
cost_flow_cap	[kEUR/MW]	Nominal investment costs. The cost per unit of the decision variable *flow_cap*
cost_flow_out	[kEUR/MWh]	Variable operational and maintenance costs
cost_flow_in	[kEUR/MWh]	Cost of the fuel going into the technology (i.e. uranium price, hydrogen price)
cost_om_annual_investment_fraction	[%]	Adds part of the investment costs of the technology as additional cost to represent the fixed O&M costs

Table F.2: Supply and conversion constraints

Constraint	**Unit**	**Description**
link_to	[dmnl]	Node where transmission goes to
link_from	[dmnl]	Node where transmissions comes from
template	[dmnl]	This is a predefined template that selects the type of transmission that is needed for the system. These can be *hv_transmission, subsea_transmission or hydrogen_transmission*
flow_cap_min	[MW]	Minimal flow capacity of the transmission line
flow_cap_max	[MW]	Maximal flow capacity of the transmission line
distance	[km]	The distance of the transmission line between two nodes

Table F.3: Transmission constraints

Constraint	Unit	Description
storage_discharge_depth	[%]	Maximal percentage the storage tank can drop to
flow_cap_per_storage_cap_max	[%]	Percentage of storage it can withdraw per hour
flow_in_efficiency	[%]	Energy loss when power is stored
storage_loss	[%]	Energy lossed per hour during storage

Table F.4: Storage constraints

G

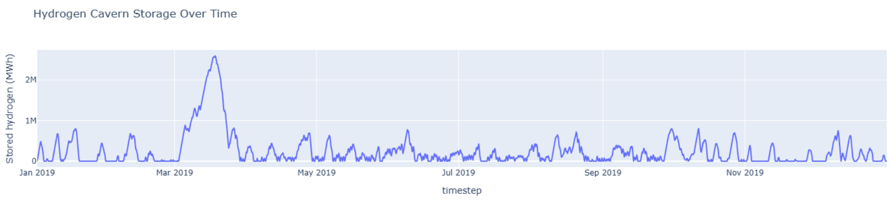
Extra model explanation and exploration

In this appendix, some extra research is done on two specific points in the model. The first part focuses on the large amounts of hydrogen storage in the first half of March, and the second part looks into the pricing of the model and discusses possibilities of this high pricing.

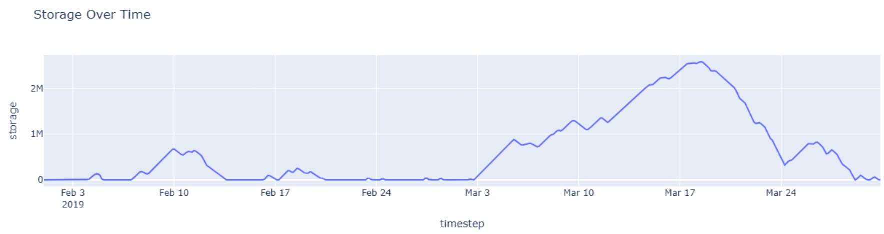
G.1. Hydrogen storage March

The base model shows a large increase in hydrogen storage in the beginning of March and a complete depletion at the end of this month. The reason why this happens needed to be explored further, and this is done in this section.

First, we took a look at the total hydrogen storage over time, seen in figure G.1a. We clearly see a large rise in storage of hydrogen in March. Zooming in, we can see a clearer image of this peak in figure G.1b.



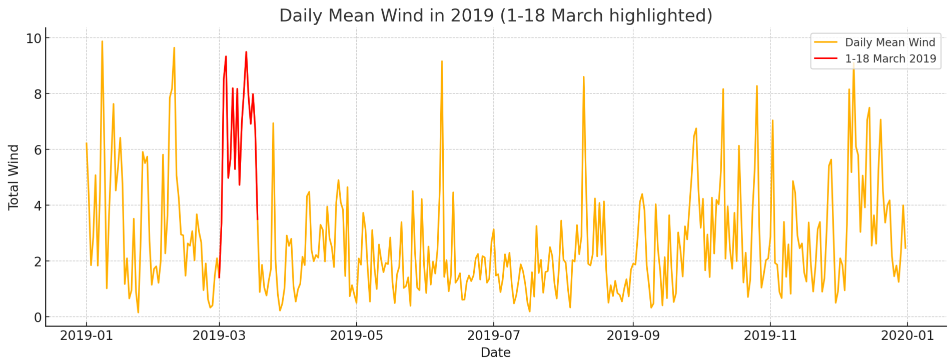
(a) Hydrogen cavern storage over time



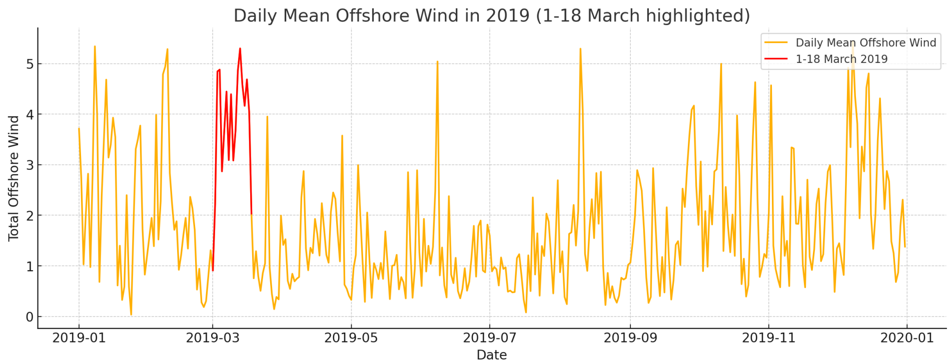
(b) Hydrogen storage in salt cavern March

Figure G.1: Storage hydrogen in salt cavern over tume

In order to explain this, we took a look into the wind and solar data of this month, and we found that wind, both onshore and offshore, is exceptionally high in this period (figure G.2a,G.2b). To back this up even more, we looked at the boxplot for wind in every month, seen in figure G.3. This showed that not only does this month have a lot of wind, but it also has the highest median of the year.



(a) Onshore wind over time



(b) Offshore wind over time

Figure G.2: Wind produced over time

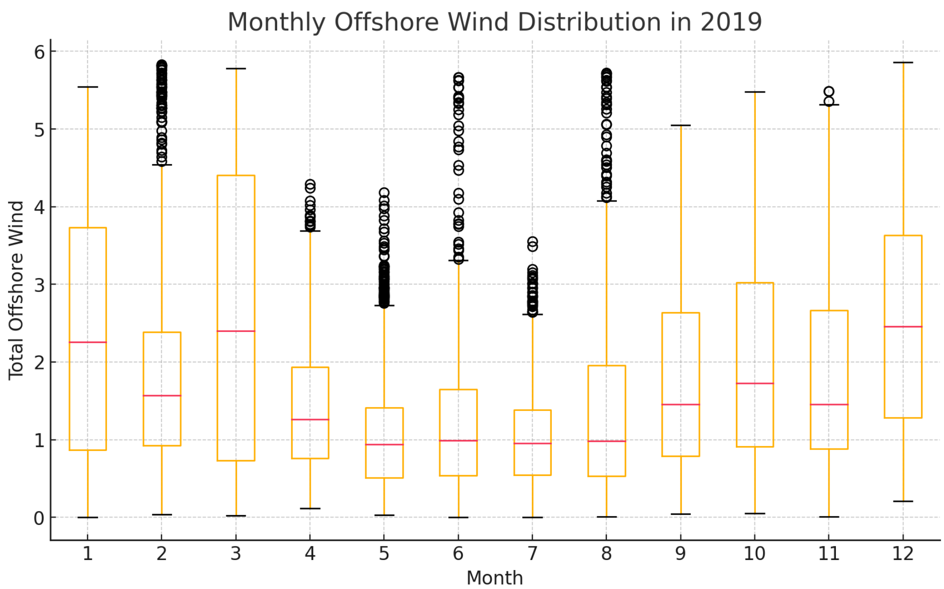


Figure G.3: Boxplot offshore wind during the year

The same thing was done for solar, as expected, there was little sun during this period, and this brought us to the conclusion that wind has the most impact on the storage of hydrogen during this period (figure

G.4).

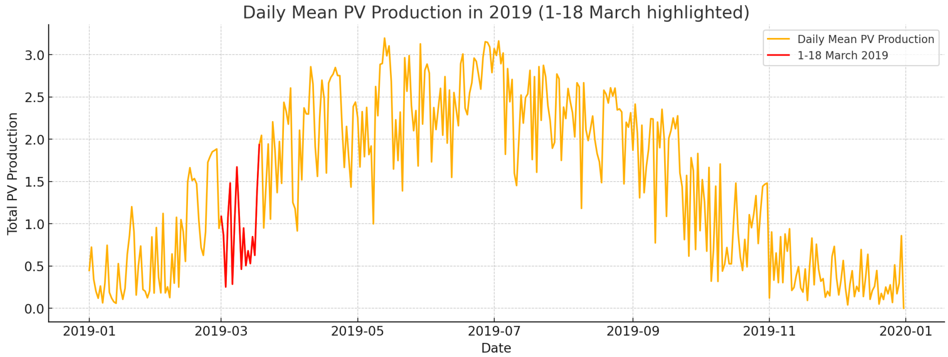


Figure G.4: Solar intensity over time

A last thing we looked at was comparing the amount of hydrogen imported with the production of hydrogen by the electrolyser over the year (figure G.5). This was done to see where the hydrogen comes from. We see that hydrogen is mostly imported during the winter months, when there is less solar power available, the electrolyser has a fairly steady production during the year. In the winter months it runs on wind energy and during the summer on solar.

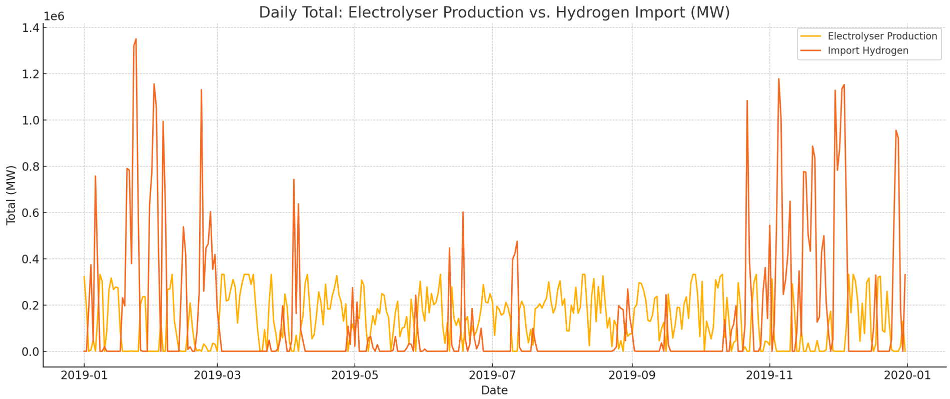


Figure G.5: Produced hydrogen versus inport hydrogen over time

During the period of 1-18 March, a total of 20.8 TWh of wind is produced. From this production, a large part is used for the regular demand of 19.9 TWh, either with electrolysers or regular direct production. The total hydrogen stored in the salt caverns during this period is 2.58 TWh. The period directly after the 18th of March (18-24), the salt caverns are being depleted, and we can see this also in the amount of hydrogen imported and produced during these days. The combined production and import during these first days is equal to 4.86 TWh, of which 4.6 TWh is from the electrolyser. The days after, this total amount is equal to 0.43 TWh, of which 0.4 TWh is from the electrolyser. This is in line with expectations since no extra hydrogen production is needed when enough is stored.

These numbers do not exactly add up, because during these days there are also other plants running. It does, however, show that the model is working the way it should based on demand, storage and production flows.

G.2. Pricing

There are two reasons why extra focus is on the pricing of the model. The first one is straightforward. Both the total yearly price of the model and the shadow prices of the model are too high. The second reason presented itself after the specific SPORES were run on SMR. In this scenario, SMR completely took over the models needed capacity, which, logically speaking, is never cost-efficient. Even with lower wind or solar months, the renewables should always be more affordable.

In order to dig deeper, the marginal cost of the technologies was calculated with the following formula:

$$\text{marginal\_generation\_costs} = \frac{\text{variable\_cost}}{\text{generation}} \tag{G.1}$$

This was then compared to the shadow price calculated by the model itself. The average price returned by the model is 1197 euros per MW. The expected value lies around 100 euros per MW. To compare these results, we looked at the hourly marginal generation cost and the shadow price of node NL11 in two separate time periods. We looked at the first hour of the year and then at the hour with the highest shadow price. The first table (G.1) shows the marginal cost in the hour 00:00:00 on 01-01-2050. Assuming the shadow price in this hour is set at the most expensive running plant, this table suggests the shadow price should be equal to 10,000,000 euros per MW (the numbers are in kEUR). Now, the model's shadow price for this hour is 1093 euros per MW. Even if we were to ignore the lost load because of its very low outflow, the following plant in the merit order is BECCS-rebuilt at 191.7 euros per MW. This means the model's shadow price is either far too high or far too low.

Techs	**marginal_cost**	**flow_out**
lost_load	10000	2.25E-06
BECCS_rebuilt	0.1917	0.0237
SMR	0.0274	2.2924
nuclear	0.0269	0.0770
hydro_ocgt_new	0.0048	0.0388
hydro_ocgt_rebuilt	0.0048	0.0380
hydro_ccgt_new	0.0043	0.0556
hydro_ccgt_rebuilt	0.0043	5492.6613
wind_offshore_AC	0.0028	1971.6877
wind_offshore_DC	0.0028	25946.9746
CAES	0.0026	0.0728
wind_onshore	0.0019	4021.7029
li_ion_battery	0.0017	0.2008
flow_ion_battery	0.0010	0.0156

Table G.1: Marginal cost and flow out at 00:00:00 01-01-2050 at node NL11

We now take a look at the second hour to examine, the hour with the highest shadow price. This is 01-02-2050 at 18:00:00. The shadow price for this hour in node NL11 is 47,713 euros per MW. Again, in this hour we see a very small amount of lost load present, and after that the BECCS-rebuilt is the most expensive plant in the merit order at 191.7 euros per MW. Looking at the two tables, the only significant difference is the li-ion battery outflow, and this is not the price setter for the hour.

Techs	marginal_cost	flow_out
lost_load	10000	2.17E-06
BECCS_rebuilt	0.1917	0.0339
SMR	0.0274	2.3085
nuclear	0.0268	0.0902
hydro_ocgt_new	0.0047	0.2664
hydro_ocgt_rebuilt	0.0047	0.7338
hydro_ccgt_new	0.0043	0.1360
hydro_ccgt_rebuilt	0.0043	5502.7017
wind_offshore_AC	0.0028	523.5041
wind_offshore_DC	0.0028	6889.1981
CAES	0.0026	0.1939
wind_onshore	0.0019	539.4325
li_ion_battery	0.0017	3426.5723
flow_ion_battery	0.0010	0.0373

Table G.2: Marginal cost and flow out at 18:00:00 01-02-2050 at node NL11

After looking at the tables and not finding anything specific, there is one extra thing to look at, namely the actual cost of the plants in these hours. This is calculated by multiplying the marginal cost with the flow out of the plants. In the first hour, the most expensive plant is offshore wind DC, with a cost of 72133 euros. The total cost for this hour is 108491 euros, producing 37.4 GW. For the hour with the highest marginal price, 01-02-2050 18:00:00, the most expensive plant is the hydrogen-to-power CCGT-rebuilt plant. The cost for this hour is 23386 euros. The total cost is 50917 euros, producing 16.9 GW. These numbers do not give an indication of why the marginal price is so high, and thus further research is needed for the pricing of the model.

Lastly, the research on pricing was expanded to all hours of the year, and we found that an outflow of lost load is present in every single hour of the year, but only for a very small amount. This could be a reason for the price to be too high at all hours. These high marginal prices might also be the reason for the high model price. This in itself is something more research is needed for and will not be solved in this paper, but it can be an explanation for the high prices. It can then also be the reason why the SMR SPORE, when given an incentive to maximise, takes over almost all installed capacity. If lost load is indeed in the merit order and somehow impacts the price, this amount is so much higher than other technologies that relatively renewables and SMRs do not differ so much in price anymore. This is why the model then picks the SMR over installing wind turbines both onshore and offshore.