The Impact of Technology Targets on the Design of a Climate Neutral European Energy System

by

Giel van der Weerd

Student number 4451678

Delft University of Technology

First Supervisor:	Dr. Stefan Pfenninger
Daily Supervisor Assistant:	Dr. Francesco Sanvito
Thesis Committee Member:	Prof. Dr. Ir. Jan Kwakkel
Project Duration:	October, 2022 - December, 2023
Faculty:	Faculty of Technology, Policy and Management, Delft

TU Delft

Executive Summary

The European energy system faces one of its greatest challenges: transitioning from a system dominated by fossil-based energy sources to a completely climate neutral system in 2050. Energy system models provide useful tools that can help to navigate this complex task of designing a future energy system by modelling future systems and assessing the impact of future design choices.

Current literature adopts either a step-wise optimisation towards a final configuration of an energy system or deploys a modelling to generate alternatives (MGA) approach to generate a diverse set of system configurations. While the first approach provides temporal insights, it may biased and miss less trivial solutions, the second approach offers robustness but lacks insights into timing of technology deployments and neglects existing infrastructure. This highlights a gap in combining the strengths of both approaches to understand the dynamic between short-term decisions and long-term flexibility, while being robust under changing conditions.

The purpose of this study is to develop a method that combines the strengths of both modelling approaches. A method is developed and applied to two case studies to uncover how policy targets influence the maneuvering space towards a climate neutral European energy system. Many European nation states have set ambitious targets to increase renewable generation capacity while also phasing out fossil-based power generation. It is important to analyse impact of such targets on the rest of the energy system in the short- and the long-term. Aggressive phase-out or growth of deployed infrastructure might work in the short term but could restrict flexibility of options further into the future.

This study uses spatially explicit practically optimal results (SPORES) for 2030 and 2050 provided by the sector-coupled Euro-calliope model, which is an adaptation of the MGA approach. Energy system characteristics were found by analysis of the distributions of primary energy sources and power sector technology deployments. Trade-offs were uncovered by computing Pearson correlation of technology deployments on national and European scale. A k-means clustering algorithm was applied to condense the set of hundreds of SPORES to manageable amount of scenarios that is more accessible for policymakers. The scenarios reveal trends and trade-offs between the two different time-frames. Finally, two case-studies were presented that use a filtering of the SPORES to reveal the impact of the 2030 PV capacity target in Germany and the 2030 offshore wind capacity target in the Netherlands on the maneuvering space of their respective future energy systems. Key finding of this study include:

- Phase-out of fossil-based energy sources by 2050 is enabled by a doubling of renewable electricity generation by 2030 and a more than ten-fold increase of renewable electricity generation in 2050.
- Solar (PV) and wind turbines are must-have technologies by 2050, however trade-offs exist in the the proportional balance between them, and the timing and location of deployment.
- Early phase-out of coal-fired power generation can reduce flexibility in the system as it is often accompanied by high deployment of gas turbines and PV that could create lock-in risk.
- Germany's ambitions to deploy 215 GW of PV by 2030 requires increased coal-fired generation capacity to remain in the cost-efficient design space of 2030. Thus the PV target introduces lock-in risk of coal-fired power generation, which requires a complete phase out by 2050.
- The Dutch offshore wind target of 21 GW by 2030 introduces a potential conflict between deployment of offshore wind and growth of PV and onshore wind that is required for 2050.

These findings contribute to research by offering a methodology that improves understanding of the dynamics within the European energy transition. This study has, for the first time, placed MGA solutions in the context of the multi-decade transition. By analysing the change between the current system, the design space spanned by the 2030 and 2050 SPORES, new insights about the time dependent trade-offs within the energy system and the limitations of the SPORES method have emerged.

Contents

List of Figures

List of Tables

1 Introduction

The European Union has committed to reduce greenhouse gas emissions by 55% by 2030 and reaching climate neutrality by 2050 [1]. In order to fulfill this commitment, the European energy system needs a radical transformation that requires complex policy making and investment decisions. The highly integrated nature of the European energy system adds complexity to decisions that impact the design space of future infrastructures. For example, many European nation states have committed to deploy significant renewable power generation capacity by 2030. While these ambitious commitments to replace fossil based power generation with renewable should be encouraged to decrease carbon emissions, it is important to assess the impact of these targets in the context of the broader system including its climate neutral configuration in 2050.

It is crucial to understand the impact of such decisions in order to navigate the transition towards a climate neutral European energy system. Energy system modelling is a useful mathematical tool that can assist in making such decisions that impact the design of the European energy system [2, 3].

Existing research in this field generally takes one of two approaches to model the transition of the European energy system towards climate neutrality; (1) step-wise optimisation in five to ten year time intervals under multiple scenarios, or (2) generating a large set of sub-optimal system configurations. While the first approach provide better guidance of technology deployment decisions through time, the scenarios introduce bias and are prone to overlook non-trivial solutions. The second approach solves this drawback by generating a diverse set of system configuration, however, at the cost of providing insight into feasible paths towards these solutions. The problem is that it is equally important to consider a diverse range of final solution in a given maneuvering space as it is to understand how to reach these solutions.

The purpose of this report is to address this problem by answering the following research question: *"How do current technology deployment targets in the power sector affect the maneuvering space of a climate neutral European energy system design in 2050?"* To answer this question in a structured manner, the following sub-questions are formulated:

1. *"What are the key characteristics and trade-offs of future configurations of the European energy system?"*
2. *"How can we assess the impact of technology deployment targets on the maneuvering space of future system configurations of the European energy system?"*

The method chosen to answer these questions is data analysis of a Modelling to Generate Alternatives (MGA) approach to the European energy system called the spatially-explicit practically optimal results (SPORES) of the Euro-Calliope workflow building on the Calliope energy system modelling software as is presented by Pickering, Lombardi, and Pfenninger [4]. A more detailed deception of what MGA and the SPORES method are, is given in chapter **??** The analysis of this report is limited to the impact of technology deployment targets in the power sector. This study will use a case-study on the PV target capacity set by Germany and the offshore wind capacity target set by the Netherlands to illustrate the impact of technology deployment targets on the maneuvering space of a climate neutral energy system.

The method that is presented in this report can also be applied to technology deployments or other policy targets in the power sector as well as other sectors as the SPORES result contain configurations describing the integrated power, heat, and transport sector of the European energy system.

This report is organised as follows. First, relevant literature related to the field of modelling the transition of the European energy system is reviewed leading to the identification of the research gap in Chapter 2. Chapter 3 details the methods that were deployed to answer the research questions. Thereafter, Chapter 4 provides an overview of all results including a case study. Finally, Chapter 5 discusses key findings and presents suggestions for further research.

2
Literature Review

The purpose of this literature analysis is to assess the current state-of-the-art of energy system modelling research focusing on the transition of the European energy system to become climate neutral in 2050. Important related studies are identified and reviewed to address the knowledge gap and define the focus of this research project.

2.1. Modelling the Transformation of the European Energy System

A literature search was performed on Scopus, ScienceDirect, and Google Scholar. The transition of the European energy system is an important and urgent topic, driving rapid advancements in the field of energy system modelling. Therefore attention is payed to the date op publication in order to select literature that is up to date with state-of-the-art energy system modelling. Because the energy system in Europe is a highly integrated system, the literature review is focused on research that models the European energy system as a whole.

The terms that were used in the search queries to identify relevant scientific articles are summarised in table 2.1. This table shows the number of results that were found for each search engine and the amount of relevant articles that were selected for a review. The search terms were searched in the title, keywords, and abstract of the articles. Determining the relevance of each article was based on reading the abstract.

Search terms	Search engine	Results
("European energy system") AND ("model" OR "optimal") AND ("decarbon*" OR "carbon" OR "sustainab*")	Scopus	62
("European energy system") AND ("transition" OR "pathway") AND ("near optimal")	Science Direct	15
("Europe") AND ("energy transition") AND ("model")	Google Scholar	46

Table 2.1: Literature search queries

Energy system modelling is a useful mathematical tool that can assist decision making about the design of the European energy system [2, 3]. Models can provide insight into the real choices, associated risks, trade-offs and investment strategies related to the transition towards a climate neutral energy system [5, 6]. Recent studies have shown that energy system models can provide useful insights into the design of a future European energy system [4, 7, 8, 9].

Modelling the transition of systems such as the European energy system under highly uncertain circumstances faces three key challenges. Firstly, it is difficult for energy system models to provide solutions that remain useful and robust in highly uncertain and rapidly changing environments [6, 10]. Secondly, modelling energy systems is well suited for techno-economic analysis. However, it is likely that sub-optimal solutions will be preferable over a economically optimal solution because of non-economic factors such as regional self-sufficiency, social acceptance and political feasibility [11, 12, 13, 14, 15]. Moreover, models provide theoretic approximations of the real world [6]. Translating modelling results into concrete actions remains challenging. Lastly, energy is highly integrated across multiple sectors of our society. Therefore, it is crucial to implement a sector-coupled model to obtain a realistic approximation of an energy system.

Existing studies that model the transition of the European energy system can be divided into two categories; (1) 'myopic' approach that models step-wise pathways towards a future outcome and (2) a 'snapshot' approach that generates multiple configurations for a specific year.

2.1.1. Traditional Approach to Modelling Pathways

The traditional approach to modelling the transition of an energy system is characterised by a step-wise optimisation in time-intervals, usually between five to ten years. This approach begins with the current state of the energy system and computes an economically optimal configuration for the next step under carbon emission constraints. This method enables researchers and policymakers to address uncertainty and enhance the robustness of the solution. Typically, this process is repeated across various scenarios, usually ranging from two to four scenarios.

Auer et al. [16] apply the traditional method of modelling pathways to the transition of the European energy system towards 2050 under four decarbonisation scenarios. The scenarios were established by combining two out of three key drivers for the transition; (1) a societal revolution driven by strong public support, (2) a technology revolution driven by innovation, and (3) a policy revolution driven by regulations and institutions. GENeSYS-MOD was used as a tool to model the energy use of four sectors in the European energy system considering 30 countries (EU25, UK, Switzerland, Norway, Turkey, and the Balkan region. Capacity expansion is modelled in five-year time intervals between 2015 and 2050. All scenarios succeed in decarbonising the European energy system. However, a transition driven by regulations and institutions seems to be the least risky strategy as this results in an earlier reduction of carbon emissions compared to other scenarios. Furthermore, the results show that high renewable energy penetration is necessary regardless of the driving factors of the transition. The research also demonstrates that residential and commercial heating, and passenger transport sectors need to be electrified for 50% or more before 2035.

Kigle, Ebner, and Guminski [17] use a high resolution, sector coupled model to study the transformation of the European energy system towards 2050 in five-year intervals under the emission reduction scenario solidEU. Four major energy consuming sectors were modelled; (1) households, (2) industry, (3) transport, and (4) services. Socio-political aspects of the transition as described by the solidEU scenario are integrated as inputs into the model. A re-evaluation factor is added to the initial investment cost to ensure that the investment cost are recouped during the lifetime of the technologies. Solar PV, on- and offshore wind capacities, dominate the final configuration of the modelled energy system by generating the majority of the final electricity consumption.

Seck et al. [18] analyse the role of hydrogen in the transformation of the European energy system towards climate neutrality in 2050 by soft linking three different models. A TIMES-type model (MIRET-EU) is used to model the energy use of five sectors in the European energy system; (1) Industry, (2) Transport, (3) Services and commercial buildings, (4) Residential buildings, and (5) Agriculture. The HyPe model was used to consider hydrogen imports from Russia, Ukraine, the middle-East, and North Africa. An aggregated energy system model was used to optimise the cost of the pathway towards 2050 with ten-year time intervals. This model includes a technological learning effect that is represented by a fixed price reduction every time the investment in a technology doubles. The results were generated under two policy scenarios. The Technology Diversification scenario considers a wide range of technologies to minimise the cost of the transition under the European Climate law. The target for renewable technologies in 2030 is increased from 32.5% to 40% under the Renewable Push scenario. Hydrogen demand reaches 30 Mt by 2030 and exceeds 100 Mt by 2050 under both scenarios. solar PV, on- and offshore wind are important under both scenarios as they provide the majority of installed capacity.

A study conducted by Victoria, Zeyen, and Brown [7] uses a sector coupled model called PyPSA-Eur-Sec [19]. The model consist of the electricity, heat, and transport sector in a very high resolution.

Their model optimises for steps of 5 years from 2020 to 2050. The research finds different paths of technological transformations under global warming temperatures between 1.5 and 2.0 degrees Celsius. This study finds similar transformations, however, the timing of scale-up of important technologies differ. Also, this research argues that a near cost optimal transition requires enormous transformations to take place before 2035, and that wind and PV deployment play a major role in the transformation of the European energy system.

A crucial benefit of modelling pathways in a step-wise process is the fact that it provides insight into necessary short term decisions taking into account the state of the current system. Moreover, optimising total system cost under carbon emission constraints in a step-wise manner better aligns with shorter time horizons of investors and policy makers making the models less susceptible to long term assumptions, such as the discount factor. The pathways approach also allows for integration of re-evaluation mechanisms to address problems caused by short-term decision making. There are two main disadvantages to modelling under a small number of scenarios. Firstly, designing scenarios is a complex task that is prone to introduce cognitive bias that can easily overlook non-trivial solutions as they are designed with preconceptions of the present. Secondly, the results of modelling a limited number of scenarios could become impractical as conditions can be expected to change significantly during a multi-decade transformation of such a complex system as the European energy system.

2.1.2. Modelling to Generate Alternatives

Modelling to generate alternatives (MGA), initially applied to energy system modelling by DeCarolis [20], is a method to generate many near-optimal alternative solutions to enhance robustness and flexibility of modelling solutions, well suited for high uncertainty associated with multi-decade transition of an energy system. Having a design space that consists of a diverse set of feasible energy system configurations as a final output helps researchers and decision makers to expose trade-offs and explore options. This is especially important considering that policymakers usually have a strong interest in less then optimal solutions as they are often faced with challenges beyond techno-economic feasibility. The goal of MGA is to effectively explore the design space around the optimal solution, aiming to find maximally diverse alternative solutions. MGA does this, by altering the structure of the mathematical problem by iterating the optimisation process for multiple decision variables within a chosen slack of the optimal cost [20].

Research presented by Pedersen et al. [14] implements a method called Modelling All Alternatives (MAA) as an improved version of MGA to model the European power system of 2030. This research uses an open-source modelling tool called PyPSA. The MAA algorithm ensures that the solution space converges towards 224 near-optimal feasible solutions under a cost relaxation of 10%. Analysing correlations between the solutions, this study shows that PV capacity has a strong link with battery storage. Also, hydrogen storage shows a significant inverse relationship with backup capacity, suggesting that both can act as a backup during times when renewable energy supply is limited. The research clearly shows that the MAA approach is able to identify regions of the near-optimal solutions space that are not identified by the more traditional Modelling to Generate Alternatives (MGA) approach. However, this comes at a computational cost that deems the method inapplicable to very detailed energy system models that require several hours to solve.

Another method, building on the MGA approach is the SPORES method proposed by Lombardi et al. [21]. The SPORES method uses location specific technology capacities as decision variables in the iterative process of finding sub-optimal alternatives. This results in spatially explicit practically optimal results (SPORES) that add spatial diversity within the same technology mix to the existing MGA approach. This approach was implemented by Pickering, Lombardi, and Pfenninger [4] to generate a diverse set of configurations for a sector-coupled model of the European energy system that complies with the 2050 European climate targets. This approach results in a design space of 441 SPORES. Energy consumption is considered in four categories; (1) building heat, (2) synthetic fuel use for non-electrifiable industry processes including aviation and shipping, (3) transport by land, and (4) electricity consumption. Key technologies for a carbon neutral European energy system include wind energy, solar PV, bio fuels, intra-European transmission, storage, electrification of the heat and transport sector, and use of controlled vehicle charging.

A key advantage of having a large set of diverse solutions is that the solution space is more likely to be robust as circumstances change. Also, the MGA approach can be a useful tool for policy makers as it provides insight into trade-offs that can be overlooked by traditional scenarios. This approach, however, lacks insight into the path of the transition towards a climate neutral system as it only provides 'snapshot' solutions of a final state of the energy system. Another drawback of this method is that it does not consider current installed capacities. This can lead to solutions that seem optimal but are impractical in reality as it is not possible to build a new energy system from scratch.

2.2. Knowledge Gap

The existing literature primarily takes one of two modelling approaches: a more traditional step-wise optimisation from now until 2050, and the MGA approach that generates a diverse set of potential system configurations for a specific year in time. While the step-wise approach offers valuable insights into required decisions through time, it is limited by cognitive biases in scenario design and is prone to overlook less trivial alternatives. On the other hand, the diverse solution set of the MGA approach offers robustness against changing circumstances and reveals otherwise overlooked solutions. However, it lacks a clear insight into the temporal dimension of the transition as the solutions only provide insight into the possible final outcomes of a system. Also it takes a greenfield approach that neglects the practicality of existing infrastructure. Comparison of these approaches exposes a knowledge gap in integrating the strengths of both approaches to provide a modelling framework that offers insight into the dynamics between short-term decision making and maintaining flexibility in the long-term, while also offering insights that stay robust under changing conditions. This leads to the following formulation of the main research question of this research:

"How do current technology deployment targets in the power sector affect the maneuvering space of a climate neutral European energy system design in 2050?"

This study provides a unique methodology, for the first time using design space consisting of near optimal solutions provided by the SPORES method of Lombardi et al. [21] to construct pathways towards are carbon neutral European energy system in 2050. This approach combines the benefits of having a diverse set of optimal solutions as proposed by the MGA approach with the benefit of starting from a current system and building pathways in a step-wise manner as proposed by the more traditional approach.

Addressing this knowledge gap will benefit researchers and policy makers working on the transition towards a climate neutral European energy system. It will address the problem of providing insight into important trade-offs that exist in the near-optimal design space of a future energy system while also allowing for analysis of the impact of more immediate actions needed to realise a future energy system. This will benefit politicians and policy makers as it will provide insight in the trade-offs that need to be discussed in order to reach consensus about the design of the European energy system. For researchers this research can expose MGA solutions that are impractical in reality because of the current state of the system, thus exposing a need further research to improve the model.

To address this knowledge gap, the spatially-explicit practically optimal results (SPORES) for the year 2050 of the sector-coupled European energy system model provided by Pickering, Lombardi, and Pfenninger [4] are used as a starting point. The Euro-calliope model offers a very high resolution sector-coupled model of the European energy system. This study takes the MGA approach offered by the SPORES method as a starting point because it offers greater flexibility than taking the traditional approach of modelling pathways. It is easier to add a temporal dimension to the MGA solutions than to extend the diversity of the more traditional pathways approach due to computational complexity. This research is extended by providing a method to analyse the design space of SPORES results for the year of 2030 and 2050, and by identifying pathways between them.

3

Methods

This chapter provides the methods used to answer the research questions. Figure 3.1 provides an overview of the methods used for this research. First, section 3.1 discusses the data that was used as an input for this study. Resource availability is also mentioned in this section. Section 3.3 describes how the k-means clustering algorithm was implemented to reduce dimensions of the SPORES to identify a more manageable amount of scenarios. Finally, section 3.4 provides a description of the methods used to assess the impact of technology deployment targets on the maneuvering space of a future European energy system. The data and scripts required to produce results are provided in a GitHub repository as mentioned in Appendix A.

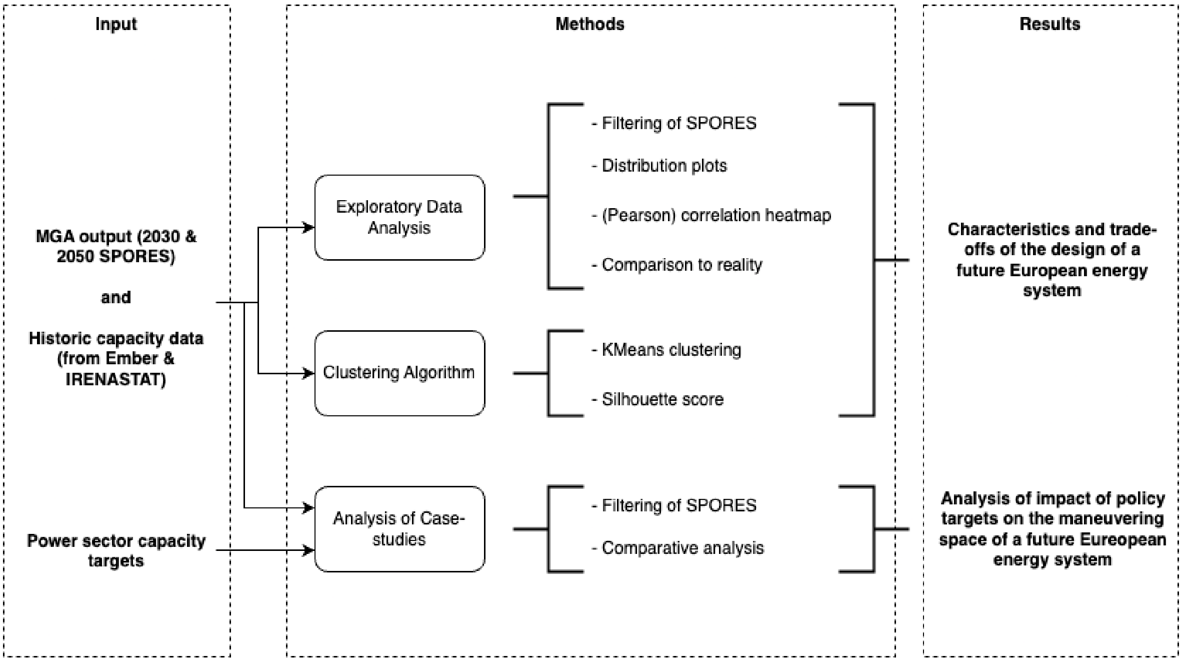


Figure 3.1: Methods overview

3.1. Data

3.1.1. Calliope

This study is primarily based on the analysis of an energy system model that is build using the Calliope framework [22]. Calliope is an open-source tool that enables user-friendly modelling of energy system models. The tool can be applied on multiple scales ranging from local energy systems such as cities to fully integrated continental energy systems. The model implements linear optimisation to minimise the cost of an energy system. Calliope is designed to run smoothly on high performance clusters and is equipped to deal with high resolution energy data.

The Calliope workflow allows users to model energy systems by defining technologies, regions with corresponding energy production potential, and energy demand. Besides energy in the form of electricity, the model allows for supply, conversion, transmission and consumption of different energy carriers. This enables more complete analysis of the integrated power-, heat, and transport sector. After defining the input variables and constraints, a linear optimisation problem is solved for a complete year resulting in a cost-optimal configuration of the energy system that was defined.

Calliope has been applied to model many energy systems such as local energy systems such as Cambridge, UK (Pickering and Choudhary [23]), national energy systems such as Italy (Lombardi et al. [21]), and the continental energy system of Europe (Pickering, Lombardi, and Pfenninger [4] and Tröndle et al. [15]).

The development of the Calliope framework is openly accessible via GitHub (`https://github.com/calliope-project/calliope` [22]). Updates are available on Zenodo (Pfenninger et al. [24]) and documentation is provided at: `https://www.callio.pe/`.

3.1.2. SPORES Method: an Extension of MGA for Energy Systems

The SPORES (spatially explicit practically optimal results) approach is an extension to the 'modelling to generate alternatives' (MGA) methodology applied to the field of energy system modelling. The main purpose of the method is to generate a diverse set of solutions for future energy systems and it specifically suited for high resolutions models.

The SPORES methodology stands out in the field of energy system modelling due to its focus on finding, spatially as well as technologically diverse solutions. Unlike traditional approaches, the SPORES approach not only seeks configurations with varying technology mixes but also distinctly different spatial deployments. This focus on location-based insights is especially valuable as it offers insights into geographical fairness and social acceptance concerns related to concentration of technology deployment in specific regions.

The extension of the MGA method provided by Lombardi et al. [21] to find SPORES is an iterative process that works in three general steps; finding the cost-optimal solution, assigning weights to decision variables, and generation of SPORES. The cost-optimal solution is identified by minimising the total annualised system cost including the CAPEX and OPEX for a whole year of operation for each decision variable. The decision variables are defined as the installed capacity and the energy production for each location-technology combination. After finding the economic optimum, positives weights are assigned to the decision variables with non-zero values in the cost-optimal solution. In the initial approach of Lombardi et al. [21] weights are assigned based on relative deployment of a technology in a certain location compared to the maximum potential for deployment at this location. Besides this relative deployment method, Lombardi, Pickering, and Pfenninger [25] provided three other approaches to assign weights; the integer method, the random method and the evolving-average method. The relative deployment method prioritises spatial diversity of solutions. Therefore, it is ideal for studies that focus on understanding the variation of technology deployment across different regions. The integer method, as taken by Pickering, Lombardi, and Pfenninger [4], is simplistic and therefore best suitable for preliminary explorations where quick insights into the system are required. However this approach could lead to many decision variables having similar weights, reducing efficiency. Randomly assigning weights can be used to explore a wide variety of configurations without any pre-existing bias. This method is best applied to uncover non-intuitive solutions that might not emerge from a more structured approach. Finally the evolving-average approach keeps record of past iterations and allocates weights based on deviations from average capacities of previous solutions. This approach can help to assess how each new solution compares to the average of previously found configurations increasing sparsity of solutions. Generally speaking, the relative-deployment and integer method are best suited to find spatially diverse solutions while the random and evolving average method are best suited for finding notably different solutions from a technology mix perspective [25]. After assigning weights, a solution called a SPORE, is found by minimising the sum of all location specific technology deployments multiplied by their respective weights within a pre-defined slack of the optimal cost.

In terms of the SPORES that were used for the purpose of this study different methods were used. The 2030 SPORES were generated using the parallel approach described by Lombardi, Pickering, and Pfenninger [25] where the integer method was used to find the base SPORES and the relative-deployment was used to find secondary technology-explicit SPORES that target a system-wide minimisation or maximisation of a particular technology. In total, 190 SPORES were generated for the European energy system of 2030. The 2050 SPORES, as provided by Pickering, Lombardi, and Pfenninger [4], simply uses the integer approach to find solutions, however having a larger sample size of 441 configurations. For both the 2030 as well as the 2050 SPORES, a cost slack of 10% was used.

3.1.3. Sector-coupled Euro-Calliope Model

For this research, the SPORES results as an output of the Euro-Calliope model were used. The model includes 35 countries and divides Europe in 98 regions. The Euro-Calliope model of 2030 is build on a national resolution to reduce computational complexity and because national resolution is deemed sufficient for the propose of this research. The output of the already existing model for 2050, build by Pickering, Lombardi, and Pfenninger [4], is aggregated to match the national granularity of the 2030 model output. Each region is modelled as node that is connected to other areas based on current and future electric grid connections based on the European project "e-Highways2050" [26]. Each region is defined by the variety of possible technologies, their corresponding production potential and limitations, and the energy demand. Exchange of energy between regions is facilitated by the electric grid or exchange of various types of fuel. The model does not consider currently installed generation capacities.

The model build by Tröndle et al. [15] initially only described the power sector in Europe and was later expanded with other energy carriers such as heat, synthetic fuels, and transport, to achieve a sector-coupled representation of the power-, heat-, and transport sector in Europe [4]. This achieves a more realistic approximation of the real European energy system as Pickering, Lombardi, and Pfenninger [4] prove total energy demand is nearly three times as high as electricity demand only. Sector coupling allows this research to analyse the impact of decisions in the power sector on other system metrics beyond the power sector. This approach is essential for deriving meaningful insights, given that energy use in other sector than the power sector play a fundamental part in our society. The Euro-Calliope model can be found on https://github.com/calliope-project/sector-coupled-euro-calliope.

3.1.4. Euro-Calliope SPORES Data

To understand the impact of the power sector on the maneuvering space, it is crucial to develop a good understanding of the maneuvering space first. The maneuvering space in this study is defined by the Euro-Calliope SPORES describing cost-efficient configurations of the European energy system in 2030 and 2050. To explore the maneuvering space, the distribution of primary energy sources, power sector technologies and high level system metrics are considered.

Primary Energy Sources

The Euro-calliope model assumes that primary energy sources are not imported from or exported to regions outside of Europe, making the modelling solutions of the European energy system, self-sufficient on a continental scale by default. In the model, 7 categories of primary energy sources are considered; biofuels, coal, natural gas, nuclear heat, renewable electricity, oil and waste. Renewable electricity includes electricity generated by solar, wind, and hydro as natural resources and their potentials are based on geographical potential of each source [4].

Power Sector Technologies

The sector-coupled Euro-calliope model allows primary energy sources as mentioned above to take the energy as an input or convert it to another energy carrier [4]. This research is focused on the power sector, thus it considers conversion, transport and storage technologies that deal with electricity as an energy carrier. Seven categories of electricity generation technologies are considered; coal fired power generation, gas turbines, hydroelectric power, nuclear reactors, onshore wind, offshore wind, and photovoltaic (PV) systems. Combined cycle gas turbines (CCGT) and combined heat and power (CHP) are aggregated in the category gas turbines. For CHP, the complete capacity, being the sum of installed capacities dedicated to heat and power, is considered to match the convention used in the historic capacity dataset provided by Ember climate. Hydro consists hydro electric stations that use run-of-river or reservoirs to generate electricity and PV consists of roof mounted PV systems and PV systems placed in open field. Wind technologies are not aggregated because cause of importance of wind energy (both have higher capacities than most other technologies) and the difference in land use between onshore- and offshore wind, sets them apart significantly. Battery electric storage systems (BESS) are considered as a storage technology that can charge and store electricity to be discharged at a later moment. Finally international transmission lines are considered as a technology that is enables exchange of electricity between countries. Because the SPORES data is provided on a national resolution for 2030 and a regional resolutions for 2050, only the international transmission lines are regarded. The inter-regional transmission lines included in the 2050 dataset are not considered.

High Level System Metrics

While this research focuses on the power sector, it is important not to lose the ability of the sector-coupling of the Euro-calliope model. To assess the impact of the power sector beyond technology deployment, five high level system metrics provided by Pickering, Lombardi, and Pfenninger [4] are considered. The respective electrification of the transport and heat sector are computed as the percentage of total sector demand that is met by electricity. The geographical equity of power generation is considered as the gini-coefficient of electricity production. The gini-coefficient ranges between 0 and 1 where 0 represents the most equal distribution of electricity generation and 1 represents a maximally unequal distribution of electricity production. Total electric storage discharge capacity and average national import of electricity are considered to assess the need for storage and transport technologies in the power sector.

The raw SPORES results of 2050 generated by Pickering, Lombardi, and Pfenninger [4] are obtained from: https://zenodo.org/record/6546817. For the year 2030 a similar set of SPORES was generated following the same workflow as for 2050. The raw output of the 2030 SPORES is unavailable online, however, the processed data for the 2030 and the 2050 SPORES that can be used to reproduce the analysis of this study are deposited to GitHub. The source code and processed data are deposited to GitHub: https://github.com/gvanderweerd/SPOREServays.

3.1.5. Historic Capacity Data

To say something about the impact of technology deployments on future energy system configurations described by the SPORES results it is crucial to obtain data about currently installed capacities. This data serves as a starting point for assessing the impact of technology deployments on the maneuvering space of future European energy systems. Placing the SPORES results in the context of currently installed capacity is important to ensure that the transition from now to desired system configurations in 2030 and 2050 is not only thematically feasible but also practically implementable. Historic capacity data used in this research is obtained from two sources; Ember and IRENASTAT.

This study primarily relies on data provided by Ember Climate [27]. This source is chosen as it aggregates data from multiple sources based on the quality of available data in a country-specific way resulting in a dataset of best possible quality. This dataset represents the current nameplate capacity of various technologies in the countries that correspond with the technologies in the Euro-Calliope model. While the dataset provided by Ember Climate provides insight into the historic capacity related to wind power, does not provide a distinction between currently installed onshore- and offshore wind capacities. Also, the dataset obtained from Ember Climate aggregates PV capacity and solar thermal capacity under the name ”Solar”. The SPORES dataset, however, only contains PV as solar power technology. Therefore, the data related to wind and solar capacity in the ember dataset is disregarded and another source (IRENASTAT) is used to fill the gap. To match the SPORES dataset, historic data for each of the 35 countries included in the Euro-Calliope model is downloaded and processed. Historic total capacities for the region ”Europe” are calculated as the sum of these 35 countries to ensure the results of the SPORES dataset and the historic capacity are consistent on a continental scale. To compare the total capacities in the European energy system the sum of all countries is used instead of the data that can be downloaded for the region ”Europe” in the dataset provided by Ember Climate. The dataset of Ember climateis openly available at https://ember-climate.org/data/data-tools/data-explorer/ and the data provided by IRENASTAT can be accessed on https://pxweb.irena.org/pxweb/en/IRENASTAT [27, 28].

3.2. Identifying Characteristics and Trade-offs

To expose characteristics in the existing maneuvering space between now, 2030, and 2050, the distributions of the respective primary energy sources, power sector technology deployments, and system-level metrics are considered and, where possible, placed into the context of the current state of the energy system. To identify trade-offs between respective technology deployments and system-level metrics, correlations are computed for 2030 and 2050. The standard Pearson method is used to compute the correlation. A high negative or positive correlation value indicates a strong connection between the installed capacity of two technologies. A high positive correlation means that technologies tend to be installed together, while a high negative correlation means that technologies are installed at the expense of each other. Low correlation means that there is no clear coupling between the installation of the two technologies. Correlation coefficients are calculated using the Pearson method. Self-correlation is excluded from the figure because it is always 1. Hydro and Nuclear are not included in the figure because their capacities have been frozen across all the near-optimal energy system configurations.

3.3. Identifying Scenarios for Future Energy System Configurations

3.3.1. Reducing Dimensions: k-means Clustering

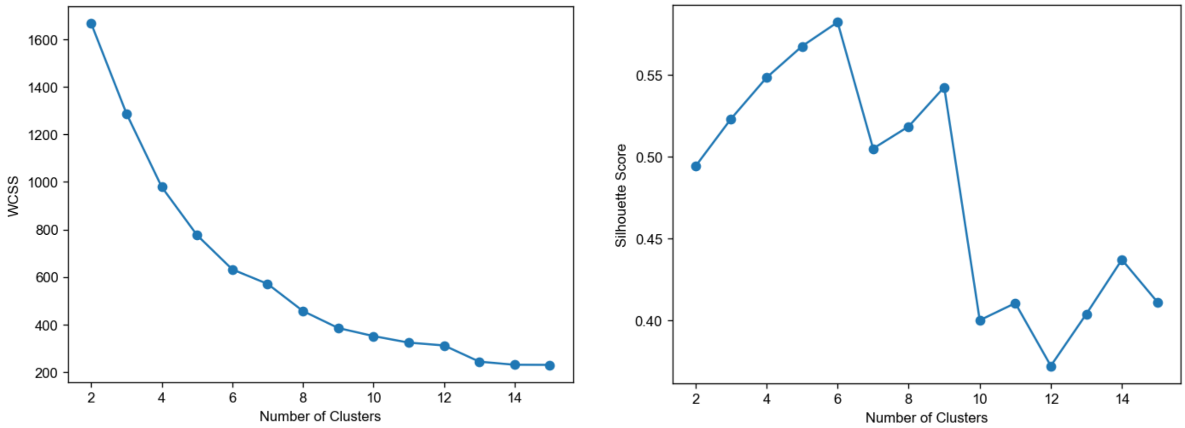
The set of system configurations as a result of the SPORES method, provided by Lombardi et al. [21] does not directly expose the characteristics and trade-offs of future system configurations. The number of SPORES results comes with an inconvenience; the number of results and amount of dimensions within them complicate the process of extracting characteristics and trade-offs. To better understand future system configurations, it is important to reduce the dimensions of the SPORES results. The k-means clustering algorithm provided in the Python package sklearn (sklearn.cluster.k-means) is used as a method to group SPORES into scenarios in terms of similar investments in power generation technologies in Europe.

3.3.2. Choosing the Number of Scenarios: Elbow Method vs. Silhouette Score

The number of clusters for the k-means algorithm is determined using the elbow method, however, when the elbow point is unclear, the silhouette score is considered. In the case where multiple cluster numbers have similar silhouette scores, the smaller number of clusters is selected to reduce the number of dimensions.

The Elbow method calculates the Within-Cluster Sum of Squares (WCSS) for a range of cluster numbers. The WCSS can be computed by taking the sum of the distance squared between each point and the centroid in a cluster. The relation between the number of clusters K and the WCSS looks like an elbow, as depicted in Figure 3.2a. At first, increasing the number of clusters radically decreases the WCSS value. However, after a certain number of clusters, the effect of more clusters becomes less pronounced, creating an elbow shape. The optimal number of clusters is chosen at the point of the Elbow. Sometimes, identifying the ’point’ in the Elbow curve is not obvious. In these cases, the Silhouette score can be considered to make a more objective choice for the optimal number of clusters. The silhouette score is a metric that is used to measure the similarity of a data point with its cluster compared to other clusters. Its values range from -1 to 1. A high silhouette score suggests that the data point fits well within its cluster and has low similarity with other clusters.

Figure 3.2 shows the results of applying the Elbow method for k-means clustering of 2050 SPORES results based on the installed capacity of power generation technologies in Europe, resulting in an optimal number of 6 clusters. Finding the elbow point in figure 3.2a is an ambiguous task. Also, it is difficult to implement this method programmatically, leaving this method prone to become inconsistent or biased. Therefore, the silhouette score method is applied for this study. Figure 3.2b shows that the optimal number of clusters in this case is 6 clusters. The optimal number of clusters is determined for



(a) Elbow method

(b) Silhouette score method

Figure 3.2: Identifying the optimal number of clusters for k-means clustering using the Elbow method and Silhouette score method

2030 and 2050 SPORES results on a continental scale, but also a national scale for France, Germany, Italy, the Netherlands, Spain, and the UK.

3.3.3. Descriptive Scenario Labelling

While successful in reducing the number of datapoints, clustering the SPORES dataset as described above does not immediately help decision makers understand the SPORES dataset more easily. The 'cluster' number that is assigned to each SPORE does not translate any meaning to a user working with the dataset. Therefore, this study considers a clusters as a scenario that should have a name conveys the essence of the scenario in an understandable manner. To assign a descriptive and understandable name to each scenario, a systematic approach is taken based on the distinctive technology deployment characteristics of each scenario. By doing so, the primary features of each scenario can be conveyed in a concise and descriptive label.

To describe each scenario based on its distinctive technology deployment characteristics, the median capacity of each technology in a given scenario was compared to the 25th and 75th percentiles of each technology's capacity across all scenarios. The percentile thresholds were used to to determine if the median technology deployment in a specific scenario can be considered as 'low' (when the median technology deployment is below the 25th percentile) or as 'high' (when the median technology deployment is higher than the 75th percentile). A median technology deployment for a scenario between the 25th and the 75th percentile can be considered as moderate. For each scenario, the deployment of its technologies that can be considered low or high are reflected in the name. For example a scenario named "High Gas turbines, Low Battery & Coal & Onshore wind & PV" means that the median deployment of gas turbines are greater than the 75th percentile, and the median deployments of Battery, Coal and Onshore, and PV are lower than their respective 25th percentile deployment. All technologies that are not represented in the name have moderate deployments (between their 25th and 75th percentile thresholds). When a scenario does not have any median technology deployments above the 75th percentile or below the 25th percentile, the scenario is called "No extreme deployments".

3.4. Assessing the Impact of Power Sector Technology Deployment Targets on Future Maneuvering Space

To analyse the impact of technology deployment targets set by European nations it is important to collect target capacities and place them in the context of currently deployed capacity and the design space spanned by the SPORES. Table 3.1 summarises technology deployment targets for Europe and five major countries in terms of primary energy supply. A focus on analysing targets for technology deployments of coal, onshore- and offshore wind, and PV is chosen because these technologies require the strongest change in technology deployments as confirmed by the results in chapter 4.1. These are also the technologies that nation states usually have committed targets for.

It is difficult to find targets for the European continent as there is no overarching agency that has a mandate to commit technology deployments for all countries included in the Euro-calliope model. However, the targets set by the EU can provide a reasonable approximation. For PV capacity the EU has adopted the EU Solar Energy Strategy as part of the REPowerEU Plan, setting the PV target capacity to 600 GW by 2030 [29]. The target onshore- and offshore wind capacity for Europe in 2030 are approximated by combining targets from EU member states and the United Kingdom. Total pledged capacities for onshore- and offshore wind capacities of EU member states equal 329 GW and 111 GW by 2030 [30]. The UK has committed to 30 GW of onshore wind and 50 GW of offshore wind by 2030 [31, 32]. The total target coal capacity in Europe is estimated as the currently installed capacity minus the sum of all legally binding coal phase-out commitments, which equals 108 GW by 2030 [33].

Finding committed target capacities for individual nations is less difficult. Each of the five major energy-consuming countries has committed to phase out coal-fired power generation by 2030 [34, 35]. Target capacities for PV, onshore- and offshore wind in France, Italy and Spain are obtained from the National Energy and Climate Plans (NECPs) [36, 37, 38]. For Germany, the target capacity of PV, onshore- and offshore wind are obtained from Lepesant [39]. The Netherlands has the ambition to realise a complete phase-out of all coal power plant capacity [40]. While the country does not have strict capacity targets for onshore wind and PV, it has committed to generate at least 35 TWh of electricity using a combination of onshore wind and PV. The offshore wind capacity target in the Netherlands is obtained from [30]. Target capacities for the UK originate from Lubbock [41] for PV, from RenewableUK [32] for onshore wind, and from Department for Business, Energy Industrial Strategy [31] for offshore wind. This study presents two case-study that provide a more detailed analysis of the impact of technology deployment targets on the maneuvering space of the future energy system. The first case study performs an analysis of the PV target in Germany and the second case study performs an analysis of the offshore wind target capacity in the Netherlands (see chapter 4.4 and 4.5).

Table 3.1: Target capacities (PV, Onshore wind, Offshore wind, and Coal) of Europe and five major energy producing nations

Country	Technology	Capacity 2022	Capacity target 2030
Europe	Coal	122.3 GW	108 GW
	Onshore wind	203.2 GW	359 GW
	Offshore wind	27.8 GW	141 GW
	PV	205.8 GW	600 GW
France	Coal	2.5 GW	0 GW
	Onshore wind	20.6 GW	34.7 GW (2028)
	Offshore wind	0.5 GW	4.4 GW
	PV	17.4 GW	48.1 GW
Germany	Coal	40.4 GW	0 GW
	Onshore wind	58.2 GW	115 GW
	Offshore wind	8.1 GW	30 GW
	PV	66.7 GW	215 GW
the Netherlands	Coal	3.5 GW	0 GW
	Onshore wind	6.2 GW	- GW
	Offshore wind	2.6 GW	21 GW
	PV	18.8 GW	- GW
Italy	Coal	6.2 GW	0 GW
	Wind	11.8 GW	28.1 GW
	PV	25.1 GW	80 GW
Spain	Coal	3.0 GW	0 GW
	Wind	11.8 GW	62 GW
	PV	20.5 GW	76 GW
UK	Coal	5.2 GW	0 GW
	Onshore wind	14.8 GW	30 GW
	Offshore wind	19.9 GW	50 GW
	PV	14.7 GW	40 GW

Figure 3.3 visualises the maneuvering space of PV in Germany. The maneuvering space can be defined as the space spanned by currently deployed capacity and all possible cost-efficient solutions of 2030 and 2050. To assess the impact of these targets on the maneuvering space between now, 2030 and 2050, the target and required average growth rate to reach the target are visualised in the distribution of 2030 and 2050 SPORES. Extrapolating the growth rate from the target in 2030 to 2050 gives the threshold at which deployment of the technology in question needs to accelerate compared to realised growth rate when the 2030 target is met. In the case of PV deployment in Germany, the target capacity by 2030 is 215 GW. Assuming this target is met and linear growth is continued at the same pace, the capacity in 2050 will reach 585.9 GW. The 2030 and 2050 SPORES are then categorised according to these values. The SPORES in 2030 are classified by 2 categories; (1) the SPORES, colored in green, that meet the target capacity by 2030 and (2) the SPORES, colored in red, that fail to meet the target capacity by 2030. The SPORES for the year 2050 can be classified in three categories; (1) SPORES, colored in purple, that do not meet the 2030 target, even by 2050, (2) SPORES, depicted in blue, that do not require increased growth rates compared to the growth rate that is required to realise the 2030 target, and (3) SPORES, shown in orange, that require increased growth rates between 2030 and 2050. These five categories, are visualised using their respective colors in figure 3.3, along with realised technology deployment of years 2020 to 2022 in black. Each subset of SPORES can be plotted in different distributions to assess the impact on the maneuvering space. Results are worked out for two case studies; Germany's PV capacity target of 215 GW by 2030 (section 4.4) and the offshore wind capacity target of 21 GW by 2030 in the Netherlands (section 4.5).

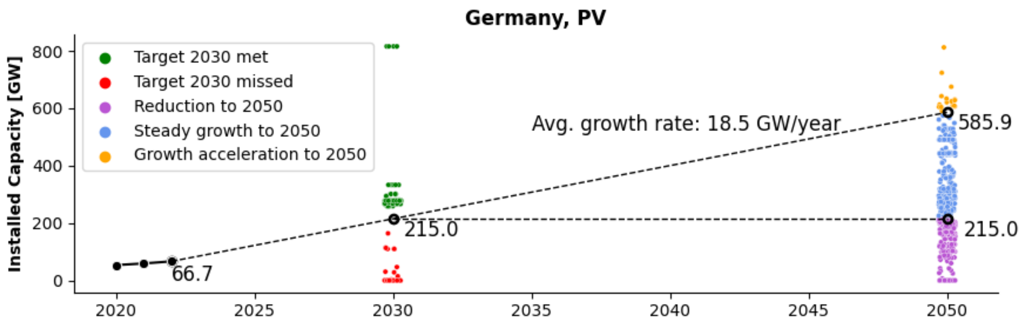


Figure 3.3: Cost efficient maneuvering space of PV in Germany between 2022 and 2050

4 Results

4.1. Characteristics and Trade-offs of Future European Energy Systems

To guide the transition towards a sustainable European energy system, it is crucial to understand the characteristics and trade-offs that exist in the design space of a future system configuration. This section presents the characteristics of the European energy system in 2030 in terms of primary energy supply, installed capacities in the power sector, and high-level energy system metrics. Trade-offs between competing interests are presented as correlation heat maps that show coupling between installed capacities of certain technologies in Europe and six major energy-supplying countries, and the high-level energy system metrics.

4.1.1. Primary Energy Supply

As of 2030, conventional energy sources, such as coal, natural gas, and oil, maintain their status as dominant suppliers of primary energy (see figure 4.1). However, Europe's ambitious goal to become world's first climate neutral continent by 2050 necessitates phasing out of these fossil primary energy sources.

During the transition from 2030 to 2050, the dominance of fossil-based energy sources is projected to be overtaken by renewable electricity generated from sources such as solar-, wind-, and hydropower. To facilitate the transition towards climate neutrality, the supply from renewable electricity sources requires significant growth. Renewable electricity experiences a more than two-fold increase from 1056 TWh in 2022 to at least 2281 TWh in 2030 [42]. Between 2030 and 2050 required growth of renewable electricity amounts to 400-600 TWh/year (equivalent to 5.7%-10.1% CAGR). This underlines the urgency and magnitude of required investments in the renewable power sector.

Furthermore, there is an emerging narrative around the potential of biofuels. Between 2030 and 2050, the use of biofuels as a means of primary energy supply could experience significant growth. However, this is not an absolute necessity in the power sector as relatively low use of biofuels also remains possible. However, in the context of a sector coupled European energy system, it is likely that biofuels will play a crucial role as it is a relatively cheap primary energy source. The question remains how to allocate biofuels, as multiple sectors are competing for its use as a primary energy source. Even if biofuels are not allocated for electricity production, they can be allocated to the heating sector or used as liquid fuels for other processes. While biofuels are not an absolute must-have in the power sector, choices can be made in the allocation on the sector level.

Figure 4.1 seemingly indicates a relatively low, and static contribution of nuclear heat as a primary energy supply between 2030 and 2050. While nuclear has often been cited as a potential bridging technology in the transition to a low-carbon future, Euro-calliope currently does not provide a complete representation of its role because only bery limited expansion beyond currently installed capacity is allowed in specific countries. In most countries, among which Germany and the Netherlands, deployment of nuclear capacity is not possible.

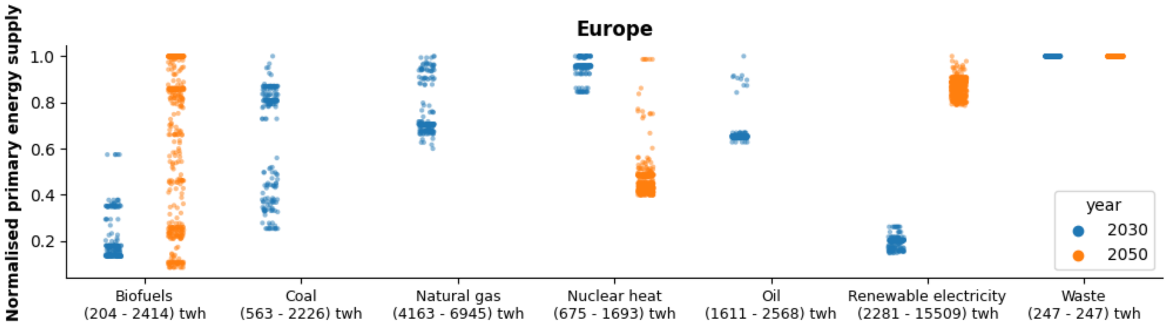


Figure 4.1: Distribution of total primary energy supply (TPES) per source in Europe

4.1.2. Installed Capacity in the Power Sector

To accommodate the transition towards a system dominated by renewable electricity generation, a major shift in the deployment of technologies in the power sector is required. The distributions of deployment in 2030 and 2050 for power generation technologies, electric battery storage, and international transmission are visualised in figure 4.2. The projected battery storage capacities are projected to increase from 0-90 GWh in 2030 to 0-1187 GWh by 2050. This surge underscores the growing potential for battery electric storage systems (BESS) in a system that is dominated by the use of renewable electricity, as previously discussed. While the growth potential is impressive, the deployment of BESS is not an absolute necessity, given that many solutions exist with little to no deployment of BESS.

The model reveals, as expected, that a complete phase-out of coal-fired power generation is necessary by 2050, with an installed capacity in 2030 ranging between 22-154 GW in 2030. Placing this in the context of currently installed capacity, which dropped from 210 GW in 2021 to 206 GW in 2022, reveals that the current rate of decommissioning needs at least a two-fold increase to about 8.7 GW per year to achieve the upper limit of 154 GW by 2030 and maintain within the cost-optimal design space provided by the Euro-calliope model [27]. This emphasises the urgency to transition away from coal-fired power generation as quickly as possible.

According to the Euro-calliope model, the potential of gas-fired power generation grows from 20-457 GW in 2030 to 23-1532 GW in 2050. Currently, the installed capacity of gas-fired power generation amounts to 356 GW, suggesting that Europe is already nearing the upper limit of the cost-efficient design space in 2030 [27].

Because the Euro-calliope model cannot expand the installed capacity of hydropower and nuclear, it is difficult to conclude the impact of for example, phasing-out nuclear on the one hand, and the potential for newer generation nuclear reactors. The roles of hydro and nuclear might be crucial, however, the way that they are currently modeled prevents further analysis to identify characteristics and trade-offs in the context of their deployment in a future European system.

The potential for international transmission capacity appears to growing, suggesting an increasingly interconnected European power grid. However, drawing comparisons with 2030 is limited as the data provided by the Euro-calliope model of 2030 does not allow for the expansion of the electrical grid. The model uses a static value of 206 GW in 2030 and permits significant growth towards 1601 GW in 2050. Currently, the installed international transmission capacity amounts to 194,9 GW and is expected to grow to 271,2 GW [43].

While solutions with low wind deployment in 2030 and 2050 are possible, the trajectory between 2030 and 2050 suggests that wind deployment will likely grow. Analyzing the distribution of onshore wind and offshore wind separately suggests that neither is an absolute must-have technology in 2050. However, when the total capacity of onshore- and offshore wind turbines is considered, the minimum required capacity of wind turbines in 2050 amounts to 1178 GW. Therefore, wind turbines as a power source must be considered as an absolute must-have technology for the future European energy system, however, there is still flexibility in the placement of wind on land versus placement of wind on the sea.

The data as visualised in figure 4.2 indicates PV systems as a crucial component to Europe's future energy landscape. Besides two outlier solutions, PV deployment in 2050 requires a minimum capacity of approximately 1 TW, marking it as an absolute must-have technology. While solutions that achieve this threshold by 2030 already exist within the cost-efficient design space, the majority of the SPORES in 2030 lie below 1 TW of PV deployment. For reference, PV deployment in the European Union increased from 162,6 in 2021 to 195.4 in 2022 [44]. When the SPORES are filtered for relatively low offshore wind deployment in 2050 (0-500 GW), the solutions having 0 and 320 GW of PV in 2050 remain feasible, however, the next lower bound of required PV capacity amounts to 1572 GW. Similarly, a relatively low onshore wind deployment of 0-1000 GW in 2050 pushes the minimum required PV deployment in 2050 to 1952 GW. This underlines PV system's status as an essential technology to Europe's future energy system.

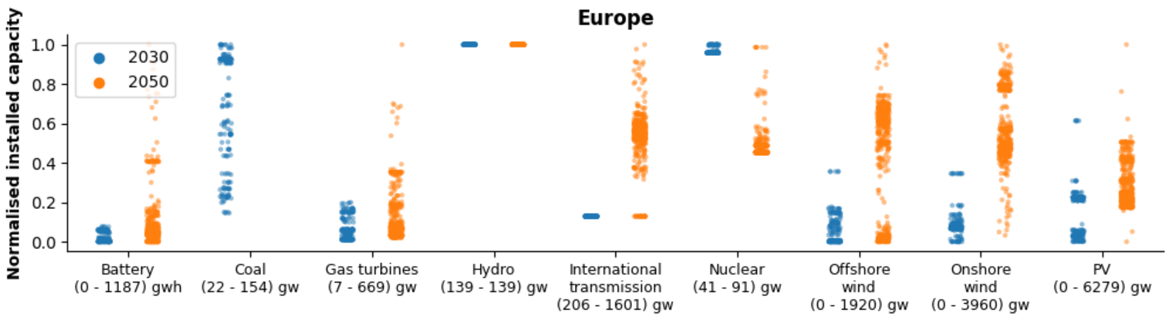


Figure 4.2: Distribution of power sector technology deployments in Europe

4.1.3. Energy System Metrics

The metrics reveal a difference in the timing of the electrification of the transport sector compared to the heat sector. By 2030, the transport sector will have a significant potential for electrification, ranging from 53% to complete electrification. Conversely, the heat sector in 2030 can be electrified for 27% at best. However, the data indicates a significant increase in potential for heat sector electrification in 2050, suggesting that a highly electrified heat sector is not only feasible but also likely, given the concentration of most SPORES at the upper end of the distribution (figure 4.3).

The geographical distribution of electricity production remains within a similar range (0.54 - 0.74) between 2030 and 2050. The range indicates that the geographical distribution of electricity production will be moderately unequal. A lower bound of 0.54 means that it will not be possible to achieve a perfectly equal distribution of electricity production across countries, while an upper bound of 0.74 indicates that extremely disproportionate geographical distributions are also not possible. This effect can be explained because great differences exist between countries in terms of resources and electricity demand, making it logical that some inequality in electricity production exists. The absence of extreme disparity is also logical as the transport of electricity between countries is not always possible and expansion of international transmission is often expensive.

A decisive aspect of the future of the European energy system lies in the potential deployment of storage discharge capacity and international exchange of electricity as both provide solutions for intermittency problems in a system dominated by renewable electricity as a primary source of energy. The metrics, visualized in figure 4.3, suggest that while there is significant potential for growth in storage capacity, growing from 0-3 TW in 2030 to 0-11 TW in 2050, this growth is not a must-have. Similarly, the average national import of electricity displays a potential, from 5.3-13.6 TWh in 2030 to 4.0-75.8 TWh in 2050. The distribution of average national import of electricity in figure 4.3, shows a likely increase in average national import as most of the 2050 SPORES are located above the range in 2030, however, this growth is not an absolute necessity as SPORES also exist in the lower region of the distribution.

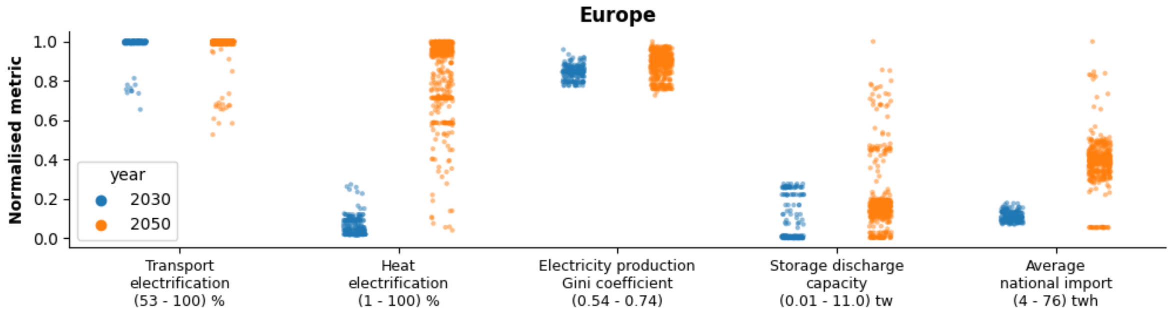


Figure 4.3: Distribution of high-level energy system metrics in Europe

4.1.4. Trade-offs

Trade-offs between the deployment of various technologies in the power sector and system-wide metrics can be identified through a detailed correlation analysis. Figures 4.4 and 4.5 respectively represent the correlation heatmaps of technologies in the power sector in Europe, France, Germany, Italy, the Netherlands, Spain, and the United Kingdom (UK), and the system-wide metrics for 2030 and 2050. Tables 4.1 and 4.2 provided an overview of the strongest correlations per region. Examining how changes in the deployment of technologies and system-wide metrics are related provides insight into the interplay between technologies and metrics and the potential synergies or conflicts between them. Such understanding allows stakeholders to make informed decisions, balancing the deployment of technologies with desired system outcomes.

Trade-offs in 2030

The 2030 correlation heatmap, visualised in figure 4.4, reveals gas turbines as a potential alternative to coal-fired power generation given their high negative coupling. This effect is strongest in Italy, Germany, and Europe as a whole. In Europe as a whole, the deployment of offshore wind also has strong negative correlations with the installed capacity of coal-fired power generation. However, within France, Germany, Italy, Spain, and the UK, this effect is not prevalent. This suggests that as coal phase-out initiatives gain traction, the adoption of gas turbines and offshore wind can provide an alternative.

Another strong inverse coupling emerges between the electricity production gini-coefficient and the deployment of battery storage and gas turbines. Essentially, firm capacity in the form of gas turbines and the flexibility of battery storage enable countries to become more self-sufficient in their energy needs because they provide a controllable source of electricity that can be tailored to local demand, reducing the need for import of electricity from other regions. The heatmap suggests that battery storage and gas turbines can play a role in decentralising electricity production and creating a more equal geographical distribution.

The observed positive correlation between PV and coal deployment in Europe, France, and Spain, and to a smaller extent in Germany and Italy, may seem counterintuitive at first. However, the coupling of PV and coal deployment can be explained by the increased need for dispatchable generation such as coal, especially during nighttime. Coal-fired power generation is one of the cheaper solutions to solve the intermittency problem caused by the high deployment of solar power. In Italy and the UK, PV is deployed alongside battery capacity to provide dispatchable generation.

A limitation of the 2030 Euro-calliope model is its fixed approach towards the deployment of international transmission. This static modeling means that it is not possible to identify relationships between the deployment of generation technologies and the deployment of international transmission lines. For future iterations, it is important to model the expansion of international transmission lines to accommodate an increasing exchange of electricity between countries.

Table 4.1: Overview of strong, region-specific correlations in 2030

Region	**Correlations**
France	(I) Positive correlation between gas turbines and batteries (II) Positive correlation between PV and coal
Germany	(I) Negative correlation between coal and gas turbines
Italy	(I) PV is coupled with coal and mostly batteries (II) Negative correlation between PV and gas turbines
the Netherlands	(I) PV is coupled with batteries (II) Negative correlation between onshore and offshore wind
Spain	(I) PV is coupled with coal (II) Negative correlation between PV and onshore wind
UK	(I) PV is coupled with batteries (II) Negative correlation between offshore and onshore wind
Europe	(I) PV is coupled with batteries and coal (II) Gas turbines have a negative correlation with coal
System metrics	(I) Flexibility reduces the electricity production gini. Gini coefficient increases with offshore wind, decreases with battery, coal, and gas.

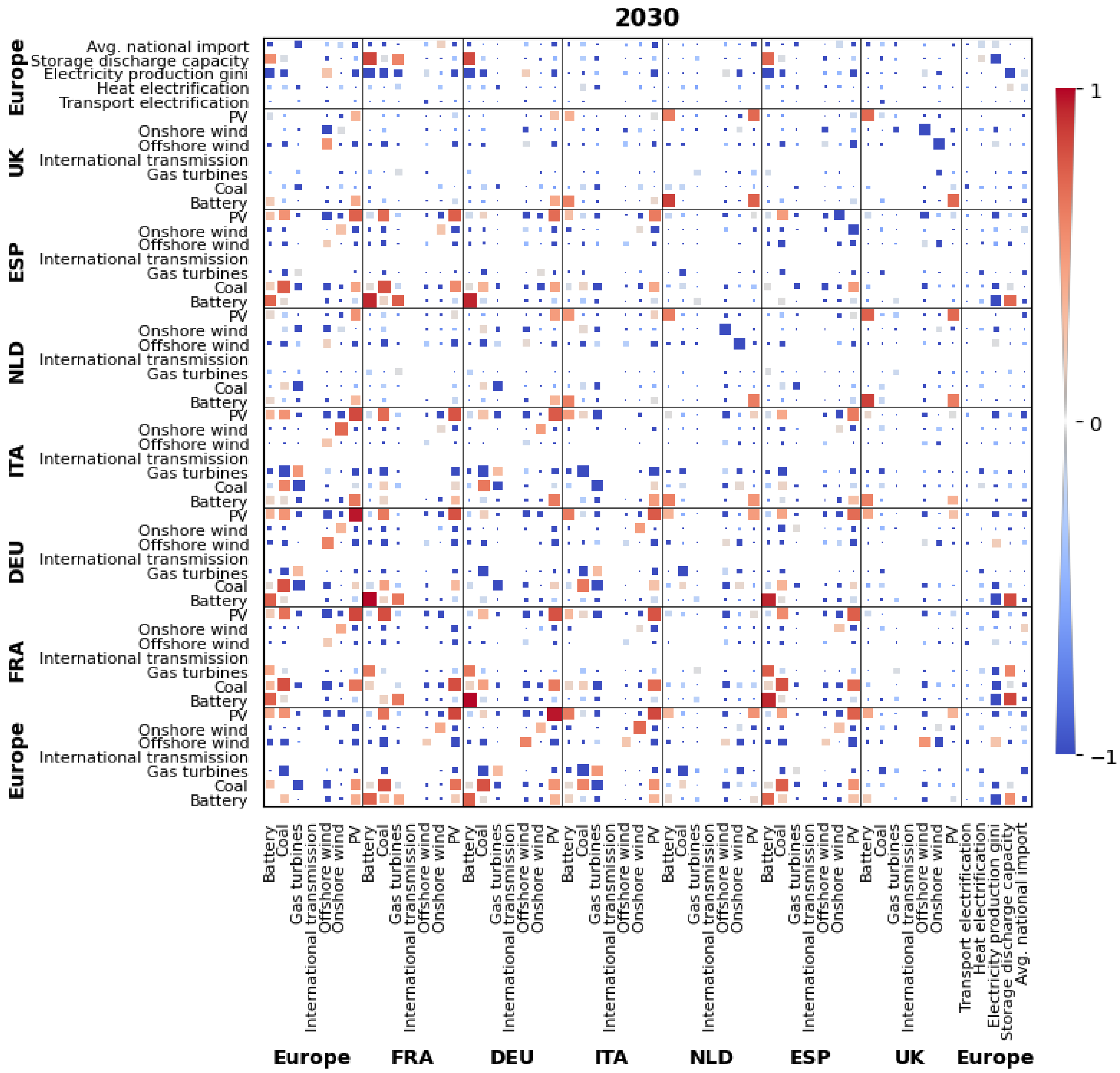


Figure 4.4: Correlation of Deployed Technology Capacity in the Power Sector across all 190 SPORES in 2030

Trade-offs in 2050

By 2050, a strong negative coupling between deployment of onshore and PV, with offshore wind becomes apparent. This effect is present in all regions visualised in figure 4.5 except for Spain. This indicates that most countries can choose between onshore and offshore wind deployment or go for a combination of both. Also, there is a clear indication that PV can replace deployment of offshore wind. These relations can be important to address problems with land availability in the face of social and/or political discussions around what land should and should not be used for.

Another clear trade-off can be identified between the deployment of gas turbines and the international exchange of electricity. As coal-fired power generation is completely phased out in 2050, gas turbines fired with bio- and synthetic fuels provide the only form of dispatchable generation in the power sector. Figure 4.5 shows a clear negative coupling between the deployment of gas turbines and international transmission capacity and the average national import of electricity. The deployment of gas turbines can be important to achieve self-sufficiency on a national scale. Moreover, the deployment of gas turbines shows a strong negative correlation with heat sector electrification. This effect can be explained by the fact that combined heat and power (CHP) plants are grouped with CCGT generating units, thus reducing the necessity for heat sector electrification.

Figure 4.5 displays a clear trend where the increased deployment of PV and onshore wind results in a more equitable distribution of electric production. This can be attributed to the widespread feasibility of installing these technologies across countries, in contrast to the geographically limited potential of offshore wind. In contrast to PV and onshore wind, the deployment of offshore wind shows a strong positive correlation with the electricity production gini-coefficient. This becomes important in the decisions that need to be made around the scale of supply and balancing of electricity in the European energy system. Deployment of PV and onshore wind in combination with battery storage favor a more equitable energy system in terms of electricity production that relies more on the supply on a national scale, whereas deployment of offshore wind favors a system that relies on international balancing and transmission.

Interesting relations emerge between the expansion of international transmission capacity to specific countries and the deployment of generation capacity in Europe. In the United Kingdom, increased international transmission capacity triggers more offshore wind in Europe and substitutes PV and onshore wind. In all other countries, the deployment of country-specific transmission capacity could potentially reduce the installation of gas turbines and PV.

Table 4.2: Overview of strong, region-specific correlations in 2050

Region	Correlations
France	(I) PV and onshore wind have a negative correlation with offshore wind (II) Gas turbines have a negative correlation with international transmission
Germany	(I) PV and onshore wind have a negative correlation with offshore wind (II) Batteries and gas turbines have a negative correlation with international transmission
Italy	(I) Onshore wind is negatively correlated with offshore wind (II) Gas turbines and PV have a negative correlation with international transmission
the Netherlands	(I) Onshore wind is negatively correlated with offshore wind (II) Gas turbines have a negative correlation with international transmission
Spain	(I) No strong correlations
UK	(I) PV and onshore wind have a negative correlation with offshore wind (II) International transmission has a negative correlation with batteries, gas turbines and PV
Europe	(I) PV and onshore wind have a very strong negative correlation with offshore wind (II) Gas turbines have a negative correlation with international transmission
System metrics	(I) Deployment of PV and onshore wind decrease the electricity production gini. The Gini coefficient increases with offshore wind. (II) International transmission capacity is coupled with average national import of electricity

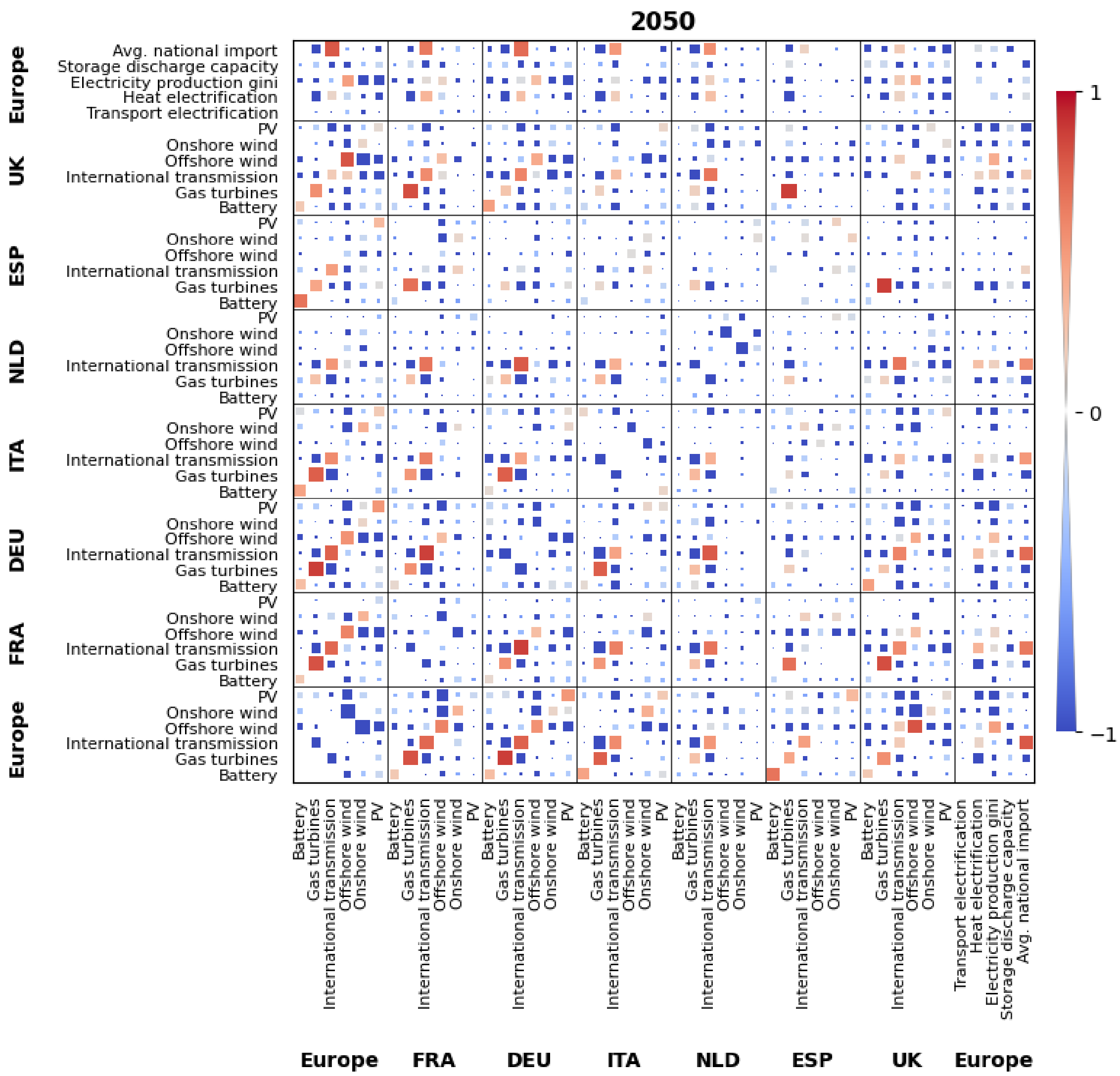


Figure 4.5: Correlation of Deployed Technology Capacity in the Power Sector across all 441 SPORES in 2050

4.2. SPORES of 2030 Compared to Currently Installed Capacity

Pickering, Lombardi, and Pfenninger [4] and Lombardi, Pickering, and Pfenninger [25] have proved that the SPORES method applied to the Euro-Calliope model provides useful insights into the maneuvering space for the European energy system of 2050. However, this approach does not take currently installed capacities into account when exploring the solutions space. Especially for the energy system of 2030, which is already in the near future, it can be expected that this approach delivers some solutions that are impractical in reality.

In Europe, most countries have committed to expanding renewable power generation capacity and to decommissioning coal-fired power plants [33, 36, 37, 38]. Therefore, it is unlikely that European countries will see the decommissioning of PV or wind capacity or expansion of coal-fired power capacity. Looking at the results in Chapter 4.1, significant investments are required to facilitate the transition from an energy system dominated by fossil-based energy sources towards a system largely dependent on renewable electricity as a means of primary energy supply. One sure thing is that coal-fired power generation needs to be completely phased out by 2050 making it highly unlikely that currently installed capacities of coal power plants will increase in the short- and long term. Moreover, countries are intensifying efforts to increase the deployment of wind technologies and PV systems to reach committed sustainability targets. Because the SPORES method finds distinctly different SPORES by minimising and maximising deployment for different technologies, the algorithm will likely find SPORES that are not realistic in the context of the expected growth in renewable power generators and the decline of coal-fired power plants. The 2030 SPORES can be tested for its realism in practice by filtering the SPORES based on the assumption that the installed capacity of onshore- and offshore wind, and PV will not decrease between now and 2030, and installed coal capacity will not increase between now and 2030. In light of this assumption, the fourth column shows the amount of SPORES that would be realistic given the currently installed capacity of that technology. The fifth column shows the amount of SPORES that are realistic if SPORES are filtered based on the previously mentioned assumptions for all technologies in one specific region. The results of this analysis are presented in table 4.3.

Table 4.3: Share of 2030 SPORES that is realistic based on currently installed capacities (as of 2022)

Region	Technology	Capacity in 2022	Realistic share of 2030 SPORES	
			Per technology	Per region
Europe	Coal	122.3 GW	135/190	27/190
	Onshore wind	203.16 GW	164/190	
	Offshore wind	27.79 GW	90/190	
	PV	205.79 GW	135/190	
France	Coal	2.51 GW	94/190	0/190
	Onshore wind	20.64 GW	39/190	
	Offshore wind	0.48 GW	36/190	
	PV	17.4 GW	108/190	
Germany	Coal	40.36 GW	69/190	0/190
	Onshore wind	58.17 GW	27/190	
	Offshore wind	8.13 GW	58/190	
	PV	66.66 GW	102/190	
Italy	Coal	6.17 GW	45/190	0/190
	Onshore wind	11.75 GW	30/190	
	Offshore wind	0.03 GW	59/190	
	PV	25.08 GW	127/190	
Spain	Coal	2.95 GW	60/190	1/190
	Onshore wind	29.30 GW	49/190	
	Offshore wind	0.01 GW	84/190	
	PV	20.52 GW	120/190	
UK	Coal	5.23 GW	103/190	0/190
	Onshore wind	14.83 GW	143/190	
	Offshore wind	19.93 GW	57/190	
	PV	14.66 GW	30/190	

Table 4.3 shows that indeed the SPORES method identifies many energy system configurations that would be impractical in reality because current renewable energy capacity is already exceeding the proposed deployments by the SPORES. This result is in line with expectations as the SPORES method is specifically designed to explore the edges of the design space. This is a fair approach for a system that lies further into the future, such as in 2050, as there is plenty of time left to adapt the system configuration. However, for a system that should be realised in less than 7 years, this greenfield approach taken by Pickering, Lombardi, and Pfenninger [4] and Lombardi, Pickering, and Pfenninger [25] seems to become less practical.

4.2.1. Refining the SPORES Approach: Ensuring Practical and Realistic SPORES

The are a few conceivable solutions to address the issue of finding many impractical SPORES for the energy system of 2030. A short description of each solution is provided below.

Increasing sample size of the base run

A straightforward way to solve the previously described issue would be to generate more base SPORES instead of technology-explicit SPORES. The base run does not target system-wide minimisation or maximisation of technologies as the technology-explicit objective does. These technology-explicit SPORES are likely to be impractical in the short term due to extremely high or low deployments of specific technologies that would not be realistic. This will increase computation time but having more base run SPORES will increase the chances that there are also more realistic solutions compared to the current state of the energy system.

Hard constraints

Another option to increase the practicality of the 2030 SPORES is to introduce hard-coded boundary conditions on the technology deployments in each region. This can be done for all technologies in the Euro-calliope model. This, however, might be a time-consuming task as data is not always available. Collecting historic capacity data for each of the 98 regions in the Euro-calliope model could be difficult as most are sub-national regions. This study however, provides all the required data (see chapter 3.1.5) to generate 2030 SPORES on a national geographic resolution in a brownfield approach for the power sector instead of the greenfield approach that led to many impractical solutions. To explore the benefits of decommissioning to some degree, the boundary conditions could be set at a capacity value that is lower than the current capacity but in a realistic range. This would allow SPORES to be found that deploy some decommissioning of, for example, PV. However, this would not allow the model to decommission all currently installed PV capacity as this would not be realistic. When data for all technologies is not available boundary conditions could be set only for technologies that have readily available historical data and of which it is almost certain that installed capacity is likely to increase or decrease (e.g. PV capacity).

Filtering out impractical solutions

Finally, the most simple approach to deal with impractical SPORES would be to simply filter them out. All SPORES with capacities below current capacities could be filtered out. It might be useful to consider the possibility of some degree of decommissioning of certain technologies in certain regions. Instead of filtering out all SPORES below current installed capacities, it could be possible to filter out SPORES with unrealistic differences between the currently installed capacity and the suggested capacity of the SPORE but not the ones where the differences are small. A big advantage of this method is that it does not require re-running existing SPORES. It can be implemented as a way of filtering SPORES based on practicality as a post-processing step. A downside is that this approach merely filters out impractical SPORES and does not find more realistic ones.

4.3. Scenarios for Future Energy System Configurations

This section presents the scenarios resulting from the clustering algorithm as described in section 3.3 for Europe, Germany, and the Netherlands. A scenario is defined as a cluster of SPORES in a given year with similar technology deployments in the power sector. Each scenario is given a descriptive name based on the median technology deployments within the scenario in comparison with the complete distribution of SPORES that span the design space for the given year. Technology deployment is considered 'low' when the median capacity value lies within the 25th percentile of the complete distribution and 'high' when the median value exceeds the 75th percentile capacity value of the total distribution of deployments. First, the scenarios in 2030 and 2050 for the power sector in Europe are described. Thereafter, the scenarios for 2030 and 2050 for the power sectors of Germany and the Netherlands will be presented similarly.

The optimal number of scenarios that are found using the k-means clustering algorithm in combination with the silhouette score method are stated in table 4.4 with their corresponding silhouette score. The silhouette score ranges from -1 to 1, where a value close to 1 indicates that a data point matches well to its cluster and poorly to other clusters. The silhouette score can be interpreted as follows. Values close to 1 mean that the clusters are far apart from each other, and distinguished. A silhouette score close to 0 means that clusters are close and not separated. Silhouette scores close to -1 mean that clusters are not identified correctly. From the results in table 4.4, it can be concluded that the clustering algorithm performs reasonably well as all silhouette scores are greater than 0.5. Although it seems to perform better for the 2030 SPORES than the 2050 SPORES. This could be attributed to the fact that there are more than twice as many SPORES in 2050 compared to 2030. More SPORES increases the variability within the dataset as finding maximally diverse solutions is inherent to the process of finding SPORES. This can lead to less distinctive clusters of SPORES.

Table 4.4: Optimal number of scenarios in 2030 and 2050 for power sectors in Europe, France, Germany, Italy, the Netherlands, Spain, and the UK based on the highest average silhouette score

Country	Year	Optimal number of scenarios	Silhouette score
Europe	2030	13	0.712
	2050	6	0.581
France	2030	14	0.784
	2050	14	0.455
Germany	2030	13	0.744
	2050	12	0.377
Italy	2030	15	0.786
	2050	11	0.414
Netherlands	2030	13	0.725
	2050	6	0.565
Spain	2030	15	0.781
	2050	11	0.476
United Kingdom	2030	14	0.800
	2050	13	0.366

4.3.1. Scenarios in Europe

Considering total technology deployments for the European power sector as the sum of all countries in the Euro-calliope model, 13 scenarios in 2030 and 6 scenarios in 2050 were identified and visualised in figure 4.6. Looking at the general trend, a notable increase in installed technology capacities can be seen from 2030 to 2050 regardless of the scenario. The degree to which certain technologies need to grow between 2030 and 2050 however varies. Scenarios in 2050 are dominated by some combination of PV, onshore-, and offshore wind. The SPORES are distributed relatively even across scenarios in 2030, whereas most SPORES in 2050 belong to scenario 4, which contains 236/441 SPORES as can be seen in figure 4.6.

Technology deployments within each scenario in figure 4.6 represent the median capacity for each technology for all SPORES within the specific scenario. Technology deployment is considered 'high' when the median capacity is located in the upper quartile of the total set of SPORES. Similarly, a technology deployment of a scenario is considered 'low' when its median capacity belongs to the lower quartile of the capacity distribution (see chapter **??**). A more detailed visualisation of the distribution within each scenario is provided by Appendix **??**.

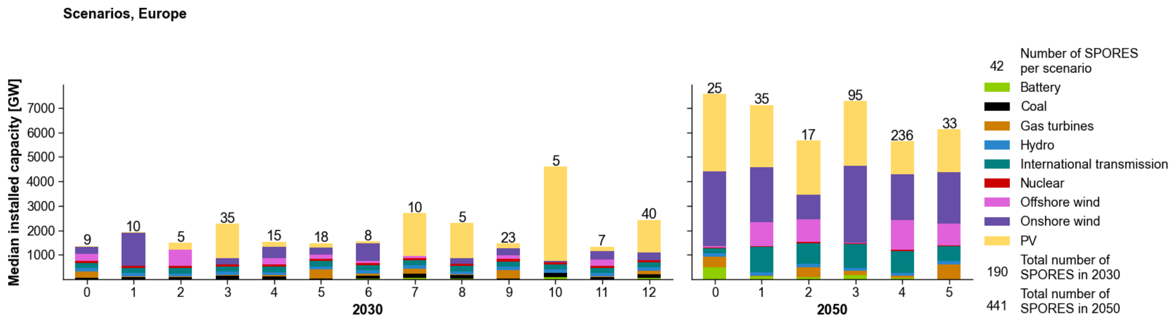


Figure 4.6: Median technology deployments for each scenario for the European power sector in 2030 and 2050. Each bar represents a stack of the median technology deployments within this scenario. The number on top of each bar represents the number of SPORES within this scenario.

These scenarios can be used to assess options for policymakers that want to target specific deployments. Table 4.5 provides a comprehensive overview of policy decisions and their corresponding scenarios for the European power sector in 2030. Table 4.6 provides a similar overview of the scenarios of the European power sector in 2050 These scenarios provide a rough understanding of characteristics and trade-offs that belong to the design space of a future energy system. For example, Europe could assess the options for an early phase-out of coal-fired power generation. While a complete phase-out of coal-fired power generation does not exist in the design space spanned by the 2030 SPORES, low deployments in 2030 are possible (scenarios 0, 5, and 9). Low deployment of coal is made possible with high deployment of other firm capacity (scenarios 5 and 9 see high gas turbine deployment while scenarios 0 and 9 see relatively high nuclear deployment). Low deployments of coal are always accompanied by low deployment of batteries. Deploying little PV by 2030 (scenarios 0, 1, 5, 6, 11) is either accompanied by high deployment of wind turbines (scenarios 0, 1, 6, 11) or by firm capacity in the form of gas turbines (scenario 5). Conversely, high deployment of PV in 2030 (scenarios 3, 7, 8, 10) is always accompanied by low onshore- or offshore wind capacity.

The scenarios of the European power sector in 2050 are characterized by high deployment of PV in combination with some form of wind energy (onshore- or offshore wind). Most scenarios deploy nearly 1 TW of international transmission capacity (scenarios 1, 2, 3, 4, and 5). Deploying less international transmission capacity is possible if high battery capacity is realized (scenario 0) or if Europe deploys a lot of firm capacity in the form of gas turbines. The only scenario in 2050 (scenario 4) without extreme deployments contains most SPORES by a wide margin (236/441 SPORES). Table 4.6 shows there are no scenarios that have a low median deployment of PV. Outlier SPORES with very low PV deployments can be found in scenario 3. Also, there are no scenarios in 2050 that see a high median deployment of offshore wind. Very high deployments of offshore wind can be found in scenarios 1 and 4. These outlier SPORES can be found in figures B.16, B.18 and B.19 in Appendix B.

Table 4.5: Europe 2030 scenarios

Policy decision	Scenarios
Low Battery	0, 5, 9
High Battery	7, 12
Low Coal	0, 5, 9
High Coal	7, 8, 10
Low Gas turbines	1, 2, 3, 8
High Gas turbines	5, 9
Low Nuclear	1, 2, 5, 8, 10
High Nuclear	0, 7, 9, 11
Low Offshore wind	3, 8
High Offshore wind	0, 2, 4, 11
Low Onshore wind	2, 7, 10
High Onshore wind	1, 4, 6
Low PV	0, 1, 5, 6, 11
High PV	3, 7, 8, 10
No extreme deployments	-

Table 4.6: Europe 2050 scenarios

Policy decision	Scenarios
Low Battery	5
High Battery	0, 3
Low Gas turbines	1
High Gas turbines	0, 2, 5
Low International transmission	0, 5
High International transmission	1
Low Nuclear	1
High Nuclear	2
Low Offshore wind	0, 3
High Offshore wind	-
Low Onshore wind	2
High Onshore wind	3
Low PV	-
High PV	0, 1, 3
No extreme deployments	4

4.3.2. Scenarios in Germany

For the power sector in Germany, the clustering algorithm has identified 13 scenarios in 2030 and 12 scenarios in 2050 (see figure 4.7. Just as for Europe, nearly all scenarios in 2050 see a significant increase in total installed capacity in the power sector between 2030 and 2050. In 2050, scenario 9 contains most SPORES (97/441) while in 2030 scenarios 7 and 9 contain only 2 SPORES or less. Apart from these scenarios, the scenarios in Germany have no extreme concentrations of SPORES within a specific scenario. Scenarios in 2050 always rely on a combination of PV and wind, sometimes combined with gas turbines or battery storage, whereas scenarios in 2030 rely more on either PV or wind technologies accompanied by coal or gas turbines.

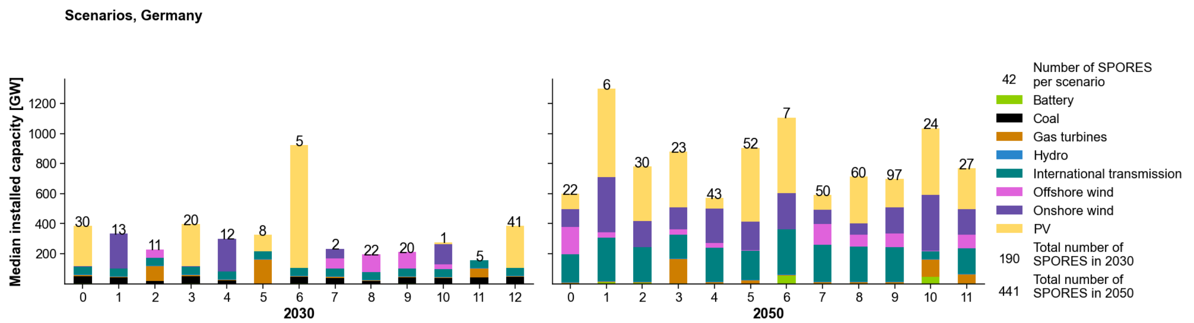


Figure 4.7: Median technology deployments for each scenario for the power sector of Germany in 2030 and 2050. Each bar represents a stack of the median technology deployments within this scenario. The number on top of each bar represents the number of SPORES within this scenario.

All scenarios in 2030 are characterized by a combination of an intermittent renewable energy source (PV, or wind) and firm capacity in the form of coal and/or gas turbines. In 2030, there are no scenarios that deploy a combination of PV and wind as most scenarios deploy an 'all-in' strategy on either PV or wind. It is unlikely that these scenarios will play out because Germany has seen significant deployment of PV and wind in recent years, which would be costly to decommission by 2030. A complete phase-out of coal-fired power generators by 2030 is possible in Germany (scenario 5). A coal phase-out, however, requires a very high deployment of gas turbines. This highlights the role of flexible capacity in transitional stages where transmission capacity cannot grow that fast and batteries are significantly more expensive. Relatively low deployment of coal power plants goes hand in hand with low deployment of batteries (see table 4.7). However, in 2030, battery capacity is so small that it is barely noticeable. Germany has a lock-in risk for PV and gas turbines looking at scenarios 5 and 6. Scenario 5 in 2030 deploys a very high-capacity gas turbines, that would need to be decommissioned by 2050 to have flexibility of choosing other scenarios in 2050. Similarly, scenario 6 in 2030 deploys more PV than all scenarios in 2050. Regardless of how realistic it would be for Germany to deploy over 600 GW of PV by 2030, it would be unwise to do so as most of it would have to be decommissioned by 2050 to reach other scenarios.

The scenarios in 2050 for the power sector of Germany is dominated by high deployments of a combination of PV, wind, and international transmission capacity. All scenarios deploy at least 200 GW of capacity that can provide flexibility (international transmission capacity, gas turbines, and batteries). In most scenarios, this flexible capacity makes up for 20-30% of total installed capacity. Reduced transmission capacity is can only be achieved by high deployment of gas turbines (scenarios 3, 10, and 11), including high battery deployment in the case of scenario 10. Lower deployments of PV are always accompanied by high onshore wind capacity (scenario 4) or high offshore wind capacity (scenarios 0 and 7).

Table 4.7: Germany 2030 scenarios

Policy decision	Scenarios
Low Battery	2, 4, 5, 8
High Battery	0, 3
Low Coal	2, 5, 6
High Coal	6, 12
Low Gas turbines	12
High Gas turbines	2, 5, 11
Low Offshore wind	4, 5
High Offshore wind	7, 8, 9
Low Onshore wind	2, 5
High Onshore wind	1, 4, 7, 10
Low PV	2, 4, 8, 11
High PV	3, 6
No extreme deployments	-

Table 4.8: Germany 2050 scenarios

Policy decision	Scenarios
Low Battery	0, 5
High Battery	1, 2, 6, 10
Low Gas turbines	0, 1, 2, 6
High Gas turbines	3, 10, 11
Low International transmission	0, 3, 10, 11
High International transmission	1, 6, 7
Low Offshore wind	2, 5, 6, 10
High Offshore wind	0, 7
Low Onshore wind	7, 8
High Onshore wind	1, 4, 6, 10
Low PV	0, 4, 7
High PV	1, 5, 6, 10
No extreme deployments	9

4.3.3. Scenarios in the Netherlands

Similar to Europe as a whole and Germany, the scenarios in the Netherlands all see a significant expansion of installed capacity between 2030 and 2050. Many scenarios see the deployment of only either PV, onshore- or offshore wind without any of the other technologies (scenarios 0, 2, 4, 5, 6, 7, 8, 9 12 in 2030 and scenarios 1 and 2 in 2050 in figure 4.8). While these solutions provide interesting insights, adopting an 'all-in' strategy on one power generation technology is not likely to materialize as the Netherlands has currently installed considerate amounts of PV, onshore- and offshore wind. The distribution of SPORES across scenarios is relatively even in 2030 whereas the SPORES in 2050 seem to be concentrated more in the scenarios relying on wind. The median installed capacities per technology for the 2030 and 2050 scenarios are visualized in figure 4.8. Tables 4.9 and 4.10 categorize the scenarios based on high or low deployment per technology.

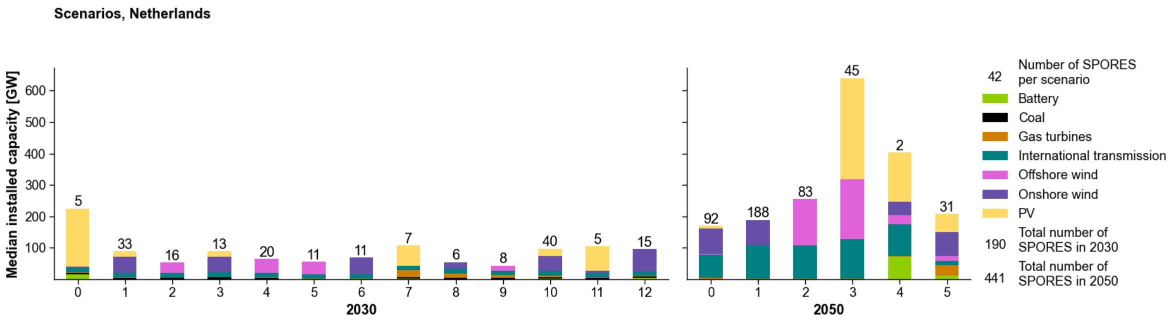


Figure 4.8: Median technology deployments for each scenario for the power sector of the Netherlands in 2030 and 2050. Each bar represents a stack of the median technology deployments within this scenario. The number on top of each bar represents the number of SPORES within this scenario.

The power sector of 2030 in the Netherlands is mostly reliant on high PV deployment (scenarios 0, 7, 10, 11), high wind deployment (scenarios 2, 4, 5, 6, 12) or high gas turbine capacity (scenario 7, 8, 9, 10). In 2030, high deployment of onshore wind is always accompanied by low offshore wind deployment (scenarios 6 and 12) and conversely, high offshore wind deployment always forces low capacity of onshore wind (scenarios 2, 4, 5). When the power sector relies on high PV capacity for its energy needs, high deployment of firm capacity is needed. Scenario 0 solves extreme PV deployment with very high battery deployment in combination with high coal-fired power generation. In the case of scenario 11, only high coal-fired power generation capacity is used in combination with high deployment of PV. Scenarios 7 and 10 deploy lots of gas turbines to deal with the intermittency caused by high PV capacity. Deploying extremely high PV capacity by 2030, in the case of scenario 0, introduces a lock-in risk for PV as the PV deployment exceeds the PV deployment of the majority of scenarios (and SPORES) in 2050. This scenario is, however, not likely to materialise because the Netherlands would have to increase PV deployment from 19 GW in 2022 to more than 150 GW by 2030. To realize low deployment of coal-fired capacity, high wind capacity is always required. Scenarios 2 and 5 use high deployment of onshore wind and scenario 6 deploys high offshore wind capacity. These scenarios are always accompanied by low battery capacity.

In 2050, high deployment of PV in the Netherlands is possible combined with high firm capacity. Scenario 3, deploys high international transmission to deal with high PV capacity combined with high onshore wind deployment. Scenarios 4 and 5 deal with the intermittency of PV by deploying relatively high battery capacity. In the case of scenario 5, this is also accompanied by high deployment of gas turbines. When the Netherlands deploys relatively high wind capacity, low deployment of international transmission capacity becomes infeasible. Scenarios 1, 2, and 3 in 2050 rely on only onshore-, or offshore wind. While these scenarios contain nearly all SPORES (363/441) it is not likely that these scenarios are realistic since the Netherlands has already deployed significant PV, onshore- and offshore wind capacity. Most scenarios in 2050 see a significant expansion of international transmission capacity in combination with little to no deployment of gas turbines and batteries. Scenario 5 in 2050 is the only scenario that deploys little international transmission capacity while scenario 4 sees expansion of the power grid accompanied by high deployment of battery capacity. This scenario however contains only 2 SPORES. Decreasing the deployment of international transmission capacity by 2050 can be realized by high deployment of batteries and gas turbines while using a mix of wind technologies and PV (scenario 5).

Table 4.9: The Netherlands 2030 scenarios categorized for relatively low and high deployment of each technology

Policy decision	Scenarios
Low Battery	2, 5, 6, 8, 9, 11
High Battery	0, 7, 12
Low Coal	2, 5, 6
High Coal	0, 3, 4, 7, 8, 9, 11, 12
Low Gas turbines	1
High Gas turbines	7, 8, 9, 10
Low Offshore wind	6, 7, 11, 12
High Offshore wind	2, 4, 5
Low Onshore wind	2, 4, 5, 7, 9
High Onshore wind	6, 12
Low PV	2, 5, 6, 8, 9
High PV	0, 7, 10, 11
No extreme deployments	-

Table 4.10: The Netherlands 2050 scenarios categorized for relatively low and high deployment of each technology

Policy decision	Scenarios
Low Battery	3
High Battery	4, 5
Low Gas turbines	-
High Gas turbines	0, 5
Low International transmission	0, 5
High International transmission	3
Low Offshore wind	-
High Offshore wind	2, 3
Low Onshore wind	2, 3
High Onshore wind	1
Low PV	-
High PV	3, 4, 5
No extreme deployments	-

4.4. Case Study: Germany's 2030 PV Target of 215 GW

Before analyzing the impact of Germany's 2030 PV capacity target, it is important to understand the maneuvering space of its energy system in 2030 and 2050. Figures 4.9 and 4.10 respectively visualize the distribution of Germany's primary energy supply and technology deployment for 2030 and 2050. Figure 4.9 shows that coal, oil, and natural gas are the main primary energy sources in 2030 to be replaced by renewable electricity, electricity import, and biofuels in 2050. Reduced dependency on coal as a means of primary energy supply is possible in 2030 as configurations exist with energy supplied by coal amounting to as low as 38 TWh. However, natural gas will remain a must-have source of energy as all solutions require a natural gas supply of at least 817 TWh. Respectively, the supply of coal and natural gas in 2021 amounted to 623 TWh and 896 TWh [45].

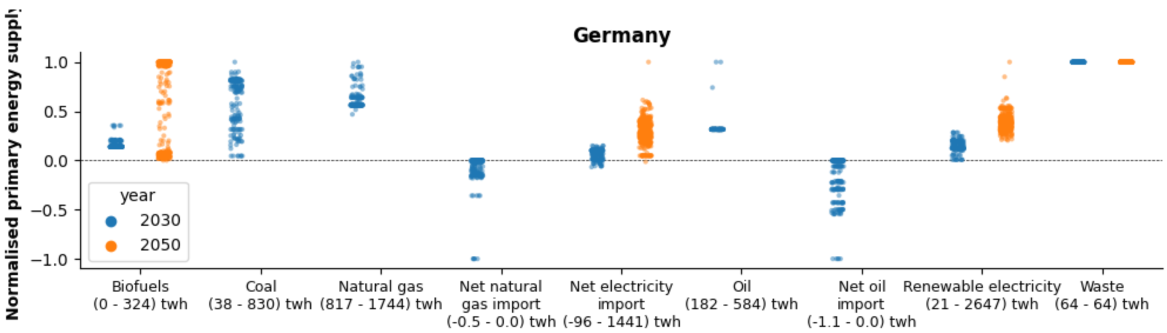


Figure 4.9: Distribution of total primary energy supply (TPES) per source in Germany

Looking at the distribution of technology deployments in the power sector, as visualized in figure 4.10, it becomes clear the wind and solar power will dominate Germany's future energy system. Neither solar nor wind seems to be an absolute must-have technology as low deployments for both exist. Compared to currently installed capacities of 66.7 GW PV, 58.2 GW of onshore wind and 8.1 GW of offshore wind leave significant room for growth towards future systems. With increasing potential for intermittent renewable energy sources, there is also significant potential for growth in battery capacity and international transmission capacity. As of 2022, Germany has 40 GW of coal-fired power generation and 25 GW of gas turbines installed. Technically, a small deployment of coal is still possible, however, it is more likely that deployment of coal will decrease towards 2030 as it needs to be completely phased out by 2050. For gas turbines, a significant increase in deployment is possible both in 2030 and 2050. However, as natural gas will be phased out in 2050, the turbines need to switch to running on synthetic fuels between 2030 and 2050.

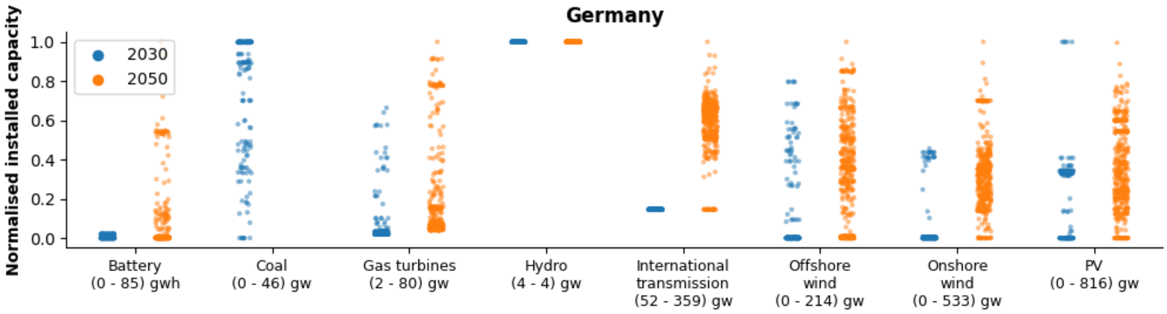


Figure 4.10: Distribution of power sector technology deployments in Germany

To meet Germany's target capacity of 215 GW by 2030, an average growth rate of 18.5 GW/year is required. This is an ambitious target considering the growth of PV capacity between 2021 and 2022 amounted to 7.3 GW. Apart from a set of outlier 2030 SPORES (requiring over 800 GW of PV by 2030) the 2030 SPORES are evenly distributed around the target. A total of 96/190 SPORES meet the target of at least 215 GW of installed PV capacity by 2030. Assuming this target is met, 16/441 SPORES in 2050 still require higher average growth than 18.5 GW/year while further growth between 0 and 18.5 GW/year is sufficient for 226/441 SPORES, leading to installed PV capacity between 215 and 585.8 GW in 2050. A reduction of PV capacity from 215 GW in 2030 is also possible as 199/441 SPORES in 2050 deploy less than 215 GW of PV in Germany.

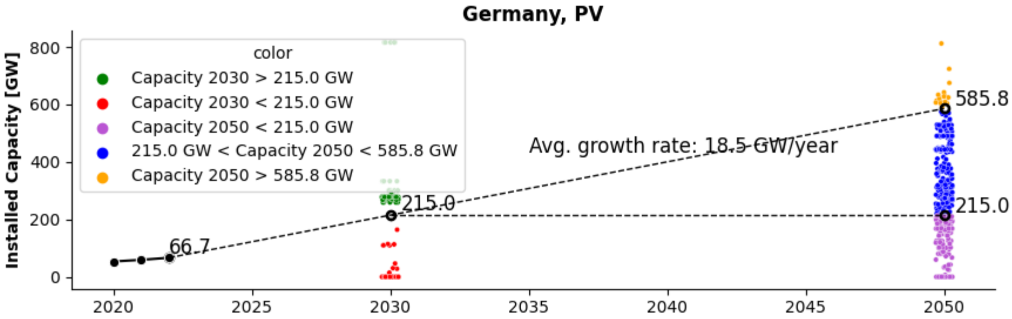


Figure 4.11: Trajectory to PV capacity target in Germany

Impact on Primary Energy Sources

Figures 4.12 visualizes the impact of Germany's 2030 PV target capacity on the maneuvering space considering the primary energy supply per source. For each source, the left distribution represents the 2030 SPORES and the right distribution represents the 2050 SPORES. The colored SPORES represent the subset of SPORES as shown in figure 4.11. All other SPORES are visualized in grey. Interestingly, meeting the 2030 target PV capacity of 215 GW forces high reliance on coal as a primary energy source. Coal is favored over natural gas as it provides a cheaper source of energy for dispatchable power generation. Supply of natural gas in 2030 is constrained to a maximum of 1113 TWh when the PV target is met while the minimum needed coal supply is raised to 574 TWh. Maintaining steady growth between 2030 and 2050 towards a PV deployment in the range of 215 of 585.8 GW in 2050 does not affect the maneuvering space of 2050 significantly (see the blue SPORES in figure 4.12). Only the range of renewable electricity supply in 2050 is slightly reduced by Reducing the distribution of renewable electricity to a minimum of 540 TWh and a maximum of 1607 TWh.

If the deployment of PV is accelerated after meeting the 2030 target to reach an installed PV capacity of over 586 GW, the maneuvering space experiences a stronger impact as visualized by the orange SPORES in figure 4.12. Deploying more than 586 GW of PV by 2050 significantly raises the minimum required supply of biofuels and renewable electricity to 254 TWh and 1089 TWh respectively. Also, accelerating PV deployment to above 586 GW forces Germany to become a net importer of electricity as the minimum net import of electricity is raised to 203 TWh.

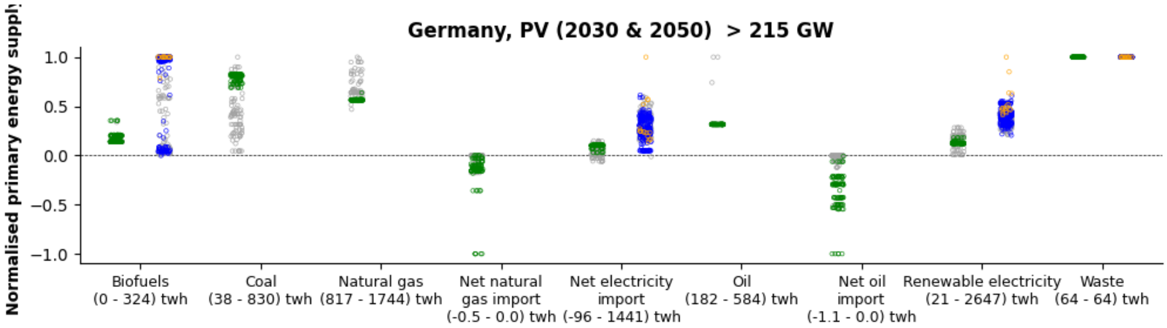


Figure 4.12: Change in distribution of TPES when PV target in Germany is achieved

The impact of failing to meet the target PV capacity on the distribution of primary energy sources is barely noticeable (figure 4.13). Only SPORES with extremely high renewable electricity supply (larger than 1469 TWh) become infeasible. In terms of the potential for the use of biofuels and other sources, the range of the SPORES distribution remains unaffected. Moreover, we can see that the configurations are available when filtering out the spores characterised by high PV deployment can rely on smaller values of coal deployment when flexibility can be provided by CHP and CCGT plants. Worthwhile to mention that CCGT power plants might be re-purposed in 2050 to run on syn-fuels. Looking at figure 4.13, it becomes clear that in order to keep low coal (early phase-out), the best strategy might be to invest in wind instead of solar. Well, still investing in solar but any value of wind is compatible with 2050.

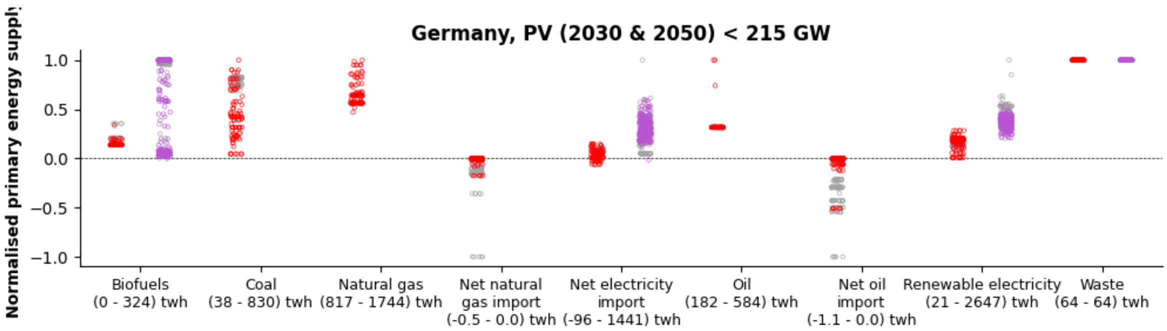


Figure 4.13: Change in distribution of TPES when PV target in Germany is failed

Impact on Technology Deployments

Figures 4.14 and 4.15 show the impact of Germany's 2030 PV target capacity on deployment of other technologies within the power sector. The green SPORES in figure 4.14 represent the subset of 2030 SPORES that meet the PV target by 2030. In line with the analysis on energy supply per source, the deployment of coal capacity is pushed to the upper range of the distribution while the deployment of gas turbines is pushed to the lower end of the distribution. Deploying at least 46 GW of coal-fired power generation is required to remain in the cost-efficient design space that is defined by the set of 2030 SPORES. This is not in line with Germany's ambition to completely phase out coal by 2030 [35] and it creates a lock-in risk for coal-fired power generators that could hinder a complete phase-out of coal-fired power generation that is required to achieve carbon neutrality by 2050. Moreover, deploying more than 215 GW of PV by 2030, limits deployment of onshore- and offshore wind to 20 and 3.4 GW respectively. However, Germany has currently deployed 58.2 GW of onshore wind and 8.1 GW of offshore wind. This underlines the importance of revising the SPORES approach to better suit analysis in shorter term as was described in section 4.2. While the data should be improved, it can still be concluded that deployment of wind turbines onshore- and offshore remains low when the PV target capacity. This could cause problems down the line for wind capacity as significant deployment of onshore- and offshore wind is required by 2050 (see the blue 2050 SPORES in figure 4.14). Maintaining steady growth between 2030 and 2050, limiting PV deployment to 215-586 GW by 2050, has little impact on the maneuvering space in 2050 as the range of the 2050 distribution remains the same.

When PV deployment is accelerated to above 586 GW in 2050, the impact on the maneuvering space becomes stronger. With high PV deployment in 2050, Germany requires at least 146 GW of onshore wind. Also, additional growth in international transmission capacity is required, raising its minimum deployment to 146 GW. Deployment of batteries, offshore wind, and gas turbines remain more flexible as solutions exist throughout the complete range of the distribution. However, because increasing the PV capacity above 586 GW leaves only 16 SPORES in 2050, the distribution becomes less continuous.

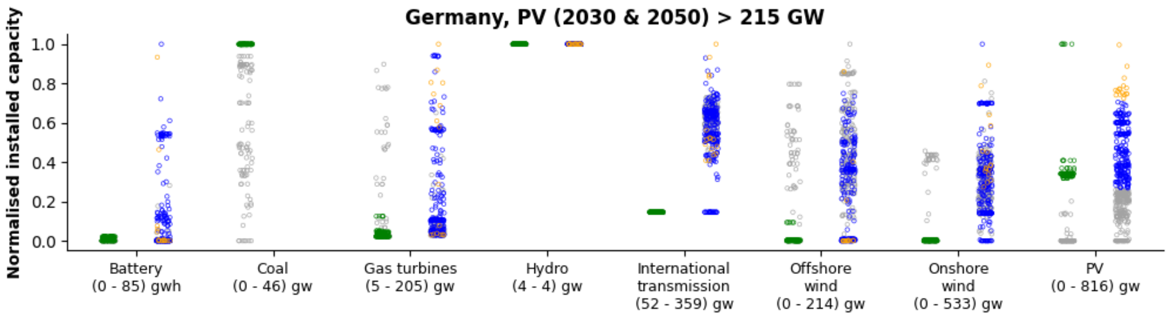


Figure 4.14: Change in distribution of technology deployments when PV target in Germany is achieved

Figure 4.15 visualises the impact of not meeting the PV target capacity in terms of technology deployments in the power sector. In 2030, the range of installed capacities for all other technologies remain unaffected, as can be concluded by looking at the red SPORES. If PV capacity is kept below 215 GW even in 2050, the impact on the maneuvering space remains little. However, keeping PV deployment below 215 GW in 2050 increases minimum deployment of international transmission capacity to 146 GW. Having low PV deployment in 2050 also reduces the need for firm capacity, decreasing maximum gas turbine deployment to 133 GW and maximum battery deployment to 24 GW.

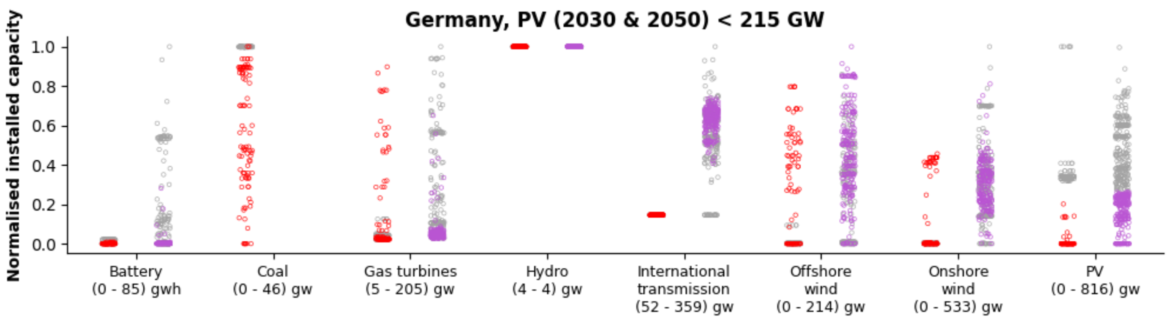


Figure 4.15: Change in distribution of TPES when PV target in Germany is failed

4.5. Case Study: The Netherlands' 2030 Offshore Wind Target of 21 GW

The Netherlands has committed to an offshore wind target capacity of 21 GW by 2030. This section evaluates the impact of this target on the maneuvering space of a future energy system in the Netherlands. First, the maneuvering space is defined by figures 4.16 and 4.17. Figure 4.16 shows that fossil based energy sources such as coal, natural gas and oil, still provide most energy for the Netherlands as of 2030. While it is possible to phase out nearly all coal use by 2030, natural gas and oil still provide at least 116 and 219 TWh, respectively. By 2050, all fossil based energy sources are completely phased out. Between 2030 and 2050 there is a significant increase in potential for use of renewable electricity as a means of primary energy growing from 227 TWh in 2030 to a maximum potential of 2539 TWh by 2050. Although there is an increase in potential of biofuels between 2030 and 2050, its overall contribution to the total primary energy supply in the Netherlands remains limited. Also, the Dutch energy system has the option to become a net importer as well as a net exporter of electricity both in 2030 and 2050.

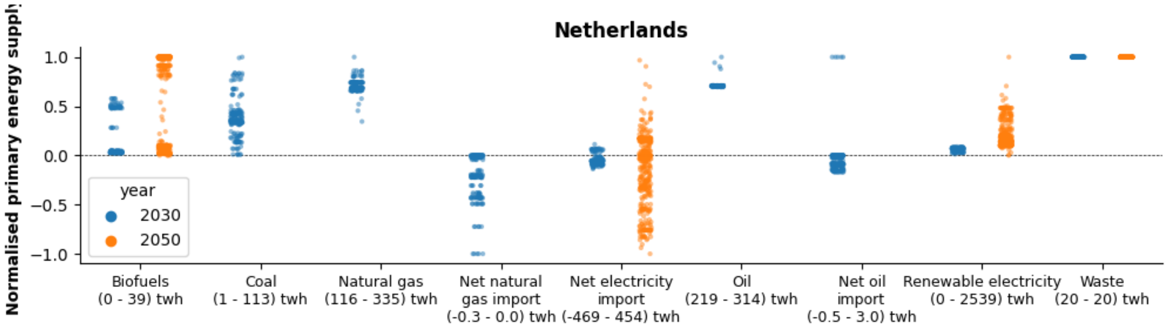


Figure 4.16: Distribution of total primary energy supply (TPES) per source in the Netherlands

The distribution of technology deployments in the Dutch power sector shows a phase-out of all coal-fired power plants accompanied by a significant increase in the deployment of offshore wind (growing from 47 GW in 2030 to 432 GW in 2050) and PV (growing from 184 GW in 2030 to 512 GW in 2050) capacity by 2050 (figure 4.17). The maximum installed capacity of the onshore wind capacity experiences a slight increase from 71 GW in 2030 to 82 GW by 2050. Moreover, a significantly increased deployment of international transmission capacity to exchange electricity with neighboring countries could be economically viable. The installed capacity of battery technology remains limited to 21 GWh apart from 2 outlier SPORES in 2050.

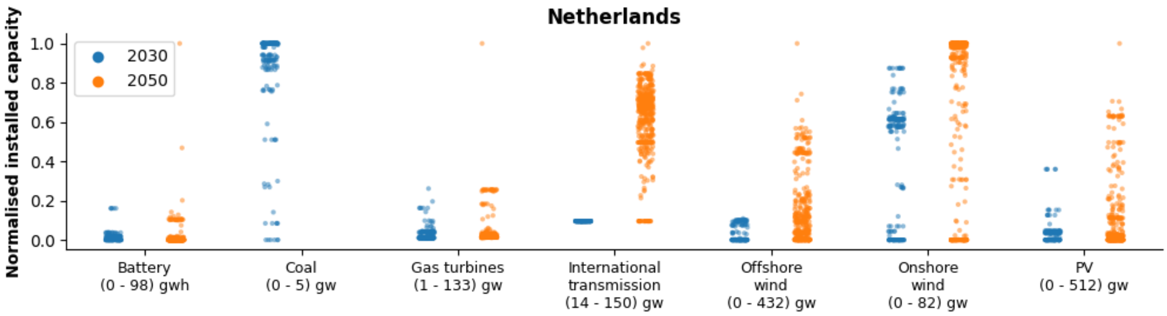


Figure 4.17: Distribution of power sector technology deployments in the Netherlands

To meet the offshore wind capacity target of 21 GW installed by 2030, the Netherlands needs to install new offshore wind capacity at an average growth rate of 2.1 GW/year. This is an ambitious target considering the currently installed capacity amounts to 2.6 GW. In 2030, only 43/190 SPORES (23%) meet 2030 offshore wind target. Even by 2050, only 217/441 SPORES (51%) deploy more than 21 GW of offshore wind. Extrapolating the growth rate that is required to meet the 2030 target towards 2050, sees offshore wind deployment in the Netherlands grow to 67.1 GW by 2050. While this is already over 25x compared to current offshore wind capacity in the Netherlands, there is a huge potential to increase offshore wind deployments up to 400 GW by 2050. In 2050, 97/441 SPORES (22%) deploy between 21-67.1 GW of offshore wind, whereas 120/441 SPORES (27%) deploy more than 67.1 GW.

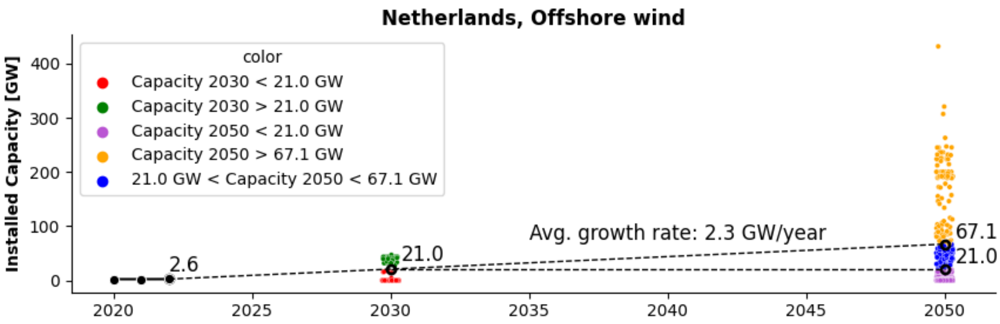


Figure 4.18: Trajectory to offshore wind capacity target in the Netherlands

Impact on Primary Energy Sources

The green 2030 SPORES in figure 4.19 show that meeting the Dutch offshore wind target by 2030 significantly reduces coal use as a primary energy source, reducing its maximum use from 113 TWh to 52 TWh. Meeting the offshore wind target by 2030 also favors the Netherlands to become a net exporter of electricity, however becoming a net importer is still possible. Maintaining the growth of offshore wind towards 2050, leading to offshore wind deployment between 21 and 67.1 GW by 2050, provides the Netherlands with flexibility to choose between being a net importer or a net exporter of electricity. However, this also limits the potential for the supply of renewable electricity to 570 TWh in 2050. Increasing offshore wind deployment beyond 67.1 GW by 2050 significantly boosts the potential for renewable electricity as a source of energy (see the yellow 2030 SPORES in figure 4.19). This level of offshore wind deployment also forces the Netherlands to become a net exporter of electricity.

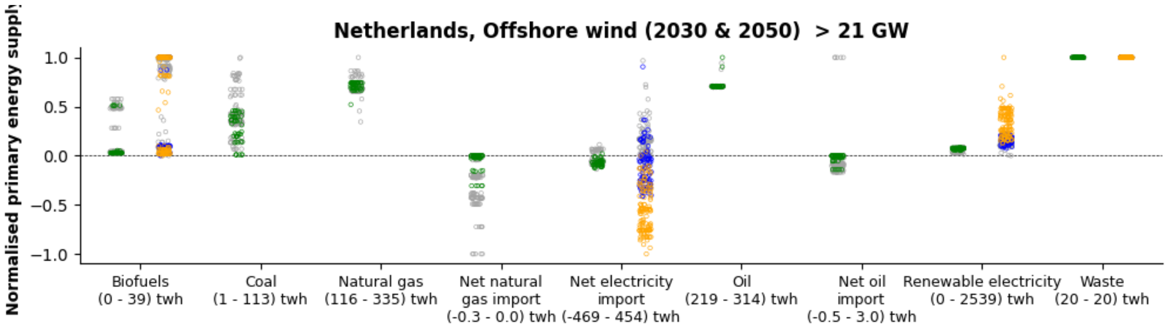


Figure 4.19: Change distribution of TPES when offshore wind target in the Netherlands is achieved

Failing to deploy 21 GW of offshore wind capacity by 2030 does not have a significant impact on the distribution of technology deployments of other technologies in 2030 (see the 2030 SPORES colored in red in figure 4.20). However, failing to deploy at least 21 GW of offshore wind by 2050 forces the Netherlands to import significant amounts of electricity in most 2050 SPORES (see the 2050 SPORES colored in purple in figure 4.20)

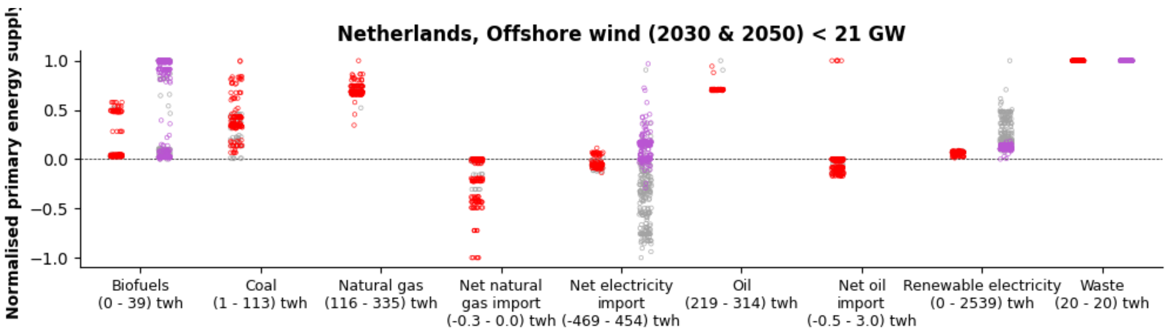


Figure 4.20: Change distribution of TPES when offshore wind target in the Netherlands is failed

Impact on Technology Deployments

Achieving the offshore wind target of 21 GW by 2030 and maintaining this capacity towards 2050 raises feasibility concerns for onshore wind and PV deployment between 2030 and 2050. When the Netherlands achieves the target of 21 GW installed offshore wind capacity by 2030, the deployment of all other technologies except coal decreases. Solutions exist within the complete range of coal deployment (0-5 GW). However, the maximum required deployments of batteries, gas turbines, onshore wind, and PV in 2030 are significantly reduced (see the green 2030 SPORES in figure 4.21). This effect is especially strong on the potential for PV and onshore wind in 2030. Meeting the offhore wind target by 2030 reduces the maximum deployment of the cost-efficient design space from 184 GW to 20 GW for PV and from 71 GW to 4 GW for onshore wind. In the long term, this raises concern for the maneuvering space in 2050. Looking at the blue and yellow 2050 SPORES in figure 4.21, we can see that many solutions require significant deployments of onshore wind and PV by 2050 if the offshore wind capacity stays above 21 GW by 2050. When the deployment of these technologies is kept to a minimum in 2030 to stay within the cost efficient design space of 2030 assuming the offshore wind target is achieved, it might be difficult to ramp up the deployment of onshore wind and PV quickly enough to reach the deployments situated in the upper region of the distribution in 2050. This is not a problem for the deployment of batteries and gas turbines as these deployments stay low in 2050.

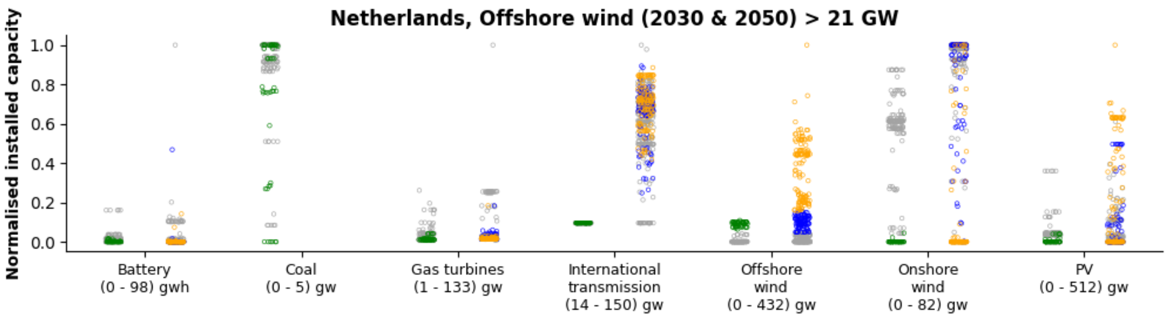


Figure 4.21: Change distribution of technology deployments when offshore wind target in the Netherlands is achieved

Failing to meet the offshore wind target by 2030 rules out a complete phase-out of coal power plants and potentially creates a lock-in risk for gas turbines. When offshore wind deployment in the Netherlands stays below 21 GW by 2030, the minimum deployment of coal power plants increases to 1.1 GW by 2030. The red 2030 SPORES in figure 4.22 show that failing to meet the offshore wind target also introduces increased deployments of gas turbines. This creates a lock-in risk for gas turbines when offshore wind deployment is increased beyond 21 GW in 2050 to catch up for the missed 2030 target (see yellow and blue 2050 SPORES in figure 4.21). When offshore wind deployment in 2050 exceeds 21 GW, the maximum required deployment of gas turbines is 8 GW (apart from 1 SPORE). In the case that offshore wind deployment is increased beyond 67.1 GW in 2050, the maximum required deployment of gas turbines even decreases to 4 GW. These levels might be impossible to reach when high deployment of gas turbines is required in 2030 in case the offshore wind target is missed.

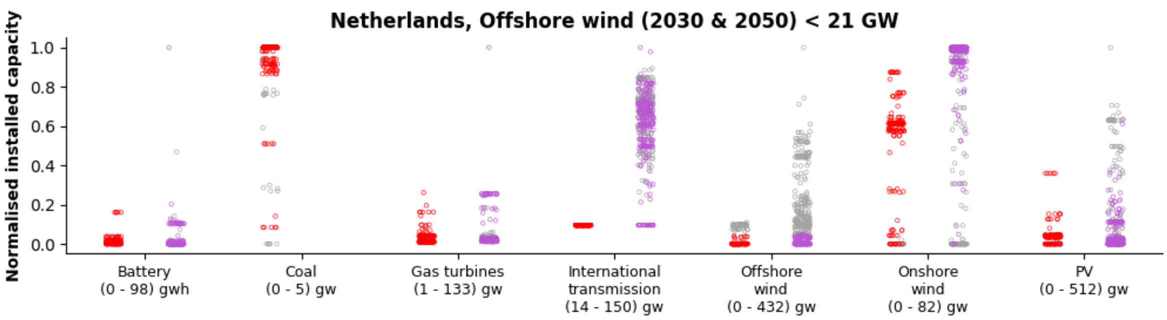


Figure 4.22: Change distribution of technology deployments when offshore wind target in the Netherlands is failed

5 Discussion and Conclusion

Chapter 4 of this study presents a description of the characteristics and trade-offs of the European energy system and two case-studies that assess the impact of policy targets on the manoeuvring space of a future energy system. This chapter provides insight into and interpretation of the results of this study. It also details the limitations of the methods used and offers recommendations for future research. Finally, the main outcomes are recapped in the conclusion.

5.1. Discussion

The distribution plots in section 4.1 show that the European energy system will transition from a system that relies mostly on fossil-based energy sources in 2030 to a system in 2050 where renewable electricity is the dominant primary energy source. Natural gas will be the major source of energy as a minimum of 4163 TWh is required. Oil and coal provide a minimum of 1611 and 563 TWh hours, respectively. By 2050 all these sources are completely phased out. Renewable electricity to accommodate the phase-out of fossil-based fuels as a primary energy source, the generation of renewable electricity needs to increase from 1056 TWh in 2022 to at least 2281 in 2030 and a minimum of 12190 TWh in 2050. In terms of technology deployments in the power sector, the results show that coal power plant capacity is on a decline from 206 GW in 2022 to a range of 22-154 GW in 2030 to complete phase-out by 2050. The potential for gas turbines sees a significant growth from 20-457 GW in 2030 to 23-1532 GW in 2050. However, the turbines will need to run on bio- or synthetic fuels because natural gas will be phased out. The results presented in section 4.1 show that wind turbines and PV are a must-have technologies in 2050. Minimum required capacity for wind turbines in 2050 amounts to 1178 GW and apart from 2 outlier SPORES, the minimum required PV capacity equals 1572 GW. Considering the high-level energy system metrics presented in chapter 4.1, it can be concluded that transport sector has the potential to be completely electrified by 2030. Whereas the heat sector majority of heat sector electrification will likely be realised between 2030 and 2050. By 2030, the sector can be electrified for 27% at best, while full electrification by 2050 is possible. The geographical distribution of electricity production is expected to be moderately unequal, with values ranging between 0.54 and 0.74. There's a noticeable potential for growth in storage capacity, ranging from 0-3 TW in 2030 to 0-11 TW in 2050. The average national import of electricity also shows potential growth, but it's not deemed as an absolute necessity.

The projected growth in renewable electricity underscores the need for investments in the power sector. Also, the current rate of decommissioning of coal power plants suggests that more aggressive measures might be needed to stay within a cost efficient design space. While, neither PV, nor wind turbines are an absolute must-have technology in 2030 significant deployments are required in 2050. While deployment of PV and wind turbines in 2030 is not required, early expansion of installed capacities must be considered by policy makers because both technologies see higher than 1 TW required capacities by 2050. This highlights the importance of taking into account the long-term in strategic energy planning. Lastly, the potential growth in storage and transmission capacities suggests that while there are opportunities for expansion, they aren't strictly necessary. The moderate inequality in electricity production across countries stress the challenges of achieving a balanced distribution, given the geographical differences in resources and demand. This flexibility could become important in navigating the challenges and uncertainties of the energy transition in Europe.

The correlation heatmaps presented in section 4.1 provide insights into the trade-offs between technology deployments on a European and national scale. In 2030 we observe a strong coupling between PV and coal power plants, especially in Europe, France, and Spain. Also, we observe a strong negative correlation between gas turbines and coal power plant, mostly prevalent in Europe, Italy and Germany. Finally, there is a strong negative correlation between flexible capacity in the form of batteries and gas turbines with electricity production gini, meaning higher deployment of batteries and gas turbines result in a more equitable distribution of electricity generation. The correlations change in 2050. PV and onshore wind have a strong negative coupling with offshore wind in 2050. Spain is the only region where this effect is not present. In contrast to batteries and gas turbines in 2030, PV and coal see a strong negative correlation with the electricity production gini in 2050. Also, expansion of international transmission with the UK triggers more offshore wind in Europe which indirectly substitutes PV and onshore whereas for other countries, increased international transmission capacity reduces deployment of gas turbines and PV

Strong coupling of PV and coal power plants in 2030 highlights a trade-off between high PV deployment and an early phase out of coal-fired power generation. As more PV is deployed in preparation towards 2050, more coal power plant capacity should be installed to keep the system cost efficient, potentially hindering ambitions for an early phase-out of coal-fired power generation. Moreover, because gas turbines and coal power plants have a negative correlation, the increased coal power plant capacity that accompanies high PV deployment could hinder the deployment of gas turbines. In 2050, there is a clear trade-off between PV and onshore wind with offshore wind. Also, in 2050 most countries experience a clear trade-off between installation of international transmission capacity to import foreign electricity as a replacement of PV and often gas turbines. This stresses the importance of cooperation of nations in strategic energy planning. Not every country can build out transmission capacity as generation units have to be placed somewhere.

The results in chapter 4.2 show that the SPORES algorithm finds many SPORES in 2030 that see technology deployments below currently installed capacity (as of 2022). SPORES in 2030 are considered realistic when the capacity for solar and wind is equal to or larger than installed capacity as of 2022 and such that the capacity of coal-fired power plants is equal to or smaller than the installed capacity in 2022. Applying this filter on the 2030 SPORES classifies only 27/190 SPORES as realistic considering total technology deployments of PV, onshore- and offshore wind and coal in Europe. Applying the same filtering on total technology capacities in France, Germany, Italy, Spain and the United Kingdom leaves only 1 realistic SPORE or even no realistic SPORES at all. This effect can be attributed to the fact that the SPORES method finds a large portion of its SPORES by minimising or maximising specific technology-location combinations. By doing this, the algorithm finds solutions at the extremes of the design space. While this is interesting to generate insights into trade-offs of future systems, it is impractical for the energy system of 2030. This underlines the drawback of the greenfield modelling approach, especially in the short-term.

The k-means clustering algorithm as presented in this study succeeds well in reducing a dataset of hundreds of SPORES to a more manageable amount of scenarios. The algorithm was applied to the power sectors of Europe, France, Germany, Italy, the Netherlands, Spain and the United kingdom in 2030 as well as 2050. For power sectors of all previously mentioned regions in 2030 the average silhouette scores are between 0.7 and 0.8. Generally speaking, the performance of a clustering algorithm is considered to be good when the average silhouette score lies between 0.5 and 1, meaning that scenarios are different from each other and SPORES within a scenario have high similarity. The performance of the clustering algorithm seems to be lower for the set of 2050 SPORES as 2050 scenarios for all countries have average silhouette scores that are significantly lower (between 0.35 and 0.6) compared to the respective 2030 scenarios. It is likely that this effect can be attributed to the fact that the set of 2050 SPORES contains more than twice as many solutions as the set of 2030 SPORES.

From the analysis of the scenarios in Europe, Germany and the Netherlands in section 4.3 it becomes clear that a significant expansion of installed capacity in the power sector is required between 2030 and 2050. The European scenarios in 2030 indicate that low coal deployment is feasible with high deployment of other firm capacities. Specifically scenarios 5 and 9 show high gas turbine deployment, while scenarios 0 and 9 have relatively high deployment of nuclear. Furthermore, scenarios with low coal deployments consistently coincide with low battery deployment. There is also a noticeable trend where high PV deployment is offset by low wind deployment and vice versa. By 2050, all scenarios in Europe rely heavily on PV and onshore wind. In cases with relatively less onshore wind, higher offshore wind deployment kicks in. Interestingly, the scenarios without any extreme deployments contains the majority of SPORES in 2050, with 236 out of 441. In 2030, the only way Germany can phase out coal is through extreme gas turbine deployment as seen in scenario 5. This approach, however, poses a lock-in risk of gas turbines, limiting the flexibility in 2050 as most of the scenarios in 2050 do not deploy much gas turbines. this emphasises the importance of flexible capacity during transitional stage towards climate neutrality, especially when feasibility of expanding transmission capacity in the near term is limited and batteries are more costly. All German scenarios in 2050 deploy at least 20-30% (200 GW) of capacity that can provide flexibility, which includes international transmission capacity, gas turbines, and batteries. Additionally, any reduction in PV deployment is consistently compensated by either increase onshore- or offshore wind. The 2030 scenarios for the Netherlands show that high onshore wind deployment is always paired with low offshore wind deployment and vice versa. For 2050, the only scenario that does not require significant expansion of international transmission capacity relies heavily on gas turbines and battery capacity. Moreover, any high deployment of wind is always accompanied by high international transmission capacity.

The overarching trend between 2030 to 2050 is a shift towards renewable sources, particularly PV, onshore- and offshore wind, combined with an expansion of international transmission capacity. This transition, while promising for sustainability introduces challenges. For Europe, the 2030 scenarios suggest a balance between coal, nuclear, and gas turbine deployments. The inverse relationship between PV and wind deployments indicates that there is a need to optimise the mix of these sources to solve intermittency. Germany's scenarios in 2030 underline the challenges of transitioning away from coal. The lock-in risk of gas turbines associated with an early phase-out of coal-fired power highlights the need for strategic planning that balances near-term decline of carbon emissions with long-term flexibility. In the Netherlands, the trade-off between onshore and offshore wind deployments suggest that geographical and infrastructural considerations play an important role in the design of the energy system. By 2050, the heavy reliance on international transmission capacity underscores the interconnected nature of the European energy system and the importance of national- and regional coordination.

The findings in chapter 4.4 show that the target of 215 GW installed PV capacity in Germany by 2030 has most impact on the use of fuels as a primary energy source and on the deployment of fossil-based power generation and wind energy. Meeting the target PV capacity by 2030 increases minimum required coal supply from 38 to 574 TWh and decreases maximum use of natural gas from 1744 to 1113 TWh. In terms of technology deployments, meeting the PV target by 2030 increases required coal-fired generation capacity from 0 to 46 GW (compared to 40 GW in 2022) and limits maximum onshore- and offshore wind deployment to 20 GW and 2.4 GW respectively. Extrapolating growth from 215 GW towards 2050 results in a PV capacity in 2050 of 586 GW. Deploying more than 586 GW by 2050 increases minimum use of biofuels from 0 TWh to 254 TWh, while keeping the deployment of PV in 2050 between 215 GW and 586 GW has little to no restricting impact on the energy system. Failing to deploy 215 GW by 2050 raises required international transmission capacity from 52 to 146 GW, however also reduces the need for firm capacity (i.e. batteries and gas turbines).

There are multiple implications of these findings. On one hand, prioritising PV deployment restricts the growth of wind technologies towards 2030 that are also crucial for the energy system in 2050 and prevents an early phase-out of coal fired power generation locking in coal fired power generation that needs to be decommissioned by 2050. A conservative approach that fails to meet the PV target by 2030 seems to have little impact on deployment of other technologies. In 2050, deploying between 215 and 586 GW of PV provides most flexibility for Germany as it has little to no restricting impact on the distribution of deployment of other technologies. Deploying less than 215 GW of PV by 2050 increases reliance on international transmission lines while reducing deployment of firm capacity signalling that it is cheaper for Germany to rely on electricity generation in other countries than build out controllable power sources.

The results as presented in chapter 4.5 highlights that the Dutch offshore wind capacity target of 21

GW by 2030 presents both opportunities and challenges, looking at the expected effects on coal use, deployment of onshore wind and PV, and the nation's position as an electricity importer or exporter. By 2030, only 23% of SPORES achieve the offshore wind target of 21 GW installed in the Netherlands. By 2050, this number increases to 51%. Achieving the 2030 offshore wind target significantly reduces maximum coal use in the Netherlands, from 113 to 52 TWh. However, meeting the Dutch offshore wind target in a cost efficient manner is not in line with ambitions to increase deployment of onshore wind and PV as the target reduces the maximum deployment of onshore wind from 71 to 4 GW and from 184 to 20 GW for PV. Failing to meet the offshore wind target capacity by 2030 rules out an early phase-out of all coal-fired power capacity. Also, when the 2030 target is missed, many of the corresponding SPORES see relatively high deployment of gas turbines by 2030 (up to 27 GW). Extrapolating growth from 21 GW towards 2050 results in 67 GW of offshore wind capacity by 2050. Offshore wind capacity between 21-67 GW in 2050 provides the Netherlands with flexibility to choose to become net importer or net exporter of electricity. Deploying less than 21 GW forces the Netherlands to become a net importer, while offshore wind capacity greater than 67 GW forces the country to become a net exporter of electricity. Offshore wind capacities exceeding 21 GW by 2050 reduce the potential for gas turbine deployment from 133 to 8 GW.

The data from chapter 4.5 underscores the challenges associated with scaling up offshore wind capacity in the Netherlands. While benefits of achieving the the 2030 target include a significant reduction of coal usage, the trade-offs in terms of onshore wind and PV deployment cannot be ignored. The potential conflict between achieving the offshore wind target to provide a cost-efficient configuration for the energy system in 2030 and ramping up onshore wind and PV deployments as a preparation for the energy system of 2050 underlines the need for a more balanced approach to energy system planning that takes into account short-term as well as long-term effects. However, not meeting the 2030 offshore wind target rules out a complete phase out coal power plants and introduces a risk of becoming overly reliant on gas turbines. The realised offshore wind capacity also has a significant impact on discussions around self-sufficiency as low levels of offshore wind deployment can force the Netherlands to become a net importer of electricity.

5.1.1. Limitations

The methods used in this study have some limitations and underlying presumptions. The most significant of these limitations are detailed below.

Scenario selection based on silhouette score

Determining the number of scenarios for the clustering algorithm solely based on the silhouette score sometimes leads to clusters where there is a lot of overlap between scenarios because range of certain technology deployments is so big (meaning the within cluster sum of square distances to its centroid (WCSS) is large. This is especially true optimal number of scenarios decreases. For the purpose of this research, this approach was taken as it offers a fully automated process and does not rely on manually picking the elbow point in the WCSS plot because this is often an ambiguous process.

Representing scenarios using the median capacity value

In this study all 2030 and 2050 scenarios for Europe, Germany and the Netherlands are summarised in a figure that visualises the median capacity value for each technology in each scenario. A downside of this approach is that it does not necessarily represent a specific SPORE. While this approach offers a very quick and simple overview it might be better to represent a scenario using the most representative SPORE, meaning the SPORE that is closest to the cluster centroid.

Euro-calliope

The Euro-calliope model of the European energy system has some limitations and assumptions that are important to keep in mind. First of all, the Euro-calliope model provides a closed system that does not exchange energy with regions outside of the 35 countries that were included in the model. This is useful to analyse the design of as system where Europe becomes less dependent on energy sources originating from other regions. However, for short to medium term analysis (e.g. of a system that meets climate targets of 2030) it is unlikely that Europe can become fully independent in providing its energy needs as the continent currently relies heavily on import of natural gas and liquid natural gas from other continents to meet its energy needs.

SPORES method
It is important to keep in mind that different search methods for finding SPORES can lead researchers to draw different conclusions, as proven by Lombardi, Pickering, and Pfenninger [25]. Moreover, the current search methods all deploy a greenfield approach to finding SPORES, meaning that currently installed capacity and possible decommissioning cost are not accounted for. Especially when the SPORES are used for analysis of energy systems in the near future, such as 2030, the current approach finds many SPORES that are impractical in reality.

5.1.2. Recommendations
Given the exploratory nature of this study, many areas for potential future research emerged. This section provides some recommendations for the main areas for future research.

Improving practicality of shorter term SPORES
This research proposes three possible starting points for future research to solve the previously described limitation of finding many unrealistic SPORES in 2030. Firstly, the sample size of the base-run could be increased in order to find more SPORES with moderate technology deployments. Secondly, historic capacity data gathered for the purpose of this research could be used to introduce boundary conditions to apply the SPORES method as a brownfield approach to generate more realistic SPORES for 2030. Finally, the impact of a simple filtering of unrealistic 2030 SPORES on the design space of the energy system in 2030 could be assessed.

Improving clustering algorithm
The clustering algorithm could be improved by comparing results of different clustering algorithms and different performance metrics. As previously described, picking the optimal number of scenarios solely based on the highest average silhouette score sometimes defines scenarios thus increasing overlap between scenarios which makes them less distinct. To deal with this problem it might be useful to manually pick a preferred number of scenarios by visual inspection of the WCSS (Within-Cluster Sum of Square). This study has shown that clustering the SPORES solutions can provide interesting insights that are more easy to interpret. However, besides k-means clustering, which is a centroid based clustering algorithem, there are many other methods to cluster large datasets (e.g. hierarchical clustering or density-based clustering). Clustering large datasets such as the SPORES to reduce complexity and generate more accessible insights is an interesting area for future research.

Expanding research to other sectors
Extending the scope of the analysis proposed in this study beyond the power sector to analyse the interplay between policy targets and their impact on different sector in the energy system could provide interesting insights. This study has focused on policy targets and dynamics in the power sector of the European energy system. While a few key metrics such as heat- and transport electrification provide basic insight into the dynamics between the power sector and other sectors, there is room for future research to investigate the impact of policy targets and technology deployments across different sectors. This methods written in this research are generic and can easily be applied by choosing a different set of 'features' on which to run the analysis. For example, one could assess the impact of policy targets for other metrics than just technology deployments (e.g. renewable electricity supply, energy-or fuel autarky, sector electrification).

5.2. Conclusion
This study aims to combine the strengths of the traditional pathways approach and the modelling to generate alternatives (MGA) approach to modelling the European energy transitions. By doing so, this study aims to assess the impact of policy target on the maneuvering space of a future European energy system. To provide such insight, analysis was performed on a set of energy system configurations for 2030 and 2050 provided by the SPORES method that was applied to the sector-coupled Euro-calliope model of the European energy system. The analysis of the distribution of the design space, the correlations between technology deployments, and of scenarios in 2030 and 2050 has given insights into the

characteristics and trade-offs of a future European energy system. Furthermore, the analysis of two case-studies provide insight into the impact of policy targets on the maneuvering space of the transition towards a climate neutral European energy system.

This distribution plots in combination with the technology correlation heatmaps provide interesting insights into the characteristics and trade-offs of the design of a future European energy system. As expected, the European energy system between now and 2050 can be characterised by a transition away from fossil-based energy sources to renewable sources. The trade-offs that were identified stress the complexity of balancing of deployment decisions to realise a cost efficient system on short-term with strategic investment in technologies that are required to realise a cost efficient energy system in the long run. Also the trade-offs between international transmission capacity and power generators clearly indicate the importance of coordination between nation states in order to navigate the transition effectively.

The SPORES method, while insightful for understanding the design space of future energy systems, has limitations in its short-term application, particularly for 2030. Most of the SPORES identified by the algorithm see lower than current technology deployments. This underscores the challenges of greenfield modeling approaches for near-term modelling problems.

The k-means clustering algorithm effectively reduces the complex datasets of SPORES into more accessible scenarios, especially for the smaller set of 2030 SPORES. However, its performance appears to decrease for the set of 2050 SPORES, possibly due to the larger amount of solutions. This highlights the need for refining clustering approaches when dealing with larger datasets. Reducing the SPORES to a manageable amount of scenarios proves to be effective to better understand the SPORES. However, it was difficult to use them to use them to develop a comprehensive understanding of the impact of policy targets on the maneuvering space of a future European energy system. Therefore, later during the project, a case-study analysis based on filtering was chosen to answer the main research question. Although the clustering algorithm and scenarios do not directly answer the main research question, they provide interesting insight.

The scenarios that were identified by the clustering algorithm provide important insights into the characteristics and trade-offs of future energy systems. Also, a comparison of short-term scenarios of 2030 with long-term scenarios of 2050, shows that it is possible to identify lock-in risk of infrastructure that is present in 2030 but has to be decommissioned by 2050. The lock-in risks identified in Europe, Germany, and the Netherlands is specific scenarios emphasise the importance of including analysis of long-term effects in energy system planning. Decisions made in the short term can have long-lasting implications that can limit the flexibility in the future.

Both case studies underscore the importance of a balanced and strategic approach to deployment of certain technologies, ensuring that one technology does not limit the potential of others while also taking into account required deployment of certain technologies further in the future. In both cases, ambitious targets to expand capacity of a certain renewable power generator by 2030 reduces the potential for other renewable power sources. In the case that Germany meets its ambition to deploy 215 GW of PV by 2030, the energy system requires increased coal-fired capacity to remain in the cost-efficient design space of 2030, introducing lock-in risk of a technology that requires a complete phase out by 2050. The Dutch case study shows that the offshore wind target of 21 GW by 2030 introduces a potential conflict between deployment of offshore wind and growth of PV and onshore wind that is required for 2050. While both targets offer a way of meeting the electricity demand in a cost-efficient way by 2030, they raise concerns for the feasibility of a completely climate neutral energy system in 2050 because systems in 2050 mostly rely on a combination of PV and wind energy.

References

[1] European Commission. “European green deal: delivering on our targets”. In: (2021).

[2] Toshihiko Nakata, Diego Silva, and Mikhail Rodionov. “Application of energy system models for designing a low-carbon society”. In: *Progress in Energy and Combustion Science* 37.4 (2011), pp. 462–502.

[3] David Connolly et al. “A review of computer tools for analysing the integration of renewable energy into various energy systems”. In: *Applied energy* 87.4 (2010), pp. 1059–1082.

[4] Bryn Pickering, Francesco Lombardi, and Stefan Pfenninger. “Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system”. In: *Joule* (2022).

[5] Diana Süsser et al. “Open energy system modelling to support the European Green Deal”. In: *F1000Research* 11 (2022).

[6] Philip Voll et al. “The optimum is not enough: A near-optimal solution paradigm for energy systems synthesis”. In: *Energy* 82 (2015), pp. 446–456.

[7] Marta Victoria, Elisabeth Zeyen, and Tom Brown. “Speed of technological transformations required in Europe to achieve different climate goals”. In: *Joule* 6.5 (2022), pp. 1066–1086.

[8] Georgios Mavromatidis and Ivalin Petkov. “MANGO: A novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems”. In: *Applied Energy* 288 (2021), p. 116585.

[9] Matija Pavičević et al. “The potential of sector coupling in future European energy systems: Soft linking between the Dispa-SET and JRC-EU-TIMES models”. In: *Applied Energy* 267 (2020), p. 115100.

[10] Warren E Walker, Robert J Lempert, and Jan H Kwakkel. “Deep uncertainty”. In: *Delft University of Technology* 1.2 (2012).

[11] Daniel Rosenbloom. “Pathways: An emerging concept for the theory and governance of low-carbon transitions”. In: *Global Environmental Change* 43 (2017), pp. 37–50.

[12] Johan Lilliestam et al. “Policy pathways for the energy transition in Europe and selected European countries”. In: *Update September 2019. MUSTEC project deliverable* 7 (2019).

[13] Georgios Xexakis et al. “Models on the wrong track: Model-based electricity supply scenarios in Switzerland are not aligned with the perspectives of energy experts and the public”. In: *Renewable and Sustainable Energy Reviews* 134 (2020), p. 110297.

[14] Tim T Pedersen et al. “Modeling all alternative solutions for highly renewable energy systems”. In: *Energy* 234 (2021), p. 121294.

[15] Tim Tröndle et al. “Trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity in Europe”. In: *Joule* 4.9 (2020), pp. 1929–1948.

[16] Hans Auer et al. “Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5° C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE”. In: *e & i Elektrotechnik und Informationstechnik* 137.7 (2020), pp. 346–358.

[17] Stephan Kigle, Michael Ebner, and Andrej Guminski. “Greenhouse Gas Abatement in EUROPE—A Scenario-Based, Bottom-Up Analysis Showing the Effect of Deep Emission Mitigation on the European Energy System”. In: *Energies* 15.4 (2022), p. 1334.

[18] Gondia S Seck et al. “Hydrogen and the decarbonization of the energy system in europe in 2050: A detailed model-based analysis”. In: *Renewable and Sustainable Energy Reviews* 167 (2022), p. 112779.

[19] Tom Brown et al. *PyPSA-Eur-Sec: A Sector-Coupled Open Optimisation Model of the European Energy System*. https://pypsa-eur-sec.readthedocs.io/en/latest/. 2023.

[20] Joseph F DeCarolis. "Using modeling to generate alternatives (MGA) to expand our thinking on energy futures". In: *Energy Economics* 33.2 (2011), pp. 145–152.

[21] Francesco Lombardi et al. "Policy decision support for renewables deployment through spatially explicit practically optimal alternatives". In: *Joule* 4.10 (2020), pp. 2185–2207.

[22] Stefan Pfenninger and Bryn Pickering. "Calliope: a multi-scale energy systems modelling framework". In: *Journal of Open Source Software* 3.29 (2018), p. 825.

[23] B Pickering and R Choudhary. "District energy system optimisation under uncertain demand: Handling data-driven stochastic profiles". In: *Applied energy* 236 (2019), pp. 1138–1157.

[24] Stefan Pfenninger et al. *calliope-project/calliope: Release v0.6.10*. https://doi.org/10.5281/ZENODO.7547770. Accessed on 2023-09-05. 2023.

[25] Francesco Lombardi, Bryn Pickering, and Stefan Pfenninger. "What is redundant and what is not? Computational trade-offs in modelling to generate alternatives for energy infrastructure deployment". In: *Applied Energy* 339 (2023), p. 121002.

[26] ENTSO-E and others. *eHighways 2050 Final Reports*. Tech. Rep. ENTSO-E, 2015.

[27] Ember Climate. *Electricity Data Explorer*. https://ember-climate.org/data/data-tools/data-explorer/. Accessed on 2023-09-19. 2023.

[28] IRENA. *IRENASTAT Online Data Query Tool*. https://pxweb.irena.org/pxweb/en/IRENASTAT. 21. 2023.

[29] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. *REPowerEU Plan*. Tech. rep. European Commission, 2022.

[30] WindEurope. *Wind energy in Europe: 2022 Statistics and the outlook for 2023-2027*. Tech. rep. WindEurope, 2023.

[31] Department for Business, Energy Industrial Strategy. *UK signs agreement on offshore renewable energy cooperation*. https://www.gov.uk/government/news/uk-signs-agreement-on-offshore-renewable-energy-cooperation. Accessed on 2023-09-25. 2023.

[32] RenewableUK. *The onshore wind industry prospectus*. Tech. Rep. RenewableUK, 2021.

[33] Beyond Fossil Fuels. *Charts / All of Europe's existing and planned coal power plants (by status)*. https://beyondfossilfuels.org/coal/. Accessed on 2023-09-25. 2023.

[34] Beyond Fossil Fuels. *Europe's Coal Exit: Overview of National Coal Phase Out Commitments*. https://beyondfossilfuels.org/europes-coal-exit/. Accessed on 2023-09-25. 2023.

[35] Third Generation Environmentalism Ltd. *Germany on track to exit coal*. https://www.e3g.org/news/germany-on-track-to-exit-coal/. Accessed on 2023-09-22. 2023.

[36] European Commission. *Final NECP 2021-2030 of France*. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en. Accessed on 2023-10-02. 2019.

[37] European Commission. *Draft Updated NECP 2021-2030 of Italy*. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en. Accessed on 2023-09-22. 2023.

[38] European Commission. *Draft Updated NECP 2021-2030 of Spain*. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en. Accessed on 2023-09-22. 2023.

[39] Gilles Lepesant. "Higher Renewable Energy Targets in Germany: How will the Industry Benefit?" In: (2023).

[40] European Commission. *Draft Updated NECP 2021-2030 of the Netherlands*. https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en. Accessed on 2023-10-02. 2019.

[41] John Lubbock. *Solar Energy UK analysis cautiously welcomes UK government's 'Green Day' solar commitments*. https://www.solarpowerportal.co.uk/solar_energy_uk_analysis_cautiously_welcomes_uk_governments_green_day_solar/. Accessed on 2023-09-25. 2023.

[42] Council of the European Union. *Infographic - How is EU electricity produced and sold?* https://www.consilium.europa.eu/en/infographics/how-is-eu-electricity-produced-and-sold/. Accessed on 2023-09-16. 2023.

[43] Ember Climate. *Electricity Interconnection Europe*. https://ember-climate.org/data/data-tools/electricity-interconnection-europe/. Accessed on 2023-09-19. 2023.

[44] Statista Research Department. *Cumulative solar photovoltaic capacity in the European Union* from 2017 to 2022*. https://www.statista.com/statistics/497540/connected-and-cumulated-photovoltaic-capacity-in-the-european-union-eu/. Accessed on 2023-09-19. 2023.

[45] International Energy Agency. *Germany Data Explorer*. https://www.iea.org/countries/germany. Accessed on 2023-10-02. 2023.

A
Source Code

The processed data and source code required to reproduce the results are provided in a GitHub repository at: https://github.com/gvanderweerd/SPOREways. Figure A.1 provides an overview of how the source code is structured and how the scripts should be executed to reproduce the results provided in Chapter 4.

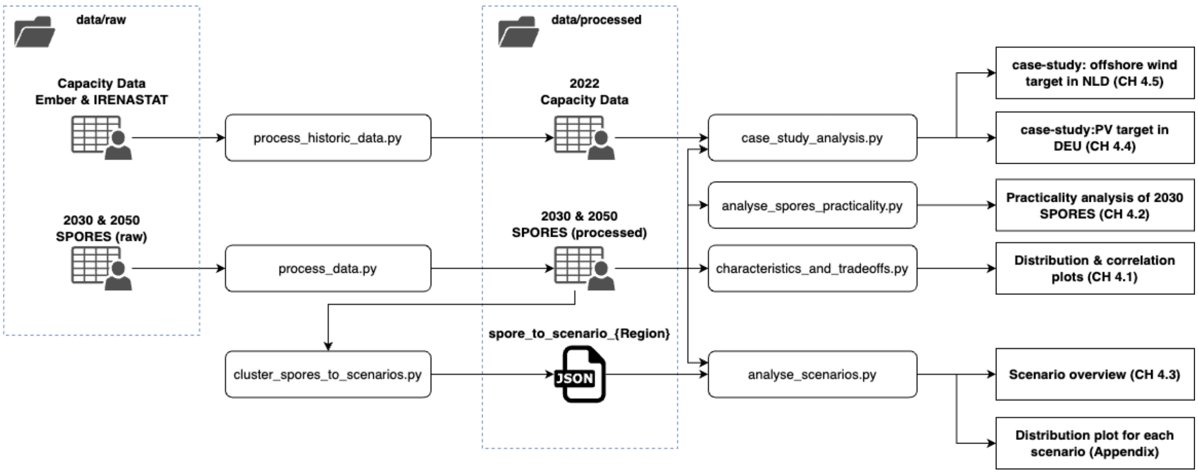


Figure A.1: Flowchart of source code structure

B

Analysing Scenarios

B.1. Scenarios in Europe

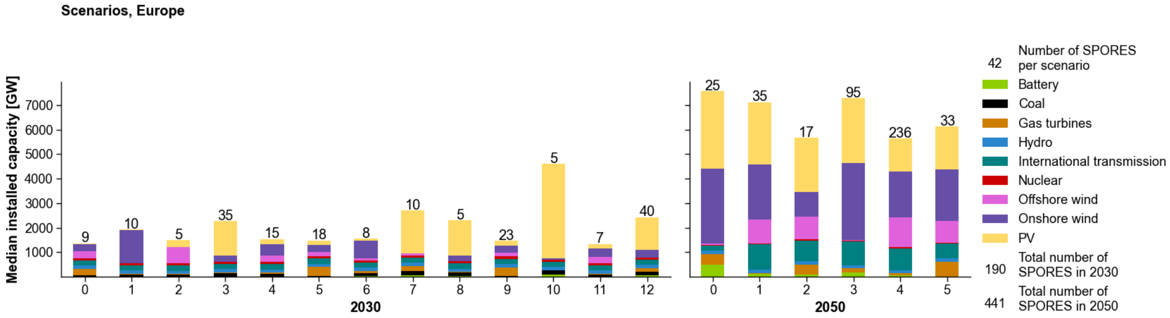


Figure B.1: Europe scenario overview for 2030 and 2050

B.1.1. 2030

Table B.1: Scenario names, Europe 2030

Scenario no.	Name
0	High Nuclear & Offshore wind, Low Battery & Coal & PV
1	High Onshore wind, Low Gas turbines & Nuclear & PV
2	High Offshore wind, Low Gas turbines & Nuclear & Onshore wind
3	High PV, Low Gas turbines & Offshore wind
4	High Offshore wind & Onshore wind
5	High Gas turbines, Low Battery & Coal & Nuclear & PV
6	High Onshore wind, Low PV
7	High Battery & Coal & Nuclear & PV, Low Onshore wind
8	High Coal & PV, Low Gas turbines & Nuclear & Offshore wind
9	High Gas turbines & Nuclear, Low Battery & Coal
10	High Battery & Coal & PV, Low Nuclear & Onshore wind
11	High Nuclear & Offshore wind, Low PV
12	High Battery

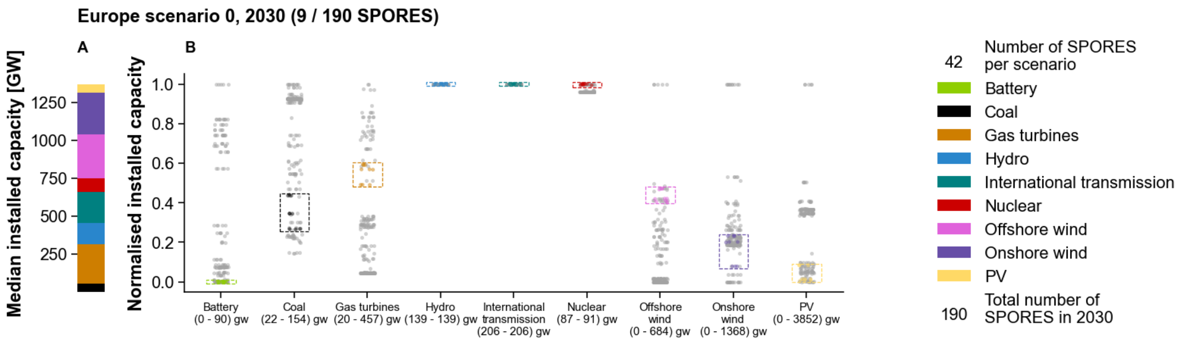


Figure B.2: Europe scenario 0 in 2030

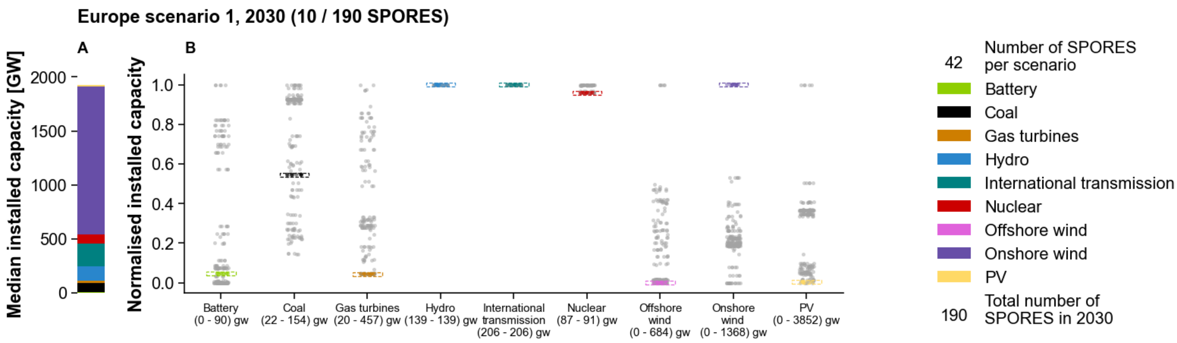


Figure B.3: Europe scenario 1 in 2030

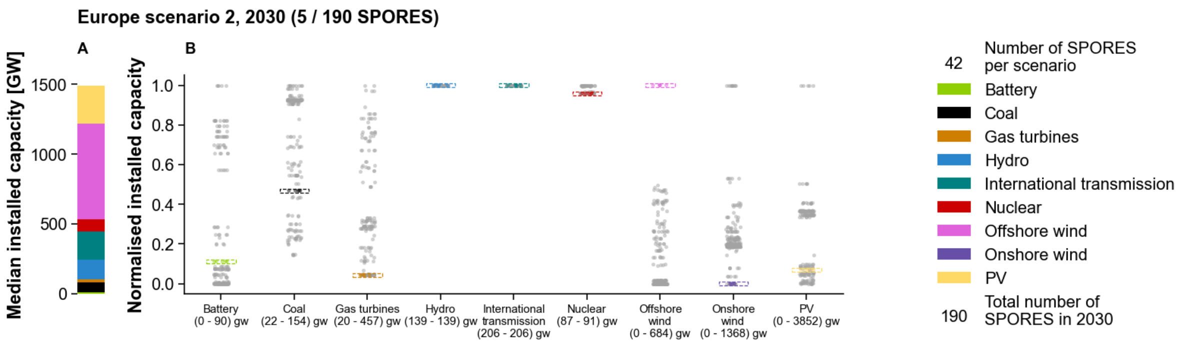


Figure B.4: Europe scenario 2 in 2030

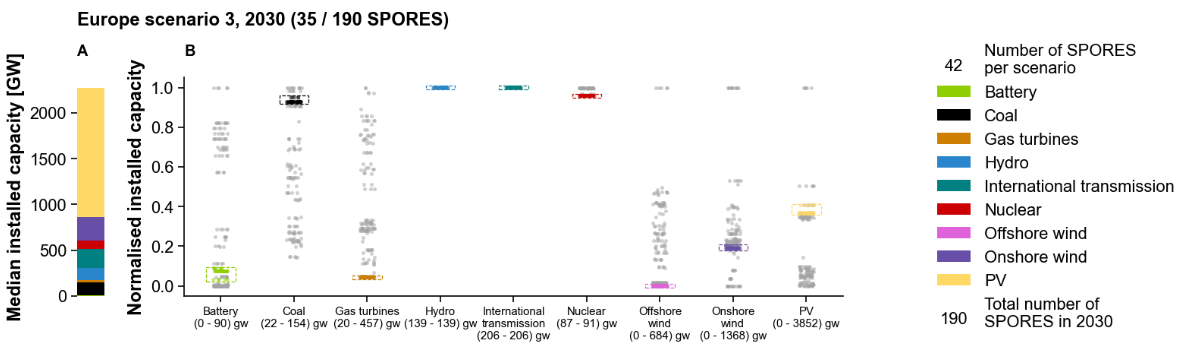


Figure B.5: Europe scenario 3 in 2030

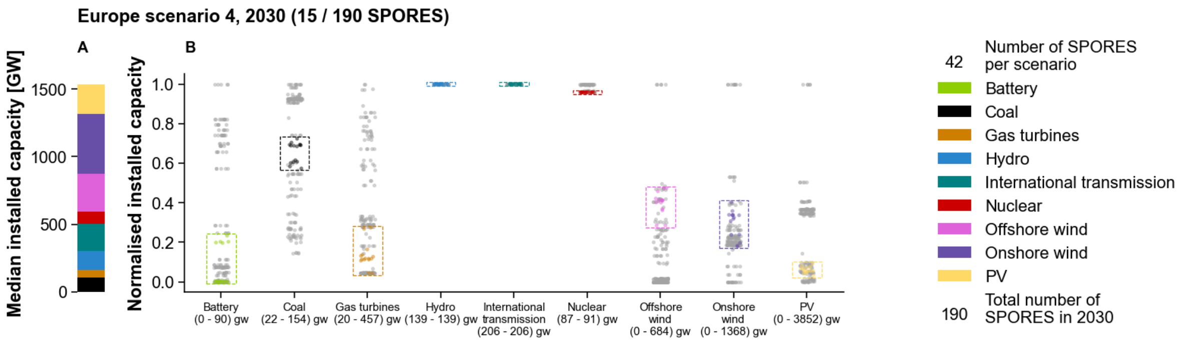


Figure B.6: Europe scenario 4 in 2030

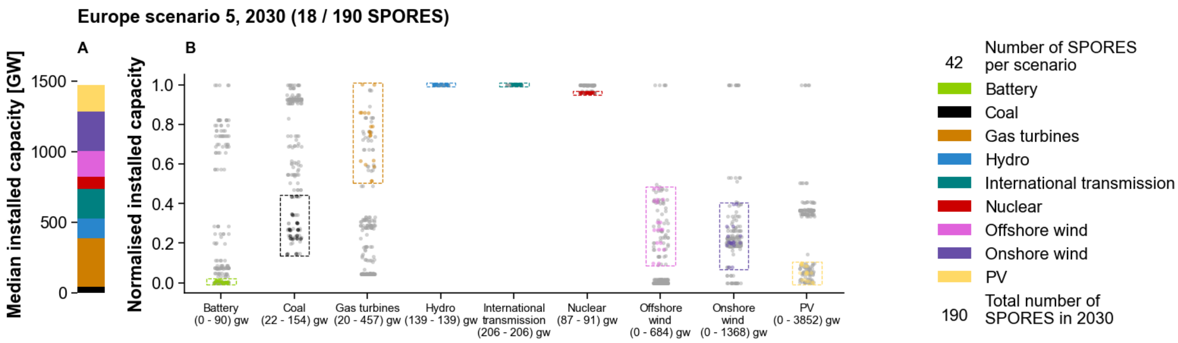


Figure B.7: Europe scenario 5 in 2030

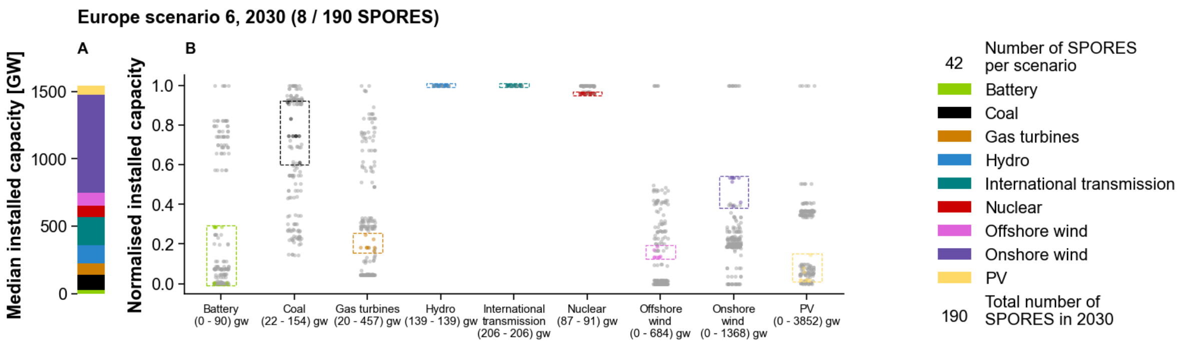


Figure B.8: Europe scenario 6 in 2030

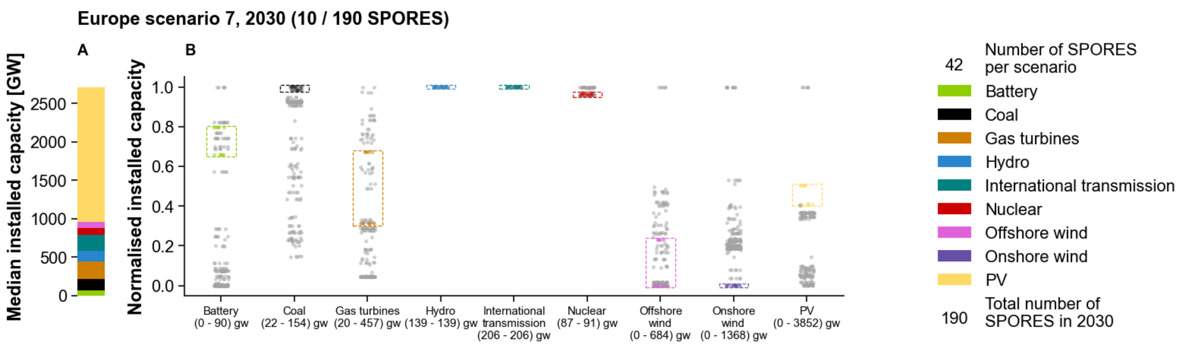


Figure B.9: Europe scenario 7 in 2030

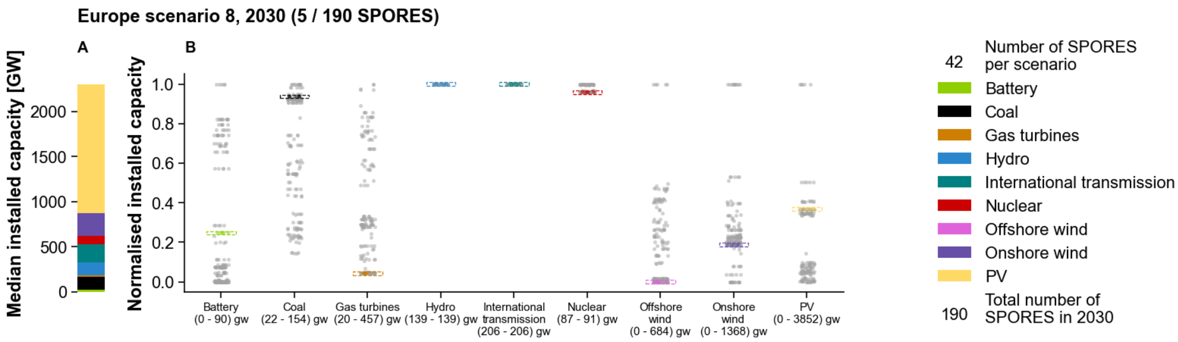


Figure B.10: Europe scenario 8 in 2030

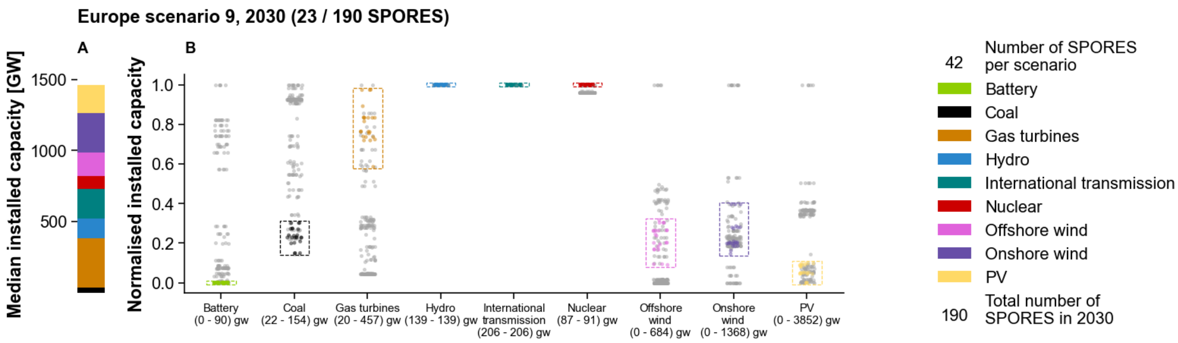


Figure B.11: Europe scenario 9 in 2030

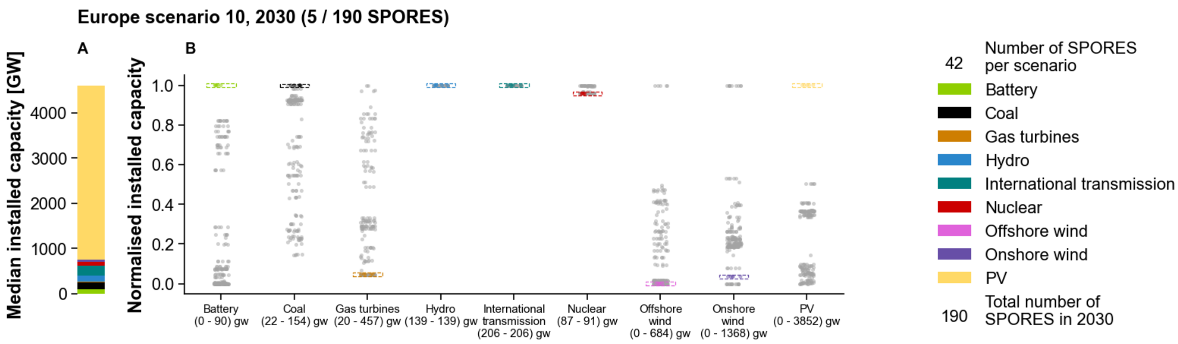


Figure B.12: Europe scenario 10 in 2030

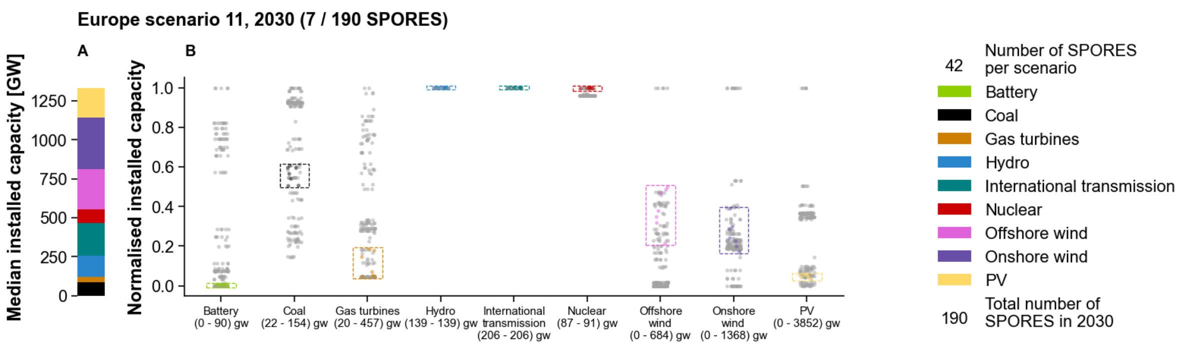


Figure B.13: Europe scenario 11 in 2030

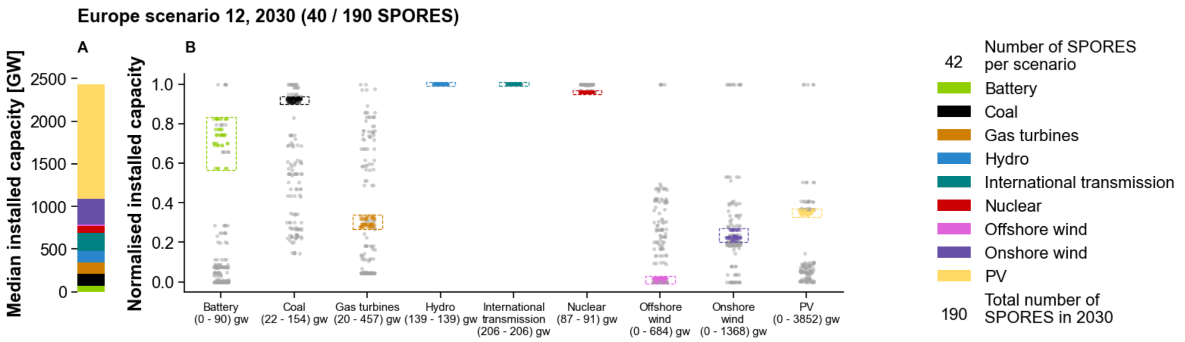


Figure B.14: Europe scenario 12 in 2030

B.1.2. 2050

Table B.2: Scenario names, Europe 2050

Scenario no.	Name
0	High Battery & Gas turbines & PV, Low International transmission & Offshore wind
1	High International transmission & PV, Low Gas turbines & Nuclear
2	High Gas turbines & Nuclear, Low Onshore wind
3	High Battery & Onshore wind & PV, Low Offshore wind
4	No extreme deployments
5	High Gas turbines, Low Battery & International transmission

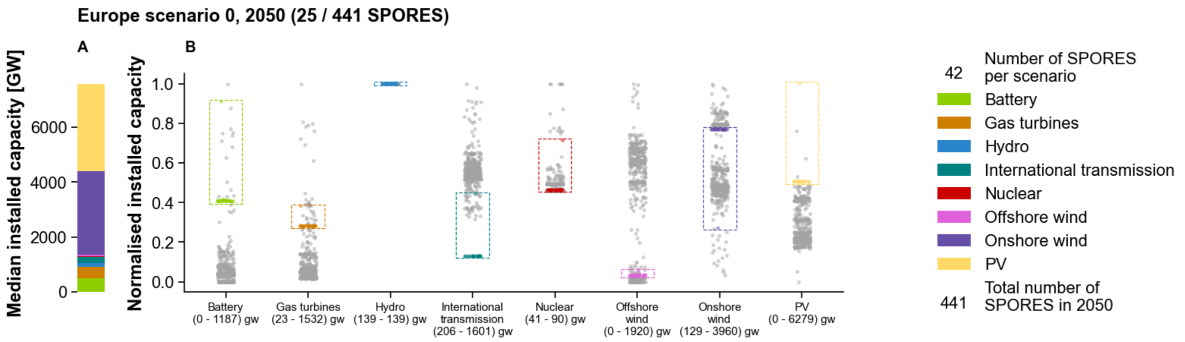


Figure B.15: Europe scenario 0 in 2050

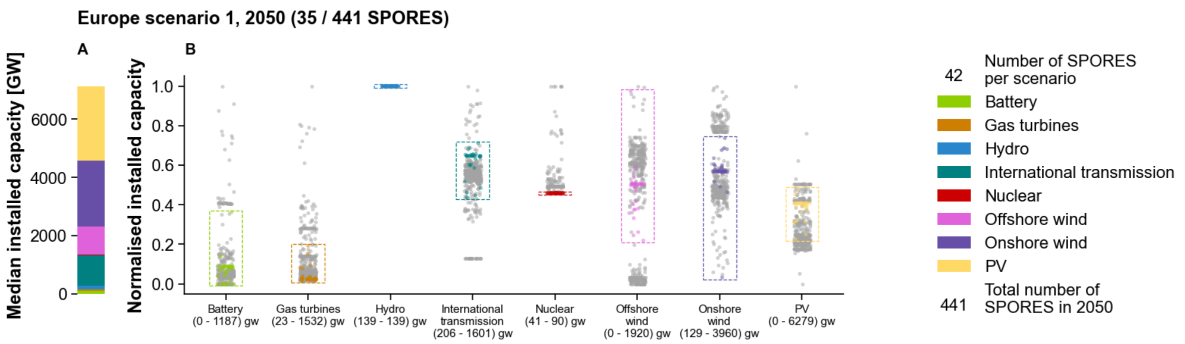


Figure B.16: Europe scenario 1 in 2050

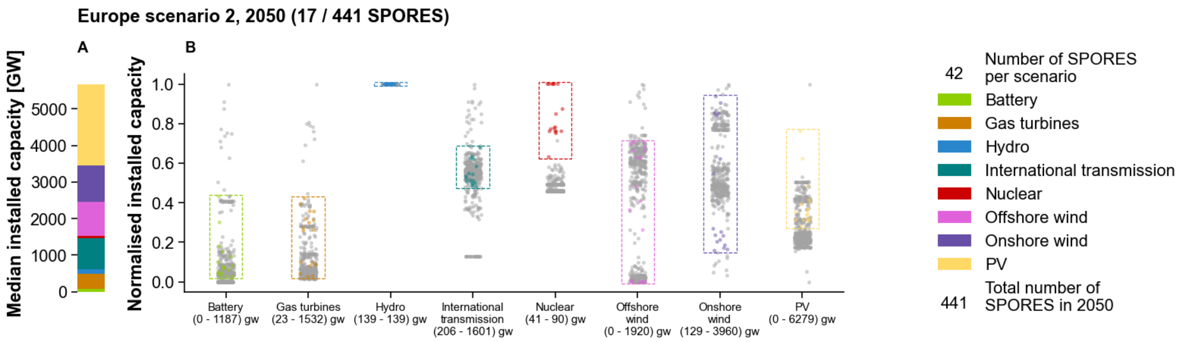


Figure B.17: Europe scenario 2 in 2050

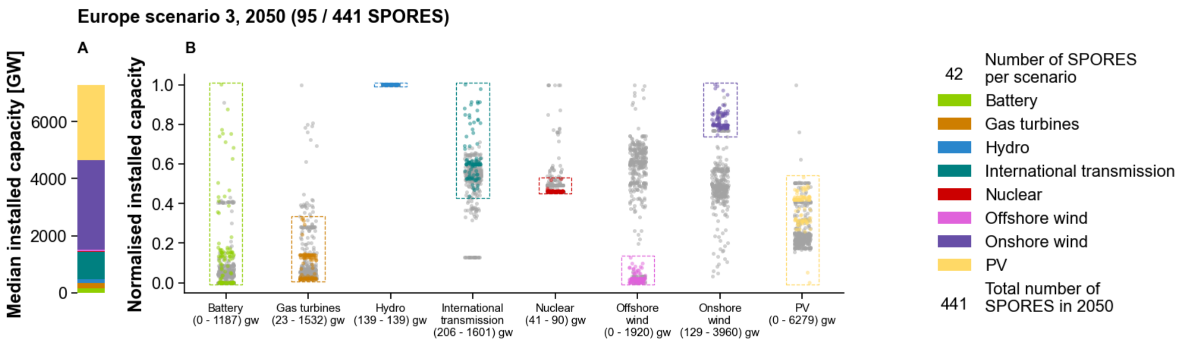


Figure B.18: Europe scenario 3 in 2050

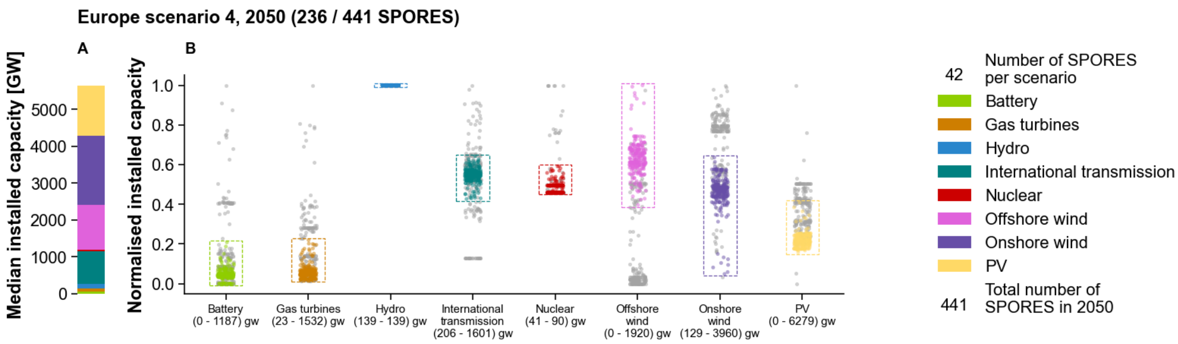


Figure B.19: Europe scenario 4 in 2050

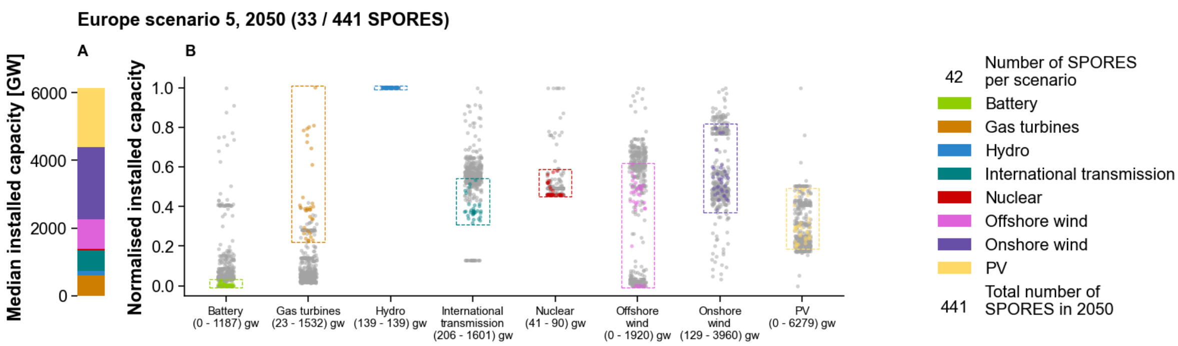


Figure B.20: Europe scenario 5 in 2050

B.2. Scenarios in Germany

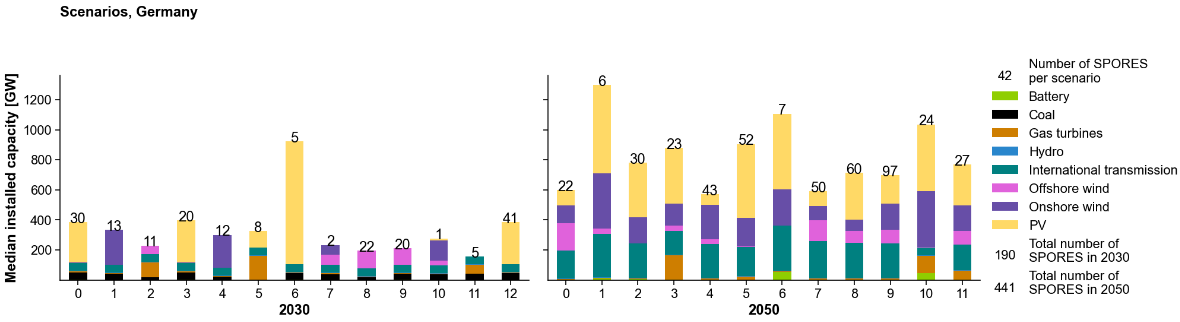


Figure B.21: Germany scenario overview for 2030 and 2050

B.2.1. 2030

Table B.3: Scenario names, Germany 2030

Scenario no.	Name
0	High Battery
1	High Onshore wind
2	High Gas turbines, Low Battery & Coal & Onshore wind & PV
3	High Battery & Onshore wind & PV
4	High Onshore wind, Low Battery & Coal & Offshore wind & PV
5	High Gas turbines, Low Battery & Coal & Offshore wind & Onshore wind
6	High Coal & PV
7	High Offshore wind & Onshore wind
8	High Offshore wind, Low Battery & Coal & PV
9	High Offshore wind
10	High Onshore wind
11	High Gas turbines, Low PV
12	High Coal, Low Gas turbines

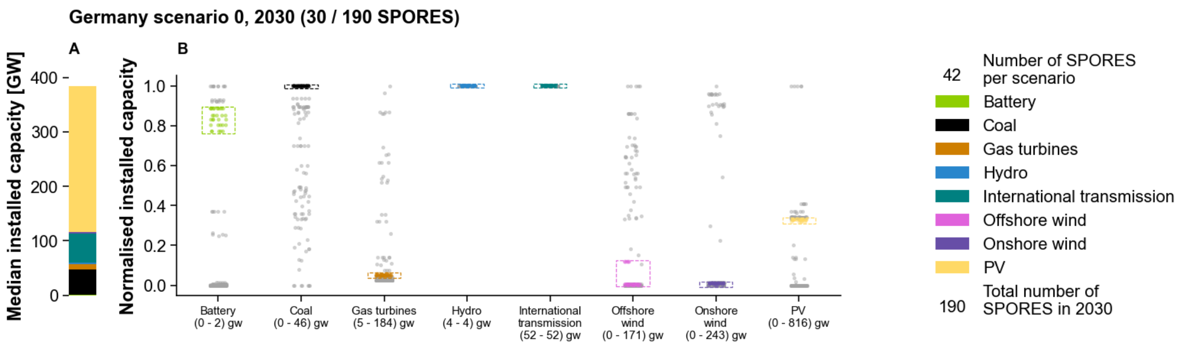


Figure B.22: Germany scenario 0 in 2030

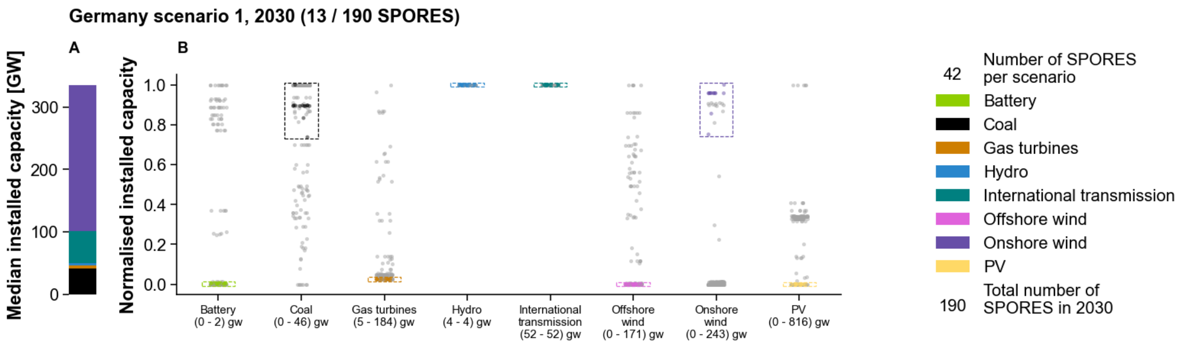


Figure B.23: Germany scenario 1 in 2030

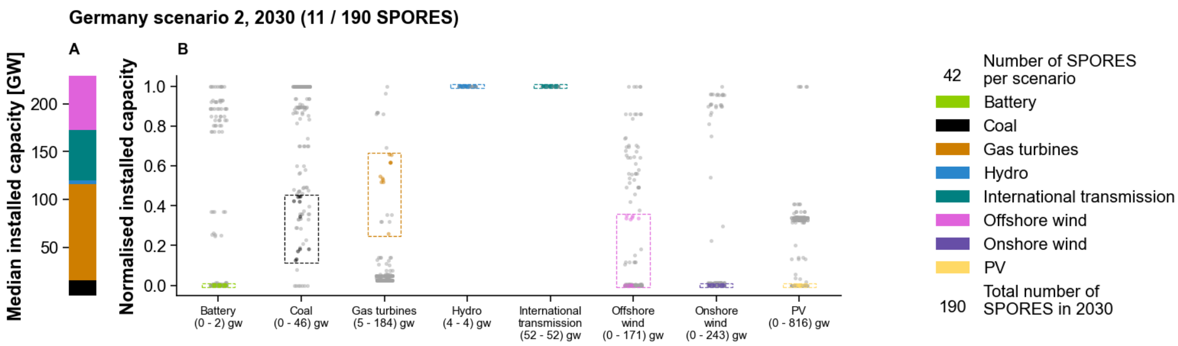


Figure B.24: Germany scenario 2 in 2030

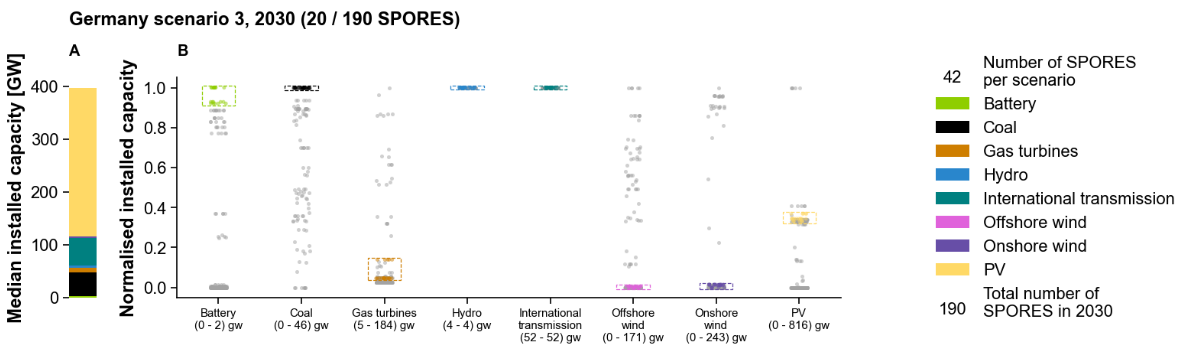


Figure B.25: Germany scenario 3 in 2030

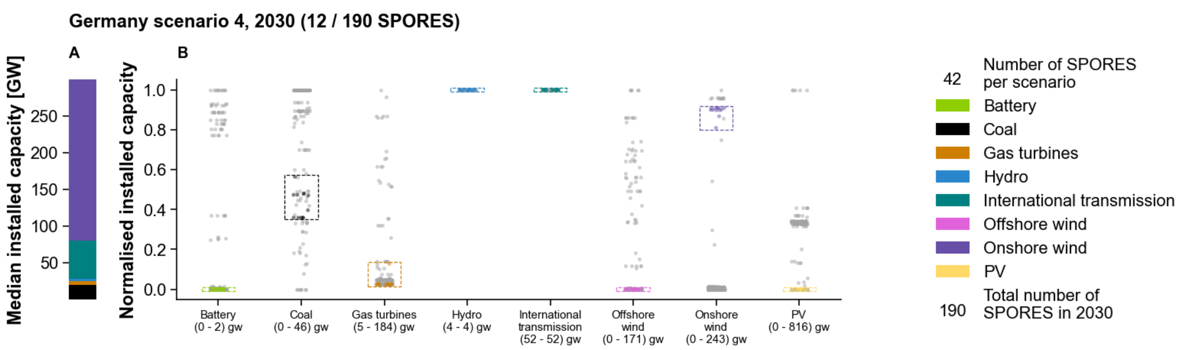


Figure B.26: Germany scenario 4 in 2030

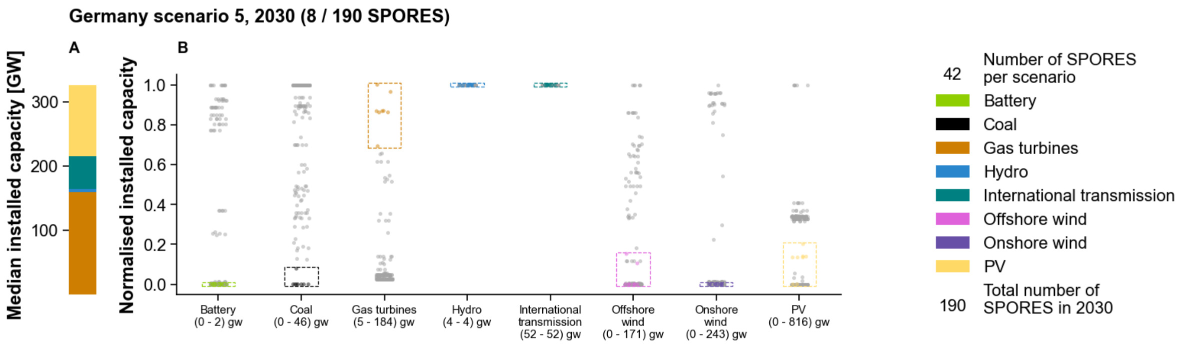


Figure B.27: Germany scenario 5 in 2030

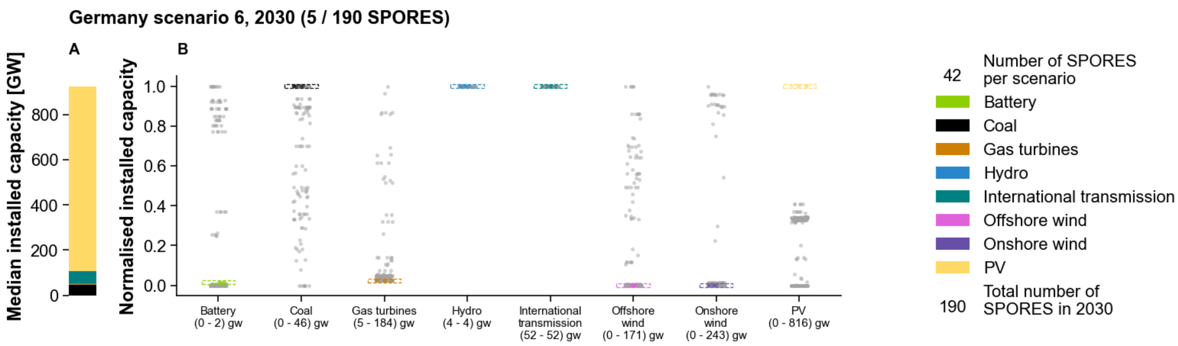


Figure B.28: Germany scenario 6 in 2030

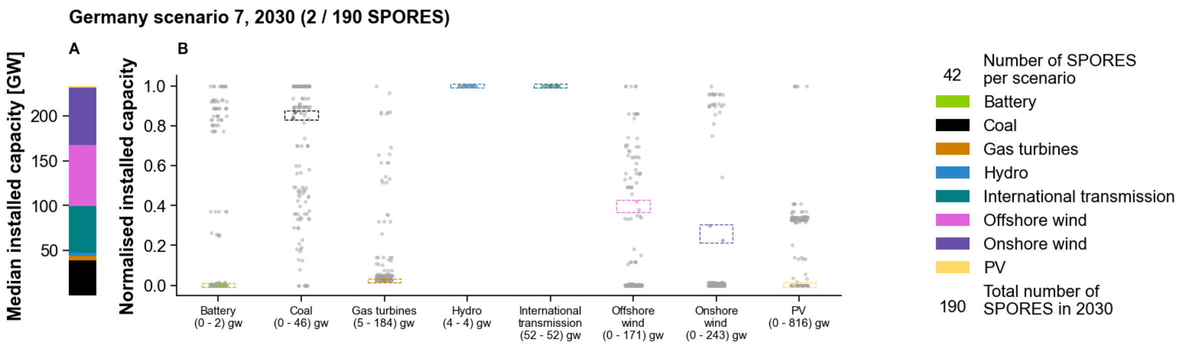


Figure B.29: Germany scenario 7 in 2030

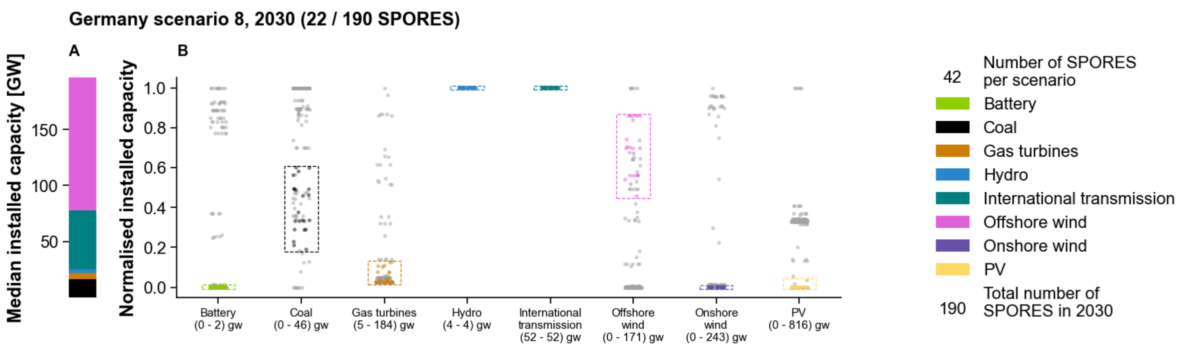


Figure B.30: Germany scenario 8 in 2030

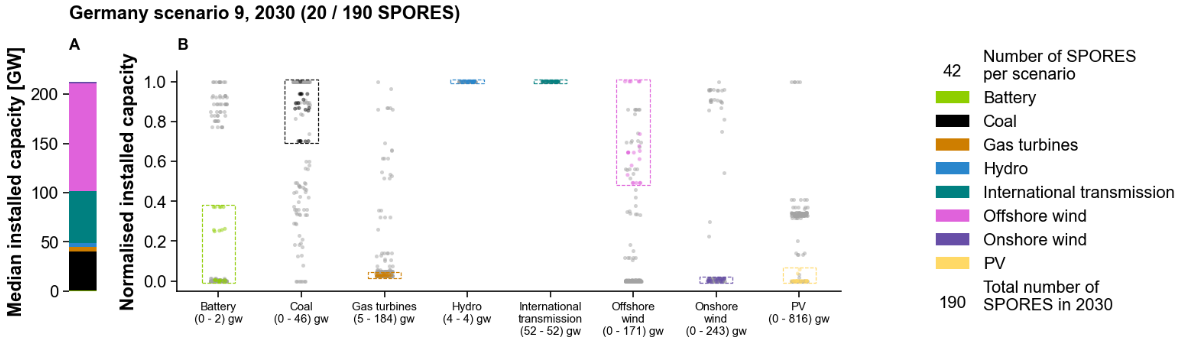


Figure B.31: Germany scenario 9 in 2030

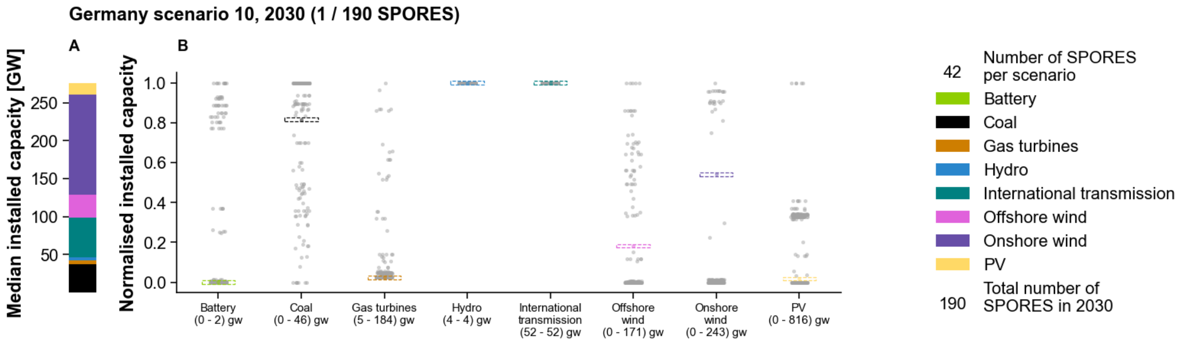


Figure B.32: Germany scenario 10 in 2030

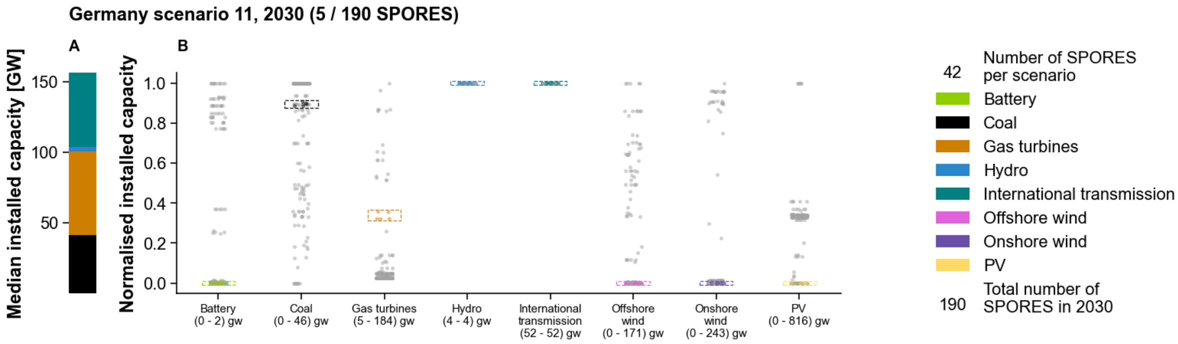


Figure B.33: Germany scenario 11 in 2030

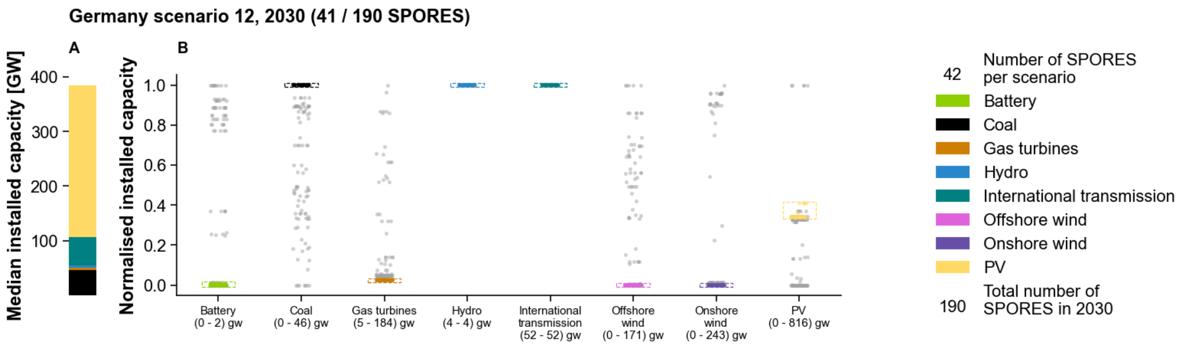


Figure B.34: Germany scenario 12 in 2030

B.2.2. 2050

Table B.4: Scenario names, Germany 2050

Scenario no.	Name
0	High Offshore wind, Low Battery & Gas turbines & International transmission & PV
1	High Battery & International transmission & Onshore wind & PV, Low Gas turbines
2	High Battery, Low Gas turbines & Offshore wind
3	High Gas turbines, Low International transmission
4	High Onshore wind, Low PV
5	High PV, Low Battery & Offshore wind
6	High Battery & International transmission & Onshore wind & PV, Low Gas turbines & Offshore wind
7	High International transmission & Offshore wind, Low Onshore wind & PV
8	Low Onshore wind
9	No extreme deployments
10	High Battery & Gas turbines & Onshore wind & PV, Low International transmission & Offshore wind
11	High Gas turbines, Low International transmission

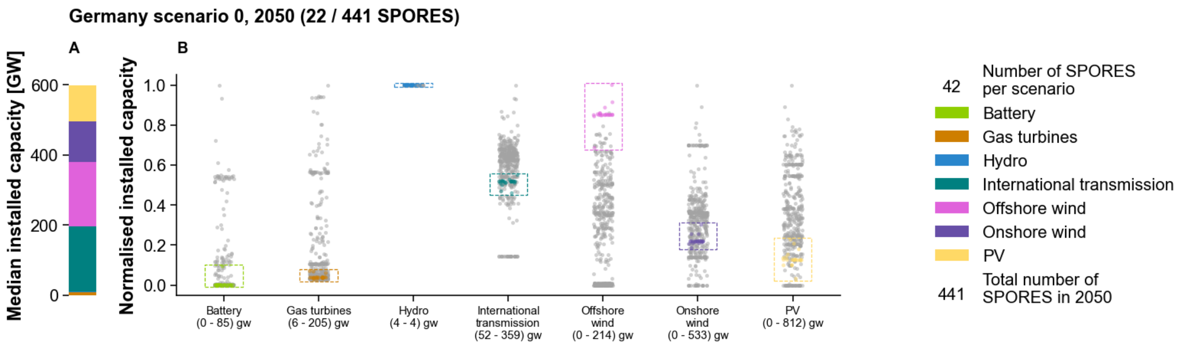


Figure B.35: Germany scenario 0 in 2050

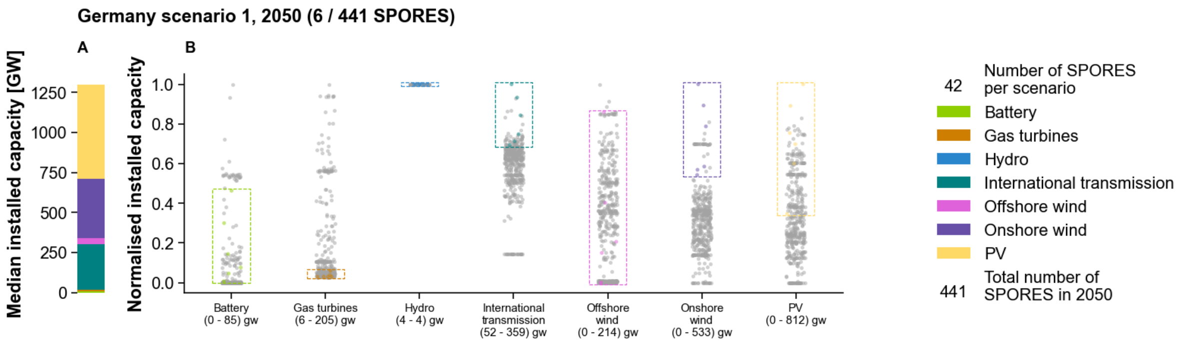


Figure B.36: Germany scenario 1 in 2050

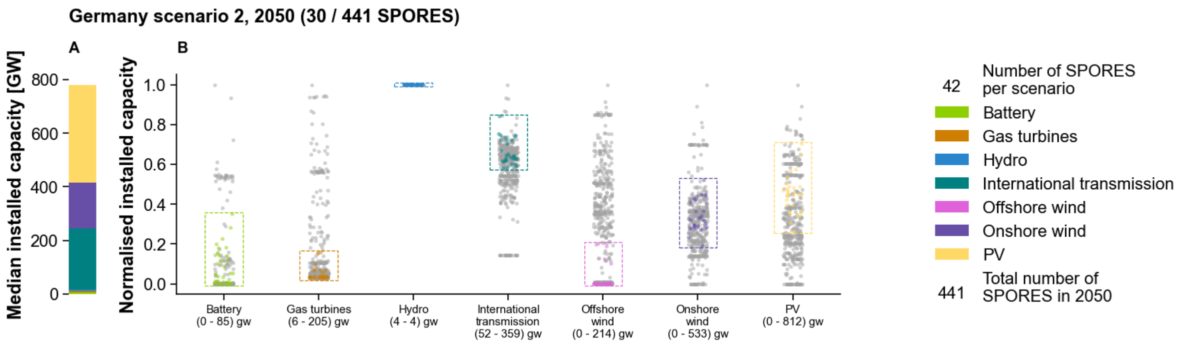


Figure B.37: Germany scenario 2 in 2050

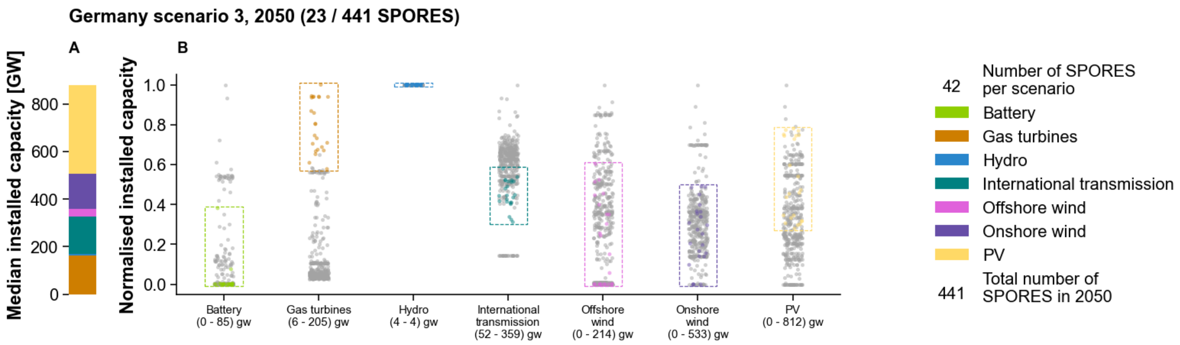


Figure B.38: Germany scenario 3 in 2050

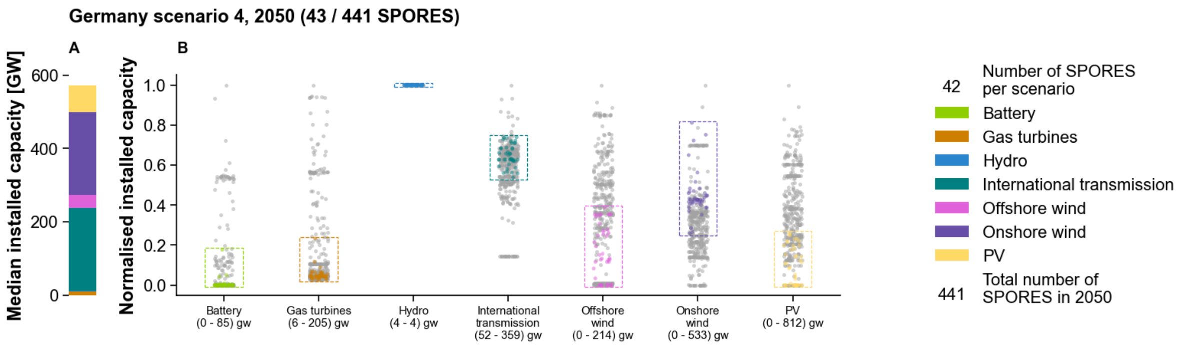


Figure B.39: Germany scenario 4 in 2050

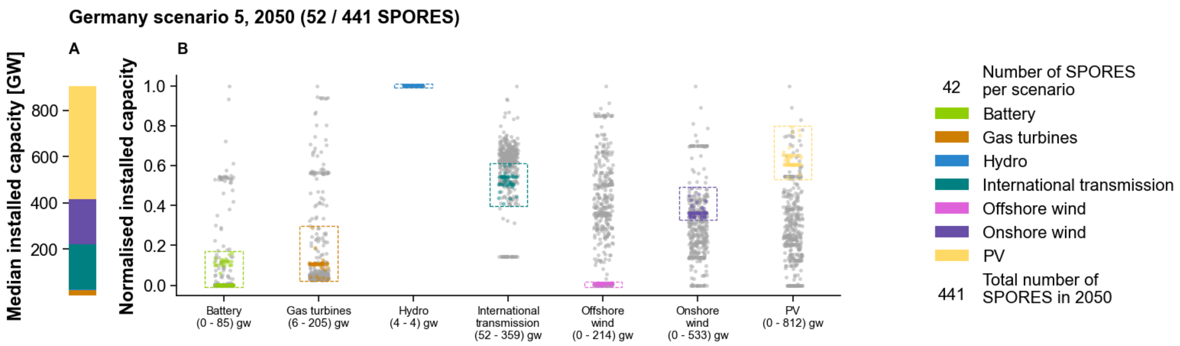


Figure B.40: Germany scenario 5 in 2050

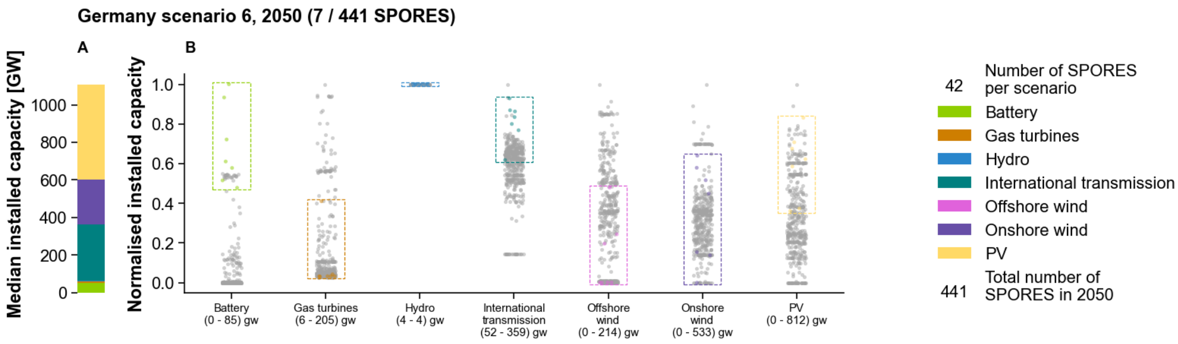


Figure B.41: Germany scenario 6 in 2050

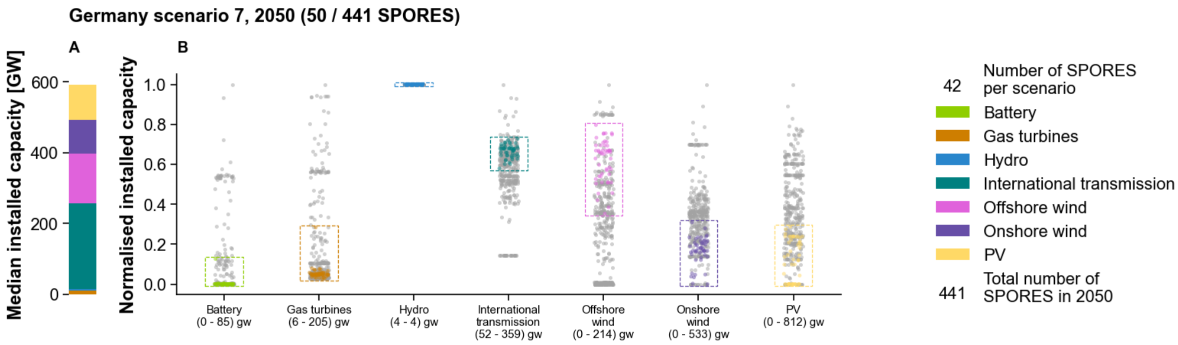


Figure B.42: Germany scenario 7 in 2050

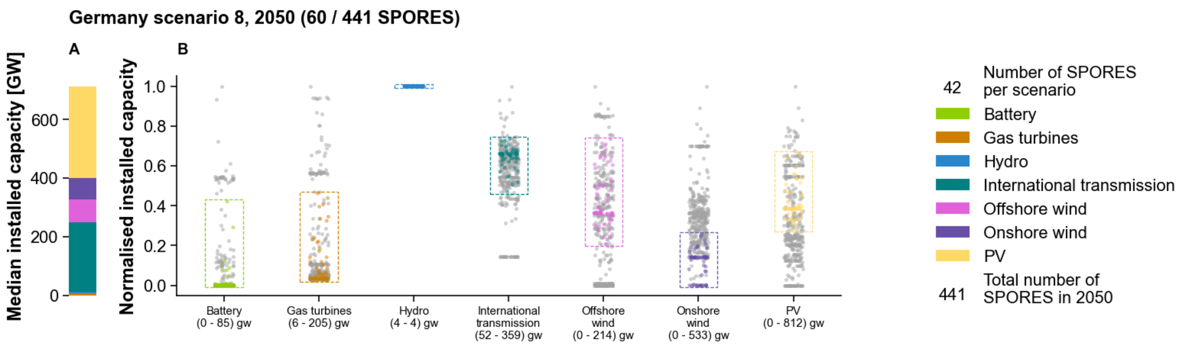


Figure B.43: Germany scenario 8 in 2050

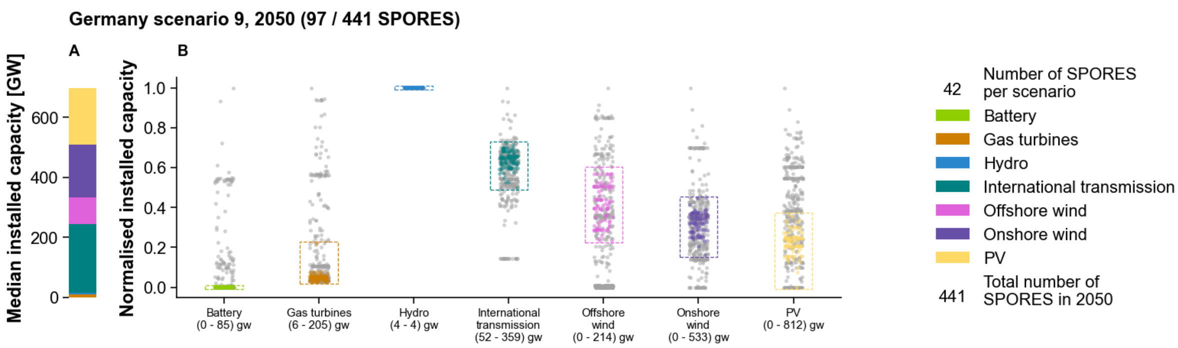


Figure B.44: Germany scenario 9 in 2050

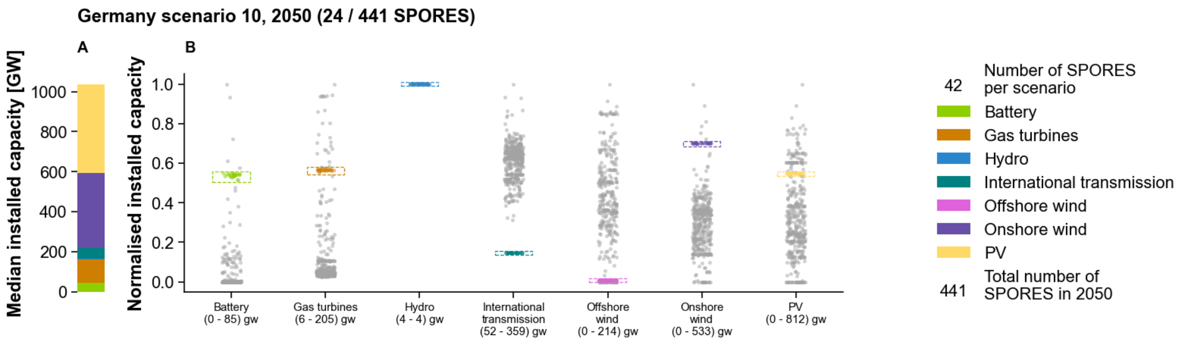


Figure B.45: Germany scenario 10 in 2050

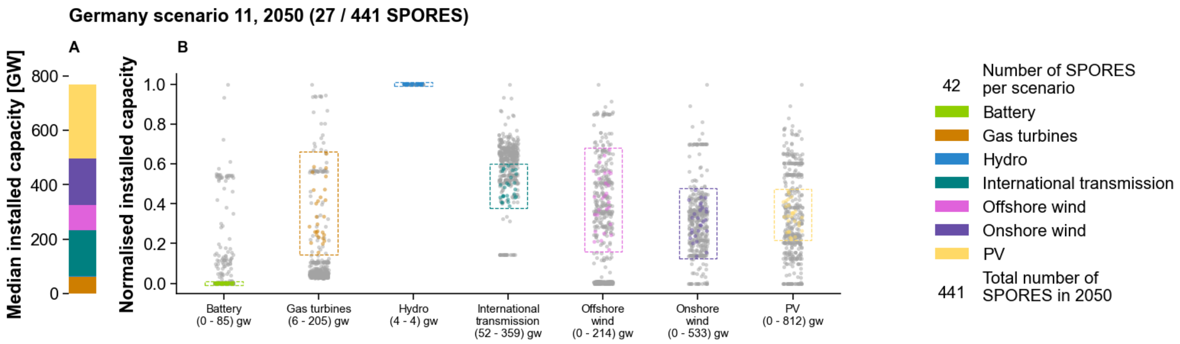


Figure B.46: Germany scenario 11 in 2050

B.3. Scenarios in the Netherlands

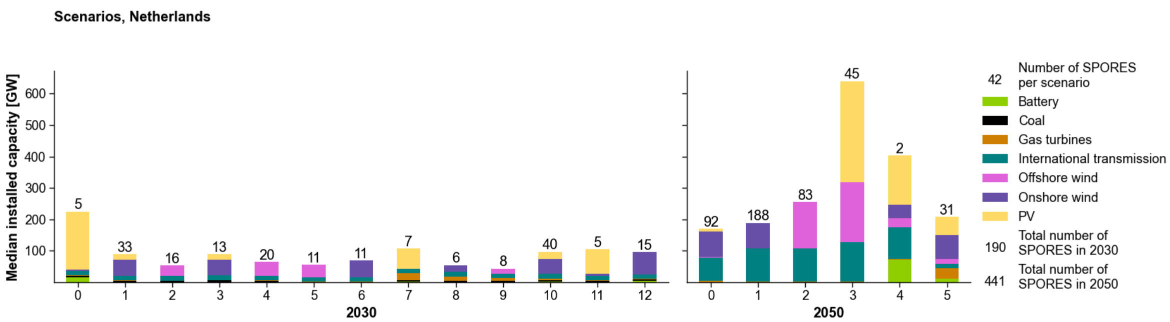


Figure B.47: the Netherlands scenario overview for 2030 and 2050

B.3.1. 2030

Table B.5: Scenario names, the Netherlands 2030

Scenario	Name
0	**High** Battery & Coal & PV
1	**Low** Gas turbines
2	**High** Offshore wind, **Low** Battery & Coal & Onshore wind & PV
3	No extreme deployments
4	**High** Offshore wind, **Low** Onshore wind
5	**High** Offshore wind, **Low** Battery & Coal & Onshore wind & PV
6	**High** Onshore wind, **Low** Battery & Coal & Offshore wind & PV
7	**High** Battery & Gas turbines & PV, **Low** Offshore wind & Onshore wind
8	**High** Gas turbines, **Low** Battery & PV
9	**High** Gas turbines, **Low** Battery & Onshore wind & PV
10	**High** Gas turbines & PV
11	**High** PV, **Low** Battery & Offshore wind
12	**High** Battery & Coal & Onshore wind, **Low** Offshore wind

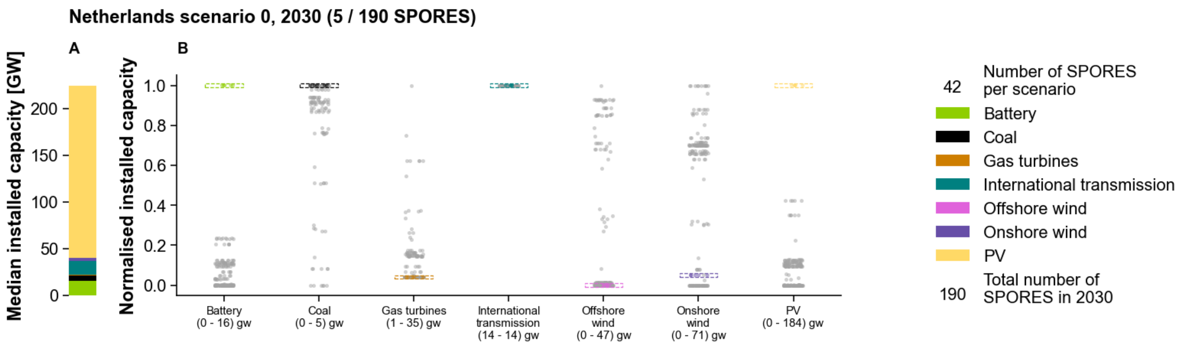


Figure B.48: the Netherlands scenario 0 in 2030

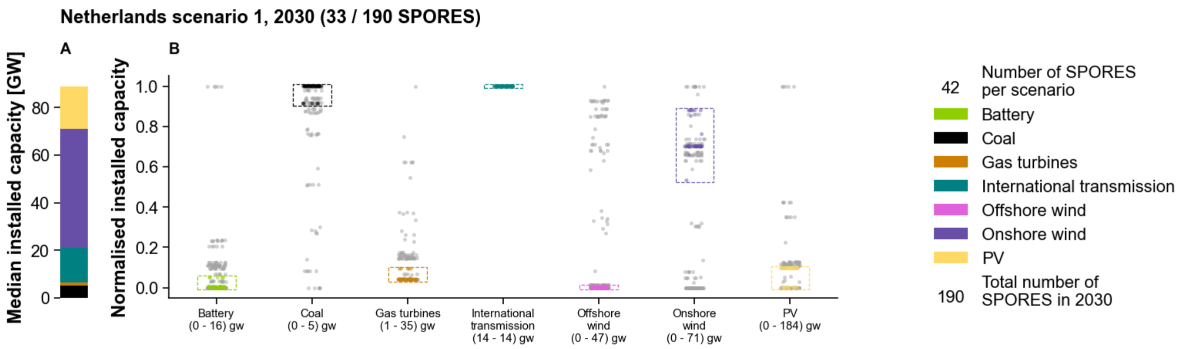


Figure B.49: the Netherlands scenario 1 in 2030

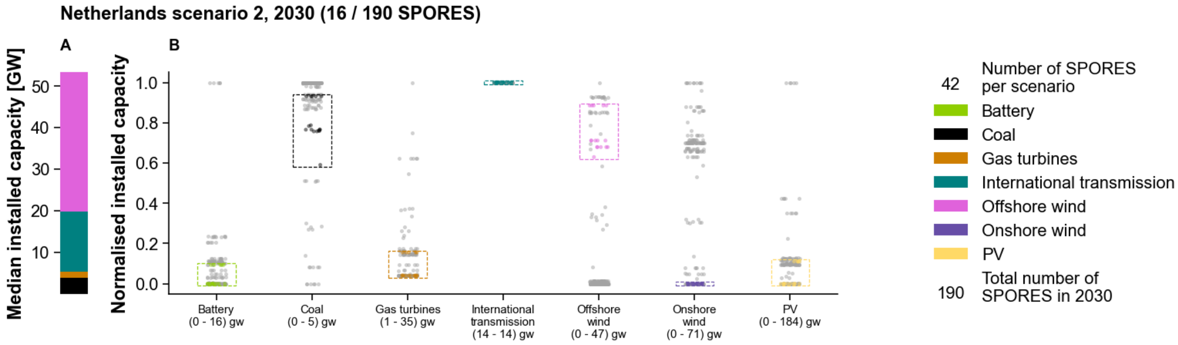


Figure B.50: the Netherlands scenario 2 in 2030

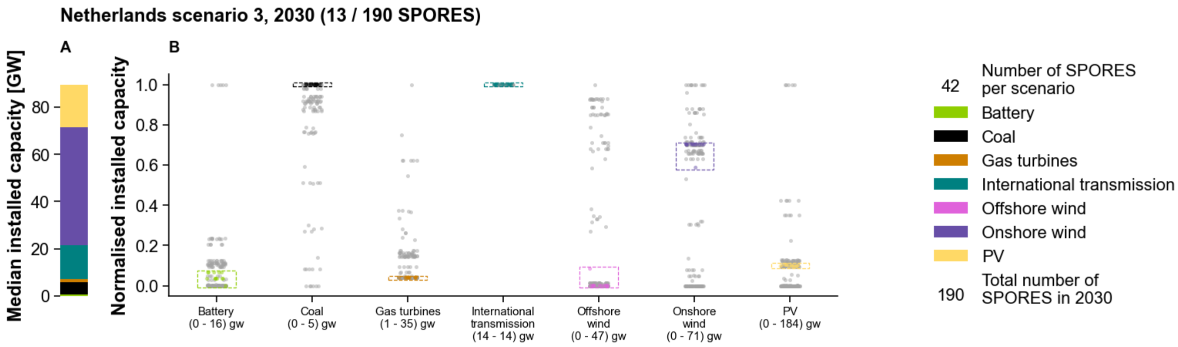


Figure B.51: the Netherlands scenario 3 in 2030

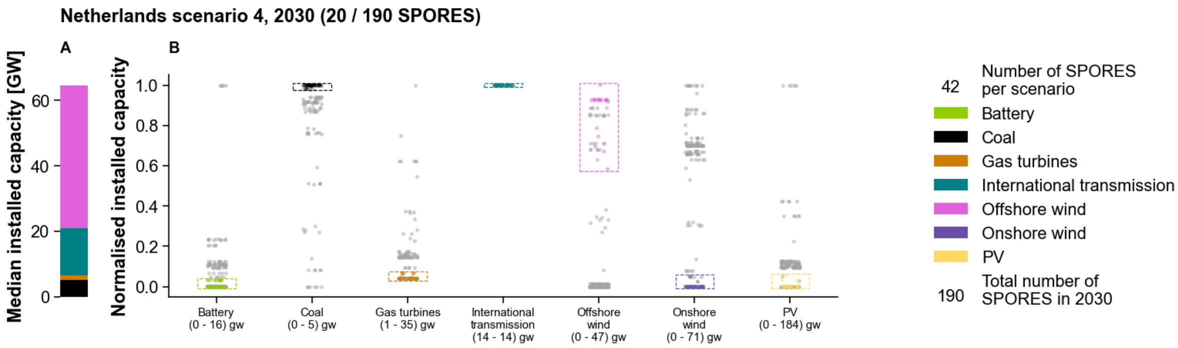


Figure B.52: the Netherlands scenario 4 in 2030

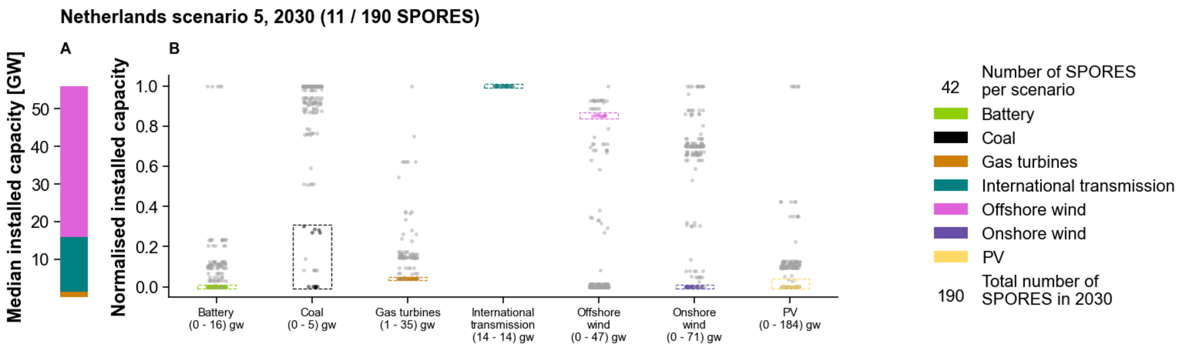


Figure B.53: the Netherlands scenario 5 in 2030

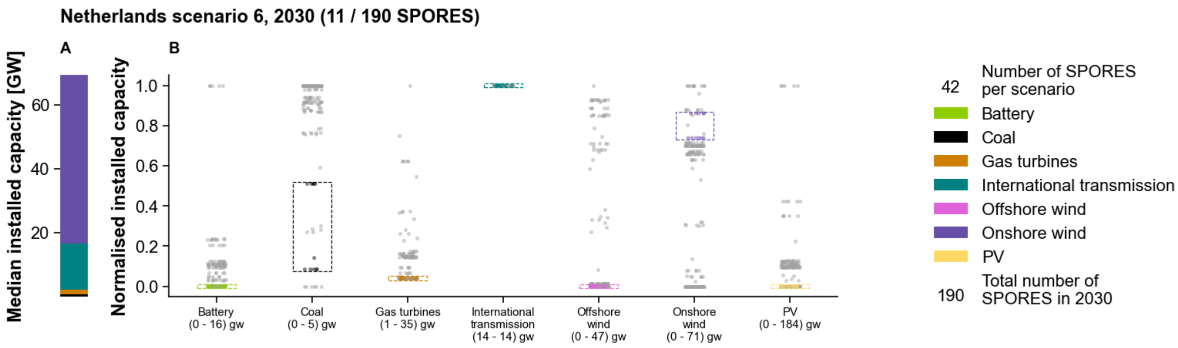


Figure B.54: the Netherlands scenario 6 in 2030

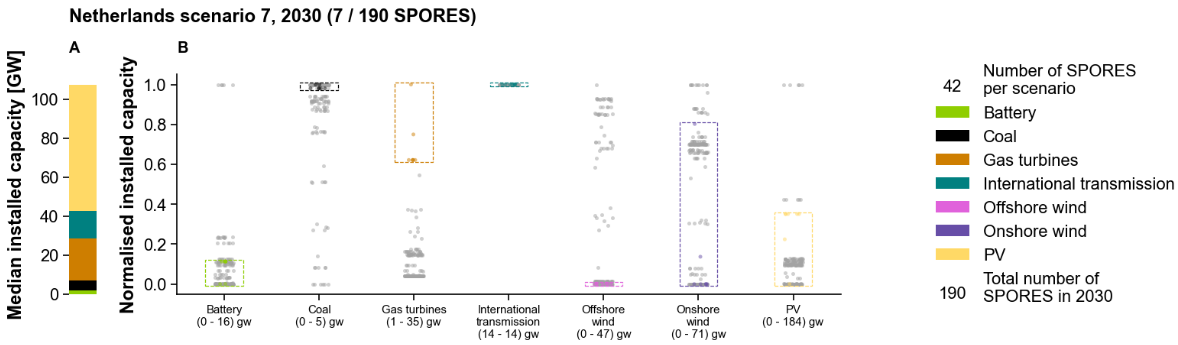


Figure B.55: the Netherlands scenario 7 in 2030

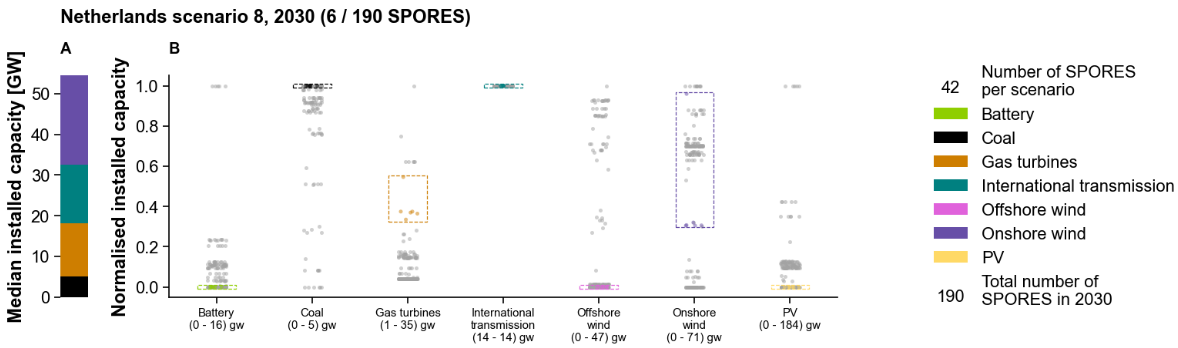


Figure B.56: the Netherlands scenario 8 in 2030

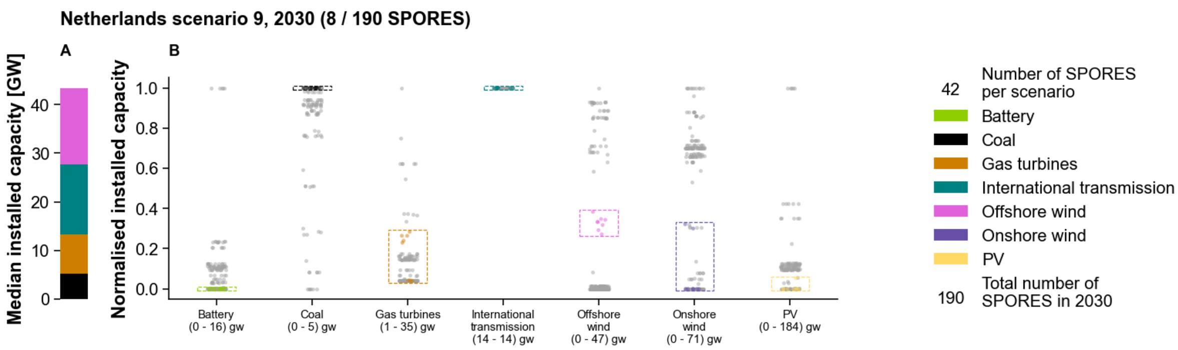


Figure B.57: the Netherlands scenario 9 in 2030

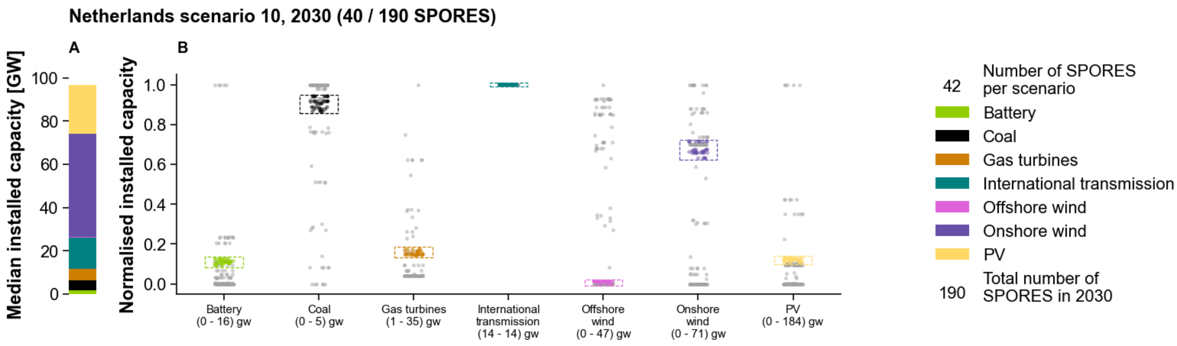


Figure B.58: the Netherlands scenario 10 in 2030

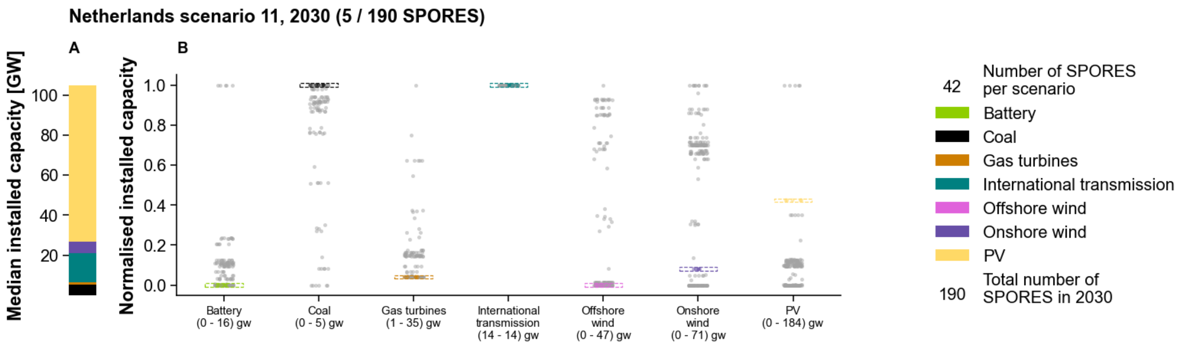


Figure B.59: the Netherlands scenario 11 in 2030

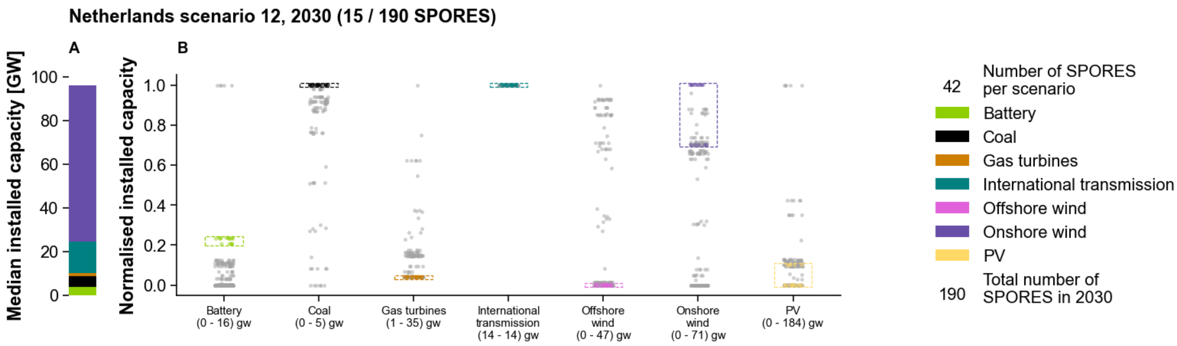


Figure B.60: the Netherlands scenario 12 in 2030

B.3.2. 2050

Table B.6: Scenario names, the Netherlands 2050

Scenario	Name
0	High Gas turbines, Low International transmission
1	High Onshore wind
2	High Offshore wind, Low Onshore wind
3	High International transmission & Offshore wind & PV, Low Battery & Onshore wind
4	High Battery & PV
5	High Battery & Gas turbines & PV, Low International transmission

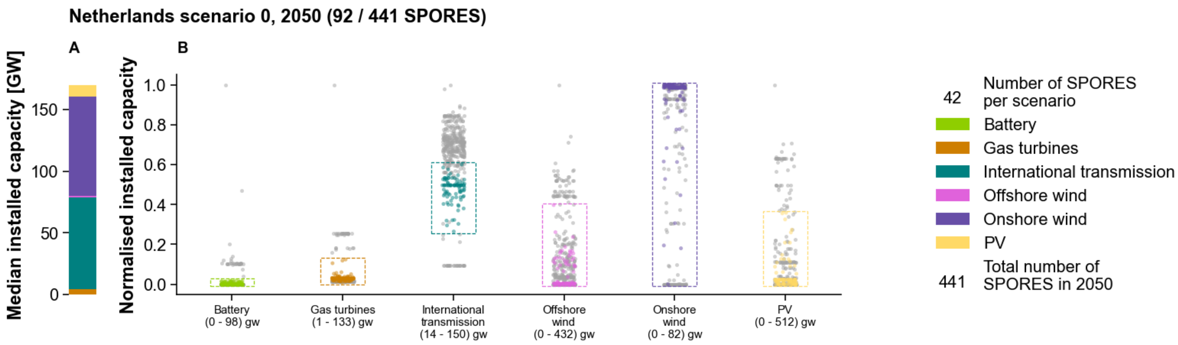


Figure B.61: the Netherlands scenario 0 in 2050

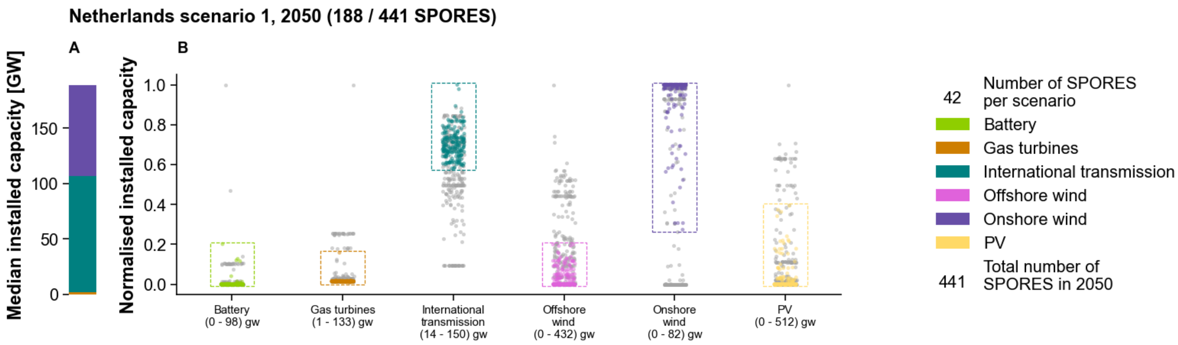


Figure B.62: the Netherlands scenario 1 in 2050

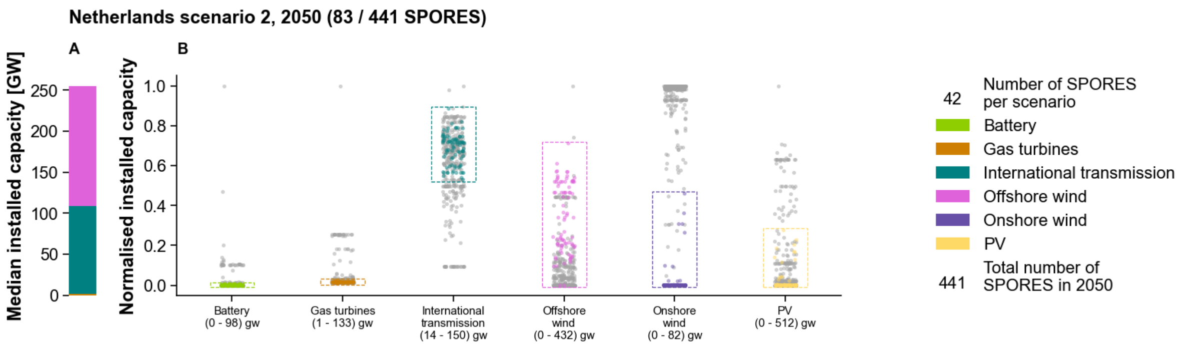


Figure B.63: the Netherlands scenario 2 in 2050

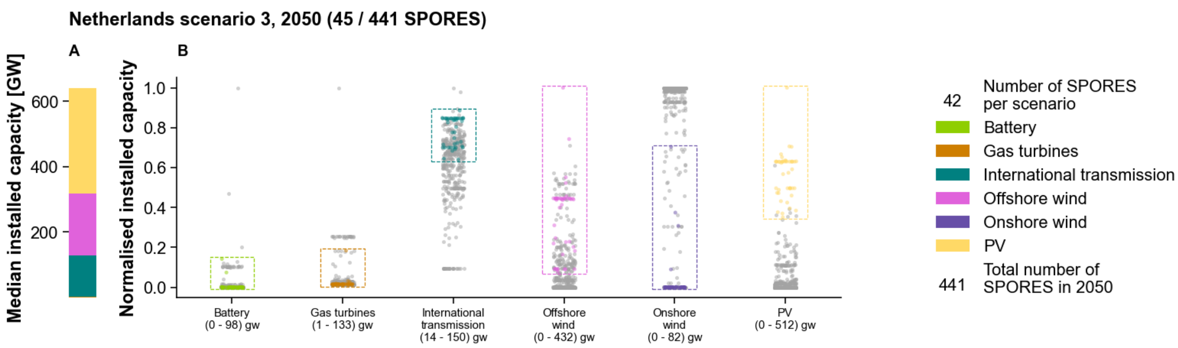


Figure B.64: the Netherlands scenario 3 in 2050

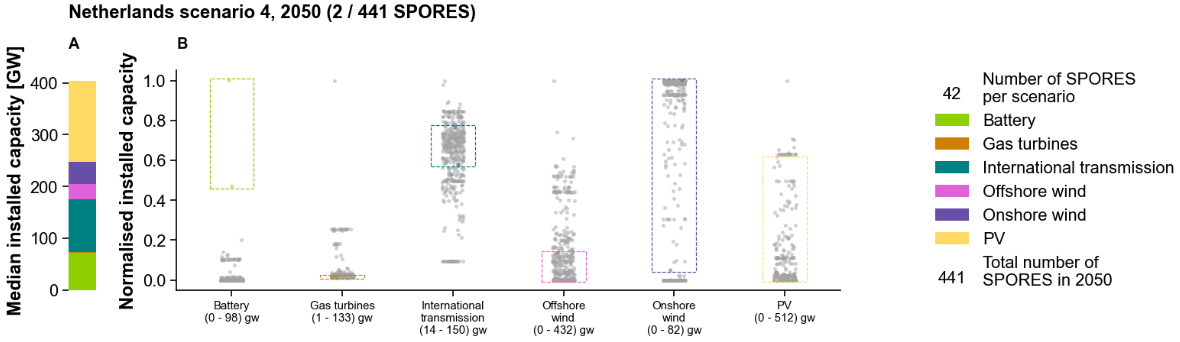


Figure B.65: the Netherlands scenario 4 in 2050

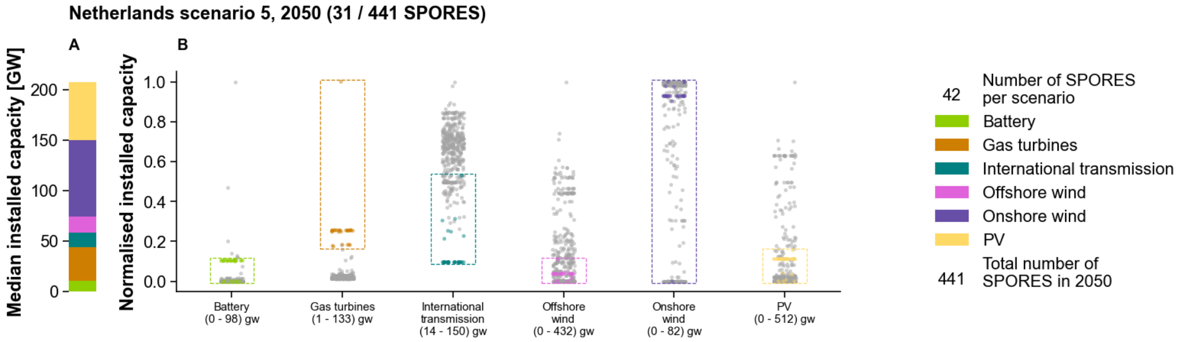


Figure B.66: the Netherlands scenario 5 in 2050