Underground Pumped Hydro Storage

The impact of UPHS on the high-voltage grid
A case study in Zeeland, the Netherlands

Master thesis - Complex System Engineering & Managament

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by

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Preface

The energy transition is facing new challenges regarding the implementation of renewable sources. The deployment of high solar and wind capacities results in a certain flexibility need, and addresses, besides economics, considerations of social, environmental, and political values. The high complexity of interaction between elements of the energy system, and the need to decarbonise it, drive me to complete the Master Complex System Engineering & Management at Delft University of Technology.

To develop Underground Pumped Hydro Storage (UPHS) in the Netherlands, Pondera Consult and Tethys Energy Storage would like to have more insight into the impact of UPHS on the high-voltage grid. This assignment fits in the perspective of socio-technical complex systems and is therefore chosen as my master thesis project. I really enjoined to do the research because I could bring all the things I have learned over the past seven years. Both the broader perspective of spatial development from my bachelor's and the more specific analytical and scientific view on technical and economic considerations of the master's are addressed. The dialogues with experts in the field and writing about the results in particular gave me the positive energy to complete the task of doing this research. This study is written to describe the added value of UPHS in the broader societal context. Whether the current market structure still fits the developments needed in the future, this report is intended for policymakers. The report shows the need to have a market model that supports innovative and socially valuable projects that might be risky, but long-term oriented.

I would thank Pondera Consult and Tetheys Energy Storage for allowing me to work on such an innovative project. Collaborating with passionate colleagues to work together for a sustainable future brings a lot of positivity. In particular, I would like to thank Martijn ten Klooster and Yvonne Neef for their trust and patience they have, and for allowing me to join conversations with the project team and stakeholders. I also got the opportunity to share the results halfway the graduation process with the project team. This was very valuable as well.

Furthermore, I would like to thank Aad Correljé and Pieter Bots from TU Delft. Philosophical discussions about the value of innovations in the energy system, required incorporations in market structures, were very valuable. Sometimes, I had some difficulties in addressing the overall value of UPHS. Aad and Pieter both helped me with this. Pieter has also taken extraordinary time to support me in learning to use Linny-R, scoping the model to something useful, and making considerations about how to make time-efficient choices. Besides, I had conversations with experts in the field about this topic. Therefore, I would like to thank Maarten Staats (Enexis), Gert Jan Kramer (Utrecht University), Jop Klaver (Pondera Consult), Joeri Vendrik (CE Delft), and Sacha Schmitter (Energy Storage NL).

Sometimes the graduation process didn't go quite smoothly, and the process seemed to go on endlessly. Pieter, Aad, and Martijn helped put things into perspective to continue with confidence and fresh courage. Eventually, I will finish the Master thesis project too, but it took a bit longer. Therefore, I would like to thank Jeroen de Veth from Pondera for giving me extra time to study for the final exam and to finalize the Master thesis.

In the background of the graduation process, my family and friends have been a great support to me and therefore I am very grateful to them. Sometimes because of my enthausiasm on the topic, but also to help me at times when I was stressed or when it was emotionally difficult due to the loss of a loved one. I am looking forward to present the results at the defence for them. My grandfather, who always believed in me, will be there in my thoughts.

W.M. (Mandy) Bouwhuis
Delft, August 2024

Executive summary

Toward 2050, the Dutch energy system will face new challenges as electrical power demand and supply increase. On the one hand, further growth in renewable capacity, especially wind and solar, will be realised. However, sectors such as the built environment, industry, mobility, and agriculture will use more electricity. The increase in power demand and supply and constraints of the Dutch power grid result in a certain flexibility need. The need for energy storage reflects economic, environmental, geopolitical, and technological considerations. However, liberalised markets, including the Dutch power market, are designed from an economic point of view without considering overall system benefits.

Underground Pumped Hydro Storage is considered as large-scale storage technology in the power system of Zeeland. It has the same concept as traditional Pumped Hydro Systems, a proven technology that is the most widely used energy storage technology in the world, but the upper basin is placed at ground level and the lower basin is at 1.5 km depth. The project has high investment costs and a long return on investment period, involves high risks and uncertainties, but has a certain technical potential resulting in overall system benefits. UPHS can contribute to the flexibility Zeeland need to accelerate the energy transition towards 2050.

To what extent UPHS can provide system beneftis is however unknown. Therefore, the power grid of Zeeland is modelled into a market-driven decision model for mixed integer linear programming by using Linny-R, to analyse the behaviour of UPHS based on the RES 1.0 Zeeland, CES Delta Schelde Regio, and II3050 scenarios. A wide range of possibilities are within the scenarios for 2030, 2040, and 2050. Therefore, scenarios have been compiled, which differ from each other in the extent to which the energy transition is completed on both the demand and supply side. The model allows simulation of power flows on the high-voltage grid. To determine the added value of UPHS model outputs are evaluated on Key Performance Indicators, i.e. curtailment, carbon emissions, power shortages, power import and power export.

Besides a more in depth analysis on the behaviour of UPHS in various months and years, four scenarios are selected to focus on, based on four main directions regarding installed renewable capacity and the use of a nuclear power plant. The results show that curtailment reduction by UPHS is higher in scenarios with more renewables and that there is some variability throughout the year. Remarkable, UPHS does not minimise power shortages in these scenarios, but there a few scenarios in which UPHS does minimise. Furthermore, UPHS decrease carbon emissions especially in winter months.

The simulations also show that UPHS is able to decrease curtailment up to 2.7 TWh per year within the selected scenarios, but the impact UPHS has on the number of hours that curtailment occurs is limited. However, a 380 kV connection between Borssele and Terneuzen is required. In general, UPHS has the potential to significantly reduce system costs. In 2050, some power shortages may occur in scenarios with the lowest installed renewable capacity, but UPHS cannot solve these. From a system perspective, the installation of smaller power storage assets might fit the problem better. Reducing the capacity by 50 % results in only 25 % fewer advantages compared to a system with 100 % capacity. The same storage facility in Borssele instead of in Terneuzen results in similar system outcomes. In addition, 2 smaller installations, 1 in Borssele and 1 in Terneuzen, even result in better system outcomes.

Without nuclear power, Zeeland will become more dependent on resources other than solar and wind power. The analysis also demonstrates that UPHS has the potential to deliver a certain security of supply, up to 50 % of the performance of nuclear power plant of 1500 MW in scenarios with high installed capacities. Some additional flexible resources are needed in scenarios with fewer installed capacities of solar and wind, but this is relatively low compared to what UPHS delivers in the system. This might be economically interesting considering the investment costs of UPHS compared to the investment costs of a nuclear power plant of a similar size. Further, UPHS has advantages over nuclear power in technical, environmental, and economic aspects. The deployment of fossil power generators can also be reduced by implementing UPHS. Only if there is less renewable power capacity installed, UPHS will increase the deployment of Seasun B.V. due to lower marginal costs than Elsta and Sloecentrale, and the functioning of the market to increase revenue streams.

Because the behaviour of UPHS is based on getting the highest possible benefit considering power import and export prices only, higher quantities of power import and export occur. This might have negative consequences elsewhere, outside the considered system boundaries of Zeeland. So, the technical potential UPHS have regarding minimising curtailment and carbon emissions does not emerge adequately. If such a project would be realised, agreements have to be made on under what conditions UPHS should be deployed. Without any governmental support, it is unlikely that UPHS will be realised by the market. High investment costs, uncertain future revenue streams, uncertain long-term policy, and a long return on investment period based on power prices only make the project a high risk. Taking into account the broader benefits of the system, the return on investment will be achieved after approximately 11 years. This includes the reduction of curtailment and the use of these quantities later on, and therefore reducing fossil power production by fossil power plants. Also the value of reduced carbon emissions is included in addressing the caused external impact. There are many more benefits, such as savings in critical material use compared to batteries and increased security of supply and self-sufficiency.

Contents

List of Figures

List of Tables

1 Introduction

The Netherlands has the ambition to be climate neutral in 2050 which means approaching 100 % share of renewables in the energy mix. Mainly to limit climate change, but also because of the finite availability of fossil fuels and to reduce the dependency on international energy suppliers (Rijksoverheid, 2017). Currently, the production of renewable energy is increasing, with the electricity production from offshore wind farms being the highest (Ministerie van Economische Zaken en Klimaat, 2021b). Electricity from renewable energy sources, and wind farms and solar panels in particular, will replace the former base load of large fossil energy producers in the future (Ministerie van Economische Zaken en Klimaat, 2016). As a result, grid operators already have challenges in managing increased supply-side power fluctuations on the grid. Because solar and wind are not always available, power from other sources are still needed. Therefore, investing in nuclear power is currently under political consideration to provide a certain base load in the future. Electric demand will also increase as a result of the electrification of industries and the built environment, and the development of green hydrogen production. However, to what extent is uncertain because green biogas and CO2 capture are also under development. Besides balancing supply and demand, there are also challenges of congestion and security of supply on the national, regional, and local levels. Several reports indicate that both the expected power demand and supply will increase, resulting in an insufficient capacity of the grid. Therefore, more flexibility in the energy system is required, both in the short- and long-term, as there are challenges in the time frames from seconds to seasons, and electricity prices will become more volatile (CE Delft, n.d.) (Ministerie van Economische Zaken en Klimaat, 2016).

To increase flexibility, the Dutch government is mainly directing the development of batteries and hydrogen as a key technology for electricity storage. Market parties are mainly focussing on batteries because of the economic opportunities current market structures provide. The existing markets market parties can trade in, determine the financial viability of a particular service and determine therefore the actual deployment of a given service in the market due to market functioning (CE Delft, n.d.; Ministerie van Economische Zaken en Klimaat, 2016). However, the development of other technologies remains underexposed, and to what extent public values are currently included can be questioned. Especially large-scale energy storage technologies are not part of the developments in the Netherlands at the moment. Currently, the Netherlands is cooperating with foreign countries that have pumped hydro storage to solve the long-term mismatch between demand and supply.

The Dutch government developed the National Plan Energy system, which shapes the energy system of 2050 and a vision to build towards. Direction is given to energy supply, energy savings, shortages, international collaboration and participation. Public values have to be integrated into the energy system of the future, which are sustainability, safety, reliability, justice, participation, economic strength, affordability, and quality of the living environment Ministerie van Economische Zaken en Klimaat, n.d.). Storage technologies have to be valued on public principles as well. This gives reason to reexamine Underground Pumped Hydro Storage (UPHS) as a large-scale energy storage technology to be applied in the Netherlands. With this, large-scale energy storage could be realised as in Norway and Switzerland.

In 2018, Jan Huynen conducted research on the implementation of Underground Pumped Hydro Storage (UPHS) in Limburg in the South of the Netherlands, which is an energy storage system similar to traditional Pumped Hydro Storage or PHS (Huynen, 2018). This system consists of an upper basin at ground level, and a lower basin at 1.5 km depth. Electrical energy is stored in the form of potential gravitational energy, by converting electrical energy into mechanical energy using hydraulic pumps during electricity surpluses. When energy shortages occur, the water will be dropped, gravitational energy will drive generators that convert mechanical energy into electrical energy. The design proposed has a storage capacity of 8,4 GWh and has controllable power up to 1,4 GW. This makes UPHS technically suitable for medium and long-duration storage, being able to capture and offer large amounts of energy, and the potential to decongest the energy system.

A well-suited location for UPHS seems to be the province of Zeeland, a coastal province in the south of the Netherlands. This area contains large industries that need to decarbonise somehow, is connected to the offshore grid, and there might be the possibility that a new nuclear plant will be constructed to provide a certain baseload. Grid reinforcements and flexibility of the energy system appear to be required to enable these developments. This goes along with trade-offs in system costs, environmental impact, system benefits, and public support. A storage facility such as UPHS may decrease curtailment and power shortages, and reduce the need for grid reinforcements and renewable and nuclear power capacity. These more technical benefits of the system have a certain value to be translated into a reduction in social costs. Taking into account the lifespan of the technology and environmental aspects as well, UPHS might have advantages over current market developments regarding energy storage. Furthermore, UPHS might provide a supporting role for industrial activities, thus accelerating the energy transition towards the use of renewable power at the regional level in Zeeland. However, it is unknown to what extent UPHS may increase the performance of the power system. Therefore, this research will anser the following research question: *What is the impact of Underground Pumped Hydro Storage on the high-voltage grid in Zeeland, the Netherlands?* This question will be answered in the broader perspective of technical, economic, environmental, and social values by using Key performance Indicators of curtailment, power shortages, carbon emissons, and power import and export quantities. Furthermore, uncertainties in the future such as higher demand, grid capacitiies, and installed renewable capacities will be taken into account.

2
Theoretical background

This research on UPHS focuses on a case study in Zeeland, assuming that the project is technically feasible. This section provides a basic understanding of the concept in technical, environmental, economic, and social aspects to compare UPHS with other energy storage technologies as well. Furthermore, the Key Performance Indicators used for determining the impact UPHS may have on the power system, are described. Furthermore, the relevant basics of institutional economics is provided.

2.1. UPHS - The concept

Traditional Pumped Hydro Storage (PHS) is the most widely used energy storage technology, accounting for over 94 % of installed global energy storage capacity, which was estimated at 158 GW in 2019 (Nasir et al., 2022). The concept of PHS can be applied under the ground too, which originated as an idea of a Dutch study group in the 1980s (J. van Duivendijk, 1997) and was analysed further as a case study in Limburg by Johannes Huynen in 2018 (Huynen, 2018) A visual representation is given in figure 2.1.

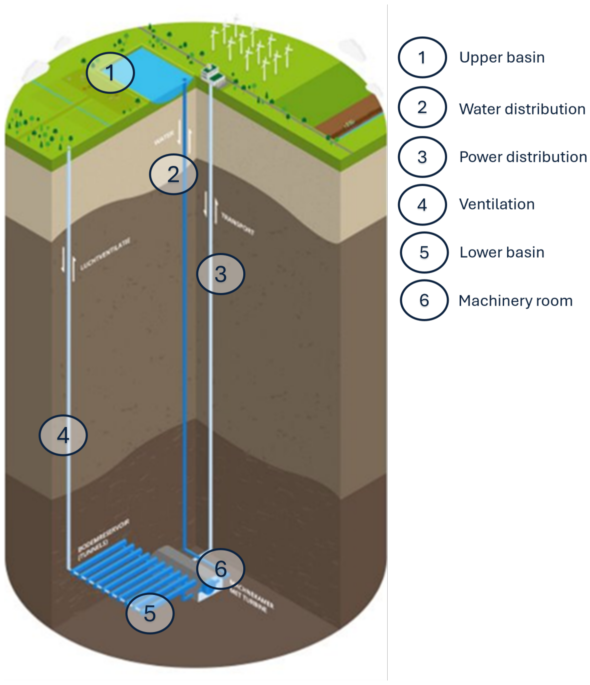


Figure 2.1: Visual representation of UPHS

Figure 2.1 shows the components of UPHS, e.g. tunnels, lower and upper basins, an underground engine room, electric motors, hydraulic pumps. The basins are connected with tunnels. There is one tunnel for water transport, one tunnel for ventilation and cables, and one tunnel for transport of material and engineers. This technical design already exists of which the specifications can be used (Huynen, 2018). UPHS includes the principles of mechanical, gravitational, and electrical energy. Furthermore, there are some geological requirements to implement this technology.

2.1.1. Technical design of UPHS

Pumped Hydro Storage applies the principle of mechanical and potential gravitational energy to store hydroelectric energy at a certain height. Therefore, two water storage reservoirs at different heights are needed, an upper and a lower basin, which is why the storage technology is normally applied in mountain areas. The processes of mechanical, gravitational, and electrical energy are shown in figure 2.2.

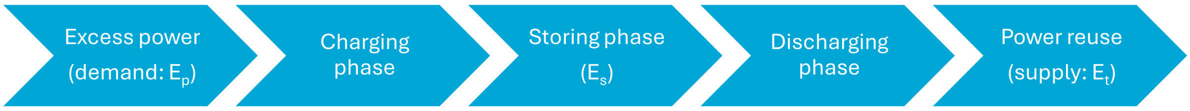


Figure 2.2: Process of power input, storage, and power output (Huynen, 2018)

Electricity surpluses are used to pump water from the lower basin to the upper basin. Surplus electricity is then converted to mechanical energy and harnessed as gravitational energy. At this moment of the process, hydroelectric energy is stored. By releasing the water back into the lower basin later, UPHS can produce electricity when required, for example during an energy shortage. Water will drop from the upper reservoir to the lower reservoir, via turbines that generate electricity. Stored gravitational energy is then converted to mechanical energy again and then to electrical energy. (Huynen, 2018J. van Duivendijk, 1997Energy.GOV, n.d.)

The equipment can be operated in both the generation and pumping mode, but it is preferred to have an electric motor (generator) and a hydraulic pump due to optimisation possibilities (Huynen, 2018). Important to note is that UPHS is a closed-loop system and that the engine room is underground. The technical specifications, used for this study, are given in table 2.1 and corresponds with the technical design of Jan Huynen.

Specification	Value	Unit
Storage capacity	8.4	GWh
Pump/generator capacity	1,400	MW
Depth/head	1,500	m
Surface upper basin	25	ha
Height upper basin	10	m
Volume upper basin	5.3×10^6	m^3
Charging time	6	h
Discharging time	8	h
Lifecycle	> 50	years

Table 2.1: Specifications of UPHS

Previous studies of UPHS systems considered similar specifications based on the most efficient storage capacity and volume, optimal depth, and locations, determined by geological conditions, the ideal layout of the underground reservoir and the most effective pump-turbine combination (Huynen, 2018;J. van Duivendijk, 1997).

The round trip efficiency of PHS typically ranges between 70 % and 85 %. These losses mainly occur in the pumping and turbine stages, both around 92 %. Other energy losses will be in transformers, motors, generators and shaft lines, which are substantially smaller than turbine and pump efficiency losses. The height difference between the two basins is the prime determinant of hydro power, determining both the power rating and the energy storage. The height difference depends on topographic circumstances. Huynen (2018) mentions that in the absence of natural height differences, the creation of an artificial head is necessary, which can be achieved by constructing a lower reservoir underground. The geological conditions have to be favourable to minimise costly civil engineering work. In addition, very large reservoirs are needed to increase the relatively low energy density: 1 m^3 water at a height of 100 m has 0.27 kWh potential energy (Huynen, 2018).

The drilling process to construct the tunnel will result in large amounts of waste in the form of rock. The amount is expected to be 5 to 20 million tonnes, which can be used for the upper reservoir or other purposes to enable the reuse of materials, a circular economy. Compared to lithium-ion batteries and electrolysers, no critical materials will have to be used or need to be recycled afterwards. Furthermore, UPHS can be fully CO2-neutral during the operational phase

One of the design aspects is the choice to use fresh or salt water in the basin. In total, $5.3{\cdot}10^6$ m^3 is needed and over 1,700 m^3 of water can evaporate per year. The water level has to be replenished to maintain the storage capacity of 8.4 GWh. Using freshwater places pressure on the freshwater supply itself, especially in summer due to drought. The use of saltwater, on the other hand, results in additional risks for the vulnerable freshwater supply, as described before. The consequences of seawater leaking with underground freshwater are unforeseen.

Multifunctional use of space can be incorporated, reducing the impact on space due to storage, and thus reducing the spatial impact. Depending on the use of fresh or saltwater, the basin can be used during dry periods for agricultural purposes, for example. However, clear agreements must be made about this. A cycle will have to be established between, for instance, rainwater collection and the withdrawal of water for irrigation by agricultural businesses. Furthermore, it could also be used for recreation if safety regulations are met. A basin could then be part of the environment rather than an object that is part of the energy system, and therefore socially more accepted.

2.1.2. Geological conditions

The concept of UPHS is a closed-loop system. The system does not exchange water with the soil, which is important to ensure freshwater supply. Freshwater in the subsurface should not be polluted, and leaks between saltwater and freshwater is not allowed. Leaks of UPHS result in water exchange with different layers in the soil. It may add unwanted saltwater from deeper layers into freshwater layers in the subsurface, which is fatal for Zeeland's freshwater supply. Liquids in the ground on the other hand can also corrode the tunnel material, and the efficiency of the system will suffer from water losses. Hence, UPHS must be realised in low porous and impermeable rocks with sufficient strength and homogeneity at the appropriate depth to withstand the relatively high pressures in the galleries (the lower reservoirs). More permeable, porous, and fractured rocks on the other hand can lead to water infiltration and exfiltration. Dinantian layers between approximately 1.0 and 1.7 km depth were initially considered promising and offer a stable rock formation to host UPHS. The Dinantian layer is present in both Limburg and Zeeland. This layer is part of the Upper Carboniferous period and is primarily composed of carbonates and evaporites. The depth of the top of the Dinantian layer is at a relatively shallow level in the South of Limburg and Zeeland. Special care should be taken during drilling as the top can be highly affected by karstification and its presence is relatively thin or not present in Zeeland, as it thins out towards the southwest. Therefore other, older rocks (e.g., Devonian age) and the London Brabant Massif should be considered as those are also present in Zeeland at the target depths. Unfortunately, this part of the Dutch subsurface has hardly been explored by drilling and seismic studies, hence a seismic survey and drilling of a research well should be initiated before selecting the exact location of the UPHS facility. Subsequently, additional characterisation of the subsurface at the designated location is needed. To eliminate the risk of faults in the subsurface, a 3D seismic study should be carried out and drill cores be taken to study the presence of fractures. (Jop Klaver, 2024)

2.1.3. UPHS applied in the Netherlands

Zeeuws-Vlaanderen and Limburg seem to be the most suitable locations for the development of UPHS in the Netherlands according to geological conditions. As described, the study of Huynen has already been carried out on the development of UPHS in Limburg (Huynen, 2018). The idea behind this was that UPHS could provide a supporting role for nuclear power that needs to produce a certain base load. The UPHS facility could therefore store surpluses of nuclear power, and release this later on during periods of higher power demand. Nuclear power was, however, never realised in Limburg, reducing the need for a large-scale storage technology at that time. Zeeland on the other hand might be more interesting nowadays, because of the vision to implement large quantities of renewable power capacities and electrification of the industry. Both developments will affect the use of the high-voltage grid and the need for grid reinforcements, which affect broader values of society.

Research has been done on the technical feasibility of Underground Pumped Hydro Storage (UPHS) and its variations. The economic, social and environmental aspects, however, have not yet been sufficiently identified. Corbijn investigated the potential benefits of implementing UPHS in the Dutch power system and concluded that UPHS provides all the benefits of battery storage (Corbijn, 2017. In addition, UPHS does not have to compete with alternative technology applications, has a substantially longer lifetime, and can be competitive with natural gas turbines in the future, and the less flexible burden on thermal power generators will result in lower costs and less renewable curtailment (Corbijn, 2017). Furthermore, Tiwari et al. (2021) pointed out that the existing policy, legal and regulatory regimes fail to recognise and support the entire spectrum of benefits that some energy storage technologies create. Therefore, a legal and regulatory framework governing UPHS should harmonise the case of land use, environment, water quality, and the electricity market (Tiwari et al., 2021).

2.1.4. Economic feasibility

The construction of UPHS involves certain costs regarding investment, capital, operational phase, and maintenance. Revenues have to be found in the energy markets in which UPHS can operate, which is also dependent on institutions. According to current market structures, a cash flow begins after a relatively long preparation and construction period that could be more than 7 years. Maximum revenues cannot be achieved instantly during the initial phase (Huynen, 2018). Market parties have to deal with high uncertainties regarding the return on investment by developing UPHS because future policy is uncertain.

Expenses of UPHS

Jan Huynen researched the project investment costs of traditional pumped hydro storage plants. The construction of UPHS, presented in table 2.2 and figure 2.3, will have high initial investment costs and capital costs. Once realised there will be operation and maintenance costs. The total costs of UPHS over its lifetime can be translated into levelised costs of storage.

Construction	Total costs [Million €]	Total share [%]	Costs per MW [€]
Shafts	247	14	29,405
Shaft installations	101	6	12,024
Subterranean spaces	82	5	9,762
Civil engineering works	709	40	84,405
Machinery	324	18	38,571
Electrical installations	52	3	6,190
Above-ground construction	37	2	4,405
Unforeseen construction costs	233	13	27,738
Total	1,785	100	212,500

Table 2.2: Construction costs of UPHS

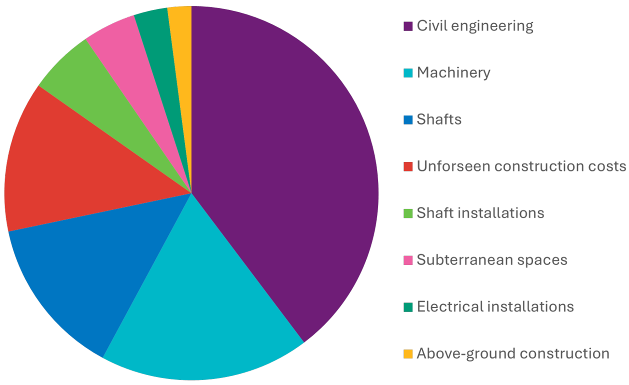


Figure 2.3: Pie chart Construction costs of UPHS

Based on plants realised after 1980 the storage investment costs vary between 604 and 1,843 €/kW. The proposed costs included investments in civil engineering work, machinery, and accessory installations. Huynen mentions that large-volume reservoirs have lower investment costs for storage €/kWh but may sometimes result in high investment costs for the installed power €/kW. Additionally, the investment costs differ substantially between the projects studied and depend on various circumstances. The investment costs between regions also differ a lot, in which China seems the lowest with 576 €/kW, then the U.S. with 720 €/kW, Europe with 1,156 €/kW and Japan with 1,292 €/kW. In conclusion, Jan Huynen estimated that UPHS can be constructed for almost 1800 million € as presented in table 2.2 (Huynen, 2018).

The capital costs are based on the WACC (Weighted Average Cost of Capital) calculation, and used as the discount rate in the annualisation of the total investment. These are the average costs for financing a project from investment by both shareholders (equity) and debt.

The operational handling and maintenance (OPEX) of PHS systems is estimated on 1 to 3 % of the investment per year. Here, every project is different as huge dams, for instance, require special care due to high water pressure. Large PHS plants, however, require lower operation and maintenance costs due to economies of scale. Jan Huynen assumed an OPEX level of 1.1 % of the total investment (Huynen, 2018).

The levelised storage cost (LCOS) is the calculation of the annual costs for capital, fuel and O&M, divided by the amount of annual electricity production/ storage. These costs depend on the amount of energy stored and discharged from a storage plant and thus depend on its application. The calculation fails to capture the full value that storage can obtain from providing flexibility and its value for the power system as a whole.

Revenues of UPHS

According to the literature, UPHS can facilitate several functions in the energy market, for flexible production, demand-side management, interconnection, and energy storage facilities (Morabito et al., 2020). A storage facility such as UPHS has the ability to respond quickly and to obtain high power rates (Olsen et al., 2015). Due to its adaptability, UPHS can deliver ancillary services for up- and down-regulation within a few seconds upon frequency deviations (Olsen et al., 2015; Rehman et al., 2015; Xue et al., 2022). Thus, UPHS can be operational both in the day-to-day market and in the ancillary service market.

The functioning of the market is partly based on system behaviour, more technically. The day-ahead and intradaymarket is designed from the perspective of balancing supply and demand, and the ancillary service market to deal with for example frequency imbalances, grid constraints, and electricity shortages. Considering the economic value UPHS can have in the day-ahead and intraday market, revenue can be derived from the differences in import and export quantities, and connecting these to the prices the moment these quantities occur. Then the economic feasibility of UPHS according to current market structures can be found. The ancillary service market is excluded from this research.

Market versus system potential

Barbour et al. (2016) found that most of the PHS developments so far has occurred under public ownership and has been aligned with periods of significant electricity infrastructure growth. Without significant policy changes, it seems unlikely that other large-scale energy storage technologies will fare significantly better in competitive wholesale markets (Barbour et al., 2016). If an increasing body of research concludes that large-scale energy technologies will result in a net societal benefit, a meaningful debate around public sector investment is merited (Barbour et al., 2016) as the necessary investment costs are often considered too high (Morabito et al., 2020). But, researchers compare capacity costs for energy storage plants instead of energy storage costs (Madlener and Specht, 2020). This does not give insight into the real costs of energy storage, in which the real lifetime or number of storage cycles are included.

The costs involved in the development of UPHS seem to be the main obstacle to surmount, because the feasibility of adopting a specific storage technology is currently a function of a techno-economic analysis (Matos et al., 2019). The current market is operating according to a merit order, in which the cheapest power generators have priority over power generators with higher marginal costs. Power storage technologies are power generators as well in this regard. Recognising social, economic, and environmental impacts should however serve as an important criterion for energy policy formulation (Tiwari et al., 2021), but information about potential obstacles in terms of policies, laws, and ecology is lacking (Xue et al., 2022). In addition, no research has been done on the added value of UPHS in the broader perspective of economic, social, and environmental aspects compared to other large-scale energy technologies. Therefore, the overall system benefits (Key Performance Indicators) should be valued. For example, a decrease in production costs will result in lower day-ahead prices because users normally have to pay the production costs of power directly to a power company. Furthermore, less curtailment will result in less need for grid-reinforcement, and less carbon emissions will result in lower negative impacts on society.

The market potential only considers the investment costs, capital costs, O&M costs, and the revenues from the differences in power bought and sold later. This results in a long term return on investment period with high uncertainties as explained before, but including system benefits may lead to different outcomes. Also, including system benefits may result in a more desired solution for society and therefore the Key Performance Indicators need to be valued.

2.2. Key Performance Indicators

An energy storage technology has the potential to add technical value to the system by changing the electricity mix towards more renewables, lowering the quantities of curtailment and power shortages, influencing the quantities and duration of import and export, and lowering the need for grid reinforcements in certain circumstances. Therefore, these assets have to decrease the deployment of fossil power generators by storing surpluses of electricity over time and releasing these quantities later on during periods of electricity scarcity. The technical value UPHS potentially has, resulting in some environmental benefits as well, can be expressed in economic value. The identification of system benefits in economic values will help recognise the broader spectrum of benefits that some energy storage technologies create. Grid operators have to cover the costs for curtailment, electricity shortages, and grid reinforcements, among other things and are paid by users of the grid. Differences in system costs, and thus social costs, caused by UPHS can be identified this way. This research will reflect on some performance indicators, known as Key Performance Indicators measuring the progress towards better system performances by UPHS. The Key Performance Indicators are curtailment, power shortages, power import and export, carbon emissions and system costs.

Curtailment

Curtailment is a consequence of a lack in transmission capacity, not being able to distribute generated power over the grid. Curtailment may also happen if the power production by renewables is higher than demand. If an energy supplier was actually selected to deliver power according to the dispatch order, but is not allowed to deliver in reality due to a lack in transmission capacity, the costs for curtailment can be adressed by assuming that a power producer of solar PV for example need to be compensated for not being able to deliver power to the grid thus missed revenues. Simultaneously, an additional power generator or power storage system somewhere else need to deliver power in advance, and need to be paid as well. These costs for redispatch are part of the transmission costs for all grid users. In case offered renewable power is not part of the accepted bids in the dispatch programme, its value can be debated.

Grid operators have contracts with producers and large consumers about the price of whether to produce or use. TenneT pays market parties that cannot produce for compensation of lost revenues and to market parties that can produce, in which the value is set out in the contracts between them. The results are high costs caused by curtailment. TenneT expects that the Energy and Power purchase costs (E&V) for the Netherlands will be € 1.5 billion in 2023 . These costs include the balancing market (FCR, aFFR, mFRR, and black-start), re-dispatch, compensation for reactive power, and grid losses. The average imbalance price over the years 2021, 2022, and 2023, is 150 €/MWh. This may be a valid representation of current balancing costs for TenneT, because producing power by a power generator elsewhere will most likely involve higher production costs than the day-ahead price and average marginal costs of fossil power plants, because these power generators have to guarantee availability at any time. In contract, the current price for rebalancing is based on generation by fossil power plants. In the future, storage technologies may also take on this role, which is likely to involve lower costs than fossil power plants (lower operational costs). This reflects potential competition and revenues in the day-ahead market because market parties prefer to enter a market in which they expect to have the highest returns.

Power shortages

Power shortages are related to the security of supply. Because solar and wind power may not be always available, other technologies than fossil power generators are needed to ensure a baseload of power to the power grid. Nuclear power is considered as one of the options, however, storage technologies may be preferred because these are flexible and nuclear power is not. Especially at higher power demands, power shortages may occur. The value of electricity shortages is the value of the lost load, which is set on € 68,887. This is the estimated amount that customers are willing to pay for receiving electricity.

Power import and export

The implementation of UPHS will cause a shift in import and export through the connection between Zeeland and the Netherlands by quantity and duration. Whether such a change is positive or negative depends on the situation and perspective, and the ultimate purpose of the storage facility. With regard to the challenges today, there is a need for more transmission capacity in the grid. Therefore, the total amount of power that will be imported or exported should be lowered. However, it can be questioned if the current market is enabling this to happen. On the other hand, higher import and export quantities may also indicate greater effective use of the grid. For example, less power needs to be curtailed and can exported later on, resulting in higher export quantities.

Carbon emissions

Carbon emissions will be reduced, because the release of stored power by UPHS will result in lower demand for power from fossil power generators. So UPHS contributes to the targets set by the Dutch government to be climate neutral in the future. To what extent emissions are minimised, depends on the type of fossil power generators that are phased out, for example, coal- or natural gas-fired. These types of generators have different characteristics and emissions.

Currently, the carbon tax is set on 80 €/tonCO2. In the future, this may change to 100 to 300 €/tonCO2 in 2030, 150 to 400 €/tonCO2 in 2040, and 200 to 600 €/tonCO2 in 2050. Assuming a natural gas plant that releases 0.37 CO2/MWh on average will have additional costs of 29.60 €/MWh if the price is 80 €/tonCO2. An increase in the carbon tax to 400 €/tonCO2, the additional costs are 148 €/MWh. An increase in the carbon dioxide tax will increase the added value of energy storage technologies in an economic context.

2.3. Institutions

The implementation of energy storage technologies stems from the need for flexibility in the energy system. The principle, storing excess energy to be deployed at a time of lower production quantities, thus creating a carbon-free energy supply. In other words, an artefact have to function in such a way that it does what it was designed to do. If not, there might be a coordination problem or market failure according to institutional economics. Therefore, the extent to which the desired value of UPHS matches the value it would add to the system should be examined, thus the functioning of the market. Subsequently, a reflection of the current institutional framework may be required, indicating a certain need for an intervention or re-regulation.

The institutional framework by Williamson can be used as it address the structure and functioning of markets, contracts, and organisations, and the role of institutions in promoting or hindering economic growth. The framework is used to understand the complexity of economic institutions and consists of four levels of institutional analysis i.e. embeddedness, institutional environment, governance, resource allocation, and employment.

Regulations are the laws and rules set by the government to promote the balance of the market and prevent its misuse. These include economic and social aspects of the market and are designed to ensure the efficiency of the market. However, an intervention is an action taken by the government to prevent or correct the outcomes of these regulations, which can be taxes or other measures. This can directly aimed at correcting market imperfections or preventing the negative effects of regulation. Both regulations and interventions can be applied in different layers in the framework of Williamson.

For achieving a climate-neutral power system by 2050, the Dutch government developed scenarios that outlines different pathways to achieve this. The so-called II3050-scenarios are designed to explore various routes based on the extent of intervention by the government and the level of international cooperation (Netbeheer Nederland, 2023. The principles provided in these scenarios are used by CE Delft in their research to the development of power supply and demand in Zeeland (Sjoerd van der Niet et al., 2020). A summary of the II3050 scenarios are provided in figure 2.4.

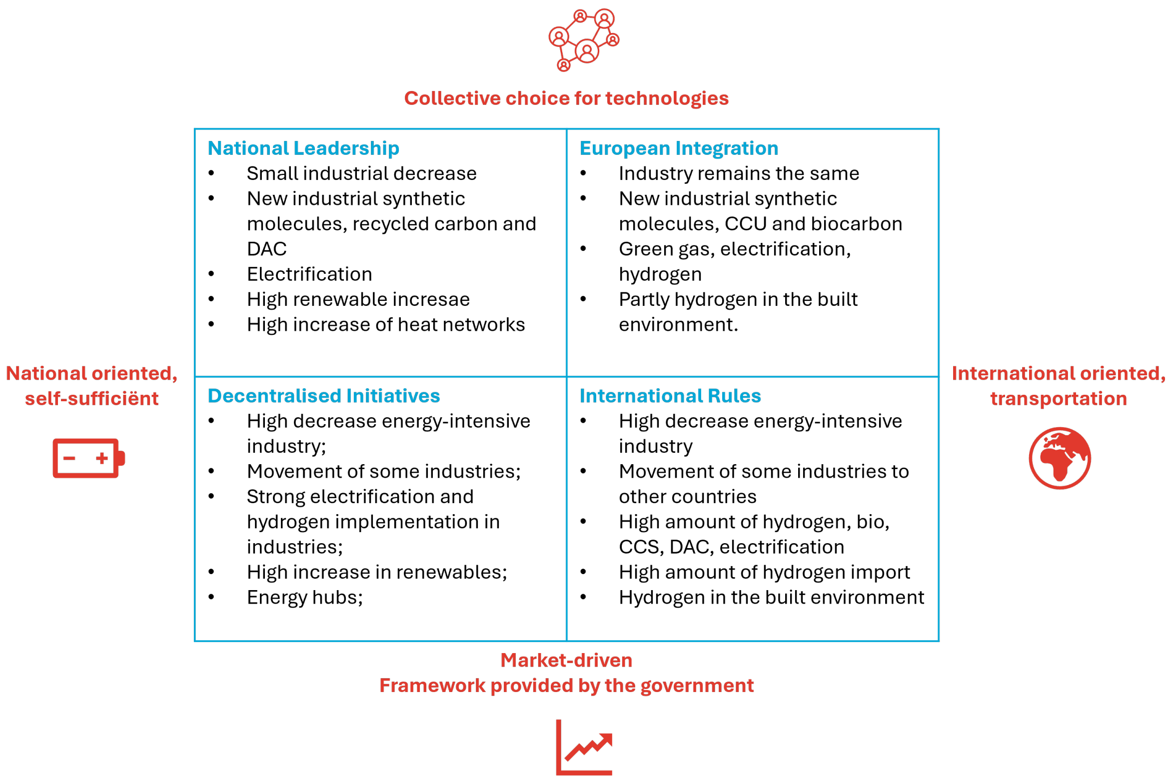


Figure 2.4: II3050 Scenario directions

3 Methodology

3.1. Research objective

Grid reinforcements and flexibility of the energy system seem to be required to allow the development of electrification and production of renewable energy in Zeeland. A storage technology such as UPHS might have advantages over batteries in the long term from a broader perspective. However, the impact of UPHS on the high voltage grid in Zeeland is unknown. Therefore, the following question is compiled as main research question: *What is the impact of Underground Pumped Hydro Storage on the high-voltage grid in Zeeland, the Netherlands?* The research outcome can be used for decision-making by investors and policymakers, as they need information about how UPHS behaves in the energy system, its benefits and disadvantages more precisely.

3.2. Research approach

A design approach will cover the research as the knowledge gap is void in the functioning of a complex socio-technical system and therefore a mixture of both the modeling approach and the design approach is needed, using a case study. On the one hand, the modeling approach is required because insight is needed into how elements of the system interact, with or without UPHS, and under various circumstances. The research also has the characteristics of a case study approach because Zeeland is used specifically, and the results cannot be directly assumed to be true for other locations.

The research will have the characteristics of both quantitative and qualitative methods. First, exploratory and quantitative research needs to be done before more modelling and more qualitative research can be conducted. Quantitative research will outline the current situation, developments, and scenarios, the concept of UPHS, and the analysis of Zeeland. This will involve technical, economic, and institutional aspects with descriptive and explanatory results. Eventually, qualitative research will be carried out. This consists mainly of modelling different situations. The results will be counterbalanced both qualitatively and quantitatively with descriptive and explanatory results.

3.3. Research questions

To answer the main question, first the impact of UPHS on the Key Performance Indicators, KPI's, needs to be analysed, and compared to scenarios in which UPHS is not involved. Subsequently, uncertainties need to be considered as well, i.e. variability in power demand, available transmission capacity, and market functioning. This includes a discussion on security of supply. Also the impact of design considerations, thus location and storage size, have to be analysed. All the gathered data can be used to determine the economic feasibility of UPSH, both from the market and system perspective. The market perspective considers the economic feasibility according to the current functioning of the market, while the system perspective considers the impact of UPHS on system costs as this will adress the added value of UPHS in a broader context. The following sub-questions are formulated, allowing to determine the impact UPHS have on the high-voltage grid in Zeeland.

1. How does UPHS perform on the key performance indicators - curtailment, power shortages, power import and export, and carbon emissions - in future scenarios of 2030, 2040, and 2050.
2. To what extent do uncertainties impact the key performance indicators of UPHS?
3. To what extent do design considerations (location and storage capacity) impact the key performance indicators of UPHS?
4. What is the economic feasibility of UPHS, both from the market and system perspective?

3.4. Research methods & data collection

To gather the data needed to answer the research question, a model will be developed that represents power flows and applied to Zeeland (case study). This includes experiments, thus, the different scenarios calculated in which both supply and demand vary, and includes the impact of certain uncertainties and the effect of design considerations. The data collected are analysed by using descriptive statistics and the MinMax Regret appraoch.

3.4.1. Modelling method

The modeling cycle consists of several steps that involve identifying variables in the situation and selecting those that represent essential features. From this a model can be formulated, and the relationships between the variables need to be described. Therefore, representations need to be created and selected, for example, graphical, algebraic, or statistical. In conclusion, performed operations need to be analysed, and the results need to be interpreted. The conclusions have to be validated, and some iterations can be made. (Oregon, 2010)

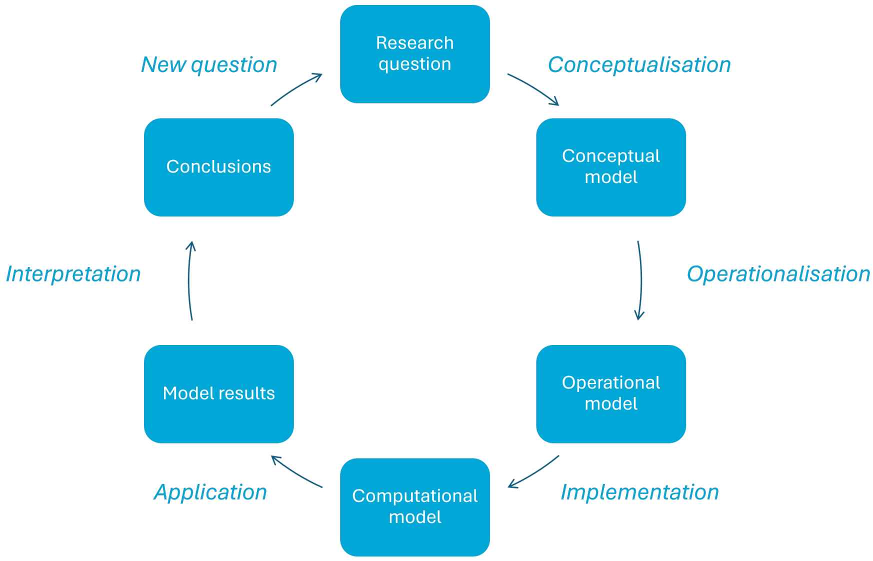


Figure 3.1: Modelling cycle, according to TB112 (course at TU Delft

More precisely, the development of a model can be divided into conceptualisation, operationalisation, implementation, application, and interpretation. This process is iterative and both verification and validation are important.

The Linny-R modeling tool is used for this research. Linny-R is an executable representation language for Mixed Integer Linear Programming (MILP) problems and is generally used for unit commitment problems. This modelling tool is developed by Pieter Bots at TU Delft. Unit commitment problems in electrical power production are part of mathematical optimisation problems in which the production of a set of power generators is coordinated to achieve the lowest production costs or highest production revenues. The model in Linny-R will thus search for the most cost-effective or most profitable solution, in which all conditions are met that are given to the model. The energy produced by fossil power generators is greater than energy from renewable sources for example, and electricity from the Dutch high-voltage grid has a certain price that fluctuates depending on both production and supply on the national level. Giving constraints to the grid representing transmission capacities, a certain price to energy shortages and curtailment, and the ability to look ahead a certain number of hours in the future, results in a complex decision model. One advantage of Linny-R over Python is that the tool is visual and, in general, user-friendly. In addition, it is possible to go through the model in a time-step way. In this way, the energy flows in the model can easily be checked, and the modeler can see what happens per time step, which is conducive for the understanding of system behaviour and the model itself. The documentation of the model developed in Linny-R is attached in Appendix A.

3.4.2. Case study & Experiments

In order to answer the main research question, "What is the impact of Underground Pumped Hydro Storage on the high-voltage grid in Zeeland, the Netherlands?", various experiments are established. Modeling the current situation indicates what the problems are currently and how this might change in the future. The experiments refer to the II3050 scenarios, and these can also be seen to the extent that the energy system contains renewable power (solar PV and wind) on the one hand and is electrified on the other. Developments regarding the production of hydrogen are not included as demand locations in the model, but in a certain way taken into account in the grow of industrial power demand.

Because the model will be cost-driven, economic factors need to be considered as well. The marginal costs are purely based on the fuels needed such as fissil materials and natural gas. Depending on the carbon emissions emitted, additional costs have to be included. However, the amount of this in the future is still uncertain and will depend on decisions by policymakers. On the one hand, natural gas prices, for example, might increase due to an increase in carbon emission tax and scarcity. On the other hand, the price of natural gas might decrease due to electrification that lowers natural gas demand and because batteries may replace natural gas power generators. The impact of competition in the power market, i.e. batteries may lead to lower energy prices as these will replace the flexible deployment of natural gas power plants, is excluded from the model. Analysing power prices in the day-ahead market, the variability increases over the years. Currently, the implementation of renewables is already at a more advanced stage than electrification, resulting in more hours of energy surpluses and negative power prices. This trend could continue in the coming years, but with the implementation of more storage technologies, the lowest energy prices might rise again, and the highest prices might decrease. Variability of power prices is needed to ensure economic feasibility of storage technologies. The research considered two datasets of power prices in order to conclude about the impact of power prices on UPHS behaviour in the energy system. Furthermore, some additional experiments were set up to provide insight into how much size and location of UPHS matter and the effectiveness of UPHS in certain grid-reinforcements,

3.4.3. Data analysis

Descriptive statistics are used to summarise and describe the data used and produces, i.e. key performance indicators and system costs. Measures such as central tendency (mean, median, mode), variability (range, standard deviation), and position (percentiles, quartiles) will be used. Inferential statistics will be applied to make predictions and draw conclusions, taking into account uncertainty. This includes hypothesis testing, confidence intervals, and regression analysis. Therefore, a representative sample is required.

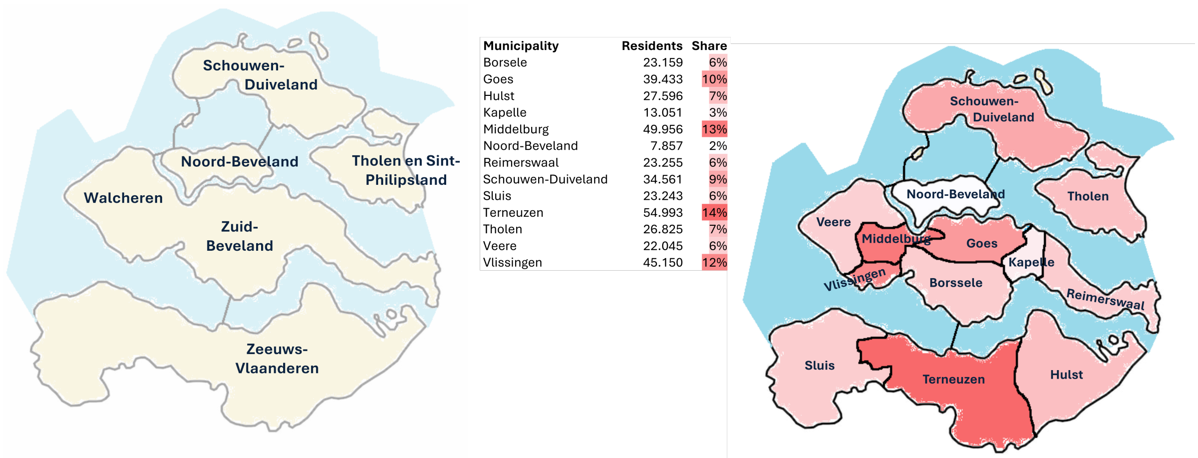
Subsequently, four specific scenarios are selected that may be representative of the future and represent a certain range of possible directions. This includes a certain capacity for renewable power, more conservative, progressive, or in between, and the realisation of a new nuclear power plant or not. The benefits of UPHS on these scenarios are translated into system costs that equals the regret of not having uPHS. The MinMax Regret approach, a tool for decision-making in uncertain situations with multiple alternatives, is used. This includes the evaluation on uncertainties and design considerations.

4

Application

4.1. Zeeland as a complex system

The province of Zeeland can be characterised as a rural area with some industrial clusters. There are some villages and small cities, but these are not high urban areas. The area is dived into several island by rivers from inland Europe, and protected from floods by the Deltawerken. Zeeland consists of more than 70 % agricultural land (CBS, 2015), and over 20 % of the Dutch industrial CO2 emissions originate from this area (Smart Delta Resources, 2021). Furthermore, Zeeland is an important connection for offshore wind farms to the mainland and even more wind farms are planned for the future.



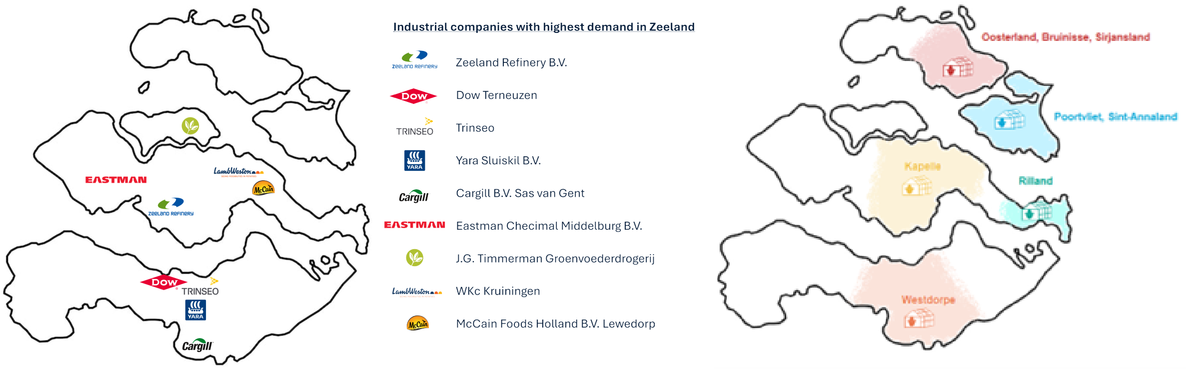
(a) Islands Zeeland

(b) Share residents municipalities Zeeland

Figure 4.1: Geographical characteristics of Zeeland

According to figure 4.1a, Zeeland consist of several islands as the Westerschelde and Oosterschelde flow through the landscape. Figure 4.5b shows the different municipalities of Zeeland. Most people are living in Walcheren, Zuid-Beveland and the municipality of Terneuzen. The division of residents in Zeeland is in line with the infrastructure density of roads, public transport, and electricity. Zeeland is very popular by tourists in summer, resulting in economic strength and more traffic movements. Another economic aspect is the connection with the ports of Antwerp and Gent made by the Westerschelde.

Most of the industrial companies are located in the municipalities of Terneuzen and Zuid-Beveland (figure 4.2a). The biggest companies, such as Dow, Yara and Zeeland Refinery, make up 75 % of the industrial electricity demand and 97 % of the natural gas demand (Sjoerd van der Niet et al., 2020). Industrial processes include turning crude oil into fuels and raw materials, cracking of hydrocarbons, production of plastics and latex binders, nitrogen fertilisers and industrial chemicals, synthetic resins by steam cracking, and food ingredients and pre-fried products. Demand of the agricultural sector is mainly for greenhouses, and is small compared to the industrial sector. Agricultural companies are concentrated in clusters divided over Zeeland as seen in figure 4.2b. Some of these are connected to residual heat of industries, others use natural gas for heating.



(a) Location biggest industrial companies in Zeeland **(b)** Agriculture clusters as of 2020

Figure 4.2: Industrial and agricultural clusters

4.1.1. Stakeholders

Involved parties that may have a certain power or interest in the project are identified. On the one hand, support for the project will be important, and potential conflicts may be prevented or resolved. Insight in the involved parties is import for the broader understanding of the complex system where UPHS is operating in, i.e. the social context and institutional economics. The stakeholder analysis provided in figure 4.3 is based on Frank Peters, 2022 Kujala et al., 2019, Lean People, 2022 and Mitchell et al., 1997.

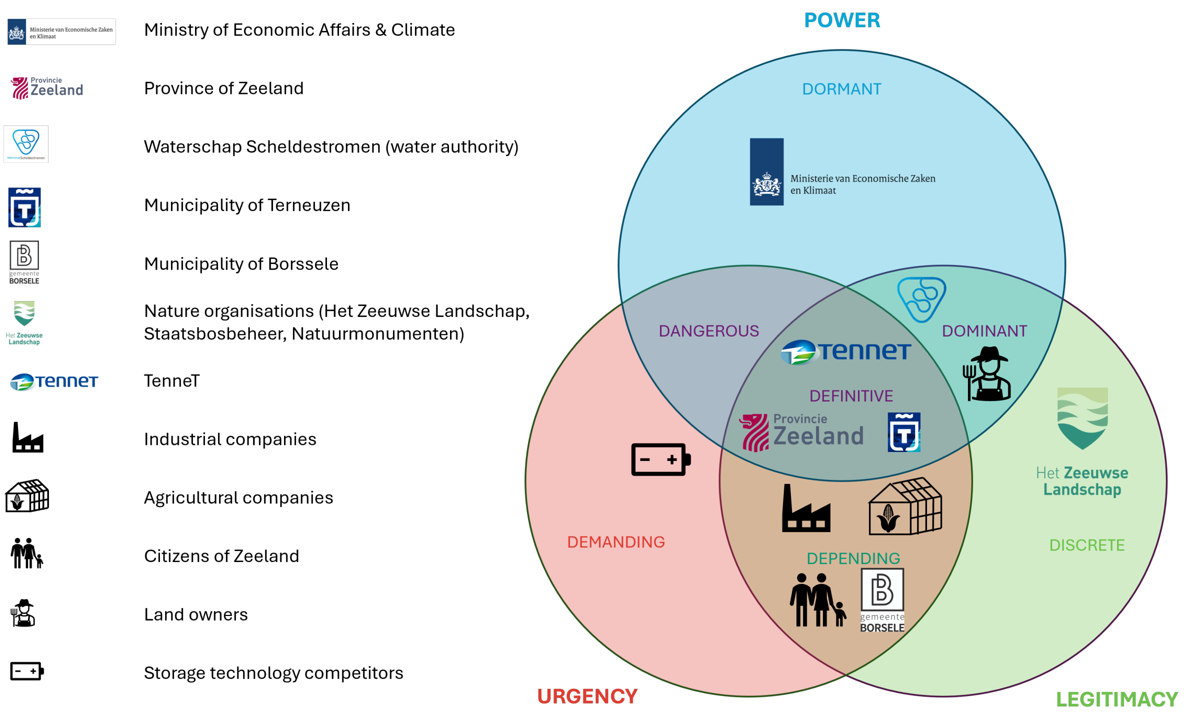


Figure 4.3: Stakeholderanalysis Zeeland

The government has an overall interest in seeing the energy transition move forward. However, at the national level, it does not matter how this happens. Indeed, an alternative to UPHS could just as well, disregarding the potential social added value of UPHS for now. However, the ministry does have the power to support a project like UPHS in the form of financial resources, but also top-down regulation.

The municipality of Borssele is also involved to some extent. This is the area where a lot of energy is produced or connected from the North Sea on the one hand, but also the area from where a 380 kV grid connection will come from and thus the connection with Zeeuws-Vlaanderen. The municipality of Borssele does not necessarily have power, but it can enter into conversations with the municipality of Terneuzen or the province of Zeeland, for example, about the importance of UPHS. Also because a nuclear plant may be built in Borssele that will have to run on a base load. Also, here correctly informing the pros and cons of different options in future scenarios is very important, as this can contribute positively to getting support for the project.

The potential added value of UPHS is directly relevant to the values from which TenneT operates, because UPHS can actually contribute to reducing grid congestion, reliability, and security of supply, and perhaps also minimize investment in additional grid connections. On the other hand, the project is also uncertain for TenneT because UPHS has a large capacity and may affect the grid in a negative way. However, the latter does not seem to be the case because the plan is to place UPHS near major sources of renewable energy. TenneT also has a lot of power because through the Ministry of Economic Affairs and Climate, which is a shareholder in the grid operator, TenneT can exert influence from above. Further, TenneT may prioritise a project such as UPHS because it benefits the system if this is allowed in the current legal framework.

There is also the province of Zeeland that has an interest in the project in several ways. On the one hand, preserving the industries, looking after the interests of residents, but also preserving jobs, and the landscape values and ecology. The municipality of Terneuzen has similar interests as the province of Zeeland, but less power as the province and TenneT. For the realization of the project, the most desirable way is that it will be realised together with the municipality of Terneuzen, province of Zeeland, and TenneT. However, if the municipality does not like the plan after all, the project may still be able to go ahead via the province or the Ministry of Economic Affairs and Climate.

4.1.2. Power supply

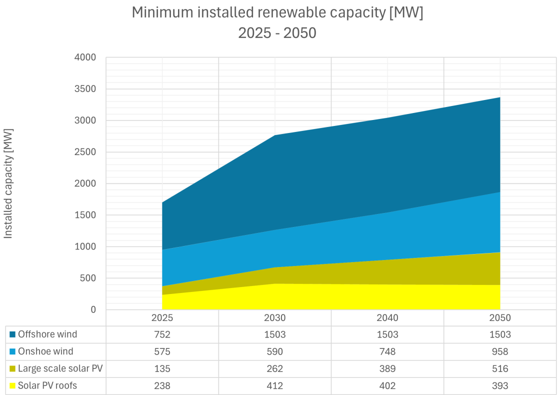
Overall, natural gas is currently the most used energy carrier in Zeeland, and electricity and petrol also have a larger share in the electricity mix. Heat, biomass, biogas, green gas and other energy carriers are used at a smaller scale. At the moment, three fossil power generators (Sloecentrale, Elsta Power, Seasun B.V.) and one nuclear plant are in operation in Zeeland. Large-scale renewable power is generated by onshore and offshore wind turbines and large-scale solar PV installations. Furthermore, small solar-PV is installed on the roofs of (residential) buildings. To phase out fossil fuels such as natural gas and oil, changes in the energy system are needed both in production and demand, but also in energy storage.

Power generator	Source	Power	Location
Sloecentrale	Natural gas	870 [MW]	Borssele
Elsta Power	Natural gas	459 [MW]	Terneuzen
Seasun B.V.	Waste heat	8.56 [MW]	Kruiningen

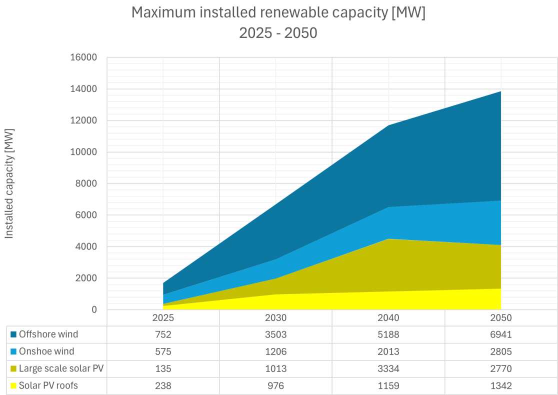
Table 4.1: Overview fossil power generators Zeeland 2025

The composition of the mix of energy carriers will change in the future, and therefore energy generation will shift. Until 2050, electricity generation by solar and wind power will increase step by step in all scenarios as described in Appendix **??**. The installed capacity and location of these installations will differ. The produced electricity depends on weather conditions, more specifically wind speed and solar intensity. Wind turbines and solar panels have different production patterns, but research shows that complementarity exists between wind and solar energy sources (Dos Anjos et al., 2015).

Figure 4.4 shows the expected installed capacity of renewable energy power generators in Zeeland from 2025 to 2050. Minimum and maximum quantities are shown based on the targets from the previous section and the II3050 scenarios or interpoloated from these numbers.



(a) Minimum renewable capacities 2025 - 2050



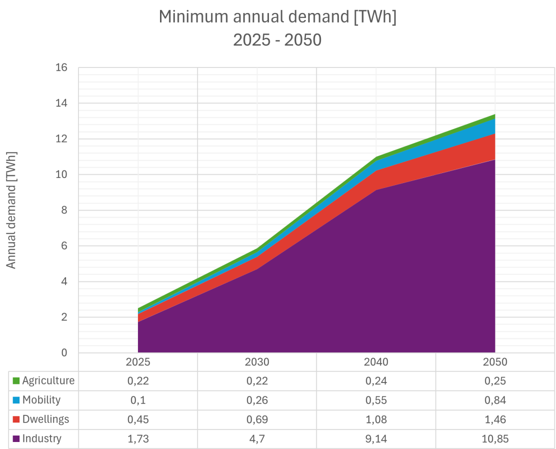
(b) Maximum renewable capacities 2025 - 2050

Figure 4.4: Renewable power development in Zeeland 2025 - 2050

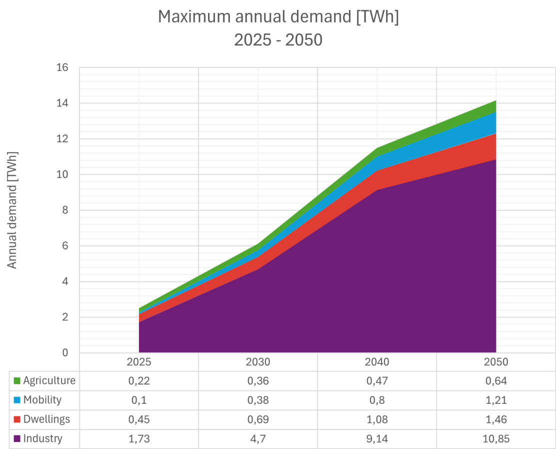
In addition to the production of renewable energy by solar panels and wind turbines there is a discussion about nuclear power. The existing nuclear power plant of 485 MW has to closed in 2033. There are discussions in politics to build one or two new nuclear plants of 1500 MW or 3000 MW and keeping the existing nuclear plant open. It is uncertain if these nuclear plants will be constructed due to social acceptance, environmental consequences, impact on the high-voltage grid and the suitability of nuclear energy in the energy system (Rijksoverheid, 2017). Whether or not to build new nuclear plants and keep the existing plant, will determine the required capacity of other power sources to meet demand and the behaviour of the power supply profile in the energy system.

4.1.3. Power demand

The electrical energy demand in Zeeland is divided into demand for industrial companies, agricultural companies, dwellings, and mobility. Figure 4.5 shows the expected yearly electricity demand based on the II3050 scenarios and existing policies. Important to note is that these consumers all have energy demand profiles that vary throughout the day, week, month, and year. Industrial demand has a flat pattern, agriculture and dwellings have a daily and seasonal pattern, and the mobility sector has a weekly pattern. This is elaborated further in Appendix A.



(a) Minimum demand 2025 - 2050



(b) Maximum demand 2025 - 2050

Figure 4.5: Power demand development in Zeeland 2025 - 2050

The industry can innovate sustainably with electrification, hydrogen, the use of biomass or bio fuels, and carbon capture. Electrification and hydrogen are the main innovations according to several reports. The increased use of electricity results in a higher electricity demand where they are located. Hydrogen technology also requires electricity, but its production is more flexible. Both scenarios will lead to a huge increase in electricity demand.

Depending on the extent to which heat networks are realised, part of the agricultural sector will use heat as a heating source, and another part will electrify. This will lead to an increase in electricity demand in certain parts of the grid.

The electrical demand in the built environment will change enormously. On the one hand some houses will be better insulated, on the other, some houses will also be electrified by heat pumps instead of heating by natural gas. The expected additional electricity consumption by heat pumps for the Netherlands in 2030 is given by CE Delft, which varies from 2.31 to 3.50 TWh per year, assuming that 725,000 to 996,000 houses will have a heat pump (Frans Rooijers et al., 2020). Solar panel ownership is also increasing among houseowners, which means more exchange at a local level, perhaps also in electricity transportation from the low voltage level into the medium and high-voltage level.

The share of electric cars is also increasing, resulting in infrastructure improvements in the form of more charging stations and a higher electricity demand. Based on the II3050 scenarios and the RES, it is assumed that most vehicles will be all all-electric in the future, and a smaller share will use hydrogen. More specifically for Zeeland, there will be 90,000 to 130,000 electric vehicles in 2030, under the assumption that there is a mix of hydrogen and electric vehicles. The number of electric vehicles can optionally increase to 170,000 if the hydrogen technology in vehicles does not develop. Additionally, the number of electric vans will increase according to the identification of national electric demand profiles (Rooijers and Jongsma, 2020). The study of CE Delft specifically for Zeeland, however, gives no mention of the increase of modalities other than electric vehicles. Therefore, the expected additional demand of 1.1 TWh for the Netherlands based on the Climate Agreement, is translated into a factor for Zeeland. The assumption is made that electric vans will grow with the same factor as electric vans. The additional electricity demand for electric vehicles in the Netherlands is expected to be 4.1 TWh, and 0.26 TWh for Zeeland specifically. Thus, Zeeland will have a share of 6.3 % of electric vehicles in the Netherlands by 2030.

The Dutch government stimulates the development of hydrogen in the Netherlands (Ministerie van Economische Zaken en Klimaat, 2021a) as it can play a key role in energy storage, industry, mobility and the built environment (Nationaal Waterstof Programma, n.d.). Due to the connection to offshore wind farms in Borssele and the potentially high demand for hydrogen by the industry in Zeeland, hydrogen might be produced in Zeeland itself. The production of hydrogen by electrolysers can be performed by the industrial companies or new energy providers, which both can be seen as a new form of industry. This will affect the energy flow through the electricity network of Zeeland and should be modelled in different scenarios. Yara and Zeeland Refinery currently have the highest share in hydrogen and that will decrease as the processes at Elsta Dow need to be carbonised. The future hydrogen demand depends on the extent to which green ammonia will be imported. Hydrogen production at the companies' locations will affect the electricity flows in the energy system of Zeeland a lot.

4.1.4. Economics

Power production by solar-PV and wind turbines depends on weather conditions and are interrelated, i.e. these show almost no simultaneity. The impact of both on the day-ahead price also depends on the installed capacities and power demand. Therefore, it is important to apply datasets of the same year. As described before, the variability of the day-ahead price is decreasing the past few years. However, due to unusual circumstances, data of the year 2019 is used. The years 2020 until 2023 show different prices as consequence of the covid pandemic and the war between Russia and Ukraïne. These events caused major changes in supply and demand of power.

Analysing the data of the year 2019 with the, the day-ahead price is most of the time lower than the marginal costs price of natural gas. In reality, the Sloecentrale has around 2600 load hours every year according to the II3050 report of Zeeland by CE Delft. To achieve this deployment the day-ahead price have to be higher than the marginal costs price around 30 % of the time, due to the principle of the market clearing price. Therefore, the dataset of the day-ahead price is multiplied by a factor of 1.2.

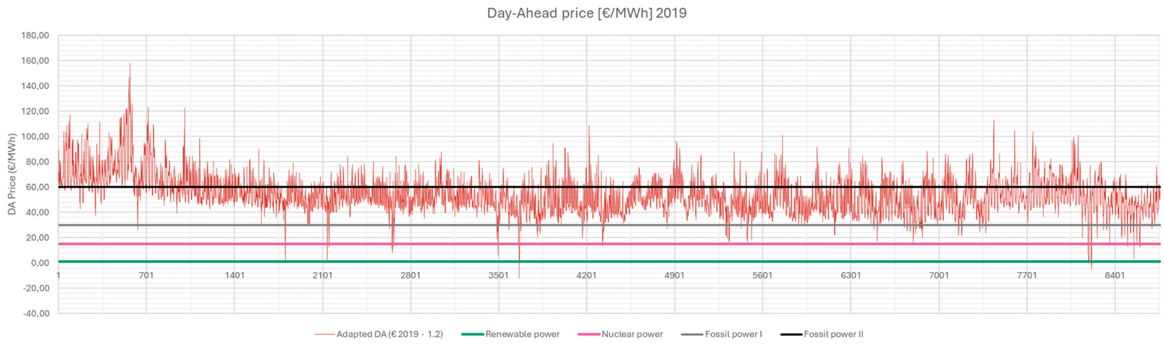


Figure 4.6: Day ahead price 2019 versus marginal costs

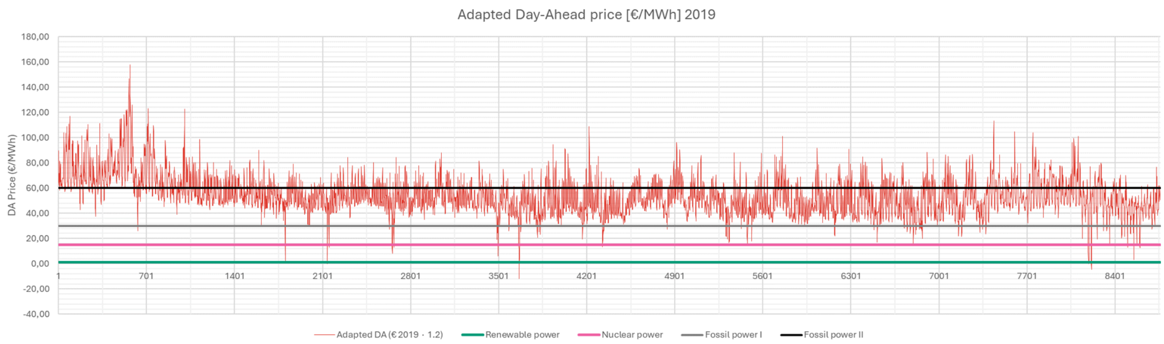


Figure 4.7: Adapted Day ahead price 2019 versus marginal costs

However, it can be questioned which dataset to use for future scenarios. On the one hand, the corrected dataset represent the current situation more. On the other hand, the integration of more renewables and storage technologies in the power system will lower the day-ahead price and phasing out fossil power generators such as a natural gas plant. To what extend this will happen depends on the available techniques, because power from hydrogen storage is less efficient than power from batteries. Furthermore, the valleys in the day-ahead price may become less because all storage systems will buy power during these moments, reasoning from market forces theses valleys will decrease in numbers, and increase in value. The original dataset of 2019 might therefore be more realistic for future scenarios.

Because the future is uncertain, and the model cost-driven, both datasets are used for further analysis of the impact of UPHS on the high-voltage grid of Zeeland. Results of both datasets will give insight in the impact of the day-ahead price on the behaviour of UPHS as well.

In reality, the scenarios in which less renewable power capacity is involved the modified datset will be more realistic, while the original dataset is more realistic for scenarios with higher amounts of renewable capacity. Besides, the quantitiy of power demand also impact the power prices. This is hoewever excluded from the model.

4.1.5. Power grid

The situation of the intermediate- and high-voltage grid in Zeeland is visualised in figure [X]. The cables of the grid are presented as lines and the conversion stations as nodes. Every cable in the grid has a certain transport capacity, which is a constraint of the system, but these may change in the future due to grid reinforcements. The built environment, industries, agriculture but also power generators are connected to conversion stations. The electricity grid of Zeeland is connected to the high-voltage grid of the Netherlands. If transportation capacity is available, electricity surpluses can be transported to the Dutch electricity grid. It is assumed that Zeeland can import electricity from the Dutch grid during electricity shortages. The maximum energy import depends on the available grid capacity. The system is changing continuously because electricity demand is growing, and the electricity mix is changing.

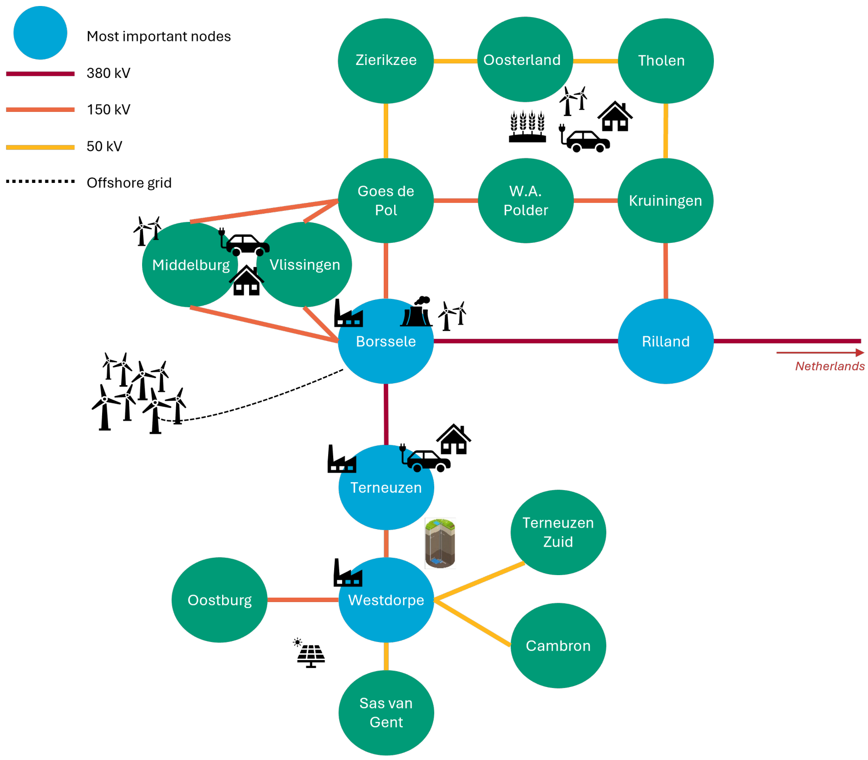


Figure 4.8: Visualisation of the intermediate- and high-voltage grid of Zeeland

Analysing the electricity infrastructure of Zeeland the locations of Borssele, Terneuzen, Westdorpe and Rilland are the most important as these are connecting the whole electricity network of Zeeland together. The high-voltage grid goes from Borssele to Rilland and in the future also from Borssele to Terneuzen according to the investment plans of TenneT (TenneT, n.d.-a). The high-voltage 380 kV grid runs further from Rilland into the Netherlands. There is also a 150 kV grid from Rilland to Borssele and from there separately to Oostburg, Middelburg and Vlissingen. In Terneuzen, Goes de Pol and Kruiningen, the 150 kV grid branches off further into a 50 kV grid.

The location in Borssele is very important in the electricity network of Zeeland as offshore wind, nuclear energy, some industry, and batteries are connected to the grid on this location. The conversion stations in Borssele convert direct current (DC) from offshore wind farms to alternating current (AC) and sent that to the 380 kV station in Borssele (TenneT, n.d.-e). The delivered alternating current can be sent directly to the 380 kV station as the alternating current is used on the national high-voltage grid (Stokman et al., 2014). The location in Terneuzen also needs to deal with large amounts of electricity as here heavy industry, onshore wind farms, and large-scale solar PV will be connected to the grid as well (Provincie Zeeland, 2023). TenneT and the ministry of Economic Affairs and Climate are planning to build a new 380 kV station in the surrounding of the Sloe area (TenneT, n.d.-b). Also a new 380 kV station in Terneuzen and Zierikzee (TenneT, n.d.-c).

4.2. Implementation in Linny-R

4.2.1. Model setup in Linny-R

The energy system of Zeeland has been translated into a model in Linny-R in which power flows in various directions within the power system can be calculated, taking into account the capacities of the power grid. Linny-R works dynamically with datasets, and in which scenario-development is easy to implement. The model includes all input variables, internal variables, output variables, equations, and created datasets from the conceptual and operational model. A full description of the development of the model is presented in Annex X according to the structure of the modelling cycle. This section only summarises the computational model and the implementation of the conceptual and operational model in Linny-R. The model diagram, an overview of all variables, is shown in figure 4.9.

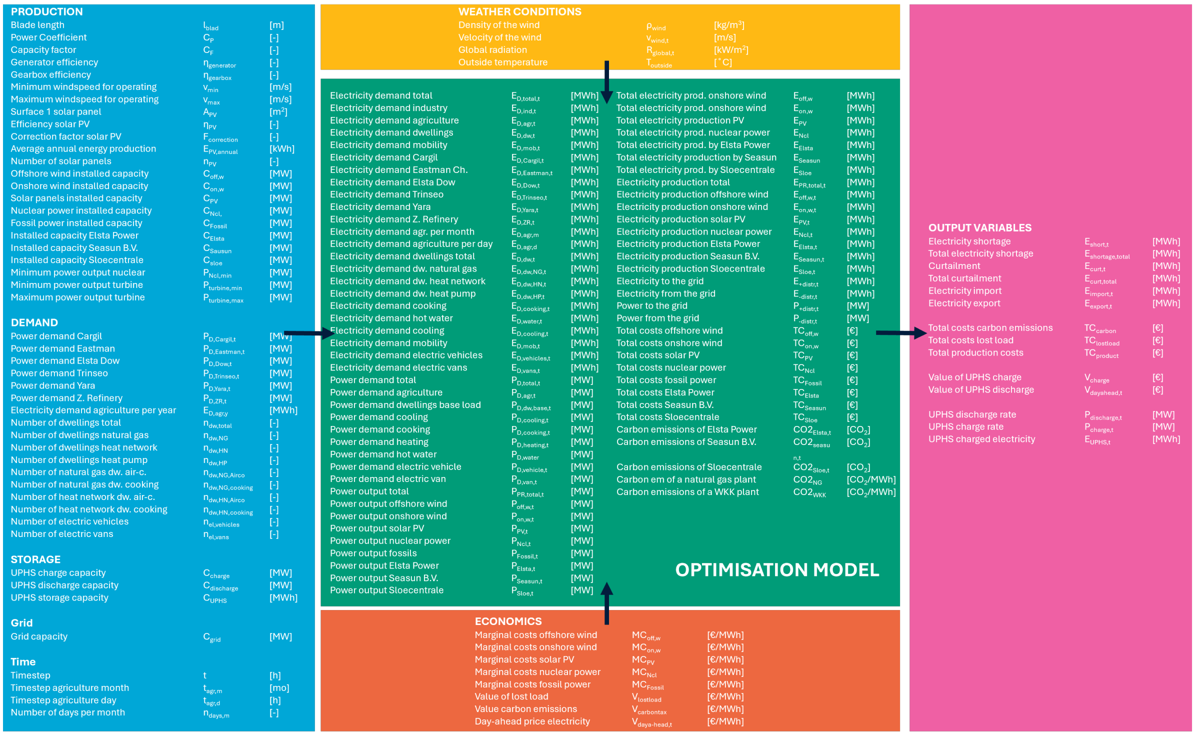


Figure 4.9: Model diagram

The model in Linny-R (figure 4.11) visualises the high-voltage grid, consisting of power lines and stations, by using processes, products, and arrows. The layout of the model corresponds with the geographical layout of Zeeland, but a simplification is made by merging the municipalities of Kapelle, Goes, Noord Beveland, Shouwen-Duiveland, and Tholen as one subarea, labelled as the remaining part of Zeeland. Products, visualised as an oval shape, can be produced or consumed by a process. A process, visualised by a square, represents the transformation of some products into other products. Clusters are used to keep the model clear, consisting of a group of processes, and visualised by squares with shadows behind.

Arrows in the model indicate the possibility of a product flow of electricity, in which the quantity depends on the grid capacity. Therefore, processes of power flows are bounded by setting the upper bounds equal to the maximum capacity. This is shown in figure 4.10. Furthermore, current can flow in one direction at a time, thus an additional process step is made to each connection between nodes and energy hubs, using a grey data product.

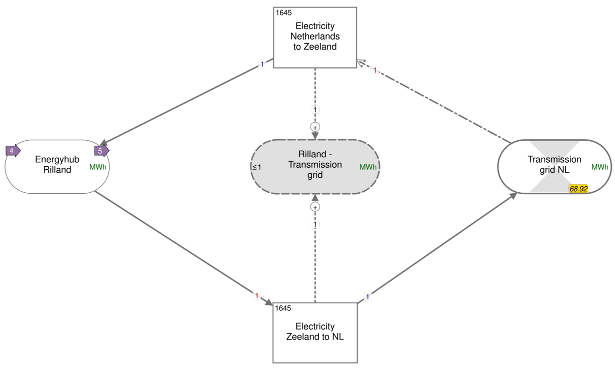


Figure 4.10: Impression model Linny-R, cable constraint

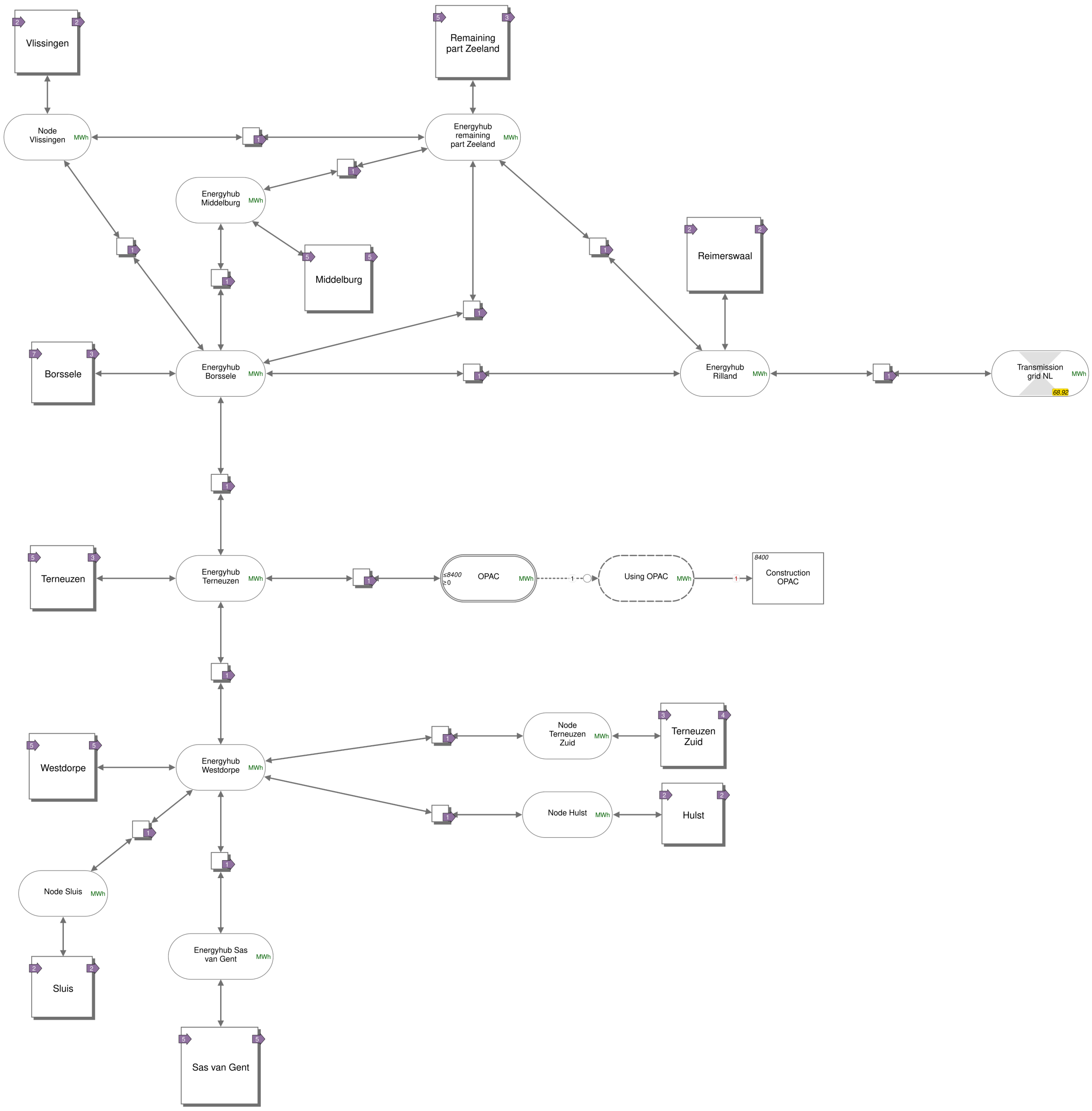


Figure 4.11: Impression model Linny-R, geographical representation

In an energy hub, both electricity is produced and used. A node is a place in the system where only power is demanded. The structure is given in by putting power generators on the left side and sectors that require power on the right side. Power can also enter and leave the energy hub to other energy hubs or nodes. In principle, the lower bound of wind power and solar PV is equal to the power that could be generated at that time, regardless of the availability of grid capacity. A lack in grid capacity can be solved by the curtailment processes, in which curtailment demands the residual power in that specific energy hub. Electricity shortages may also occur which can be solved by the shortage process, linked to the value of lost load. The model will only use processes of curtailment and shortages if there is no other solution possible. In reality, industries are being asked to scale down in case of shortages, and producers of wind and solar power cannot deliver power to the grid. This has economic consequences as these parties have to be compensated financially. Regarding renewable power production, the model assumes an equal division of power capacity over the area by surface ratio. The locations of nuclear power and fossil power generators are site-specific. An impression of an energy hub or cluster in Linny-R is presented in figure 4.12.

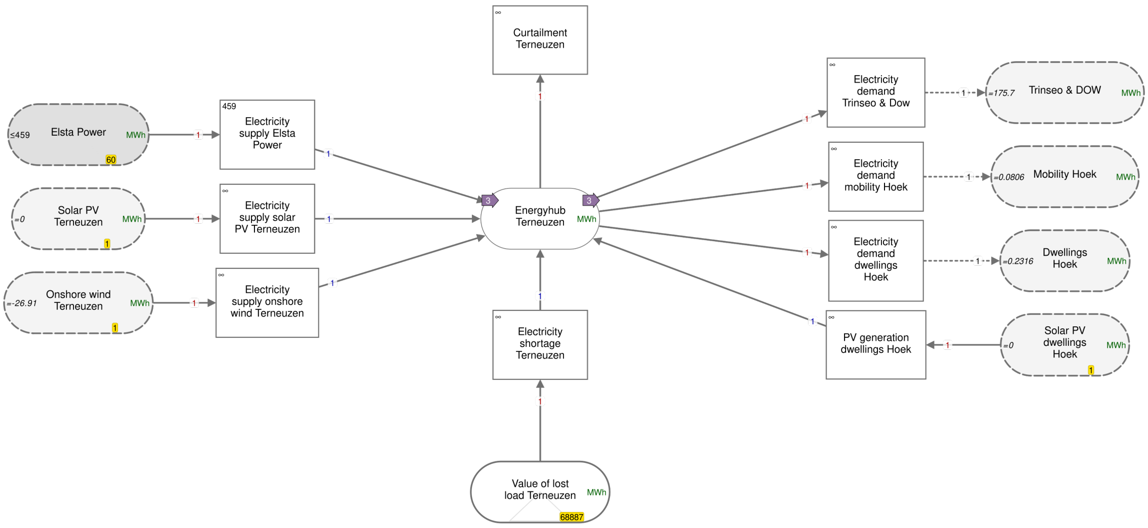


Figure 4.12: Impression model Linny-R, cluster

The storage facility of UPHS is initially modelled in the energy hub Terneuzen, but in some experiments also placed within the energy hub Borssele. The power flows to and from UPHS also include the restriction that power flow in one direction, thus that UPHS can only charge or discharge at one specific moment. This is visualised in figure 4.13.

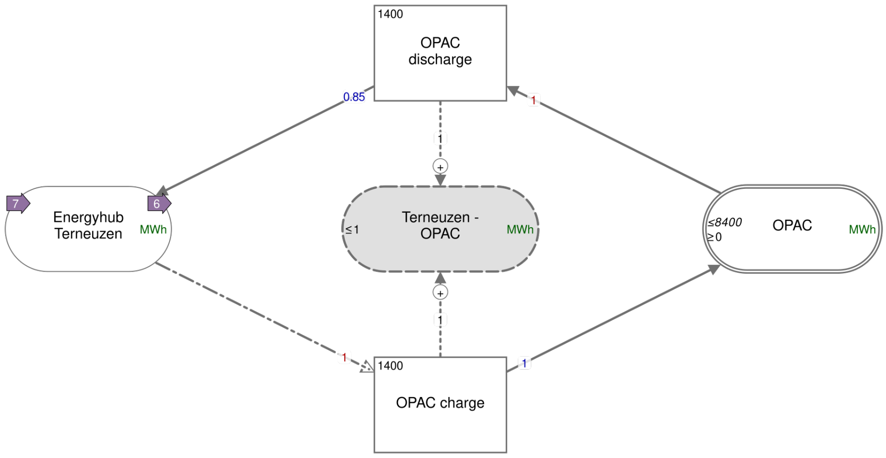


Figure 4.13: Impression model Linny-R, UPHS

4.2.2. Simulation Zeeland 2025

This section provides the model output of the Linny-R model by running the current situation. This is important to gain insight into system behaviour and to identify challenges that already occur. The electricity mix consists of nuclear power, onshore and offshore wind power, solar power, fossil power generators, and import (figure 4.14). Nuclear power has the highest share with 41 %], followed by offshore wind, onshore wind, and solar PV. Electricity from fossil power and imports have a relatively small share in the electricity mix. The total electricity production, including import, is calculated at 10.4 TWh.

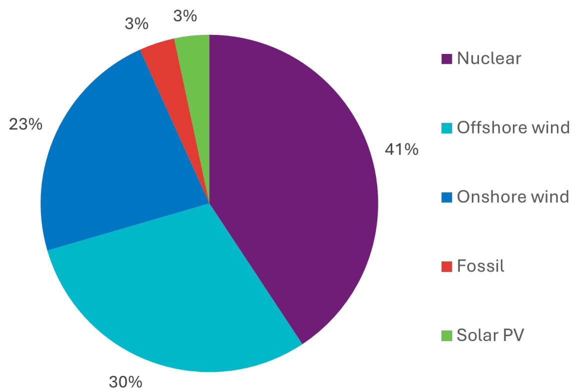


Figure 4.14: Electricity mix Zeeland 2025

In 2025, Zeeland has an annual electrical demand of 197 GWh, of which 69 % is for industrial activities, 18 % for dwellings, 9 % for agriculture, and 4 % for mobility. A nuclear power plant of 485 MW is currently sufficient to meet electrical demand, and there is still transmission capacity. Zeeland exports electricity to the Dutch grid, consisting of residual nuclear power, renewable power, and any generated power from fossil generators. To what extent fossil power is generated is determined by the market, based on marginal costs and the day-ahead price. Furthermore, power generators are operating less in summer than in winter. Figures 4.15 and 4.16 show the current situation of power supply, demand, import, export, curtailment, and shortages for the months January and June.

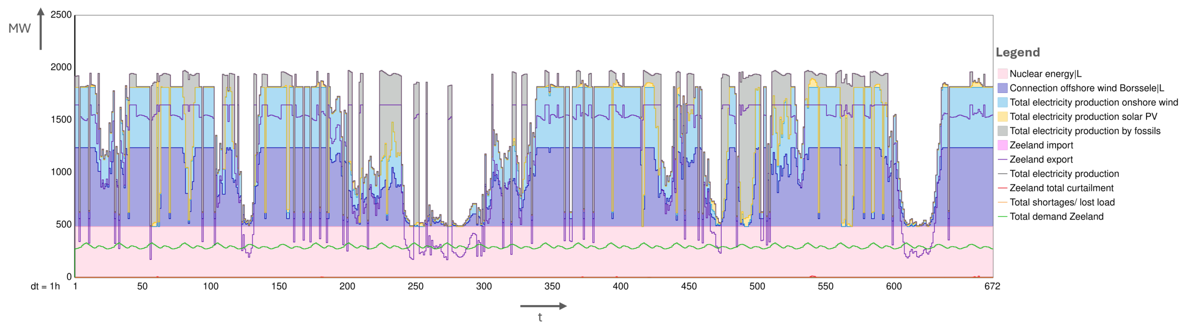


Figure 4.15: Zeeland, January 2025

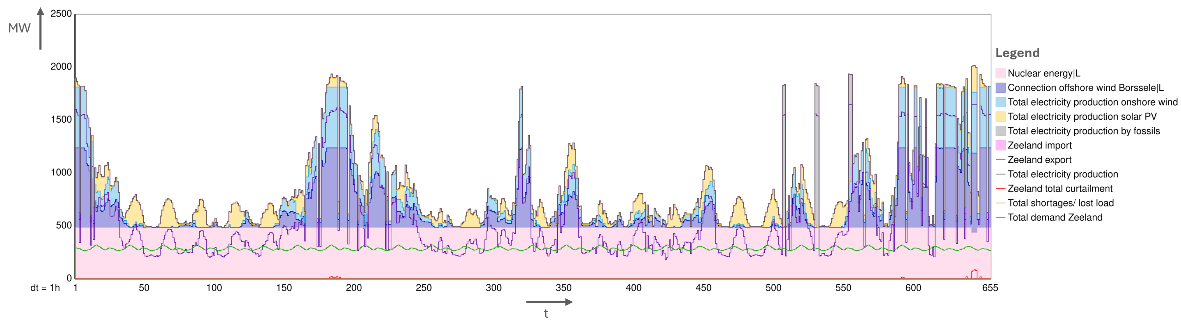


Figure 4.16: Zeeland, June 2025

Currently, the power grid seems most of the time having enough transmission capacity available as curtaillment is not happening frequently. Also quantities are neglible as these are fluctuating between 0 and 100 MW. Also, curtaillment is following the pattern of power production by solar PV. Also the export curve is not flattened indicating that the 380 kV connection does not pose significant problems so far. The total annual curtailment is similar to the average annual production of 1 offshore wind turbines with a capacity of 10 MW, or the average annual electricity consumption of 15 dwellings. This is 0.3 % of the total power generation per year. There are no electricity shortages.

The transmission capacity of the grid is only insufficient in some cases of renewable power generation. According to figures 4.17 and 4.18, curtailment occurs with regularity, especially during the simultaneity of wind and solar power, and mostly in Reimerswaal, Sas van Gent, Westdorpe, and Borssele, thus mostly in Zeeuws-Vlaanderen. Because solar power is generated mainly during summer, this results in larger quantities of curtailment in summer than in winter months, and is peaking if the export is at maximum. The remaining part of Zeeland in the Linny-R model, presented as 'other' in the graphs, has a low share in curtailment.

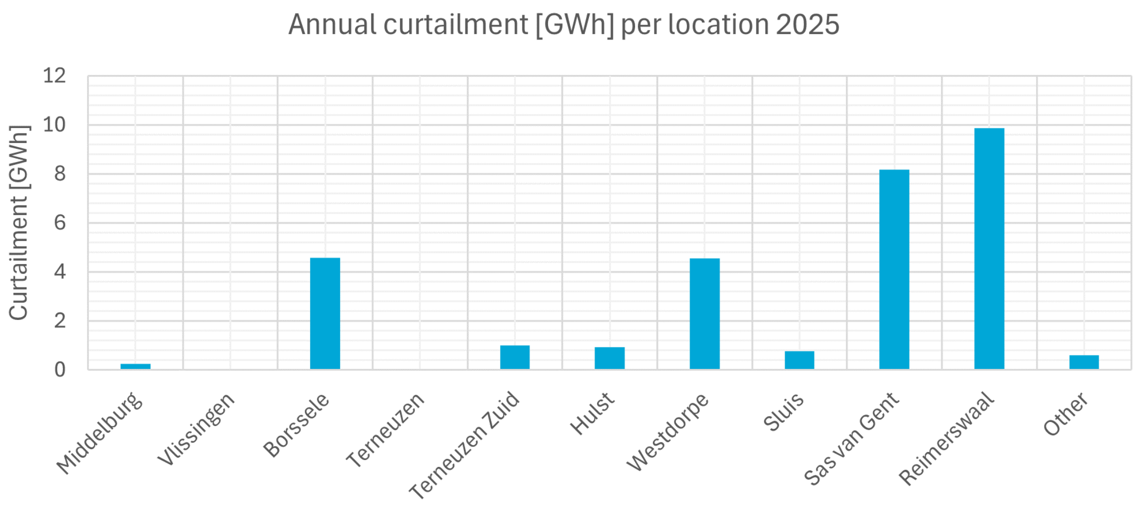


Figure 4.17: Seasonal curtailment Zeeland per node [GWh], 2025

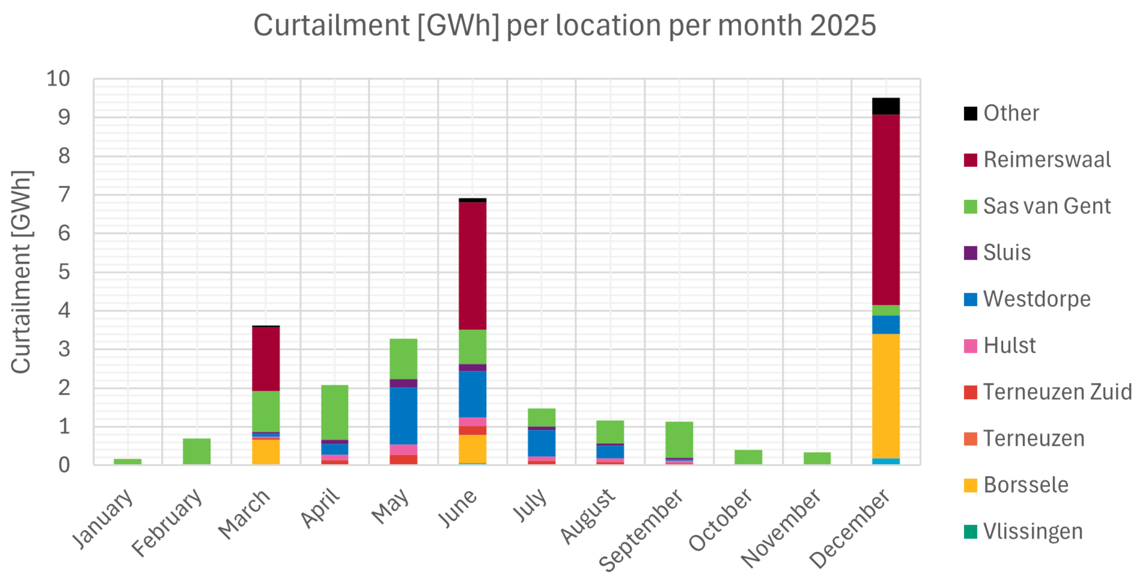


Figure 4.18: Annual curtailment Zeeland per node [%]

As seen in figure 4.19 most carbon emissions are released in winter months. The Sloecentrale has the highest share of 63 % as it has the largest power capacity. Seasun B.V. is operating more hours than the Sloecentrale and Elsta Power due to lower marginal costs, but has a much lower production capacity. As result, Elsta and Seasun B.V. are emitting similar quantities of carbon emissions. The total calculated emission is 131 kton.

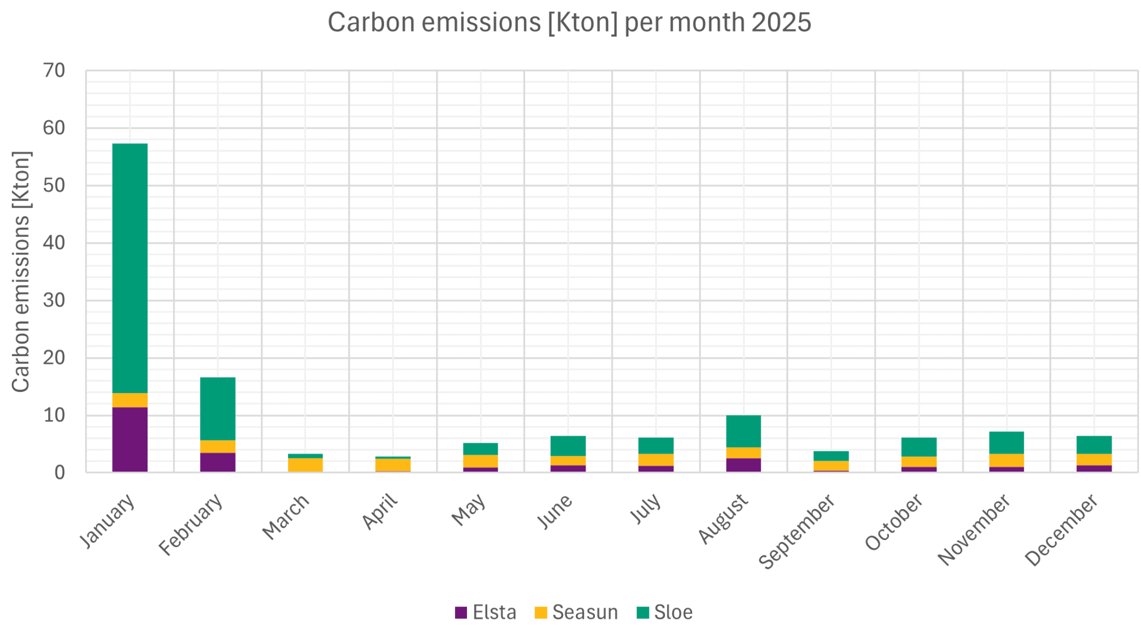


Figure 4.19: Emitted carbon emissions in Zeeland throughout the year 2025

In table 4.2 the current situation is translated into system costs in which value is given to electricity shortages, curtailment, import and export, and carbon emissions.

Component	Quantity		Value per unit		Total value
Solar PV	349,030	MWh	1	€/MWh	€ 349,030
Onshore wind	2,371,959	MWh	1	€/MWh	€ 2,371,959
Offshore wind	3,102,421	MWh	2	€/MWh	€ 6,204,842
Nuclear power	4,242,282	MWh	15	€/MWh	€ 63,634,234
Seasun BV	64,471	MWh	30	€/MWh	€ 1,934,122
Sloecentrale	220,772	MWh	60	€/MWh	€ 13,246,321
Elsta Power	67,961	MWh	60	€/MWh	€ 4,077,640
Curtailment	30,735	MWh		€/MWh	€ -
Power shortages	0	MWh	68,887	€/MWh	€ -
Carbon emissions	131,330	ton	100	€/ton	€ 13,132,997
Import	9,870	MWh	-2.16	€/MWh	€ -21,336
Export	7,907,265	MWh	-43	€/MWh	€ -337,963,920
Total system costs					- € 233,034,110

Table 4.2: Overview system costs Zeeland 2025

So far, no economic value is given to curtailment as this is not valued in the current functioning of the market. In reality, the grid operator have to pay for re-balancing costs (around 70 million € per year) but not all curtaillment can be derived from this as sometimes surplusses of power results in that even renewable power is not part of the accepted bids in the merit order. From another perspective, costs for curtailment are already captured by including the marginal costs of these quantities, and in some cases, additional marginal costs for fossil power production because of grid constraints.

The value of both electricity import and export is calculated by the Linny-R model, because these depend on the day-ahead price at a certain moment. The costs for carbon emissions is the emissions in ton multiplied by the carbon dioxide tax. From table 4.2 can be noted that the system costs are negative meaning that there is a profit. This is the result of taking into account the power that is exported to the Dutch power grid, which is almost 76 % of power produced within Zeeland.

4.3. Scenario development

A simulation model in Linny-R is developed to analyse the behaviour of UPHS in the power system of Zeeland, based on previous analyses in which the RES 1.0 Zeeland, CES Delta Schelde Regio, II3050 scenarios have provided the foundation. Electricity demand and supply will increase in the future. Alas, the extent of this increase, the policy choices regarding the operation of fossil power generators, and the construction of a new nuclear plant are uncertain. A wide range of possibilities are within the scenarios for 2030, 2040, and 2050. Therefore, scenarios have been compiled, which differ from each other in the extent to which the energy transition is completed on both the demand and supply side. The developed model in Linny-R allows simulation of the power flows on the high-voltage grid of these scenarios. To determine the added value of UPHS, scenario analysis has been carried out, and model outputs are evaluated in particular the electricity mix, electricity import and export quantities, curtailment and shortages quantities, and carbon emissions. An overview of the variables that are part of the scenario space are shown in 4.4.

Variable	Value 1	Value 2	Value 3	Value 4
Onshore wind	Low	High	-	-
Offshore wind	Low	High	-	-
Solar PV Large-Scale	Low	High	-	-
Solar PV roofs	Low	High	-	-
Nuclear power	485 MW	1500 MW	3000 MW	0 MW
Sloecentrale	Open	Closed	-	-
Elsta Power	Open	Closed	-	-
Seasun B.V.	Open	Closed	-	-
UPHS storage capacity	8400 MW	4200 MW	0 MW	-
UPHS location	Terneuzen	Borssele	-	-
Demand industry	Low	Medium	High	-
Demand dwellings	Medium	-	-	-
Demand mobility	Low	Medium	High	-
Demand agriculture	Low	Medium	High	-
Day-ahead	Dataset 2019	Dataset 2019 * 1.2	-	-

Table 4.3: Scenario-space

The analysis is done for the months January, June, and September, as these represent the different seasons of the year. Periods with significantly higher solar radiation, or a higher velocity of the wind, or both on a medium level, are in this way evaluated. Analysing these months will give more insight into system behaviour.

To determine the added value of UPHS in a broader perspective, the impact of UPHS over a year is calculated. Due to the wide range of possibilities, four scenarios are selected to focus on, which logically might happen. These are used for further interpretation as well. The installed capacities of the selected scenarios are shown in 4.20.

Variable	Scenario A	Scenario B	Scenario C	Scenario D
Onshore wind	low	high	low	low
Offshore wind	low	low	high	high
Large-Scale solar PV	low	low	high	high
Solar PV roofs	low	high	low	high
Nuclear power	off	off	on	on
Fossil power	on	on	on	off

Table 4.4: Selected scenarios for further analysis

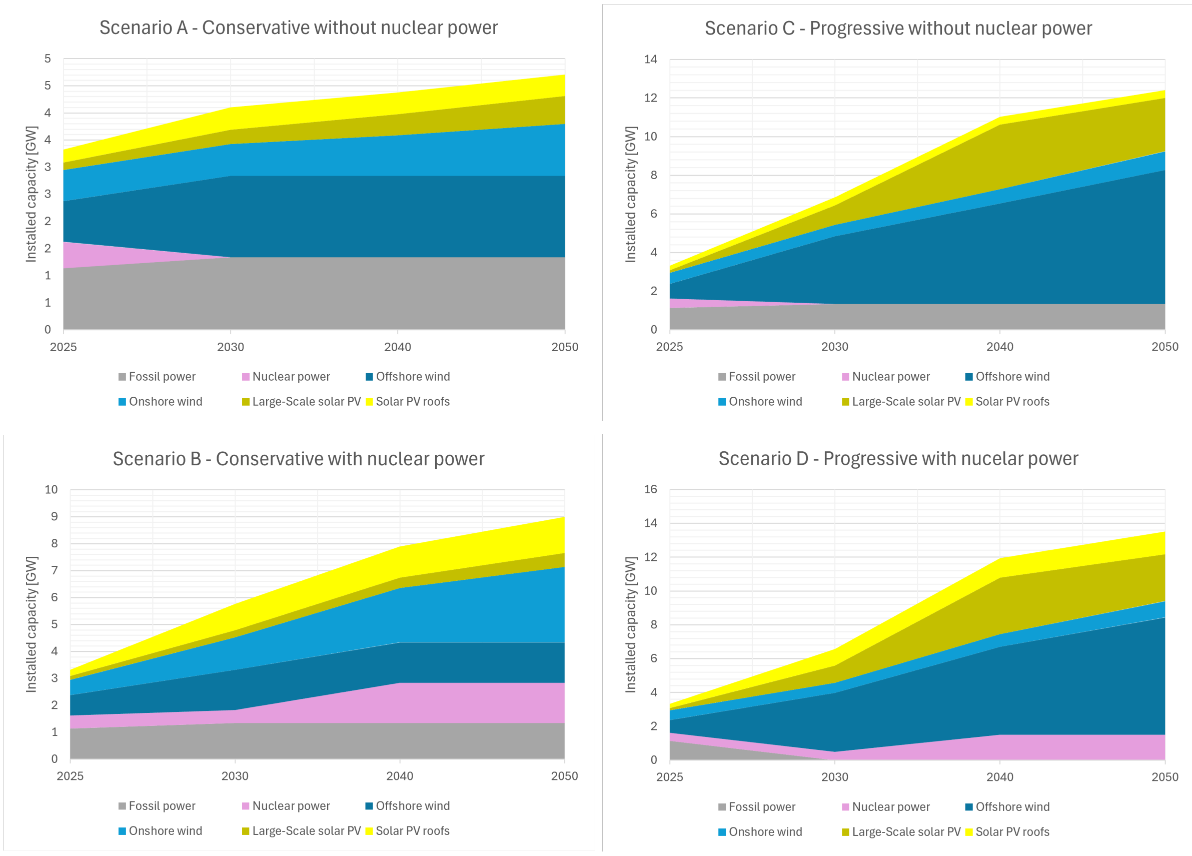


Figure 4.20: Capacity growth towards 2050 0f selected scenarios

Scenario A is a more conservative direction in which less renewable power will be realised and the existing nuclear power plant will be closed and not replaced by a new one. Scenario B and C are scenarios that consider medium renewable power capacity, in which scenario B has more a focus on onshore wind and solar PV on roofs, and scenario C more on offshore power and large-scale solar PV, as it may be hard to have both large-scale solar PV and onshore wind. Further, scenario B include a nuclear power plant; scenario C not. Whether the existing nuclear power plant will be operational, closed, or replaced by a 1500 MW power plant in 2030, or even larger, is still under discussion in politics. Both scenario B and C have fossil power plants available. Scenario D is a more progressive scenarios in which large capacities of renewable power is realised and the existing nuclear power plant will be replaced. It is assumed that in scenario D, fossil power generators are closed as these may not be beneficial anymore or because of policy decisions. The technical outcome of these scenarios will be used for benefit anlaysis from both an economical and social point of view.

5

Results

This chapter provides the results of the scenario computations where a focus has been placed on the four main directions as described in the previous chapter. Within these directions, there are again various scenarios in which supply and demand varies. For example, offshore wind capacity can be high, but the installed capacity of solar PV on roofs and offshore wind can still be low. Furthermore, because the future is uncertain, related questions considering the impact of UPHS if power demand differ, the extend to which the power grid will be expanded or not, and design aspects of UPHS itself, are included as well. Insights in these possible developments are also relevant for a further interpretation of the results. An overview of the results, summarised in annual KPI's of the year 2040 for the selected scenarios, are provided in 5.1. The dynamics of Zeeland's power system in general affected by the scenario directions will be discussed first for more context. Then the impact of UPHS on the power system is analysed using the Key Performance Indicators of curtailment, power shortages, carbon emissions, and power import and export quantities. Subsequently, because the future is uncertain in different ways, some calculations are made regarding these uncertainties.

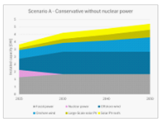
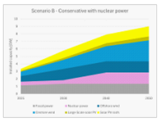
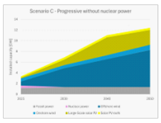
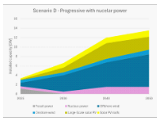
			Base Case	Borssele - Rilland 2x 380 kV	Borssele - Terneuzen 150 kV	Rilland - NL 0 [MW]	UPHS Terneuzen 4200 [MW]	UPHS Borssele 8400 [MW]	UPHS Borssele 4200 [MW]
	Scenario A	Carbon emissions [kTon]	46	-22988	-28	0,0	36	47	36
		Curtailment [GWh]	6,8	7,0	0,0	1326	6,8	7,6	7,6
		Shortages [GWh]	0,0	0,0	0,3	1127	0,0	0,0	0,0
	Conservative without nuclear power	Import [GWh]	-888	-1142	0,0	0,0	-708	-1012	-785
		Export [GWh]	-363	-645	-64	0,0	-314	-472	-388
		UPHS charge [GWh]	2718	3153	80	1327	2030	2804	2054
	Scenario B	Carbon emissions [kTon]	54	25	-0,3	0,0	49	54	49
		Curtailment [GWh]	1487	936	0,0	0,7	1161	1489	1163
		Shortages [GWh]	0,0	0,0	0,2	0,0	0,0	0,0	0,0
	Conservative with nuclear power	Import [GWh]	-238	-341	0,0	0,0	-192	-369	-274
		Export [GWh]	-1217	-991	-0,3	0,0	-930	-1340	-1009
		UPHS charge [GWh]	2264	273	1,7	1,1	1800	2326	1818
	Scenario C	Carbon emissions [kTon]	19	14	-19	0,0	17	19	17
		Curtailment [GWh]	1648	1536	0	1321	1275	1660	1285
		Shortages [GWh]	0,0	0,0	0,3	122	0,0	0,0	0,0
	Progressive without nuclear power	Import [GWh]	168	1964	0	0	62	127	1976
		Export [GWh]	-1047	-1212	-43	0,0	-863	-1092	-891
		UPHS charge [GWh]	2543	2885	51	1328	2027	2601	2048
	Scenario D	Carbon emissions [kTon]	0,0	0,0	0,0	0,0	0,0	0,0	0,0
		Curtailment [GWh]	1533	1650	47	0,7	1186	1538	1190
		Shortages [GWh]	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Progressive with nuclear power	Import [GWh]	-106	-198	0,0	0,0	-91	-159	-126
		Export [GWh]	-1289	-1460	-48	0,0	-992	-1342	-1026
		UPHS charge [GWh]	1854	2646	0,0	1,4	1468	1890	1482

Figure 5.1: Results KPI on base case and uncertainties in scenarios A, B, C, D in 2040

5.1. Overall performance

Considering medium demand scenarios, power demand in medium scenarios will range from 662 MW to 752 MW by 2030, and increase to a range from 1,219 MW to 1,395 MW through the year 2040, and from 1,490 MW to 1,739 MW in 2050. Both solar-PV and wind power with lowest installed capacities according to 2030 scenarios, already exceed power demand of 2050 at full production apart from each other, excluding the possible resort of hydrogen production. According to the study of CE Delft, including power demand for hydrogen production at industrial companies in Zeeland may result in an additional power demand of 1700 MW]. This will incrase the total power demand up to 3,3000 MW if hydrogen production is constant. In reality, green hydrogen production will mainly take place at times when renewable energy is also generated. This requiers however large capacities of electrolysers. Scenarios with high an high installed capacity of offshore wind, and further lower installed capacities of renewables, will exceed this power demand at full power production. Also higher installed capacities of large-scale solar PV will deliver the required power demand for hdyrogen production during operational hours. However, sufficient power production does not guarantee production. because production also depends on availability of transmission capacity. Additionally, different power demand, where the sensitivity mainly lies in the development of the industry's processes, will not immediately change the overall picture. Power production from solar or wind always suffices during production at full power analysing the scenarios per year. However, the time interval in which demand cannot be fulfilled by renewable power will increase at higher demands, and decrease at lower demands.

Furhtermore, despite the growth of renewables over the years, other sources than wind and solar power are needed. Regardless of how much renewable capacity is installed; the system remains weather-dependent. Sometimes, solar radiation or the velocity of the wind is too low, adressing the mismatch between renewable power supply and power demand. If necessary, it is assumed power can be imported from the Dutch power grid. Also fossil power generators may deliver depending on the merit order. Furthermore, storage facilities such as UPHS can contribute by storing surplusses of renewable power, and releasing it later on. In summer, there is a clear pattern of approximately 15 hours every day in which other sources than wind or solar are required, in the evening and night. There is however no clear pattern in winter but during winter months the system has to deal with higher consecutive hours of insufficient renewable energy production.

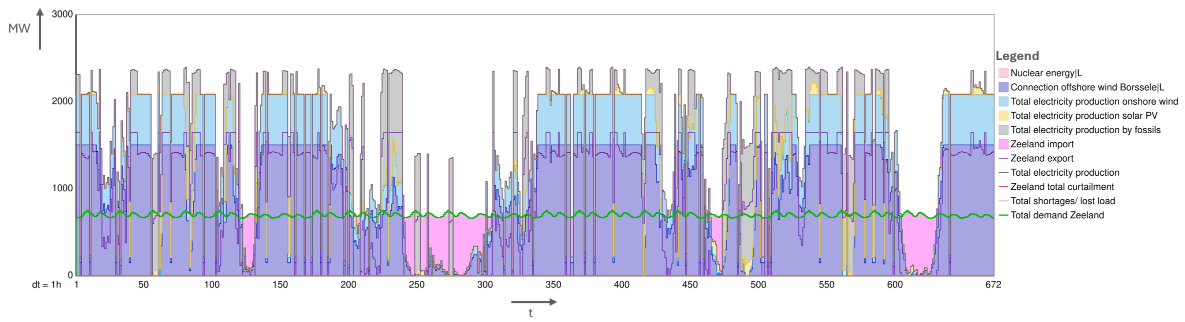


Figure 5.2: Power supply and demand January 2030, scenario direction A

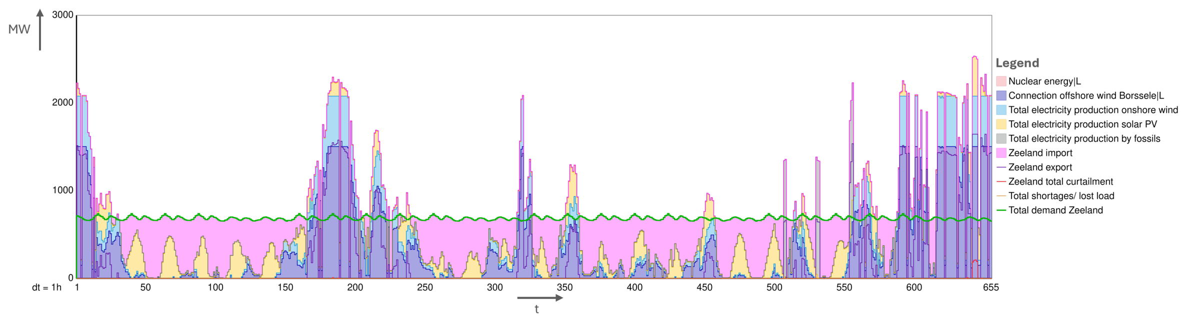


Figure 5.3: Power supply and demand June 2030, scenario direction A

Both offshore wind capacity and the existence of nuclear power significantly affect the results. Both have a significant impact on the energy mix and thus on the values of power import and export, fossil power generation, and curtailment. The construction of a new nuclear power plant results in a certain need to distribute the renewable power generated to the Dutch power grid. In 2040, almost the entire renewable production has to be exported if a nuclear power plant of 1500 MW is realised. Without nuclear power there is a mismatch in supply and demand sometimes as described before, because of weather-dependency. The required import quantities is lower than the maximum capacity of the high-voltage grid in 2040, so there is still little space for additional import quantities for hydrogen production or other purposes.

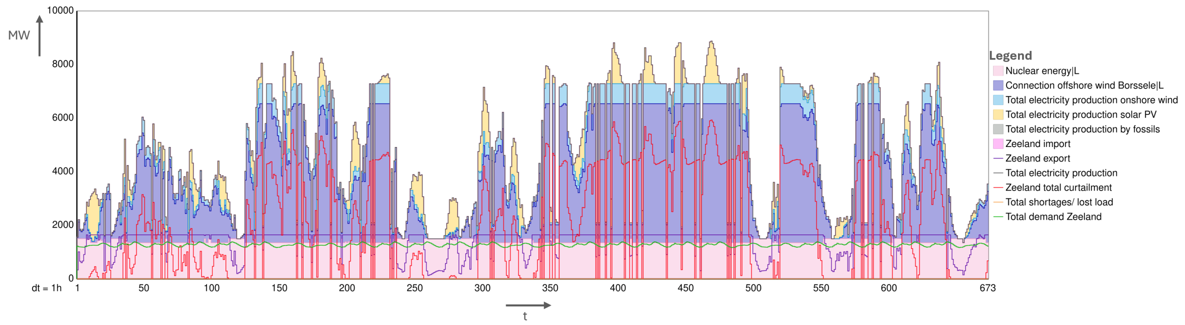


Figure 5.4: Power supply and demand September 2040, scenario direction D

Offshore wind power is connected in Borssele in huge quantities, and have to be distributed through the grid somehow. UPHS add value to Zeeland in storing renewable capacity, i.e. a part of the production does not have to be curtailled, and later on this quantity does not have to be imported or produced by fossil power plants. The added value of UPHS can be found by analysing the Key Performance Indicators.

5.2. Key Performance Indicators

The Key Performance Indicators for evaluating the impact of UPHS on the power system are curtailment reduction, power shortages, power import and export quantities, and carbon emission reduction in Zeeland. The impact of UPHS in the four selected scenarios are shown in figures 5.5 and 5.6. The results are based on medium power demand quantities and the original day-ahead dataset of 2019.

		2030				2040				2050			
		Scenario A	Scenario B	Scenario C	Scenario D	Scenario A	Scenario B	Scenario C	Scenario D	Scenario A	Scenario B	Scenario C	Scenario D
Carbon emissions [kTon]	January	20	15	23	0	14	7	21	0	12	4	19	0
	June	1	1	2	0	0	1	2	0	0	0	0	0
	September	2	1	1	0	3	1	1	0	3	0	1	0
Curtailment [GWh]	January	0	142	121	140	0	145	134	122	0	148	135	124
	June	0	55	34	68	0	68	60	92	0	86	64	98
	September	0	125	96	133	0	137	125	120	0	143	130	127
Shortages [GWh]	January	0	0	0	0	0	0	0	0	0	0	0	0
	June	0	0	0	0	0	0	0	0	0	0	0	0
	September	0	0	0	0	0	0	0	0	0	0	0	0
Import [GWh]	January	-66	-9	-28	-11	-83	20	-7	-4	-65	37	-8	-3
	June	-151	-103	-133	-83	-69	-32	-39	-22	-45	0	-45	-23
	September	-134	-38	-70	-41	-93	18	-18	-8	-61	43	-19	-8
Export [GWh]	January	16	-86	-65	-127	-16	-83	-59	-98	-6	-78	-70	-101
	June	-111	-119	-126	-119	-38	-65	-67	-96	-20	-52	-77	-103
	September	-94	-129	-136	-145	-48	-88	-111	-103	-18	-72	-120	-109

Figure 5.5: Key Performance Indicators of selected scenarios, seasonal differences

Base Case 2040 year	Scenario A	Scenario B	Scenario C	Scenario D
Carbon emissions [kTon]	46	54	19	0,0
Curtailment [GWh]	6,8	1487	1648	1533
Shortages [GWh]	0,0	0,0	0,0	0,0
Import [GWh]	-888	-238	168	-106
Export [GWh]	-363	-1217	-1047	-1289
UPHS charge [GWh]	2718	2264	2543	1854

Figure 5.6: Key Performance Indicators of selected scenarios for 1 year, 2040

The results of the selected scenarios show that curtailment reduction by UPHS is higher in scenarios with more renewables and that there is some variabilty through the year. Remarkable, UPHS does not minimise power shortages in these scenarios, but there a few scenarios in which UPHS does minimise. This finding is the opposite of the hypothesis that creates the expectation that UPHS can solve energy shortages up to a certain level. Furthermore, UPHS decreases carbon emissions especially in winter months. The subsections that follow will elaborate on the results more specifically, and addressing the results of other scenarios as well. This provides more insight into the impact of power system components on UPHS performance.

5.2.1. Curtailment

Overall, higher installed capacities of solar PV, wind power, and nuclear power, results in higher curtailment quantities. This cause relatively less curtailment reduction by UPHS in 2040 than in 2030 for example, but UPHS does not underperform in scenarios with more renewables in absolute numbers. Furthermore, it is observed that curtailment follows the pattern of the dominant renewable power generator in a certain period; i.e. wind power in January and solar power in June. The tables below show the curtailment reduction in absolute numbers for the scenarios for the months January, June, and September, in 2030, 2040, and 2050. The calculations show no differences between scenarios where fossil plants are open or closed, and therefore only the results of scenarios with and without nuclear power are shown. There are also no differences in curtailment reduction in scenarios in which the day-ahead price differs, as long as the system cannot make money by generating power on the one hand and curtailing it elsewhere.

2030		KPI - Curtailment [GWh] - Reduction by UPHS															
		OFW30-								OFW30+							
		ONW30-				ONW30+				ONW30-				ONW30+			
		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
		PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
January	Ncl0	0	0	0	0	49	51	51	54	143	142	142	142	142	142	142	142
	Ncl485	46	49	50	52	121	121	122	122	140	140	140	140	143	143	143	143
June	Ncl0	0	2	2	4	15	18	18	20	54	56	55	59	60	62	62	63
	Ncl485	15	18	19	21	35	34	34	38	60	66	66	67	68	70	69	73
September	Ncl0	0	4	5	12	46	51	52	58	123	125	125	129	134	134	134	135
	Ncl485	46	53	54	61	93	96	96	99	133	133	133	133	135	135	134	134

Figure 5.7: KPI Curtailment reduction by uPHS in 2030

2040		KPI - Curtailment [GWh] - Reduction by UPHS															
		OFW30-								OFW30+							
		ONW30-				ONW30+				ONW30-				ONW30+			
		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
		PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
January	Ncl0	0	0	0	0	40	43	44	47	145	145	145	145	148	148	148	148
	Ncl1500	123	123	124	125	134	134	134	134	124	123	123	122	116	115	115	114
June	Ncl0	0	0	1	2	12	15	16	17	61	66	68	71	73	75	45	15
	Ncl1500	35	37	42	54	56	60	63	75	86	87	85	94	88	-151	-195	-241
September	Ncl0	0	0	1	5	40	46	48	51	136	136	137	138	138	140	141	143
	Ncl1500	97	100	104	111	125	125	125	126	126	123	120	120	123	122	120	118

Figure 5.8: KPI Curtailment reduction by uPHS 2040

2050		KPI - Curtailment [GWh] - Reduction by UPHS															
		OFW30-								OFW30+							
		ONW30-				ONW30+				ONW30-				ONW30+			
		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
		PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
January	NcI0	0	0	0	0	50	51	52	53	148	148	148	148	144	143	142	141
	NcI1500	114	116	118	120	135	135	136	135	128	127	125	124	119	118	117	115
June	NcI0	0	1	1	2	12	14	15	16	72	77	86	86	83	87	91	91
	NcI1500	34	35	41	58	58	64	67	77	92	90	93	100	95	93	94	102
September	NcI0	0	0	2	6	37	41	43	47	138	141	143	144	144	145	146	146
	NcI1500	92	98	105	113	131	130	129	131	132	131	129	127	131	130	126	124

Figure 5.9: KPI Curtailment reduction by uPHS 2050

Reduction in curtailment can be up to 0.14 TWh per month in 2030, 2040, and 2050. In scenarios with lower amounts of renewables, curtailment reduction in winter covers approximately the annual production of 1 to 1.5 offshore windturbines of 10 MW, while in the scenarios with higher amounts of renewables, the curtailment reduction covers the annual production of 3 offshore windturbines of 10 MW. There seems to be a linear correlation between the impact of UPHS in curtailment reduction and the installed wind capacity in winter. In summer, curtailment is the highest in scenarios containing large installed capacities of solar PV on roofs, and reflects therefore the challenges of congestion already present in the built environment.

Especially scenarios in which a new nuclear power plant is involved (B and D), the power system have to deal with significantly higher amounts of curtailment because nuclear power increase the base load power on the high voltage grid. Only for the month January in 2030, a nuclear power plant already cause curtailment quantities similar to the annual power production of 4 offshore windturbines of 10 MW. However, scenarios with lower installed capacities of wind and solar, but including a nuclear power plant of 485 MW (B), still have less curtailment than scenarios with no nuclear power and higher installed capacities of wind and solar (C). Differences in curtailment due to the presence of fossil power plants within Zeeland are minimal. The realisation of UPHS will lower curtailment peaks both in winter and summer because UPHS charges as much as possible when curtailment occurs.

A storage facility such as UPHS will reduce the highest quantities of curtailment in scenarios in which a 1500 MW nuclear power plant is involved, and scenarios with high offshore wind capacities. Curtailment reduction in the scenario of a 3000 MW nuclear power plant is lower than in the scenario of a 1500 MW power plant, caused by the doubling of the baseload of nuclear power. This results in curtailment quantities that are almost equal to the production of renewable power. UPHS can charge, but there will be less hours available that UPHS can discharge, as there is no transmission capacity available on the high voltage grid. This implies that the construction of nuclear power with that huge capacities, will result in less flexibility of the power system as well, which, on the other hand, is needed to implement power production by renewable sources.

The higher the installed capacity of renewables, the higher the standard deviation. This can also be seen in the differences between 2030, 2040, and 2050 because there is more variability in 2040 than in 2030 for example. However, the implementation of UPHS results in less variability of curtailment. Because in sceanrios without UPHS, both the mean and standard deviation of curtailment are higher. There are no seasonal differences in these statistics. Lower variability in curtailment values implies in more stability of the system, because curtailment is fluctuating less and may therefore be solved more easily.

However, the number of hours curtailment occurs is also relevant in this. The number of hours power need to be curtailed reflects how often the power grid in Zeeland is overloaded. An increase in renewable power capacity result in an increase in the number of hours that curtailment occurs. In scenarios with less renewables, the range goes from 0 % to 56 % in January in 2030. In scenarios with higher renewables installed, this range goes from 56 % to 67 % of the hours. The impact of UPHS on the number of hours that curtailment occurs is limited as the reduction is 4 % at maximum, excepted from the scenarios with lowest renewable capacity and a nuclear power plant. Then, UPHS reduce the number of hours that curtailment occurs by 35 % to 38 % in winter in 2030. The results are decreasing in 2040 and 2050 with maximum 18 % reduction hours in january 2040, and up to 9 % in 2050. The number of hours that curtaillment occurs in January, is reduced up to 28 hours and 10 days in scenarios with higher renewables and nuclear power.

The impact in summer is less compared to winter as the highers reduction in June is up to 5% in 2030, that corresponds with maximum 53 hours of curtailment reduction which is about 2.5 days per month. In 2040 and 2050 in summer, the impact of UPHS on number of hours curtailment is even less. The decrease in impact of UPHS on the number of hours is caused by the increase in power demand. Furthermore, the construction of a new nuclear plant also increase the hours curtailment occur. UPHS will not compensate these additional hours compared to the situation without nuclear power and UPHS is not constructed.

5.2.2. Power shortages

No electricity shortages will occur in scenarios of 2030 and 2040. There might be power shortages in 2050 on the other hand, about 2 to 3 GWh over the year in the scenarios with lowest installed renewable power, especially the scenarios in which fossil power generators are closed.

2050 - January

				KPI - Import [MWh] - Reduction by UPHS															
				OFW40-								OFW40+							
				ONW40-				ONW40+				ONW40-				ONW40+			
				LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
				PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	SloeOFF	ElstaOFF	SeasunOFF	564	489	417	384	519	458	405	372	485	445	395	362	486	445	395	362
			SeasunON	419	360	301	279	382	335	289	267	366	334	288	266	366	333	288	266
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SloeON	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ncl1500	SloeOFF	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SloeON	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.10: KPI Power shortage reduction [MWh] by uPHS january 2050

2050 - June

				KPI - Import [MWh] - Reduction by UPHS															
				OFW40-								OFW40+							
				ONW40-				ONW40+				ONW40-				ONW40+			
				LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
				PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	SloeOFF	ElstaOFF	SeasunOFF	17	0	0	0	17	0	0	0	17	0	0	0	17	0	0	0
			SeasunON	3	0	0	0	3	0	0	0	3	0	0	0	3	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SloeON	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ncl1500	SloeOFF	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SloeON	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.11: KPI Power shortage reduction [MWh] by uPHS june 2050

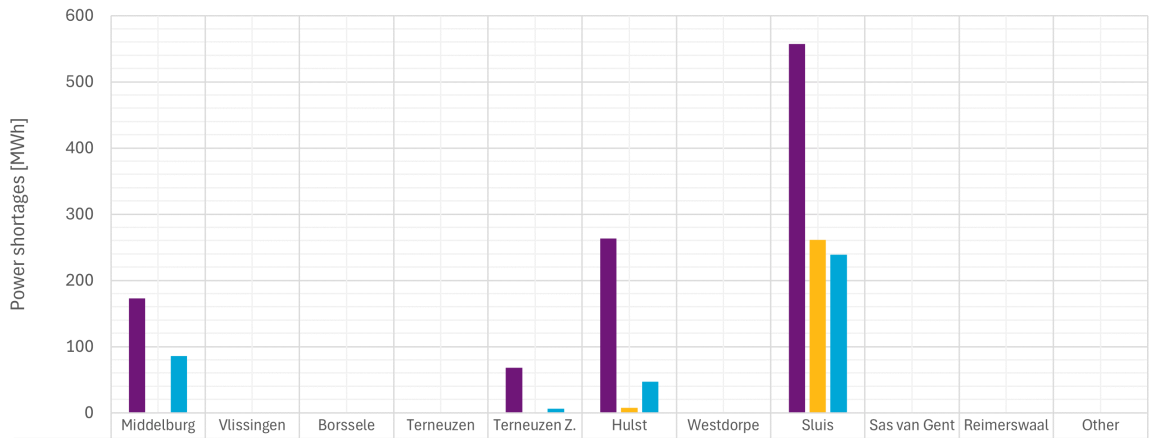
2050 - September

				KPI - Import [MWh] - Reduction by UPHS															
				OFW40-								OFW40+							
				ONW40-				ONW40+				ONW40-				ONW40+			
				LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
				PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	SloeOFF	ElstaOFF	SeasunOFF	97	73	64	64	82	62	52	52	79	58	48	48	79	58	48	48
			SeasunON	60	39	38	38	53	32	31	31	53	32	31	31	53	32	31	31
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SloeON	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ncl1500	SloeOFF	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SloeON	ElstaOFF	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		ElstaON	SeasunOFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			SeasunON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.12: KPI Power shortage reduction [MWh] by uPHS september 2050

Power shortages mainly occur in the months with lower power production from solar PV, and when energy demand exceeds the capacity of the Rilland connection and the Dutch grid, and no renewable power is produced at that time. Another important observation is that when power shortages occur, this happens when power demand is at its highest level.

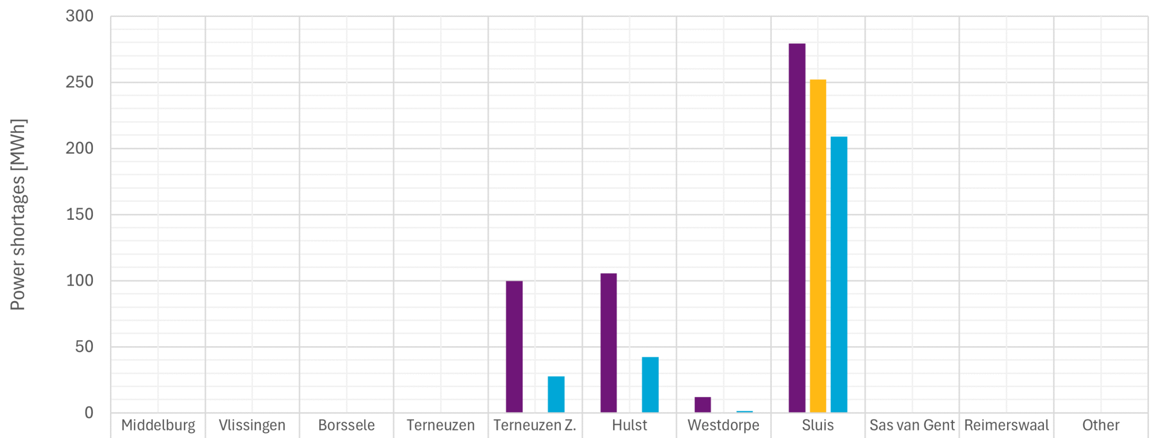
Power shortages are occuring in Hulst, Middelburg, Sluis and Terneuzen Zuid, in which Sluis has the highest amount. UPHS lowers power shortages mainly in Middelburg and Sluis, followed by Hulst. Furthermore, power shortages are occurring frequently in Hulst, and to a lesser extent in Sluis. In contrast, it occurs only occasionally in Middelburg and Terneuzen Zuid.



	Middelburg	Vlissingen	Borssele	Terneuzen	Terneuzen Z.	Hulst	Westdorpe	Sluis	Sas van Gent	Reimerswaal	Other
January	173	0	0	0	68	263	0	557	0	0	0
June	0	0	0	0	0	8	0	262	0	0	0
September	86	0	0	0	6	47	0	239	0	0	0

January June September

Figure 5.13: Power shortages 2050, no UPHS



	Middelburg	Vlissingen	Borssele	Terneuzen	Terneuzen Z.	Hulst	Westdorpe	Sluis	Sas van Gent	Reimerswaal	Other
January	0	0	0	0	100	105	12	279	0	0	0
June	0	0	0	0	0	0	0	252	0	0	0
September	0	0	0	0	28	42	1	209	0	0	0

January June September

Figure 5.14: Power shortages 2050, UPHS

The quantity of power shortages during the month of January ranges from 300 to almost 900 MWh, but UPHS does not have a significant impact in reducing power shortages. Only in scenarios where fossil power generators are lacking, UPHS will reduce power shortages by approximately 50 % at the power demand level, especially in Middelburg and Sluis, followed by Terneuzen. UPHS is thus not able to reduce power shortages completely.

Because UPHS does not seem to make any difference, and the import quantity is not always at maximum during power shortages, this indicates that somewhere else in the high-voltage power grid in Zeeland, power demand exceeds grid capacity. During power shortages, the power system is importing power and discharging UPHS, and sometimes peaks of electricity shortages are reducing, but this is not always the case.

Most power shortages are below the 5 MW demand and occur more frequently. Fewer, but still common quantities of power shortages go up to a maximum of 100 MW, which can be reduced uPHS by about 50 %. These quantities can also be solved with other, smaller storage facilities at the site of the bottleneck, such as batteries. Currently, batteries of this size are already being developed. Such developments as well as demand response were not included in this study. These however may solve power shortages if all fossil power generators in Zeeland are not operating anymore. Whether these plants will be closed depends on economic feasibility and policy decisions.

5.2.3. Power import and export

Zeeland is mainly exporting power today. The growth in power demand on the one hand, and policy decisions regarding the availability of fossil power generators on the other hand, cause a certain shift in the time duration of power export and import. This is also caused by cost-driven decisions for system costs because it might economically be more interesting to import or export power depending on the day-ahead price and marginal costs of power generators. Furthermore, the power system can either import or export energy, but not simultaneously, and therefore decisions have to be made.

Without nuclear power, Zeeland will become more dependent on other sources than solar and wind because of the increasing power demand in the future. This will result in more import quantities. In addition, UPHS will result in higher amounts of power import, especially in scenarios without nuclear power. This has to do with the functioning of the market as UPHS provides the opportunity to save on system costs by importing power at lower day-ahead prices instead of generating power by fossil power plants with higher marginal costs. In some scenarios, power import is increased by a factor up to 10. Because the day-ahead price is usually lower in June than in January, there is more power import in summer than in winter. Also, the calculations with the modified day-ahead price, thus the higher power prices, show that UPHS increase less the import quantities than in scenarios with lower import prices. Furthermore, in scenarios in which the capacity of renewables is high, import quantities increase is less due to UPHS, indicating that the higher quantity of power surpluses in these scenarios are stored by UPHS resulting in less need for power import. In conclusion, the day-ahead price and availability of renewable power and nuclear power to store in UPHS, determine the import quantity, as it is cost-driven.

2030				KPI - Import [GWh] - Reduction by UPHS															
				OFW30-								OFW30+							
				ONW30-				ONW30+				ONW30-				ONW30+			
				LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
				PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl 0	Fossill off	-53	-54	-54	-55	-19	-19	-20	-20	14	12	12	10	18	16	16	14
			Fossil on	-66	-66	-66	-66	-42	-42	-41	-40	-8	-9	-9	-9	-3	-4	-4	-4
		Ncl 485	Fossil off	-41	-41	-41	-41	-25	-26	-26	-26	-9	-10	-10	-11	-5	-6	-7	-7
			Fossil on	-43	-43	-43	-43	-28	-28	-28	-28	-14	-14	-14	-14	-10	-10	-10	-10
	June	Ncl 0	Fossil off	-145	-150	-148	-137	-130	-132	-131	-120	-101	-100	-99	-89	-91	-93	-92	-81
			Fossil on	-151	-153	-153	-141	-134	-136	-135	-124	-105	-104	-103	-92	-95	-96	-95	-84
		Ncl 485	Fossil off	-165	-146	-140	-124	-148	-132	-127	-110	-121	-104	-99	-83	-113	-97	-92	-78
			Fossil on	-166	-147	-141	-124	-149	-133	-127	-110	-121	-105	-99	-83	-113	-97	-92	-79
	September	Ncl 0	Fossil off	-133	-131	-129	-124	-94	-93	-92	-85	-39	-37	-37	-35	-29	-29	-28	-28
			Fossil on	-134	-131	-130	-123	-95	-93	-92	-85	-40	-38	-38	-36	-30	-29	-29	-28
		Ncl 485	Fossil off	-106	-98	-95	-88	-74	-70	-69	-64	-47	-45	-44	-41	-43	-41	-40	-39
			Fossil on	-105	-97	-95	-88	-74	-70	-69	-63	-47	-45	-43	-41	-43	-41	-40	-39
DA 2019 * 1.2	January	Ncl 0	Fossil on	-35	-35	-35	-35	-25	-25	-25	-24	-13	-13	-13	-13	-11	-10	-10	-10
		Ncl 485	Fossil on	-17	-16	-15	-14	-11	-11	-11	-10	-8	-8	-8	-8	-7	-7	-7	-7
	June	Ncl 0	Fossil on	-156	-151	-150	-139	-137	-132	-130	-121	-106	-103	-102	-92	-98	-96	-95	-86
		Ncl 485	Fossil on	-140	-127	-123	-112	-126	-116	-112	-100	-103	-93	-90	-77	-98	-87	-84	-73
	September	Ncl 0	Fossil on	-146	-141	-138	-131	-104	-101	-99	-92	-48	-44	-43	-40	-36	-35	-34	-32
		Ncl 485	Fossil on	-104	-96	-94	-87	-74	-70	-68	-63	-47	-45	-43	-41	-43	-41	-40	-39

Figure 5.15: Decrease in import quantities [GWh] by UPHS in 2030

2040				KPI - Import [GWh] - Reduction by UPHS															
				OFW30-								OFW30+							
				ONW30-				ONW30+				ONW30-				ONW30+			
				LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
				PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl 0	Fosill off	-51	-51	-52	-53	7	7	6	5	65	63	62	59	68	67	65	63
			Fossil on	-83	-82	-82	-82	-33	-33	-33	-32	21	20	20	19	26	26	25	25
		Ncl 1500	Fossil off	-12	-12	-12	-12	-7	-7	-7	-7	-4	-4	-4	-4	-4	-4	-4	-4
			Fossil on	-12	-12	-12	-11	-7	-7	-7	-7	-4	-4	-4	-4	-4	-4	-4	-4
	June	Ncl 0	Fossil off	-61	-74	-83	-79	-49	-63	-70	-63	-11	-19	-25	-19	-4	-17	18	51
			Fossil on	-69	-83	-91	-87	-56	-70	-77	-70	-17	-25	-32	-25	-10	-18	20	54
		Ncl 1500	Fossil off	-66	-48	-40	-33	-57	-40	-35	-28	-45	-34	-29	-22	-43	276	282	287
			Fossil on	-65	-48	-39	-33	-56	-39	-34	-28	-44	-33	-28	-22	-43	276	282	287
	September	Ncl 0	Fossil off	-91	-93	-95	-93	-49	-50	-52	-50	23	21	19	19	29	27	23	21
			Fossil on	-93	-95	-97	-94	-51	-52	-53	-51	21	19	18	18	28	26	22	20
		Ncl 1500	Fossil off	-27	-24	-21	-19	-20	-18	-16	-14	-11	-10	-9	-8	-9	-9	-7	-7
			Fossil on	-26	-23	-21	-19	-20	-18	-16	-14	-11	-10	-9	-8	-9	-8	-7	-7
DA 2019 * 1.2	January	Ncl 0	Fossil on	-40	-40	-39	-39	-21	-21	-21	-20	-5	-5	-5	-5	-4	-4	-4	-4
		Ncl 1500	Fossil on	-3	-3	-3	-2	-2	-2	-2	-2	-1	-1	-1	-1	-1	-1	-1	-1
	June	Ncl 0	Fossil on	-128	-134	-135	-126	-109	-115	-116	-108	-64	-69	-72	-61	-57	-64	-64	-51
		Ncl 1500	Fossil on	-53	-41	-36	-30	-47	-35	-31	-27	-39	-30	-27	-22	-38	-29	-25	-21
	September	Ncl 0	Fossil on	-123	-122	-120	-115	-79	-76	-75	-70	1	1	2	4	9	10	8	8
		Ncl 1500	Fossil on	-26	-23	-21	-19	-19	-17	-16	-13	-10	-10	-9	-8	-8	-8	-7	-7

Figure 5.16: Decrease in import quantities [GWh] by UPHS in 2040

2050				KPI - Import [GWh] - Reduction by UPHS															
				OFW30-								OFW30+							
				ONW30-				ONW30+				ONW30-				ONW30+			
				LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
				PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl 0	Fosill off	-34	-34	-35	-35	19	20	19	19	81	81	79	77	75	74	72	70
			Fossil on	-65	-66	-68	-68	-16	-17	-18	-18	41	39	37	36	37	35	33	32
		Ncl 1500	Fossil off	-15	-15	-16	-16	-5	-6	-7	-7	-2	-2	-3	-3	-1	-2	-3	-3
			Fossil on	-16	-16	-16	-16	-8	-8	-8	-8	-4	-4	-4	-4	-3	-3	-3	-3
	June	Ncl 0	Fossil off	-38	-53	-59	-50	-30	-41	-46	-40	18	7	5	10	23	14	9	13
			Fossil on	-45	-60	-66	-57	-35	-47	-51	-46	13	2	0	4	19	9	4	8
		Ncl 1500	Fossil off	-80	-56	-43	-35	-67	-45	-36	-28	-52	-38	-29	-23	-50	-34	-27	-22
			Fossil on	-80	-56	-43	-35	-67	-45	-36	-29	-53	-38	-29	-24	-50	-35	-27	-22
	September	Ncl 0	Fossil off	-58	-61	-65	-62	-21	-24	-26	-26	50	49	44	43	54	48	42	41
			Fossil on	-61	-64	-67	-64	-23	-25	-27	-27	48	47	43	42	52	46	41	40
		Ncl 1500	Fossil off	-37	-31	-27	-24	-23	-20	-18	-16	-12	-10	-9	-8	-9	-8	-7	-7
			Fossil on	-37	-31	-27	-24	-23	-19	-18	-16	-12	-10	-9	-8	-9	-8	-7	-7
DA 2019 * 1.2	January	Ncl 0	Fossil on	-24	-26	-27	-27	-6	-7	-8	-9	9	7	6	5	7	5	4	3
		Ncl 1500	Fossil on	-5	-5	-4	-4	-3	-3	-3	-2	-2	-1	-1	-1	-2	-1	-1	-1
	June	Ncl 0	Fossil on	-100	-107	-105	-96	-80	-88	-88	-82	-32	-41	-39	-32	-24	-31	-33	-26
		Ncl 1500	Fossil on	-65	-48	-39	-33	-55	-40	-33	-28	-46	-34	-28	-24	-44	-32	-27	-22
	September	Ncl 0	Fossil on	-94	-93	-91	-87	-56	-55	-52	-48	25	26	26	26	31	28	25	26
		Ncl 1500	Fossil on	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.17: Decrease in import quantities [GWh] by UPHS in 2050

A similar but opposite trend is evident in power exports. In scenarios with lower capacities of renewables, export quantities are lower, and so the impact of UPHS on export quantities. Also scenarios without or less fossil power capacity available, the impact of UPHS on export increase is higher than in scenarios with full fossil power capacity available. In general, the more available capacity to produce, the larger export quantities. In a few scenarios, export quantities are reduced by UPHS. This is only true for scenarios with lowest renewable capacities, no nuclear power, and fossil power generators available. Overall, an increase in import hours also means a decrease in export hours, but quantities of import and export are higher with UPHS, indicating that the power grid is more burdened.

2030				KPI - Export [GWh] - Reduction by UPHS															
				OFW30-								OFW30+							
				ONW30-				ONW30+				ONW30-				ONW30+			
				LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
				PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl 0	Fosill off	-22	-23	-24	-25	-45	-48	-48	-51	-102	-104	-105	-106	-99	-101	-102	-103
			Fossil on	16	17	16	17	-20	-21	-20	-20	-87	-87	-86	-85	-89	-89	-88	-87
		Ncl 485	Fossil off	-77	-80	-81	-83	-125	-126	-127	-127	-126	-127	-127	-127	-124	-125	-125	-125
			Fossil on	-12	-13	-14	-14	-65	-65	-65	-64	-83	-82	-81	-80	-83	-82	-81	-79
	June	Ncl 0	Fossil off	-109	-115	-113	-105	-109	-114	-113	-105	-118	-120	-119	-112	-114	-119	-118	-110
			Fossil on	-111	-114	-114	-105	-109	-114	-113	-104	-119	-120	-119	-112	-115	-119	-119	-111
		Ncl 485	Fossil off	-146	-131	-125	-113	-147	-132	-127	-113	-148	-135	-130	-119	-147	-134	-131	-122
			Fossil on	-140	-125	-119	-107	-142	-126	-121	-107	-144	-131	-126	-115	-144	-131	-126	-119
	September	Ncl 0	Fossil off	-97	-100	-99	-100	-106	-110	-111	-110	-130	-130	-131	-132	-131	-132	-132	-132
			Fossil on	-94	-95	-95	-95	-105	-108	-108	-107	-129	-129	-129	-130	-131	-131	-131	-130
		Ncl 485	Fossil off	-126	-125	-124	-125	-140	-139	-138	-135	-150	-148	-147	-145	-148	-147	-146	-144
			Fossil on	-122	-121	-121	-122	-137	-136	-135	-132	-148	-145	-144	-142	-146	-144	-144	-142
DA 2019 * 1.2	January	Ncl 0	Fossil on	-43	-42	-42	-41	-71	-69	-69	-67	-87	-85	-84	-81	-83	-80	-79	-77
		Ncl 485	Fossil on	-47	-44	-44	-42	-50	-47	-46	-44	-45	-43	-42	-40	-42	-40	-39	-37
	June	Ncl 0	Fossil on	-98	-91	-88	-77	-95	-90	-86	-75	-99	-94	-91	-81	-95	-92	-90	-81
		Ncl 485	Fossil on	-61	-46	-43	-34	-64	-50	-46	-37	-70	-61	-58	-51	-72	-63	-60	-55
	September	Ncl 0	Fossil on	-61	-58	-56	-54	-80	-80	-78	-75	-109	-106	-105	-105	-111	-108	-107	-105
		Ncl 485	Fossil on	-76	-75	-75	-77	-96	-95	-94	-93	-113	-111	-110	-110	-113	-111	-111	-111

Figure 5.18: Decrease in export quantities [GWh] by UPHS in 2030

2040				KPI - Export [GWh] - Reduction by UPHS															
				OFW30-								OFW30+							
				ONW30-				ONW30+				ONW30-				ONW30+			
				LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
				PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl 0	Fosill off	-18	-18	-19	-21	-11	-14	-16	-19	-56	-57	-59	-62	-56	-58	-60	-62
			Fossil on	-16	-16	-16	-16	-16	-19	-19	-20	-81	-82	-83	-83	-85	-85	-85	-85
		Ncl 1500	Fossil off	-115	-115	-115	-115	-117	-116	-115	-114	-100	-100	-99	-98	-94	-94	-92	-90
			Fossil on	-43	-43	-44	-44	-60	-59	-58	-58	-52	-51	-50	-49	-48	-47	-46	-45
	June	Ncl 0	Fossil off	-31	-45	-53	-48	-31	-46	-54	-49	-42	-52	-61	-59	-45	-60	-82	-110
			Fossil on	-38	-52	-59	-54	-37	-52	-59	-54	-46	-56	-65	-63	-50	-66	-90	-118
		Ncl 1500	Fossil off	-73	-60	-60	-78	-85	-74	-74	-86	-100	-90	-90	-96	-102	-488	-530	-568
			Fossil on	-65	-52	-53	-70	-78	-67	-67	-80	-93	-84	-84	-90	-96	-492	-533	-572
	September	Ncl 0	Fossil off	-52	-54	-58	-60	-56	-63	-67	-68	-83	-87	-89	-91	-80	-84	-89	-93
			Fossil on	-48	-49	-52	-54	-57	-64	-67	-67	-84	-87	-88	-90	-81	-85	-89	-92
		Ncl 1500	Fossil off	-101	-102	-105	-109	-116	-114	-112	-113	-106	-104	-103	-103	-105	-104	-101	-99
			Fossil on	-98	-99	-103	-107	-114	-111	-110	-111	-104	-102	-102	-101	-103	-102	-99	-98
DA 2019 * 1.2	January	Ncl 0	Fossil on	-71	-71	-71	-71	-81	-82	-82	-82	-109	-108	-107	-107	-104	-104	-103	-103
		Ncl 1500	Fossil on	-11	-10	-9	-9	-11	-10	-10	-9	-10	-9	-8	-8	-9	-8	-7	-7
	June	Ncl 0	Fossil on	-91	-95	-91	-78	-85	-88	-86	-77	-83	-86	-89	-82	-85	-90	-90	-83
		Ncl 1500	Fossil on	8	14	11	-5	-8	-4	-6	-18	-32	-26	-25	-33	-35	-29	-27	-36
	September	Ncl 0	Fossil on	-44	-41	-38	-35	-63	-63	-61	-57	-90	-89	-86	-85	-86	-85	-86	-86
		Ncl 1500	Fossil on	-57	-63	-69	-77	-80	-81	-83	-86	-78	-79	-81	-82	-79	-81	-81	-81

Figure 5.19: Decrease in export quantities [GWh] by UPHS in 2040

2050				KPI - Export [GWh] - Reduction by UPHS															
				OFW30-								OFW30+							
				ONW30-				ONW30+				ONW30-				ONW30+			
				LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
				PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl 0	Fosill off	-1	-2	-2	-3	-9	-10	-11	-12	-43	-43	-45	-47	-46	-46	-47	-48
			Fossil on	-6	-7	-8	-8	-15	-17	-18	-19	-74	-76	-78	-77	-75	-76	-76	-76
		Ncl 1500	Fossil off	-118	-119	-120	-121	-119	-119	-119	-119	-102	-102	-102	-101	-95	-95	-94	-92
			Fossil on	-51	-50	-49	-49	-72	-70	-68	-67	-62	-60	-58	-56	-57	-55	-52	-51
	June	Ncl 0	Fossil off	-13	-26	-31	-22	-16	-27	-31	-28	-27	-40	-48	-47	-32	-45	-52	-48
			Fossil on	-20	-33	-37	-29	-20	-31	-35	-32	-31	-44	-52	-50	-35	-49	-56	-52
		Ncl 1500	Fossil off	-86	-65	-65	-84	-98	-82	-81	-92	-114	-100	-96	-103	-117	-100	-97	-104
			Fossil on	-80	-59	-59	-77	-94	-77	-76	-88	-110	-96	-93	-99	-114	-97	-94	-100
	September	Ncl 0	Fossil off	-23	-26	-31	-32	-27	-34	-39	-42	-61	-65	-72	-74	-64	-71	-77	-79
			Fossil on	-18	-21	-26	-26	-28	-35	-38	-41	-63	-66	-72	-74	-65	-72	-77	-78
		Ncl 1500	Fossil off	-108	-106	-110	-118	-126	-122	-121	-123	-117	-114	-110	-109	-113	-109	-105	-101
			Fossil on	-105	-103	-108	-116	-124	-120	-120	-122	-115	-112	-109	-108	-111	-108	-103	-100
DA 2019 * 1.2	January	Ncl 0	Fossil on	-64	-67	-69	-69	-74	-76	-77	-78	-101	-102	-102	-102	-97	-98	-99	-98
		Ncl 1500	Fossil on	-38	-34	-31	-30	-33	-31	-28	-26	-28	-25	-22	-21	-26	-23	-21	-20
	June	Ncl 0	Fossil on	-70	-74	-70	-57	-65	-69	-63	-55	-68	-75	-77	-72	-67	-77	-79	-73
		Ncl 1500	Fossil on	-23	-7	-9	-24	-35	-25	-27	-37	-60	-48	-44	-50	-64	-49	-46	-53
	September	Ncl 0	Fossil on	-23	-20	-16	-13	-41	-41	-38	-36	-76	-75	-76	-75	-76	-78	-79	-77
		Ncl 1500	Fossil on	-61	-63	-74	-84	-89	-89	-92	-96	-88	-87	-88	-89	-88	-86	-85	-83

Figure 5.20: Decrease in export quantities [GWh] by UPHS in 2050

Statistically, UPHS results in more variability in power import and export quantities to the Dutch power grid, because the implementation of a storage facility adds degrees of freedom to the power system and the opportunity to optimise. Because, surplusses of power can be stored and used later on or exported directly. Also, cheaper power from the Dutch power grid can be imported and stored because of economic benefits. Stored power can also be released to the Dutch power grid when day-ahead prices are higher than usual, i.e. when demand is high rather renewable power supply is low. Variability is also higher in scenarios without nuclear power, and scenarios with medium and high capacities of solar and wind power. At some point of high installed capacities, however, power has to be exported as the demand within Zeeland is already met. The limitation of the power grid determines also the extent of variability of export, but overall new challenges will arise regarding maintaining grid stability and preventing blackouts.

5.2.4. Carbon emissions

Reduction in carbon emissions by UPHS is the highest in scenarios with the possibility to generate fossil power within Zeeland rather scenarios in which less renewable capacity is available. Also, the higher the day-ahead price, the more fossil power generators will operate to serve demand within Zeeland and to export power to benefit from the higher day-ahead price. Especially in these scenario's, the reduction in carbon emissions by UPHS is the highest, excluding scenarios without nuclear power. Because in scenarios without nuclear power but higher power prices, fossil power generators will produce even more power by using UPHS.

2030			KPI - Carbon emissions [kton] - Reduction by UPHS															
			OFW30-								OFW30+							
			ONW30-				ONW30+				ONW30-				ONW30+			
			LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
			PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl0	20	21	20	21	18	18	19	19	14	14	15	15	12	12	12	13
		Ncl485	25	26	26	26	23	23	24	24	17	18	18	19	17	17	17	18
	June	Ncl0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Ncl485	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	September	Ncl0	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1
		Ncl485	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
DA 2019 *1.2	January	Ncl0	-10	-10	-10	-9	-5	-3	-3	-2	17	17	18	19	17	18	18	19
		Ncl485	6	7	7	8	24	25	26	27	30	31	31	32	31	32	32	32
	June	Ncl0	10	11	12	13	9	11	11	13	11	12	13	14	11	13	13	14
		Ncl485	24	26	26	26	25	26	26	26	24	25	25	24	24	24	24	24
	September	Ncl0	18	19	19	20	14	14	15	15	11	12	12	12	10	11	11	12
		Ncl485	18	18	18	17	16	16	16	15	14	14	14	13	13	13	13	12

Figure 5.21: Reduction in carbon emissions by UPHS in 2030

2040			KPI - Carbon emissions [kton] - Reduction by UPHS															
			OFW30-								OFW30+							
			ONW30-				ONW30+				ONW30-				ONW30+			
			LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
			PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl0	14	14	14	14	13	13	13	14	7	7	7	7	5	5	5	5
		Ncl1500	27	27	26	26	21	21	21	21	18	18	18	18	17	17	17	17
	June	Ncl0	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1
		Ncl1500	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2
	September	Ncl0	3	3	3	3	0	1	1	1	0	0	1	1	0	0	0	1
		Ncl1500	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0
DA 2019 *1.2	January	Ncl0	-20	-20	-20	-20	-14	-13	-13	-12	6	7	7	7	9	9	9	9
		Ncl1500	36	37	37	37	38	38	38	38	33	33	33	32	31	31	31	30
	June	Ncl0	3	4	6	7	2	4	6	7	5	6	7	8	6	7	8	7
		Ncl1500	27	26	26	26	26	25	24	25	24	23	24	23	24	23	23	22
	September	Ncl0	15	16	17	18	9	10	11	11	6	6	7	8	5	6	7	7
		Ncl1500	16	14	13	12	13	12	11	10	10	9	8	7	9	8	7	7

Figure 5.22: Reduction in carbon emissions by UPHS in 2040

2050			KPI - Carbon emissions [kton] - Reduction by UPHS															
			OFW30-								OFW30+							
			ONW30-				ONW30+				ONW30-				ONW30+			
			LS30-		LS30+		LS30-		LS30+		LS30-		LS30+		LS30-		LS30+	
			PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+	PVR30-	PVR30+
DA 2019	January	Ncl0	12	12	12	12	11	12	12	12	4	4	4	4	3	3	4	4
		Ncl1500	25	26	27	27	18	19	19	20	16	16	17	17	15	15	16	16
	June	Ncl0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Ncl1500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	September	Ncl0	3	3	3	3	1	1	1	1	0	0	0	1	0	0	0	1
		Ncl1500	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	0
DA 2019 *1.2	January	Ncl0	-24	-23	-25	-24	-14	-13	-13	-13	5	5	6	6	6	6	6	6
		Ncl1500	27	29	30	31	31	32	33	33	28	29	29	29	26	27	27	27
	June	Ncl0	1	2	3	5	0	2	5	6	3	5	6	6	5	5	6	6
		Ncl1500	19	20	21	22	20	20	20	21	19	19	19	20	19	19	19	19
	September	Ncl0	14	14	16	17	8	9	10	11	4	5	5	6	4	5	6	6
		Ncl1500	17	15	13	12	13	12	11	10	11	10	8	8	9	8	7	7

Figure 5.23: Reduction in carbon emissions by UPHS in 2050

The more nuclear power, the higher the reduction relatively. In absolute numbers, UPHS reduces similar quantities in the 2030 and 2040 scenarios in which nuclear power is involved. Overall, power production may decrease up to 0.1 TWh per month, caused by a change in power production by fossil power generators and the marginal scalability of nuclear power, assuming that solar PV and wind can be connected to the grid in all scenarios.

In the selected scenarios of the four possible directions, carbon emissions are reduced mostly in winter months. Also, the more renewable power installed, the less carbon reduction will be achieved. Toward 2050, fossil plants are likely to operate less in the power system due to competition of other technologies, and therefore the emission reduction will be less compared to the short term.

5.3. Dealing with uncertainties

Regarding uncertainties, there might be higher power demand in the future, and therefore some grid reinforcement may be realised. Furthermore, the technical impact UPHS may have regarding security of supply is closer examined. Model calculations as presented before does not give sufficient insight in this because current market functioning is included as well. Whether certain developments and uncertainties affect the results are included in the research as well as these are important for further interpretation the impact UPHS can have. Also, the impact of some design considerations on the results are evaluated.

5.3.1. Power demand

In previous analysis, all power demand was considered at medium level. However, because the future is uncertain, demand might be lower or higher. This partly depends on technological developments, policy decisions, and societal change according to the framework of Williamson. Therefore, some calculations are made that include additional power demand for hydrogen production according to the CE Delft study. The 2040 scenarios are used in this, and additional power demand is divided equally between Zeeland Refinery, Yara, and Elsta DOW, because Yara and Elsta DOW could produce huge quantities of hydrogen in the future. This result in a power demand of more than 2300 MW for Yara and Elsta DOW only. The decision to include higher power demand at the site of Zeeland Refinery in Borssele is based on the location, as it might be logical to produce hydrogen at the location offshore wind power enters the high-voltage grid, to lower the power load of offshore wind on the high-voltage grid. The graphs below show these higher demand scenarios for scenario direction B in 2040; nuclear power is involved, however, renewable power capacity has taken a lesser recourse.

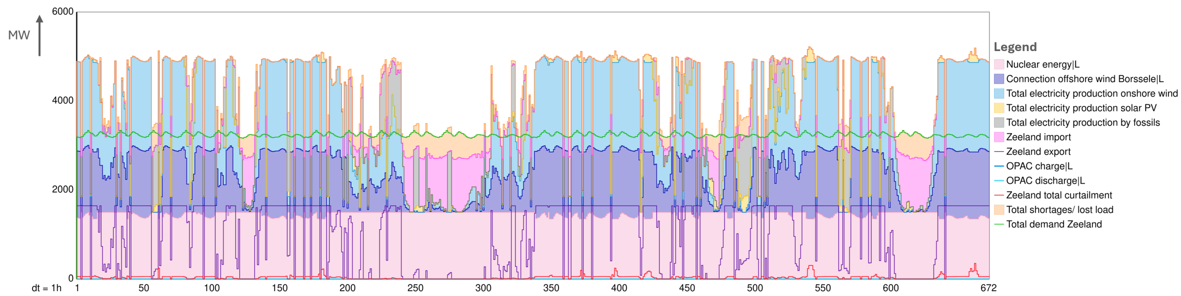


Figure 5.24: Scenario B higher demand, no UPHS, january 2040

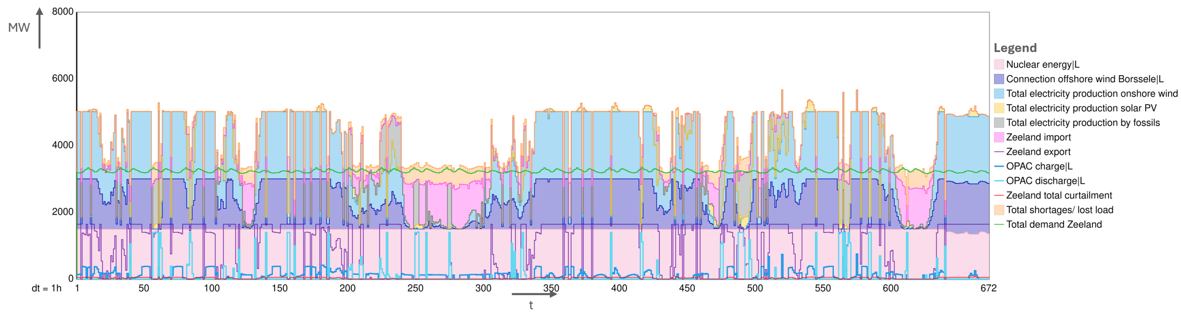


Figure 5.25: Scenario B higher demand, UPHS, january 2040

It can be seen that power production cannot always meet power demand, which happens when there is no power production from wind turbines. In medium demand scenarios, the so-called was imported by the Dutch grid. However, this is technically not possible anymore, and UPHS does not lower power shortages. Nevertheless, the impact of UPHS can be seen in curtailment reduction because curtailment quantities are less when UPHS is included. Also nuclear power is operating more constantly, leading to less production costs and a longer lifetime of the power generator.

Similar conclusions can be observed from June. There are power shortages, also in scenarios with high installed renewable capacity, during hours that there is no power production by solar PV or wind turbines. Also in June, nuclear power production is a bit more constant by using UPHS, and also the level of curtailment is lower than in scenarios without UPHS.

The results of the scenarios are evaluated on the Key Performance Indicators as well and presented below. These calculations also show variation in power demand for mobility and agriculture. The differences in impact of UPHS on these scenarios differ marginally. Already in medium power demand scenarios, industrial power demand covers approximately between 70 and 85 % of total power demand in Zeeland. In higher power demand scenarios, industrial companies will have a share of around 90 % of power demand in Zeeland.

2040 - January

			KPI - Carbon emissions [kton] - Reduction by UPHS															
			OFW40-								OFW40+							
			ONW40-				ONW40+				ONW40-				ONW40+			
			LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
			PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	AGR40-	mob40-	-19	-19	-18	-18	-5	-5	-5	-5	-1	-1	-1	-1	6	6	6	7
		mob40+	-19	-19	-19	-19	-6	-5	-5	-5	-1	-1	-1	-1	6	6	6	6
	AGR40+	mob40-	-19	-19	-19	-19	-5	-5	-5	-5	-1	-1	-1	-1	6	6	7	7
		mob40+	-19	-19	-19	-19	-6	-6	-6	-5	-1	-1	-1	-1	6	6	6	6
Ncl485	AGR40-	mob40-	-14	-14	-14	-14	-3	-3	-3	-3	0	0	0	0	6	6	6	6
		mob40+	-14	-14	-14	-13	-3	-4	-3	-3	0	0	0	0	6	6	6	6
	AGR40+	mob40-	-14	-14	-14	-14	-3	-3	-3	-3	0	0	0	0	6	6	6	6
		mob40+	-15	-15	-14	-14	-4	-4	-3	-3	0	0	0	0	6	6	6	6
Ncl1500	AGR40-	mob40-	-5	-5	-5	-4	1	1	1	1	2	2	2	3	5	5	5	5
		mob40+	-5	-5	-5	-5	-1	0	1	1	2	2	2	2	5	5	5	5
	AGR40+	mob40-	-5	-5	-5	-4	0	1	1	1	2	2	2	2	5	5	5	5
		mob40+	-5	-5	-5	-5	-1	0	0	0	2	2	2	2	5	5	5	5

Figure 5.26: Reduction in carbon emissions by UPHS, high demand scenarios, January 2040

2040 - June

			KPI - Carbon emissions [kton] - Reduction by UPHS															
			OFW40-								OFW40+							
			ONW40-				ONW40+				ONW40-				ONW40+			
			LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
			PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	AGR40-	mob40-	4	5	6	9	9	10	12	15	8	8	10	12	11	10	12	15
		mob40+	4	5	6	9	9	10	12	15	8	8	9	12	11	11	13	15
	AGR40+	mob40-	4	4	6	9	9	10	12	15	7	8	9	12	11	11	13	15
		mob40+	3	4	6	9	9	9	11	15	7	8	9	12	10	11	13	15
Ncl485	AGR40-	mob40-	6	8	12	15	9	11	15	17	8	10	13	14	10	11	14	15
		mob40+	6	8	12	15	9	11	14	17	8	10	12	14	9	11	14	15
	AGR40+	mob40-	6	9	12	15	9	11	14	17	8	10	12	14	10	11	14	16
		mob40+	6	9	12	15	9	11	14	17	8	10	12	15	10	11	13	16
Ncl1500	AGR40-	mob40-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		mob40+	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
	AGR40+	mob40-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		mob40+	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1

Figure 5.27: Reduction in carbon emissions by UPHS, high demand scenarios, June 2040

Higher demand scenarios will cause more power production by fossil power generators. There will not be enough transmission capacity available to import power from the Dutch grid to meet demand, not even when fossil plants are producing.

Analysing the impact of UPHS, in scenarios with lower installed capacities of renewable power (A and B), UPHS will cause more use of fossil power generators in Zeeland. Also import quantiteis will increase by using UPHS. This is different from scenarios with medium demand, where UPHS causes both a decrease in fossil power generation and import quantities. In scenarios with lower capacities of renewables, it is less difficult to meet power demand, resulting in more opportunities to use UPHS for storing power at lower power prices, by importing or producing at that time, and selling it later on for higher prices.

Compared to scenarios without additional power demand, the reduction in carbon emissions in both winter and summer is similar in scenarios with higher installed renewable capacities.

2040 - January			KPI - Curtailment [GWh] - Reduction by UPHS															
			OFW40-								OFW40+							
			ONW40-				ONW40+				ONW40-				ONW40+			
			LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
			PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	AGR40-	mob40-	0	0	0	0	0	0	0	0	47	47	48	48	95	94	95	97
		mob40+	0	0	0	0	0	0	0	0	47	47	48	48	92	93	95	95
	AGR40+	mob40-	0	0	0	0	0	0	0	0	47	47	48	48	93	95	97	97
		mob40+	0	0	0	0	0	0	0	0	47	47	47	47	92	93	94	95
Ncl485	AGR40-	mob40-	0	0	0	0	0	0	0	0	49	49	50	50	96	96	96	98
		mob40+	0	0	0	0	0	0	0	0	49	49	49	49	94	94	96	96
	AGR40+	mob40-	0	0	0	0	0	0	0	0	49	49	50	50	96	97	98	97
		mob40+	0	0	0	0	0	0	0	0	49	49	49	49	95	95	95	96
Ncl1500	AGR40-	mob40-	0	0	0	0	7	11	13	16	56	56	57	57	102	103	103	105
		mob40+	0	0	0	0	4	7	11	13	56	56	57	57	102	103	102	103
	AGR40+	mob40-	0	0	0	0	2	6	9	11	56	56	57	57	103	102	104	103
		mob40+	0	0	0	0	1	4	7	10	56	56	56	56	100	102	102	103

Figure 5.28: Reduction in curtailment by UPHS, high demand scenarios, January 2040

2040 - June			KPI - Curtailment [GWh] - Reduction by UPHS															
			OFW40-								OFW40+							
			ONW40-				ONW40+				ONW40-				ONW40+			
			LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
			PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	AGR40-	mob40-	0	0	0	0	0	0	0	0	11	11	13	14	27	28	30	32
		mob40+	0	0	0	0	0	0	0	0	11	11	13	14	26	28	30	30
	AGR40+	mob40-	0	0	0	0	0	0	0	0	11	11	13	14	27	28	29	30
		mob40+	0	0	1	0	0	0	0	0	11	11	12	13	26	28	30	30
Ncl485	AGR40-	mob40-	0	0	0	0	0	0	0	0	12	12	14	15	28	29	32	34
		mob40+	0	0	0	0	0	0	0	0	12	12	14	15	28	28	31	34
	AGR40+	mob40-	0	0	0	0	0	0	0	0	12	12	14	15	28	29	31	33
		mob40+	0	0	0	0	0	0	0	0	12	12	14	15	27	29	31	33
Ncl1500	AGR40-	mob40-	0	0	1	2	4	8	10	12	16	16	19	21	32	34	39	42
		mob40+	0	0	1	2	3	7	9	11	15	16	19	21	32	34	38	42
	AGR40+	mob40-	0	0	1	2	3	7	9	11	15	16	19	21	32	34	39	42
		mob40+	0	0	1	2	3	6	9	11	15	16	18	21	32	34	38	42

Figure 5.29: Reduction in curtailment by UPHS, high demand scenarios, June 2040

Also, UPHS still reduce curtailment, but these quantities are less in general. Except for January, where UPHS reduces higher quantities of curtailment in scenarios with highest renewable capacities. In addition, in scenarios with fewer installed renewable capacity, UPHS does not significantly reduce curtailment. Quantities are similar to the annual power production of 0.5 offsfhore wind turbine of 10 MW]. Due to higher power demand, surpluses of renewable power that normally is curtailed can be used directly, resulting in less curtailment overall. The impact of UPHS on curtailment is in absolute numbers less in higher demand scenarios.

2040 - January			KPI - Import [GWh] - Reduction by UPHS															
			OFW40-								OFW40+							
			ONW40-				ONW40+				ONW40-				ONW40+			
			LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
			PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	AGR40-	mob40-	-13	-14	-15	-16	4	4	4	3	24	23	23	22	41	40	40	40
		mob40+	-13	-13	-14	-14	1	1	1	1	24	23	23	22	40	40	41	40
	AGR40+	mob40-	-12	-12	-13	-14	-2	-1	-1	-1	24	23	23	22	40	41	41	41
		mob40+	-12	-12	-12	-13	-4	-4	-4	-4	24	24	23	23	40	41	40	40
Ncl485	AGR40-	mob40-	-33	-34	-34	-34	1	0	-2	-2	16	15	14	13	31	30	28	28
		mob40+	-34	-34	-34	-35	1	0	-1	-2	17	16	15	14	30	29	30	28
	AGR40+	mob40-	-32	-32	-34	-33	1	0	-1	-2	18	16	16	15	31	31	30	29
		mob40+	-32	-32	-34	-33	1	1	-1	-2	18	17	16	15	32	31	30	29
Ncl1500	AGR40-	mob40-	-23	-23	-23	-23	-8	-7	-7	-7	-2	-2	-2	-2	11	11	11	11
		mob40+	-23	-23	-23	-23	-9	-8	-8	-8	-2	-2	-2	-2	11	12	11	11
	AGR40+	mob40-	-24	-24	-24	-24	-9	-8	-8	-8	-2	-2	-2	-2	12	12	12	12
		mob40+	-24	-24	-24	-24	-10	-10	-9	-9	-2	-2	-2	-2	12	12	11	11

Figure 5.30: Reduction in import by UPHS, high demand scenarios, January 2040

2040 - June			KPI - Import [GWh] - Reduction by UPHS															
			OFW40-								OFW40+							
			ONW40-				ONW40+				ONW40-				ONW40+			
			LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
			PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	AGR40-	mob40-	-15	-16	-21	-30	-15	-17	-23	-33	-11	-10	-15	-21	-6	-4	-8	-15
		mob40+	-14	-15	-20	-29	-15	-17	-23	-33	-11	-10	-15	-21	-6	-5	-8	-15
	AGR40+	mob40-	-14	-16	-20	-30	-15	-17	-23	-33	-10	-11	-13	-21	-6	-5	-8	-15
		mob40+	-13	-15	-19	-29	-15	-17	-23	-33	-10	-10	-13	-20	-5	-5	-8	-15
Ncl485	AGR40-	mob40-	-23	-31	-42	-51	-18	-26	-37	-46	-12	-17	-24	-28	-3	-8	-15	-19
		mob40+	-23	-31	-41	-50	-18	-26	-36	-45	-12	-17	-23	-28	-3	-8	-14	-19
	AGR40+	mob40-	-23	-31	-41	-50	-18	-25	-36	-46	-12	-17	-23	-28	-2	-8	-14	-18
		mob40+	-22	-30	-40	-48	-18	-25	-35	-45	-13	-17	-23	-28	-3	-7	-13	-18
Ncl1500	AGR40-	mob40-	-27	-28	-29	-22	-20	-20	-21	-13	-16	-17	-15	-8	-7	-8	-7	0
		mob40+	-26	-28	-29	-21	-20	-20	-21	-14	-16	-17	-15	-9	-7	-7	-7	0
	AGR40+	mob40-	-26	-28	-29	-22	-20	-20	-21	-13	-16	-17	-16	-9	-7	-7	-7	0
		mob40+	-25	-28	-29	-22	-19	-20	-20	-14	-16	-17	-16	-9	-7	-7	-7	0

Figure 5.31: Reduction in import by UPHS, high demand scenarios, June 2040

2040 - January			KPI - Export [GWh] - Reduction by UPHS															
			OFW40-								OFW40+							
			ONW40-				ONW40+				ONW40-				ONW40+			
			LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
			PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	AGR40-	mob40-	-44	-44	-45	-45	9	9	10	9	-16	-16	-17	-18	-21	-21	-22	-24
		mob40+	-43	-44	-44	-45	4	5	5	5	-16	-16	-17	-18	-21	-21	-22	-23
	AGR40+	mob40-	-44	-44	-44	-45	2	3	4	4	-16	-16	-17	-17	-21	-22	-22	-23
		mob40+	-43	-43	-44	-44	-2	-1	-1	0	-16	-16	-17	-17	-21	-21	-22	-22
Ncl485	AGR40-	mob40-	-53	-53	-54	-54	10	10	9	8	-24	-25	-26	-27	-34	-35	-36	-37
		mob40+	-52	-53	-54	-54	10	9	8	8	-23	-24	-25	-26	-33	-34	-35	-37
	AGR40+	mob40-	-52	-53	-53	-54	11	10	9	9	-23	-24	-25	-26	-33	-34	-34	-35
		mob40+	-52	-52	-53	-53	10	10	9	8	-22	-23	-24	-25	-32	-34	-34	-36
Ncl1500	AGR40-	mob40-	-21	-20	-20	-20	-31	-33	-35	-36	-44	-44	-44	-43	-61	-62	-62	-63
		mob40+	-21	-21	-21	-21	-30	-30	-31	-33	-43	-44	-44	-44	-61	-61	-62	-62
	AGR40+	mob40-	-22	-21	-21	-21	-26	-28	-29	-31	-44	-43	-44	-44	-61	-62	-63	-63
		mob40+	-22	-22	-22	-22	-24	-26	-27	-29	-44	-44	-44	-44	-60	-61	-61	-63

Figure 5.32: Reduction in export by UPHS, high demand scenarios, January 2040

2040 - June			KPI - Export [GWh] - Reduction by UPHS															
			OFW40-								OFW40+							
			ONW40-				ONW40+				ONW40-				ONW40+			
			LS40-		LS40+		LS40-		LS40+		LS40-		LS40+		LS40-		LS40+	
			PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+	PVR40-	PVR40+
Ncl0	AGR40-	mob40-	-1	1	1	1	17	18	20	19	4	4	5	7	4	4	5	7
		mob40+	-1	0	1	1	16	17	19	19	4	5	5	7	4	5	5	7
	AGR40+	mob40-	-1	0	1	1	16	17	19	19	4	5	5	7	4	4	6	7
		mob40+	-1	-1	1	1	14	16	18	19	4	5	5	7	4	5	6	8
Ncl485	AGR40-	mob40-	-2	-2	-1	2	16	14	14	13	4	4	5	3	4	3	3	2
		mob40+	-1	-2	0	2	16	14	14	13	3	4	4	5	4	3	4	3
	AGR40+	mob40-	-2	-1	0	2	17	15	15	13	3	4	5	5	4	3	4	4
		mob40+	-1	-1	0	1	17	15	15	14	3	4	5	7	4	4	4	4
Ncl1500	AGR40-	mob40-	-12	-14	-17	-9	-20	-24	-25	-18	-19	-20	-21	-17	-26	-28	-31	-28
		mob40+	-11	-14	-17	-9	-19	-22	-24	-18	-18	-20	-21	-17	-26	-27	-30	-28
	AGR40+	mob40-	-11	-14	-17	-9	-19	-22	-24	-17	-19	-20	-22	-17	-26	-28	-30	-28
		mob40+	-11	-14	-16	-9	-17	-21	-23	-17	-18	-20	-21	-17	-25	-27	-30	-26

Figure 5.33: Reduction in export by UPHS, high demand scenarios, June 2040

The current infrastructure cannot supply the electricity demand that the sectors demand in higher demand scenarios. Specifically, this means that hydrogen, for example, cannot always be produced if the production site is not located closely to the power generators. The installed capacity of renewable energy is less relevant here because there are structural intervals where not renewable power is produced, and the import quantity is at maximum. A storage asset such as UPHS may reduce the quantity need but does not solve the power demand in this scale. Even in the highest renewable scenarios including a nuclear power plant of 1500 MW and UPHS, the model shows that in the month of June, there are power shortages frequently at power rates of 500 MW.

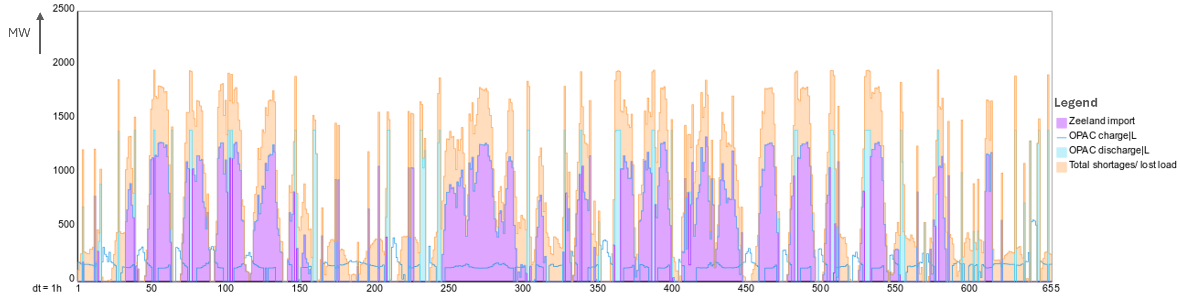


Figure 5.34: Scenario D higher demand, UPHS, June 2040

The residual power demand of 500 MW more frequently can be solved by switching off industrial processes that does not need to produce 24/7, such as the production of hydrogen. In reality, the functioning of the market will cause higher production prices during scarcity of renewable power generation. It may be then no longer economically viable to produce hydrogen. On the other hand, there might be a need for grid reinforcements, because power shortages occur structurally assuming hydrogen production constantly. A more fluctuating production profile results in even higher power demand at other times to reach the expected annual power demand. Since curtailment also occurs structurally, it makes sense to implement the additional demand where the electricity is offered. Another solution is to increase the transmission capacity of the grid at some important links in the power network of Zeeland.

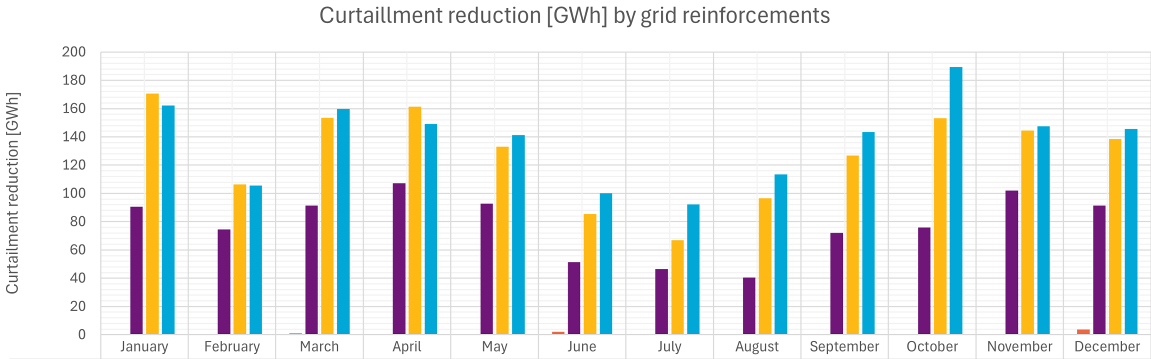
5.3.2. Transmission capacity

Availability of transmission capacity is an important factor for the behaviour and dyanmics of components within the power system. Due to the increase of renewable power supply on the one hand and increasing power demand on the other hand it may be that the grid need to be expanded. In this study, it has not been considered to what extent the current infrastructure can provide the required flexibility in the future. But the results of previous analyses show that grid reinforcements need to be considered if the expected growth in renewable power capacity to meet the targets set by 2050, according to the CE Delft study, need to be placed in the power system. Grid reinforcements include high costs and uncertainties. Previous analyses assumed that the new 380 kV connection from Borssele to Terneuzen would be built. This section also shows the impact on the behaviour of UPHS if this connection is not realised.

Grid reinforcements

The increase in both power demand and renewable power supply is resulting in high curtailment quantities as presented in previous analyses. Therefore, an additional 380 kV connection between Borssele and Terneuzen and Terneuzen and Westdorpe is included in the model and the selected scenarios are calculated for one year. Surpluses of offshore wind and nuclear power for example can be transported to the Dutch power grid more easily. Also produced power by onshore wind and solar PV may be transported more easily through the area of Zeeland itself, where UPHS may be realised.

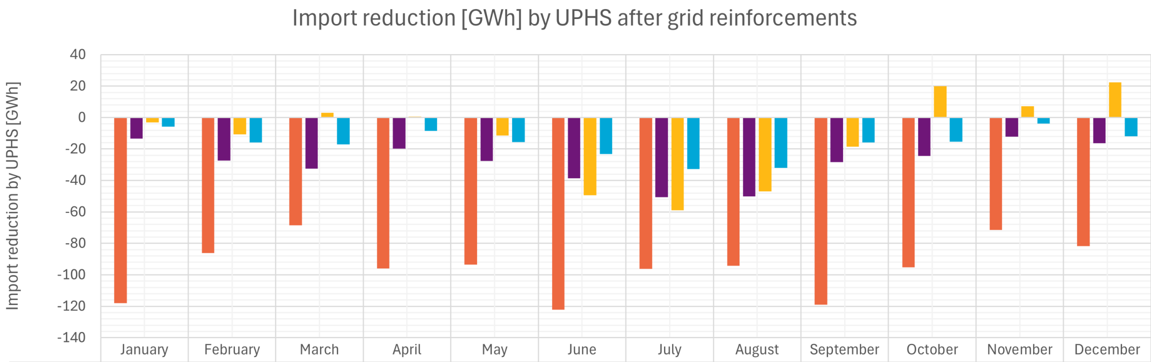
In figure 5.35 it can be observed that expanding the power grid between Borssele and Rilland and between Terneuzen and Westodrpe will lower the curtailment almost up to 200 GWh per month. Furthermore, curtailment reduction is highest in winter months.



	January	February	March	April	May	June	July	August	September	October	November	December
Scenario A	0,0	0,0	1,1	0,0	0,0	2,2	0,0	0,0	0,0	0,0	0,0	3,7
Scenario B	91	74	92	107	93	52	46	40	72	76	102	91
Scenario C	171	106	153	161	133	85	67	96	127	153	145	138
Scenario D	162	106	160	149	141	100	92	113	143	189	148	146

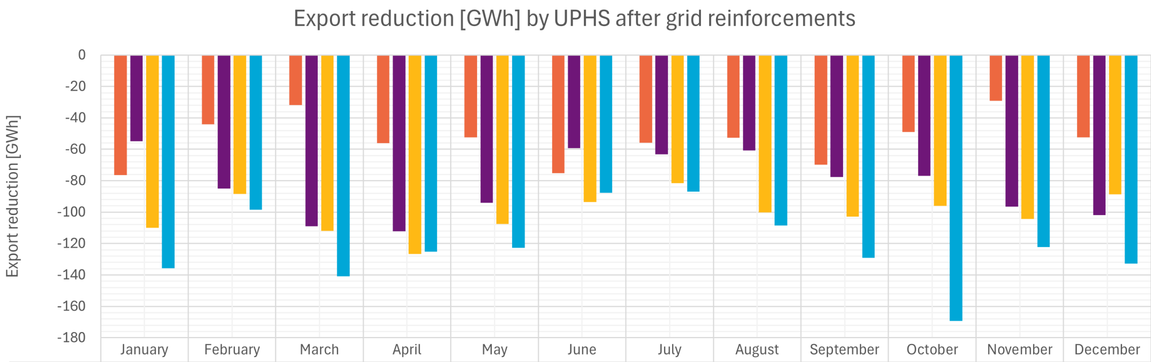
Figure 5.35: Total curtailment reduction in Zeeland per month, after grid reinforcements, UPHS involved

According to figures 5.36 and 5.37, both import and export quantities will further increase. The hours that power will be imported is reduced compared to the situation without UPHS.



	January	February	March	April	May	June	July	August	September	October	November	December
Scenario A	-118	-86	-69	-96	-93	-122	-96	-94	-119	-95	-71	-82
Scenario B	-13	-27	-32	-20	-28	-39	-51	-50	-28	-24	-12	-16
Scenario C	-3	-11	3	1	-12	-49	-59	-47	-19	20	7	22
Scenario D	-6	-16	-17	-9	-16	-23	-33	-32	-16	-15	-4	-12

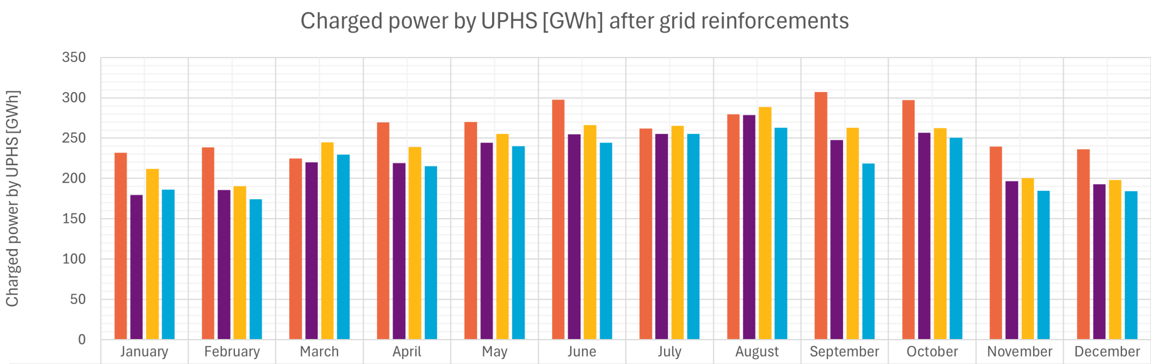
Figure 5.36: Difference in import [GWh] by UPHS after grid reinforcements (Rilland -NL) in scenarios ABCD in 2040



	January	February	March	April	May	June	July	August	September	October	November	December
Scenario A	-76	-44	-32	-56	-52	-75	-56	-53	-70	-49	-29	-52
Scenario B	-55	-85	-109	-112	-94	-59	-63	-61	-78	-77	-97	-102
Scenario C	-110	-88	-112	-127	-108	-93	-82	-100	-103	-96	-104	-89
Scenario D	-136	-98	-141	-125	-123	-88	-87	-108	-129	-169	-122	-133

Scenario A Scenario B Scenario C Scenario D

Figure 5.37: Difference in export [GWh] by UPHS after grid reinforcements (Rilland -NL) in scenarios ABCD in 2040



	January	February	March	April	May	June	July	August	September	October	November	December
Scenario A	232	238	225	269	270	298	262	280	307	297	239	236
Scenario B	179	186	220	219	244	255	255	278	248	257	197	193
Scenario C	212	190	245	239	255	266	265	288	263	262	200	198
Scenario D	186	174	230	215	240	244	255	263	219	250	185	184

Scenario A Scenario B Scenario C Scenario D

Figure 5.38: Charged power [GWh] by UPHS after grid reinfrocements (Rilland-NL) in scenarios ABCD in 2040

After grid reinforcements, UPHS will charge 2.6 TWh up to 3.2 TWh per year in the selected 2040 scenarios. Without grid reinforcements, the charged quantity vary between 1.9 TWh and 2.7 TWh]. It has to be noted that higher grid capacities allows to import higher quantities as well. Export quantities increase by an increase by renewable capacity and the implementation of UPHS. Overall, grid-reinforcements will not affect the deployment of UPHS significantly.

Absence of 380 kV Zeeuws-Vlaanderen

Previous analysis assume the planned 380 kV grid connection between Borssele and Terneuzen for being able to deliver power demand to high demanding industries. Without additional power demand, Elsta DOW and Yara together have a power demand of 1200 MW in 2050 constantly, exceeding the grid connection of 652 MW without 380 kV connection. Including additional demand for hydrogen production, power demand will be more than 2000 MW. To what extent UPHS can prevent a new 380 kV connection is not calculated yet. A new connection to Zeeuws-Vlaanderen from Borssele to Terneuzen is due to the Natura 2000 area complex, therefore costly and involves high risks. Especially high renewable power capacity in Zeeuws-Vlaanderen will lower the import need from Borssele, making the construction of UPHS even more interesting if such a 380 kV connection will not be realised.

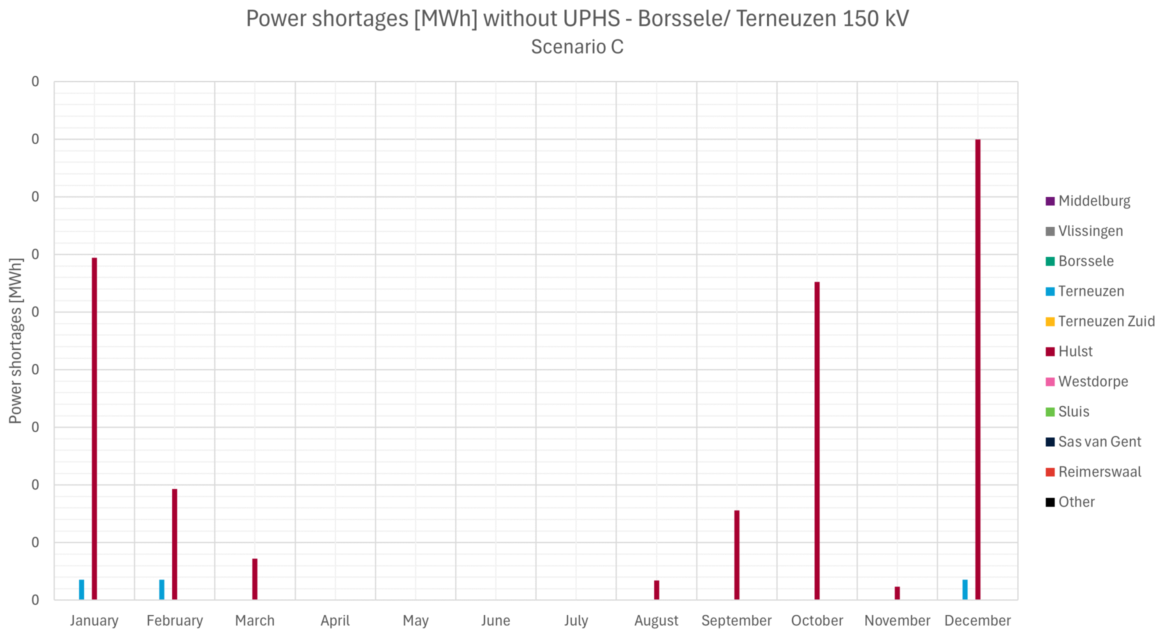


Figure 5.39: Scenario C 2040, power shortages in Zeeuws-Vlaanderen in 2040, without UPHS

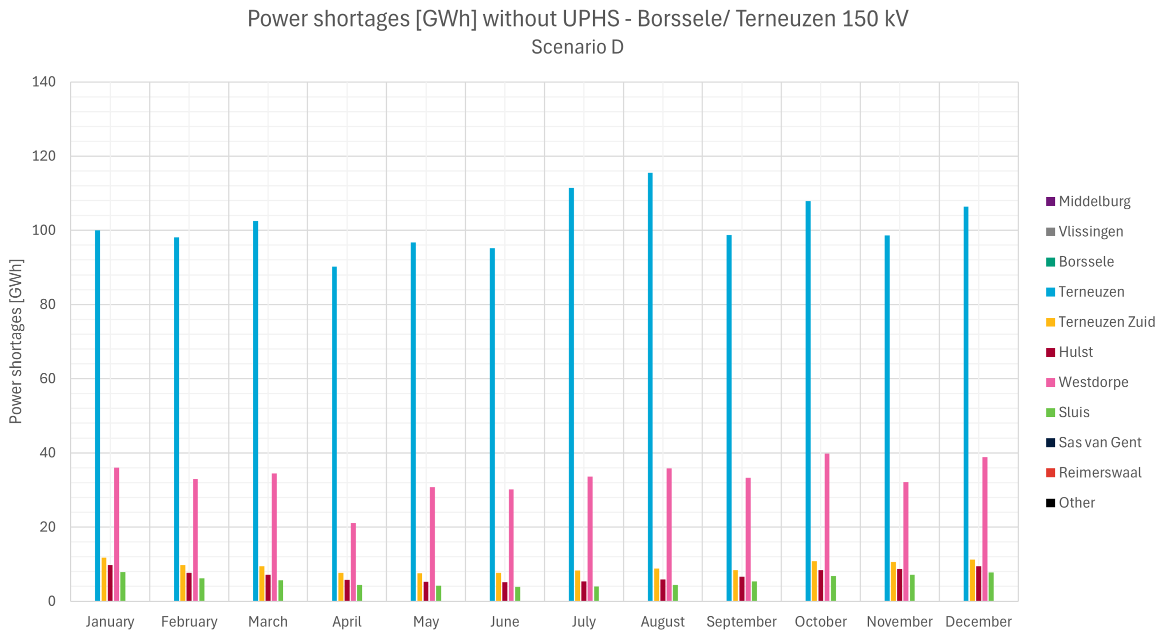
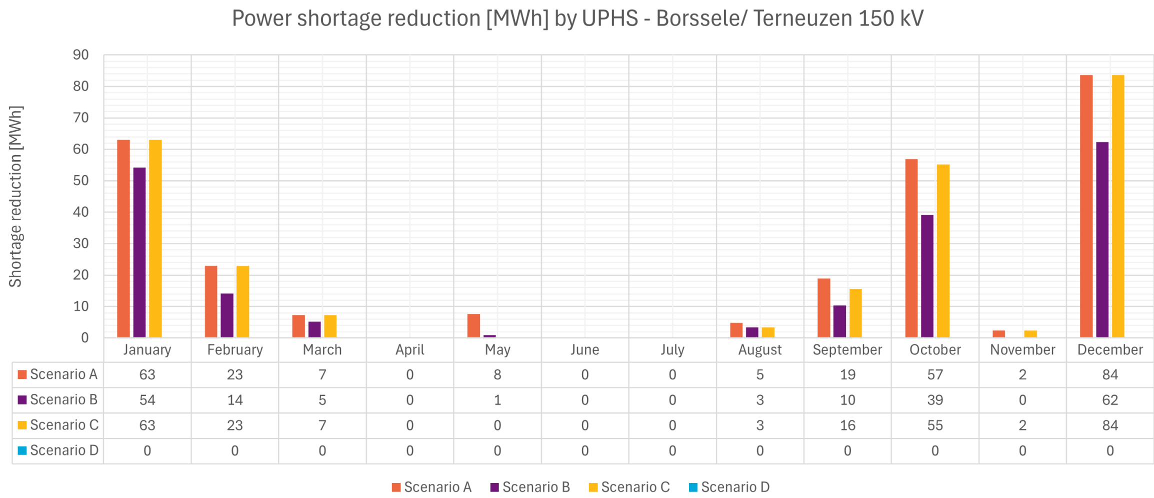


Figure 5.40: Scenario D 2040, power shortages in Zeeuws-Vlaanderen in 2040, without UPHS



	January	February	March	April	May	June	July	August	September	October	November	December
Scenario A	63	23	7	0	8	0	0	5	19	57	2	84
Scenario B	54	14	5	0	1	0	0	3	10	39	0	62
Scenario C	63	23	7	0	0	0	0	3	16	55	2	84
Scenario D	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.41: Scenario D 2040, power shortages in Zeeuws-Vlaanderen in 2040, without UPHS

Considering higher renewable capacities and the availability of fossil power generators in Zeeland, Zeeuws-Vlaanderen can produce up to 900 MW. Even in medium power demand scenarios, Zeeuws-Vlaanderen will mainly import power from Borssele. After analysing the scenarios in which the 380 kV connection is not realised, there is an electricity shortage constantly, and therefore UPHS will be deployed significantly less compared to other scenarios, i.e. 80 GWh per year will be stored. A further increase in power demand by industries, also in scenarios of direciton D, cause that UPHS will not be used anymore by the absence of a 380 kV connection to Terneuzen. Nevertheless, these dynamics will change completely if for example offshore wind will be connected to the power grid in Zeeuws-Vlaanderen too. In this regard, UPHS may contribute to minimise power shortages, without the limitation of the transmission capacity from Borssele.

Furthermore, it can be questioned to what extend UPHS can be connected to the power grid without 380 kV substation. For this reason, it is also important to examine the impact of design aspects on the results, such as a different location and storage capacity.

5.3.3. Market functioning

The results of various analyses shown above are based on the behaviour of UPHS in the current market, i.e. according to the merit order market model, and in which the power grid of Zeeland is connected to the Dutch power grid. This result in UPHS exhibiting the behaviour of a battery nowadays, i.e. power is imported at lower prices to be stored, and released later on for export at higher day-ahead prices. However, this is at the expense of the technical potential that UPHS has to offer from a systems perspective. The storage facility has the potential to make Zeeland less dependent on the Dutch power grid, mainly an interest for decarbonising industrial processes.

Previous analyses show that an increase in power demand will cause an increase in power import. This study excluded the availability of required imports, but will be more and more relevant in a power system that relies on renewable power generators with an fluctuating power demand profile and less fossil power generators. Governmental parties are therefore considering the implementation of nuclear power plants to be able to provide a certain baseload of power to the power system in the future, resulting in less dependence on fossil fuels. From another perspective, it is argued that nuclear power is needed to minimise power shortages. In contrast, a storage facility such as UPHS is designed to fulfill this function. To what extent UPHS is able to deal with power shortages need therefore be analysed as well.

Analysing the behaviour of UPHS according to the functioning of the power market, thus from an economic perspective, results in certain decisions that is not always the best solution from the system perspective. For example, in the current power market, UPHS shows a short charge/ discharge cycle because that is economically more attractive. This result in higher power import and export quantities, and therefore putting even more strain on the grid. It is, however, more desirable to store renewable power produced logically, for longer periods and use it when there is no renewable production at all, and by this minimising import and export from and to the Dutch power grid for example.

To evaluate the technical potential, the four selected scenarios are calculated for one year, in which the transmission capacity from Rilland to the Dutch power grid is set at 0 MW. Because power demand in medium demand scenarios is similar to the production of a nuclear power plant of 1500 MW, no power shortages will occur in the selected scenarios if a nuclear plant is realised. Therefore, the deployment of UPHS under these circumstances is very low. In the selected scenarios A and C (no nuclear power) there are power shortages. Similar to previous results of curtailment, UPHS will reduce about 1.1 TWh power shortages in scenario A, and 1,3 TWh in scenario C. The more renewable power, the smaller the interval renewable power supply does not meet demand.

		Nuclear power 0 MW				Nuclear power 1500 MW		
		no UPHS	Δ	UPHS	Δ	no UPHS	Δ	UPHS
Scenario A	Curtaillment	3,0	-1,3	1,7	8,8	10,5	0,0	10,5
	Shortages	4,3	-1,1	3,2	-3,2	0,0	0,0	0,0
	UPHS charge	0,0	1,3	1,3	-1,3	0,0	0,0	0,0
Scenario B	Curtaillment	7,8	-1,4	6,4	10,0	16,4	0,0	16,4
	Shortages	3,2	-1,2	2,0	-2,0	0,0	0,0	0,0
	UPHS charge	0,0	1,4	1,4	-1,4	0,0	0,0	0,0
Scenario C	Curtaillment	17,6	-1,3	16,3	10,8	27,1	0,0	27,1
	Shortages	2,3	-1,1	1,2	-1,2	0,0	0,0	0,0
	UPHS charge	0,0	1,3	1,3	-1,3	0,0	0,0	0,0
Scenario D	Curtaillment	18,2	-1,3	16,9	11,0	27,9	0,0	27,8
	Shortages	2,2	-1,1	1,0	-1,0	0,0	0,0	0,0
	UPHS charge	0,0	1,3	1,3	-1,3	0,0	0,0	0,0
Scenario B High demand	Curtaillment	9,2	-0,8	8,3	11,7	20,0	0,0	20,0
	Shortages	2,9	-0,7	2,2	-0,3	1,9	0,0	1,9
	UPHS charge	0,0	0,8	0,8	-0,8	0,0	0,0	0,0
Scenario C High demand	Curtaillment	9,7	-0,7	9,1	7,0	16,0	-0,8	15,2
	Shortages	11,1	-0,6	10,5	-5,5	5,0	-0,7	4,4
	UPHS charge	0,0	0,7	0,7	-0,7	0,0	0,8	0,8

Figure 5.42: Scenario 2040 UPHS and Nuclear replacement

To determine to what extend UPHS could replace a nuclear power plant, because both installations have a similar power output, the selected scenarios A, B, C, and D are evaluated both on the involvement of UPHS and a nuclear power plant of 1500 MW. In addition, scenario's B and C are evaluated on a higher power demand by Elsta DOW, Yara, and at Zeeland Refinery as well. In all simulations, fossil power plants are closed because of the transiation to a carbon free power system. From the system perspective, the advantage of UPHS over nuclear power is that UPHS is able to both consuming and delivering power to and from the power grid, while nuclear power only can deliver power. So, UPHS will add more flexibility to the power system overall. Similar to scenarios A and C, without a nuclear power plant of 1500 MW and a medium power demand, UPHS shows a reduction of 1.2 TWh in power shortages in scenario B, and a reduction of 1.1 TWh in scenario D assuming medium power demand.

UPHS can not achieve similar results on the KPI Power Shortage in high power demand scenarios, as the same scenario in which UPHS is not realised but a nuclear power plant of 1500 MW does. In medium demand scenarios, power shortages are much more reduced compared to high demand scenarios, but UPHS will not meet the power demand completely. Because shortages are reduced by around 50 % in higher renewable scnearios without nuclear power, some additional smaller storage facilities may solve the challenge.

The deployment of renewable power will affect the charge and discharge behaviour of UPHS. Nuclear power seems to result in more frequent charging cycles, but in all scenarios the entire capacity of UPHS will be used. This shows the suitability of UPHS as long-duration storage asset as well.

Furthermore, the deployment of UPHS instead of a nuclear power plant of similar size will result in less curtailment compared to the scenarios in which UPHS is involved, because a nuclear power has to operate and therefore increase the baseload and thus curtailment. The quantity of stored power in a year is less compared to the siutation in which Zeeland is connected to the Dutch power grid, caused by different charging behaviour from the economic perspective.

5.4. Design considerations

The previous analysis has assumed certain design specifications for UPHS, to be applied in the area of Terneuzen. Due to uncertainties regarding economic risks, stakeholder-involvement, or technical limitations, simulations are made that evaluate the impact of a lower storage capacity and different location of the storage asset.

5.4.1. Storage capacity

A smaller UPHS storage capacity results in similar quantities of carbon emission reduction, curtailment reduction, power import, and power export. Only scenario D shows larger deviations. The differences in the scenarios can be seen in the quantity of power total charged. An UPHS with a storage capacity of 4200 GWh will store about 25 % electricity less than an UPHS with a storage capacity of 8400 GWh, considering one year, and further same assumpations as the base case. The disadvantage of an UPHS with less capacity are the comparatively higher investment cost per MW of installed power. This is because drilling still needs to be done, and other expensive studies. However, once operational, a 50 % less capacity for at least Zealand in the medium demand scenarios seems to perform in the same order of magnitude on the KPIs as a UPHS with 100 % capacity. Deviations are less than 25 %, and sometimes almost 0. The amount of energy stored is also comparatively larger, but less in total quantity. These findings imply that the revenue model of a smaller storage asset may look differently.

5.4.2. Location

The area of Borssele might also be interesting due to the connection with the offshore power grid, industrial activities, nuclear power, increasing power demand due to hydrogen production, and a direct 380 kV connection to the Dutch power grid without the involvement of the Westerschelde. A storage facility of UPHS with same design speicfications results in similar system performance compared to the same asset in Terneuzen. There will be a bit more power imported and exported in quantities, but the further results differ marginally.

5.4.3. Capacity x Location

Furthermore, implementing 2 smaller UPHS facilities of both 4200 MW, i.e. 1 in Terneuzen and 1 in Borssele, will result in even higher results on the Key Performance indicators than 1 UPHS of 8400 MWh in Terneuzen. The explanation lies in the number of degrees of freedom. From the system perspective, surplusses of energy, for example offshore wind, can be stored directly at Borssele, transported to Rilland or power consumers, or transported towards Terneuzen to be stored there, rather than just to be stored in Terneuzen or transported towards Rilland or power consumers.

6 Interpretation

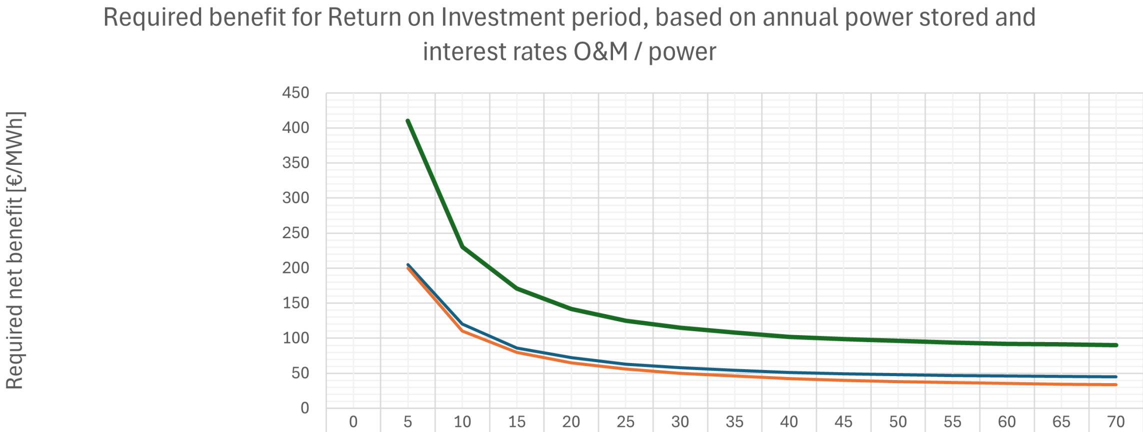
The results presented in previous chapter provided insight in the technical potential UPHS has under various circumstances for the power system in Zeeland. These insights need to be interpreted as well. In order to do this, the four realistic scenarios selected are evaluated on costs and benefits, from an economical point of view, market potential, and from the system perspective, system potential. The difference between these is that the market potential only considers a business case according to current market functioning, while the system potential includes an overall system benefits based on the Key Performance Indicators. The net benefits can be interpreted as the regret society would have if UPHS is not realised.

In today's power system, UPHS is able to store 1.9 TWh up to 2.7 TWh per year in selected scenarios, depending on the dynamics of power demand and supply in 2040, i.e. the availability of nuclear power. The range corresponds with the research of Huynen that states that UPHS can store about 2 TWh per year. Implementation of UPHS results in less curtailment and carbon emissions as power surpluses can be stored and used later on. The need for fossil power generators to operate when there is a lack in solar or wind power will decrease. From the system perspective, power generation costs are decreasing as well. The results also show that UPHS has the technical potential to be part of security of supply. Without any connection to the Dutch power grid, UPHS is able to store 1.1 TWh up to 1.4 TWh per year including high power demand scenarios. Therefore, power shortages can be minimised by 40 % to more than 70 % in medium demand scenarios, and up to 13 % in high demand scenarios. It can be concluded that UPHS does have a supporting role when it comes to security of supply in scenarios where renewable power capacity is higher, and power demand medium. Remaining power shortages could be solved locally with other, smaller technologies, such as batteries.

6.1. Economic feasibility of UPHS

The model runs show that UPHS will result in various system benefits and one could argue that UPHS should be realised. In a market-driven world, a market party needs to be willing to invest, and therefore a certain return on investment within a given time-frame is required. The investment costs are estimated at 1.8 billion € according to the research of Huynen. Furthermore, expected annual operation and maintenance (O&M) costs are 1.1 % of the investment costs, thus about 20 million € per year. In the current market, UPHS is more likely to operate in the intraday-market. Herein, power prices are fluctuating around the day-ahead price. The impact of the intraday-market on the business case is, however, not included in this research, as it is assumed that power price fluctuations of the intraday-market are following the pattern of the day-ahead market. In reality, price fluctuations more often occur resulting in a higher variability.

Assuming a Return on Investment period of 10 years, and annual stored power of 2.0 TWh, the net revenue on power has to be 120 per €/MWh, using traditional cash-flow theory. In this calculation, the Rate of Interest is set on 4.0 % as it is a long-term project, an interest of 2,5 % for O&M costs, and an interest of 1,0 % for power. Compared to historical power prices in the day-ahead market a net power benefit of 120 €/MWh is unrealistic. Hence, longer Return on Investment periods are considered as well. The required benefit has to be evaluated to indicate the economical impact when UPHS stores power, at a minimum of 1.0 TWh per year, for longer periods of time. This implies handling from the system perspective instead of an economic point of view and is based on the high demand scenarios in which Zeeland is not connected to the Dutch power grid and nuclear power is not involved. In similar but medium demand scenarios, stored power may vary between 1.4 and 1.6 TWh per year. These lower quantities in stored power may be the case if agreements are made with a grid operator on how UPHS can be deployed in the power market, for example minimising curtailment and power shortages, but not additional importing and exporting of power.



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Storage 2 [TWh], Interest 2.5 / 1.0 [%]		205	120	86	72	63	58	54	51	49	48	47	46	46	45
Storage 2 [TWh], Interest 2.0 / 2.0 [%]		200	110	80	65	56	50	46	43	40	38	37	35	34	33
Storage 1 [TWh], Interest 2.5 / 1.0 [%]		410	230	171	142	125	115	108	102	99	96	94	92	91	90

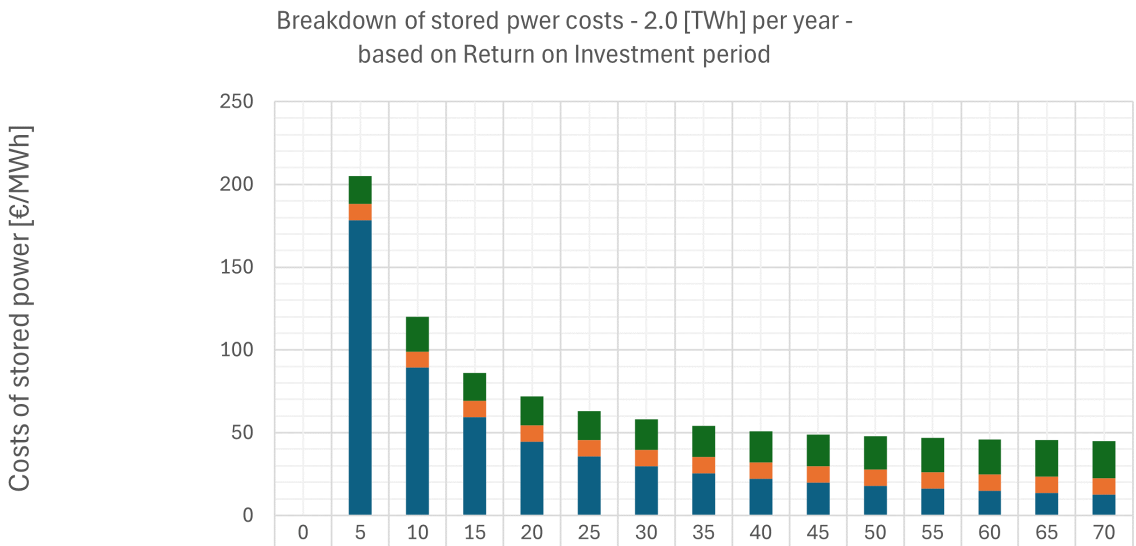
Years

Figure 6.1: Impact required Return on Investment period and interest on required net benefit

The impact of the net benefit value on the Return on Investment period becomes smaller after 25 years, the curves in figure 6.1 flatten. A benefit between 35 and 60 €/MWh stored is required to make UPHS economic feasible in the long term of 70 years. The flattened curves are not caused by differences in interest rates, but by a discounting of future cash flows by calculating the net present value. Cash flows further into the future are less weighted, resulting in that costs and benefits have a smaller impact on the final result. Assuming an interest rate of 2.0 % for O&M costs, the results give a lower required benefit of about 10 €/MWh overall. The causes are the lower interest costs for O&M and a higher benefit stream because of the higher inflation rate for power.

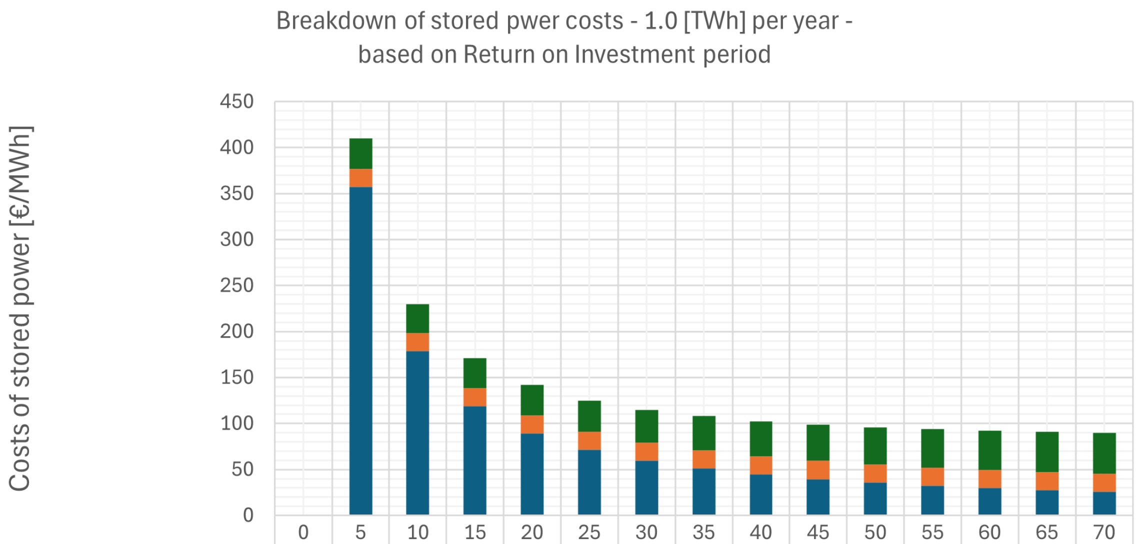
A breakdown of the costs for the total power stored during the Return on Investment period is shown in graphs 6.2 and 6.3 for both the market potential and system potential. From an economic point of view, it can be concluded that UPHS is not attractive to invest in as a market player, according to the current market functioning. The project involves high risks, due to the long return on investment period in which future power prices are uncertain and investment costs are incredibly high. The benefit solely considers the price difference between purchased power at one point, and selling this quantity for a higher price later on, in which power losses are included.

Currently, the power market is overwhelmed by renewable power, which at times results in very low or negative power prices. From a system point of view, the power system is out of balance. The required benefit may be achieved in the upcoming years, but it is a hard constraint to maintain in the long term, i.e. 10 years, because of current developments around implementation of batteries. At a certain point, power storage assets will increase the lowest prices and decrease highest prices because of competition during power surpluses and power scarcity, resulting in less variability. It will place the business case of UPHS in a longer Return on Investment period to achieve a total stored power quantity of 2 TWh per year.



Years	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Interest 2.5 / 1.0 [€/MWh]		17	21	17	18	17	18	19	19	19	20	21	21	22	22
O&M [€/MWh]		10	10	10	10	10	10	10	10	10	10	10	10	10	10
Investment [€/MWh]		179	89	60	45	36	30	26	22	20	18	16	15	14	13

Figure 6.2: Cost breakdown of 2.0 [TWh] stored power based on Return on Investment period - Market potential



Years	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Interest 2.5 / 1.0 [€/MWh]		33	32	32	33	34	36	37	38	40	41	42	43	44	45
O&M [€/MWh]		20	20	20	20	20	20	20	20	20	20	20	20	20	20
Investment [€/MWh]		357	179	119	89	71	60	51	45	40	36	32	30	27	26

Figure 6.3: Cost breakdown of 1.0 [TWh] stored power based on Return on Investment period - System potential

Scenario	Charged power [TWh]	Discharged power [TWh]	Average charged value [€/MWh]	Average discharged value [€/MWh]	Average benefit [€/MWh]
Scenario A	2.7	2.3	32	50	18
Scenario B	2.3	1.9	38	45	7
Scenario C	2.5	2.2	38	46	8
Scenario D	1.9	1.6	39	44	5

Table 6.1: Indicated average benefits scenarios ABCD in current market, day-ahead prices 2019

From table 6.1, it can be observed that the calculated average benefit of power varies between 5 and 18 €/MWh in selected scenarios. According to figure 6.2, the Return on Investment period is more than 70 years. The calculated average benefits will cover the investment, nevertheless, costs for interest and O&M are not accounted for by the benefits. Both costs and revenues may change in the future, alas, to what extent is very uncertain. With current power prices the project already needs a huge Return on Investment period to recoup the project. A higher price variability is desirable, from the economic perspective, because this will lower the Return on Investment period, and thus lower the potential for risks caused by institutional changes.

In conclusion, the project is not attractive to invest in from the economical point of view of a market party. Nevertheless the simulations of the model show that UPHS is able to reduce curtailment quantities and the deployment of fossil power generators, thus reducing carbon emissions and power production costs. UPHS also has the technical potential to increase security of supply by lowering power shortages. These advantages are not included in the traditional economic feasibility study described above, yet are very valuable from the system perspective. A disadvantage of UPHS is that it will increase the load on the grid, because both power import and export quantities to the Dutch power grid increase. The disadvantage is a result of the functioning of the power market, and because no value has been given to other system benefits, it can be questioned whether the right system choices are being made. Therefore, the additional system benefits are evaluated as well to determine the extent of a particular coordination problem according to the theory of institutional economics.

6.2. Societal value of UPHS

This section can be questioned because it has been assumed that curtailment is equivalent to saving fossil power generators.

The benefits of UPHS specified by Key Performance Indicators are translated into savings on system costs. From the societal perspective these savings are related to curtailment, emissions, and power shortages. The quantity of curtailment saved does not to have to be produced by fossil power generators later on, resulting in lower costs for power production and carbon emissions. Therefore, the amount of curtailment savings is particularly relevant. The economic value that can be given to these amounts is the difference in marginal costs of a natural gas power plant and renewable power multiplied by the quantity of curtailment. The saved carbon emissions can be expressed in an economical value too, however the exact value in the future is uncertain. Carbon emissions credits are set on 74.17 €/tonCO_2 in 2024, but may, for example, increase to 400 €/tonCO_2 by 2040. Klimaatverbond Nederland has suggested a carbon tax of 700 €/tonCO_2 to include shadow prices as well, because so far the external effects are not included in the models used for the pricing of CO_2 by governmental institutions. Most of the models are based on preventing costs, indicating the lower bound of carbon emissions, however, without prevention, social costs will be much higher. The costs for power shortages are equal to the value of lost load multiplied by the quantity. The value of lost load is the value society is willing to pay for security of supply, and is set at 68,887 €/MWh in the Netherlands.

Because the developed model in Linny-R represents the Dutch power market in Zeeland, UPHS will also import and export quantities of power, which is hard to evaluate to system benefits. UPHS provides the opportunity to import power at lower prices, store these amounts for at a later date, thereby limiting fossil power generation with higher marginal costs. An increase in power import and export quantities pressures the physical infrastructure. Furthermore, the origin of imported power is unknown. The model assumes that, because of a lower day-ahead price than fossil power generators in general, no additional carbon emissions are emitted by importing power, but this cannot be guaranteed. Further, it is way far too complex to determine to what extend exported power by Zeeland to the Dutch power grid will lower the deployment of more expensive power generators elsewhere. Besides, import and export quantities may be relevant once these exert an impact on the day-ahead price because UPHS can deliver some of the power that a fossil plant would normally provide. However, as long as the energy market is still regulated at the national level in terms of determining the day-ahead price, it has been assumed that a facility with specifications like those of UPHS does not impact the day-ahead price of power directly. Therefore, system benefits regarding lower power costs in the power market are excluded from interpretation of the benefits caused by UPHS.

Figure 6.4 shows the potential benefit UPHS has from the system perspective, providing insight in the differences between selected scenarios, Value is given to curtailment quantities that is saved as fossil power generators does not have to operate somewhere else later on. The value of lost load is set on 68.887 €/MWh and the prices of carbon emissions are set on 150 €/ton in 2030, 300 €/ton in 2040, and 600 €/ton in 2050. The real costs of carbon emissions might be even higher according to the report of Klimaatverbond Nederland.

Scenario A	Quantity	Value	Total value	
Charged power	2,72 TWh	€ -32 per MWh	€ -87.855.857	
Curtaillment				
Fossil power savings	7 GWh	€ 60 per MWh	€ 407.802	
Carbon emissions	3 Kton	€ 150 per ton	€ 377.217	
Marginal costs ren.	7 GWh	€ -2 per MWh	€ -13.593	+
			€ 771.425	
Power shortages	0 GWh	€ 68.887 per MWh	€ -	
Additional power by Seasun	3 GWh	€ -30 per MWh	€ -84.372	
Additional carbon emissions	1 Kton	€ -150 per ton	€ -143.432	
				+
		Total system cost reduction	€ 543.621	
Discharge value system	2,31 TWh	€ 0,24 per MWh	€ 543.621	
Discharge value market	2,31 TWh	€ 50,22 per MWh	€ 116.023.957	

Scenario B	Quantity	Value	Total value	
Charged power	2,26 TWh	€ -38 per MWh	€ -85.729.235	
Curtaillment				
Fossil power savings	1487 GWh	€ 60 per MWh	€ 89.206.398	
Carbon emissions	550 Kton	€ 150 per ton	€ 82.515.918	
Marginal costs ren.	1487 GWh	€ -2 per MWh	€ -2.973.547	+
			€ 168.748.769	
Power shortages	0 GWh	€ 68.887 per MWh	€ -	
Additional power by Seasun	-4 GWh	€ -30 per MWh	€ 132.078	
Additional carbon emissions	-1 Kton	€ -150 per ton	€ 224.533	
				+
		Total system cost reduction	€ 169.105.381	
Discharge value system	1,92 TWh	€ 87,87 per MWh	€ 169.105.381	
Discharge value market	1,92 TWh	€ 44,87 per MWh	€ 86.356.106	

Scenario C	Quantity	Value	Total value	
Charged power	2,54 TWh	€ -38 per MWh	€ -95.630.803	
Curtaillment				
Fossil power savings	1648 GWh	€ 60 per MWh	€ 98.891.975	
Carbon emissions	610 Kton	€ 150 per ton	€ 91.475.077	
Marginal costs ren.	1648 GWh	€ -2 per MWh	€ -3.296.399	+
			€ 187.070.653	
Power shortages	0 GWh	€ 68.887 per MWh	€ -	
Additional power by Seasun	1 GWh	€ -30 per MWh	€ -19.646	
Additional carbon emissions	0 Kton	€ -150 per ton	€ -33.398	
				+
		Total system cost reduction	€ 187.017.610	
Discharge value system	2,16 TWh	€ 86,51 per MWh	€ 187.017.610	
Discharge value market	2,16 TWh	€ 45,69 per MWh	€ 98.772.039	

Scenario D	Quantity	Value	Total value	
Charged power	1,85 TWh	€ -39 per MWh	€ -72.839.725	
Curtaillment				
Fossil power savings	1533 GWh	€ 60 per MWh	€ 91.961.376	
Carbon emissions	567 Kton	€ 150 per ton	€ 85.064.273	
Marginal costs ren.	1533 GWh	€ -2 per MWh	€ -3.065.379	+
			€ 173.960.269	
Power shortages	0 GWh	€ 68.887 per MWh	€ -	
				+
		Total system cost reduction	€ 173.960.269	
Discharge value system	1,58 TWh	€ 110,41 per MWh	€ 173.960.269	
Discharge value market	1,58 TWh	€ 44,25 per MWh	€ 69.719.584	

Figure 6.4: € Regret per scenario

In the selected scenarios the benefit, viewed from the KPIs, is mainly achieved by reducing emissions. There are benefits to reducing production costs, however the impact compared to emission costs is marginal if the carbon tax further increase in the future.

6.3. Market versus System potential

As discussed, UPHS is not attractive to invest in from an economical point of view of a market party. The average benefit, based on data of 2019, is too little to have a viable Return on Investment period. By giving system benefits economic value does result in a positive project value after about 10 years, applying the traditional cash-flow theory. The Return on Investment potential of UPHS is indicated in figure 6.5 for both the market and system perspective. The scenarios are quite similar from both perspectives. These scenarios show that UPHS has a positive project value after about 8 years considering system benefits.

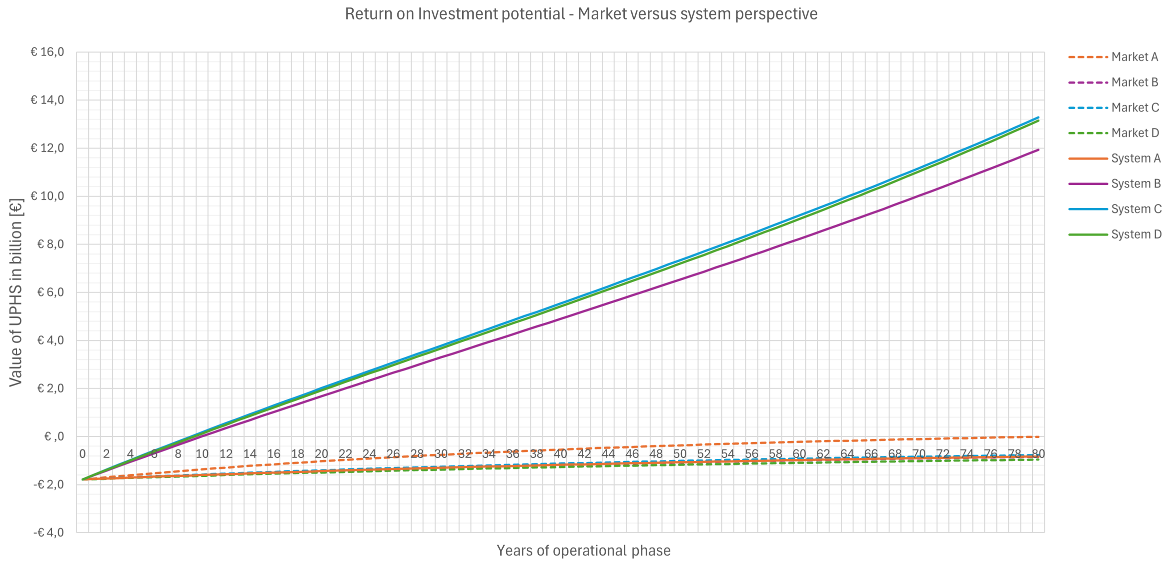


Figure 6.5: Return on Investment potential of UPHS from the market and system point of view

The potential benefits UPHS will have are not evaluated in today's power market. A market party will not invest in such a project, because system benefits cannot be taken into account in real cash flows of its own business case. From the point of view of a system operator and society, the implementation of UPHS will result in lower system costs. Therefore, governmental support is needed to help facilitate UPHS.

6.4. A broader perspective

The model shows that UPHS imports relatively cheaper electricity from places where the output may be high and saves those quantities for times of scarcity. UPHS cannot solve the entire mismatch of demand and supply in considered future scenarios in the absence of nuclear and fossil power plants. Still UPHS has the technical potential to deliver a significant contribution to the electricity balance and therefore security of supply. UPHS will behave differently due to the functioning of the market, additional agreements have to be made about operation. Depending on which party invests, the value of storage should also be considered.

Whether UPHS places additional burden on the power grid with this tactic can be questioned. Despite that the model imports electricity only if it is technically possible, the situation outside the system boundaries of the area Zeeland is not known. Therefore, this study cannot give a definitive conclusion on the impact UPHS has on the power system in neighbouring areas regarding power import and export, for example in Noord-Brabant. Depending on the distances that electricity has to be distributed before it arrives at the UPHS facility, it could result in congestion problems elsewhere outside the boundaries of Zeeland. Therefore, it is important that storage technologies are placed where the bottlenecks in the electricity network appear to be.

The results does not indicate that further grid reinforcements can be prevented, though UPHS is able to reduce the need for fossil power generators, and therefore contribute to a system in which fossil fuels are not used anymore. Industrial companies may have a too high power demand in the future, making additional power transport through the grid impossible. Further research could dive into the prevention of a new 380 kV connection, which is included in this study, from Borssele to Terneuzen, by implementating UPHS in Terneuzen and connecting offshore wind capacity in Terneuzen as well.

Determining the system benefits is quite complex. Key Performance Indicators have a certain overlap, because reduction in fossil power generators result in less production costs and less carbon emissions. However, because the model is market-driven, UPHS sometimes cause higher power production of for example Seasun B.V., resulting in lower production costs, but higher carbon emissions. Also power produced outside the system boundaries of Zeeland may cause additional carbon emissions. Higher import and export quantities put a certain pressure on the power grid of which the economic effects are unknown, also because this determine to what extent other power demand parties can connect to the power grid or not. Furthermore, the value of import and export quantities, and to what extend the value of charged and discharge power can be taken into account, can be questioned. This research excluded these because current power prices are not guaranteed for future scenarios. It also applies for curtailment reduction, of which the costs in this research are based on the marginal costs fossil power currently have, but in the future the value of curtailment may be based on the marginal costs batteries have. Curtailment may also be translated into certain savings on investment costs for additional renewable power capacity. Besides power system advantages of less curtailment and carbon emissions and an increased security of supply by lowering power shortages and increasing self-sufficiency, UPHS has other advantages as well compared to other technologies. The storage asset has a life cycle of more than 50 years and no critical materials are needed for its construction.

Several reports mention that the need for backup power will increase in the future. Some II3050 scenarios assume that missing backup power can be imported from other European countries over the interconnected grid. It should be noted that in case of lower electricity production by wind or solar in the Netherlands, this may also be the case in neighbouring countries. At least a large energy storage facility such as UPHS will make the electricity system of Zeeland, and therefore the industries that are located here, less dependent of other regions or countries. Self-sufficiency is so far not evaluated on value in the Key Performance Indicators or overall system benefits.

A limitation of this study is that the main research question will be answered by a model that is driven by theory and expectations. UPHS has not been realised in the Netherlands before, so the behaviour of UPHS cannot be evaluated from real-time data. Furthermore, the study focuses on the area of Zeeland, shaping conclusions that cannot be directly generalised to other areas in the Netherlands. Every part of the Netherlands has different system dynamics, consisting of spatial aspects and stakeholders involved.

7 Conclusion

Towards 2050, the Dutch energy system will face new challenges as both electrical power demand and supply will increase. On the one hand, further growth in renewable capacity, especially wind and solar, will be realised. On the other hand, sectors such as the built environment, industry, mobility, and agriculture will use more electricity. To what extent depends on market developments towards the use of hydrogen, biomass, or more electrified applications. The increase in power demand and supply and constraints of the Dutch power grid result in a certain flexibility need. Energy storage will be part of the solution and can be divided into short-, medium-, and long-duration storage. Batteries are entering the power grid at the moment for short-duration storage, but in countries such as Norway and Switzerland, traditional Pumped Hydro Storage is applied. This is the most widely used energy storage technology in the world and is a proven technology. The need for energy storage reflects economic, environmental, geopolitical, and technological considerations. However, liberalised markets, including the Dutch power market, are designed from an economic point of view without considering overall system benefits.

Underground Pumped Hydro Storage is considered as large-scale storage technology in the power system of Zeeland. It has the same concept as traditional Pumped Hydro Systems, but the upper basin is placed at ground level, and the lower basin is at 1.5 km depth. The project has high investment costs and a long return on investment period. Furthermore, the project involved high risks and uncertainties both in the short term as in the future, resulting in difficulty for investment, while the project has advantages over other storage technologies in a broader meaning. The area of Zeeland has to deal with the electrification of the industry as well, is connected to the Dutch offshore power grid, and has currently 1 nuclear power plant of 485 MW operating. Discussions in politics might result in a new nuclear power plant of 1500 MW or even 3000 MW in Borssele in the future. Without any storage asset or additional power demand at production sites, the power grid in Zeeland will overload in the future. UPHS can contribute to the flexibility Zeeland need to accelerate the energy transition towards 2050.

The power grid in Zeeland is translated into a market-driven decision model for mixed integer linear programming by using Linny-R. Different scenarios for 2030, 2040, and 2050 are modelled. The model simulations shows that UPHS is able to decrease curtailment from 1.0 up to 2.1 TWh per year within the selected scenarios, but the impact UPHS has on the number of hours that curtailment occurs is limited. A 380 kV connection between Borssele and Terneuzen is however required. Overall, UPHS has the potential to reduce system costs significantly. In 2050, some power shortages may occur in scenarios with lowest installed renwable capacity, but UPHS is not able to solve these. From the system perspective as well, installing smaller power storage assets might fit the problem better. Reducing the capacity by 50 % results only in 25 % fewer advantages compared to a system of 100 % capacity. The same storage facility in Borssele instead of in Terneuzen results in similar system outcomes. Further, 2 smaller installations, 1 in Borssele and 1 in Terneuzen, even result in better system outcomes.

Without nuclear power, Zeeland will become more dependent on resources other than solar and wind power. The analysis also demonstrates that UPHS has the potential to deliver a certain security of supply, up to 70 % of the performance of nuclear power plant of 1500 MW in scenarios with high installed capacities. Some additional flexible resources are needed in scenarios with fewer installed capacities of solar and wind, but this is relatively low compared to what UPHS delivers in the system. This might be economically interesting considering the investment costs of UPHS, 1.8 billion % compared to the investment costs of a nuclear power plant of a similar size, 10 to 20 billion €]. Further, UPHS has advantages over nuclear power in technical, environmental, and economic aspects.

Also, a nuclear power plant provides a certain base load almost equal to the power demand of Zeeland in medium scenarios in 2050. This reduces the need for fossil power generators on the one hand as well, but will put additional pressure on the power grid. This cause much higher quantities of curtailment compared to scnearios without nuclear power. The deployment of fossil power generators can also be reduced by implementing UPHS. Only if there is less renewable power capacity installed, UPHS will increase the deployment of Seasun B.V. due to lower marginal costs than Elsta and Sloecentrale, and the functioning of the market to increase revenue streams.

Because the behaviour of UPHS is based on getting the highest possible benefit considering power import and export prices only, higher quantities of power import and export occur. This might have negative consequences elsewhere, outside the considered system boundaries of Zeeland. So, the technical potential UPHS have regarding minimising curtailment and carbon emissions does not emerge adequately. If such a project would be realised, agreements have to be made about under what conditions UPHS should be deployed. Without any governmental support, it is unlikely that UPHS will be realised by the market. High investment costs, uncertain future revenue streams, uncertain long-term policy, and a long return on investment period based on power prices only makes the project high risk. Considering overall system benefits, from the point of view that saved curtailment equals power production savings by fossil power generators, the return on investment will be achieved after approximately 8 years. This includes the reduction of curtailment, using these quantities later on, and therefore reducing fossil power production by fossil power plants. But also the value of reduced carbon emissions are included addressing the caused external impact. There are far more benefits, such as savings in critical material use compared to batteries and an increase in security of supply and self-sufficiency.

8 Recommendations

UPHS has the potential to facilitate a function in the security of supply, based on the analysis in which Zeeland is not connected to the Dutch power grid. A connection to the Dutch power grid sometimes includes undesirable behaviour of UPHS, as it imports electricity for lower day-ahead prices, and sells these quantities later on when the day-ahead price is larger. This addresses the functioning of the current market, and within the existing market structures, UPHS is suitable to operate in the ancillary market as well i.e. redispatch, grid stability functions, and reactive power capacity or even black start. Beyond whether these markets are economically feasible for UPHS, in all cases, it is important to make good forecasts of both supply and demand. Once the amount of stored energy is released back into the grid, the security of supply cannot be guaranteed by UPHS. In a sense, society have to rely on a energy system in which fossil fuels are not used anymore.

The research identified a certain coordination problem in the market regarding behaviour of storage assets, currently completely steered by power prices. At this moment, a positive revenue stream can be maintained from a battery in Limburg charging power bought at low prices produced at the North Sea, for example. If in Zeeland less solar PV will be installed in the future, UPHS can demand high power quantities from the Dutch power grid, that may cause congestion elsewhere. Furthermore, overal system benefits are not included in the economical point of view, resulting in that projects that have system benefits for society will not be realised if these projects does not have sufficient individual return on investment. Especially when such projects include high uncertainties and risks.

8.1. Governmental support

The research demonstrate that from the market point of view the expected benefits are too low to gain a feasible return on investment period, based on day-ahead prices of 2019. The current price variability in the intra-day market cannot be guaranteed in the future due to expected competition of battery operators. So is unlikely that a market party will invest in UPHS. Because UPHS has advantages over other power storage technologies regarding technical, economic, and environmental aspects, and besides show system benefits reducing social costs, governmental support is needed, or collaboration between the government and a market party. The investment and operation and maintenance costs can then be divided, based on expected revenues in the market for a market party and expected system benefits for society. Or a certain guarantee from the government that at least a market player will not make a loss would help. However, agreements must be made on how UPHS will be deployed in the market.

8.2. Regional power dispatch

Re-regulating the distpach to smaller areas might be a solution but this is very complex. It will give incentives to the market to install storage assets close to renewable power production sites. Connections with neighbouring regions have to be assumed as interconnectors, and each region has a certain capacity for onshore wind and solar. Some areas have offshore wind as well, nuclear power, and some fossil power generators. Because of the differences between all regions, regional power prices will differ as well. For example areas with fewer capacities of solar PV will have higher day-ahead prices in summer. On the other hand, these regions still have the opportunity to buy surpluses of 'cheap' energy from other regions, if there is transmission capacity left. Every region will be an energy hub in a sense and being connected to other energy hubs.

The question is whether it is etically responsible using different power prices in the Netherlands for society. For example, some dense-populated areas might become more expensive especially when there is limited space for renewable power production. Coastal areas might provide from the advantage of offshore power. Industrial activities also affect then the power prices more locally.

More research is required to conclude about the expected benefits of storage assets using regional power dispatch. If the energy prices differ that much, the market may correct this. Areas with higher day-ahead prices due to scarcity may be interesting for storage providers if they can charge during energy surpluses. In Europe, price differences between countries are regulated as well in a European optimisation model. Countries with lower energy prices financially support countries with higher energy prices, resulting in lower costs for everyone. Implementing such a system in the Netherlands will be very complex because it will be part of a system that is already very complex. According to the IAD framework, the action arena will change. Regional grid operators will have the responsibilities that currently only the national grid operators have. Balance Responsible Parties have to operate at the regional level as well, and areas connected to Germany or Belgium have to deal with a much more complex system.

Still, the question is whether this market restructuring will incentivise market parties to invest in UPHS in Zeeland. On the one hand, UPHS can be used more and thus used more efficiently and does not have to compete with batteries in other parts of the Netherlands. Because power demand is already quite high due to expected electrification of industrial activities, the desired price variability might be higher, resulting in a shorter Return on Investment period. However, without additional research, nothing can be concluded. Even with higher price variability the project might still have a too long return on investment period.

8.3. Security of supply

Regarding security of supply, UPHS has added value and may provide up to 70 % of performance if the area of Zeeland is not connected to the Dutch power grid in medium power demand scenarios. To fill residual power shortages, smaller power storage assets can be implemented.

The investment costs of the nuclear power plant of 1500 MW might be between 10 and 20 billion €], based on ongoing projects in Canada and Great Britain. The investment costs of UPHS are estimated at 1.8 billion €]. The investment costs of UPHS are 10% to 20 % of the investment costs of a nuclear power plant, and UPHS has regarding power shortages 70 % of the value potential in contrast to nuclear power asessing security of supply. Furthermore, UPHS is more flexible than a nuclear power plant, as it can both charge and discharge at different power rates. A nuclear power plant can only deliver power to the grid and has to operate according to production constraints. Furthermore, both projects have their risks i.e. even experts do not know exactly the structure in the deeper soil, and the impacts of a nuclear disaster are unforeseen. Regarding spatial implementation and multifunctional use of space, UPHS has an advantage over nuclear power. Also, social support might be higher for UPHS than for nuclear power. Regarding resources, nuclear power requires uranium, which also implies a certain dependency on countries that can deliver this resource.

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A

Modelling the high-voltage grid in Linny-R

This chapter describes the model that is developed and used for further analysis of the added value of U-PHS on the high voltage electricity grid of Zeeland. The paragraphs follow the structure of the modelling cycle, starting with a summarised problem definition and followed by a conceptual, operational, and computerised model. The computerised model is further verified and validated, including sensitivity analysis.

A.1. Problem definition

The growth in capacity of solar and wind power generators on the one hand, and the electrification of the built environment, industry, mobility and agriculture on the other hand, result in more flexibility need of the energy system. The grid is already overloaded which results in curtailment, and therefore there is a need for grid improvements, such as grid reinforcements. Especially if current developments around more renewables and electrification are to continue to accelerate the energy transition. Investments for grid-reinforcements need to be made by the Dutch grid operator TenneT, but other solutions might be more efficient. Higher social costs as a result of curtailment and grid reinforcements may be minimised due to large-scale energy storage technologies such as U-PHS. To determine the impact and added value of U-PHS on the electricity grid in Zeeland more precisely, a model that represents the electricity flows in the high-voltage grid of Zeeland over time is required. model should be therefore a representation of the electricity infrastructure that exists of different components. These are cables, conversion stations, power generators, and demand. The spatial aspects of Zeeland need to be considered as well as demographics, location of industries and power generators matters. Also, the grid capacity is not everywhere in the system the same.

The situation of the intermediate- and high-voltage grid in Zeeland is visualised. The cables of the grid are presented as lines and the conversion stations as nodes. Every cable in the grid has a certain transport capacity, which is a constraint of the system, but these may change in the future due to grid reinforcements. The built environment, industries, agriculture but also power generators are connected to conversion stations. The electricity grid of Zeeland is connected to the high-voltage grid of the Netherlands. If transportation capacity is available, electricity surpluses can be transported to the Dutch electricity grid. It is assumed that Zeeland can import electricity from the Dutch grid during electricity shortages. The maximum energy import depends on the available grid capacity. The system is changing continuously because electricity demand is growing, and the electricity mix is changing.

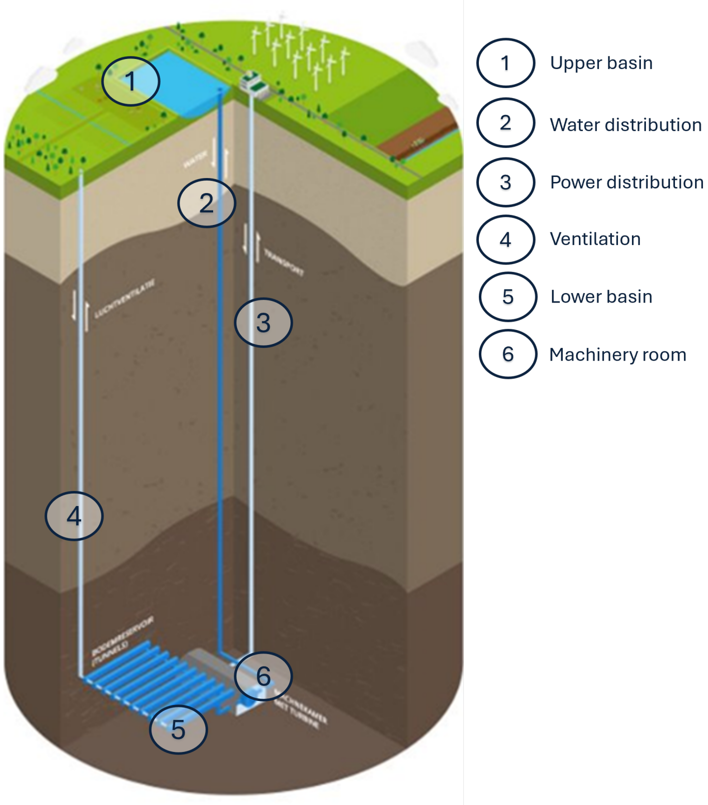


Figure A.1: Visualisation of the intermediate- and high-voltage grid of Zeeland

A.2. Conceptual model

Electricity demand depends on developments in the built environment including mobility, industries and agriculture. These sectors have to be climate-neutral in 2050, but different transition paths are possible, such as electrification, and the use of hydrogen, biomass, and biofuels. To what extent the need for electricity is, depends on the path, and will change over time as it is a transition. Spatial aspects also influence the electricity flows. The fluctuating electricity demand for dwellings is at some nodes higher than in other nodes due to differences in urban and rural areas. Industrial clusters will determine mainly the more constant but huge electricity flows. The location of power generators is also relevant for system analysis. Offshore power for example cannot be connected to the grid everywhere. While fossil power generators are present at specific locations, solar panels and wind turbines on the other hand are more distributed over Zeeland. These graphical aspects need to be taken into account to determine the added value of U-PHS in Zeeland, as this also reflects the current challenges of congestion.

A causal loop diagram is shown in the figure below. This diagram visualised the relations between the most important variables by arrows. A plus indicates a positive relation meaning if variable A increase, variable B increases as well. A minus indicates a negative relation, meaning if variable A increase, variable B decreases. The correlations provided are based on the results from the case study in Zeeland. The diagram also consists of colours. Green variables are related to the renewable energy, grey variables to fossil energy, pink variables to nuclear energy, yellow variables to the energy demand, orange variables to economics, dark-blue variables to grid characteristics, and light-blue variables are related to U-PHS.

Electricity is supplied by fossil and renewable power generators. Each power generator has a maximum power output and response time and operates according to the dispatch order. Whether a power generator is in operation depends on the marginal costs and the day-ahead price of electricity. Power generators will operate if their marginal costs exceed the day-ahead price. Renewable power generation depends further on the installed capacity, velocity of the wind, and global radiation. Fossil power generation depends further on the installed capacity but also results in carbon emissions. Carbon emissions also have a tax that are the carbon dioxide costs. These are part of the marginal costs of fossil power. Nuclear power generation depends on the installed capacity and the minimum power output. The total power output of Zeeland is the summation of renewable, nuclear, and fossil power generation.

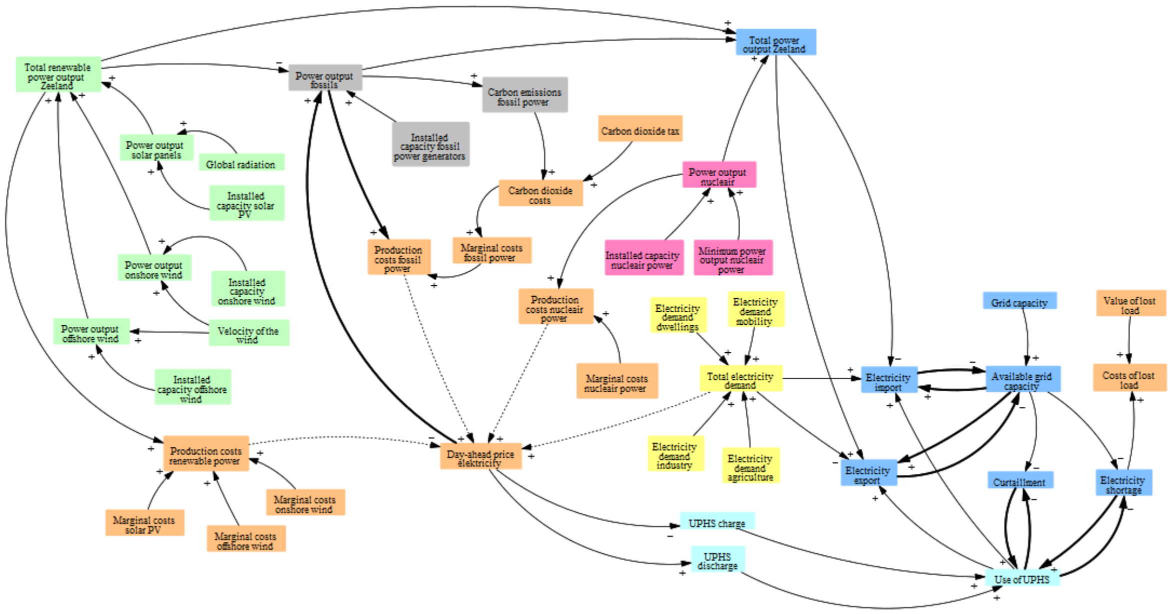


Figure A.2: Caual Loop Diagram

The total electricity demand is the summation of the electricity demand of dwellings, mobility, industry, and agriculture. The mismatch between supply and demand needs to be solved normally by importing electricity from or exporting electricity to the Dutch grid if transportation capacity is left. If electricity generation by renewable power generators does not meet demand, the day-ahead price is lower than the power generators of Zeeland, and there is enough transportation capacity left, Zeeland will import electricity from the Dutch grid. The fossil power generations of Zeeland will only supply electricity if needed and if the day-ahead price is higher than the marginal costs.

The total production costs depend on the marginal costs, the summation of production costs of renewable power, nuclear power and fossil power. However, the diagram does not show the extent to which total electricity costs are increasing or decreasing. The marginal cost of fossil power generators is much higher than that of renewable sources. The marginal cost of renewables is minimal and almost always below the day-ahead price. The total cost is then mainly driven by fossil power generators. The production costs of renewable power, nuclear power and fossil power are affecting the day-ahead price. This is not included in the model, but there is a correlation, and this is therefore indicated with a dotted line. The higher the share in renewable power the more the day-ahead price will decrease and vice versa. In general, the price of nuclear power is also much lower than that of fossil power generators, but higher than renewable sources. However, the future is uncertain in terms of scarcity and hence prices for the raw materials uranium and thorium.

Regarding available grid capacity, this is determined by the grid capacity itself in the first place. To which extent the grid is available also depends on how the system manages supply and demand. According to the diagram, it seems that available grid capacity is determined by the grid capacity itself, electricity import and electricity export. The higher the grid capacity the more grid capacity is available after supply and demand, determined by electricity import and electricity export. The total power output and the total electricity demand do not determine the available grid capacity directly, because these amounts determine to what extent electricity is needed or electricity needs to be transported over the grid, equal to electricity import and export. The higher the grid capacity the more grid capacity is available. This also results in less curtailment and fewer electricity shortages, both determined by the available grid capacity. The use of UPHS is determined by charging (consuming electricity) and discharging (delivering electricity), in the model based on the day-ahead price. According to the current market, the assumption has been made that when electricity prices are high, the supply of renewable energy is low. To meet the electricity demand, fossil power generators have to be switched on or electricity has to be imported from the grid. From both economic and environmental perspectives, it is more efficient to store electricity when there is overproduction and low energy prices. Energy may therefore be imported from the Dutch grid when transmission capacity is still available, due to low energy prices.

Thus higher electricity prices are resulting in less UPHS charge and more UPHS discharge, and lower electricity prices are resulting in more UPHS charging and less UPHS discharging. Charging or discharging is using UPHS, which results in less curtailment, less electricity shortages, more electricity export and more electricity import.

As described, the more electricity can be produced at lower marginal costs the lower the day-ahead will be. On the other hand, a high energy demand will cause a higher day-ahead price, and lower energy demand will cause a lower day-ahead price since the intersection between supply and demand determines the day-ahead price. Based on this, U-PHS will charge when there are electricity surpluses, and discharge when there are electricity shortages. It is questionable if the market is operating right because the location isn't part of the market functioning. Sometimes, batteries cause more congestion.

The technical variables that are important in answering the research question about the impact of UPHS on the grid of Zeeland, are curtailment, electricity shortages, electricity import, and electricity export. Further are economic variables such as total production costs, carbon dioxide costs, and costs of lost load important to evaluate. Both the technical and economic variables can be used to determine the added social value of UPHS. Less need for grid-reinforcements and fewer emissions result in lower social costs for example.

Over time the electricity mix will change as the installed power capacity of solar panels and wind turbines are increasing, and fossil power generators may be phased out in the future due to policy interventions or as market outcome. These developments are important as they point out the need for energy storage. The model should be able to use scenarios for 2030, 2040, and 2050.

A.3. Operational model

The operational model specifies the concepts and correlations in the model, based on the conceptual model, and is required for developing the computational model. The variables are identified by analysing the conceptual model first, and specified by the collected data of the analysis to Zeeland. Subsequently a system diagram is made of the electricity flows to visualise spatial aspects of the system as well. From the model diagram an Excel model is made to identify the correlations and missing variables. This Excel model represented a simplified electricity grid of Zeeland and does provide insight into system behaviour. This is a process step between the operational and computerised model and can be seen as an iteration step part of the iterative modelling cycle. The figure and table below show all the variables that are needed for determining the added value of UPHS.

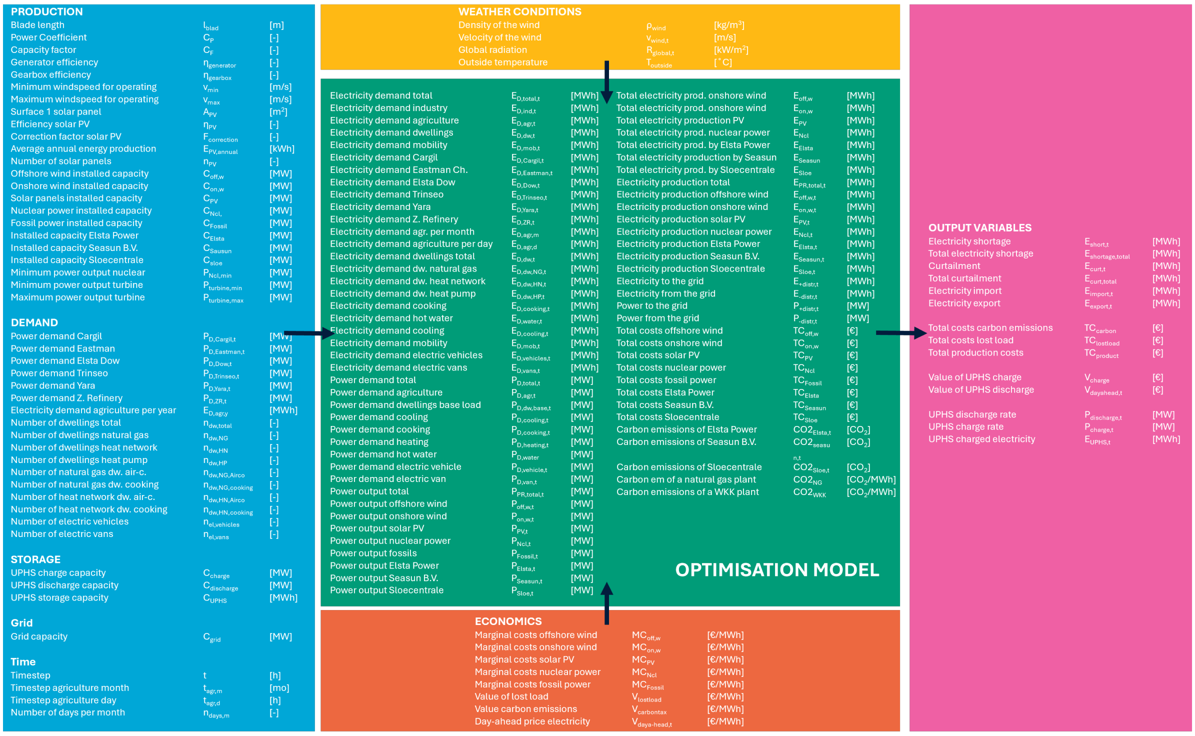


Figure A.3: Model diagram

The output variables are electricity import, electricity export, electricity shortage, curtailment, total costs of lost load, total production costs, carbon dioxide costs, and carbon emissions of fossil power. These can be presented in several graphs considering time on the x-axis and the output variables on the y-axis.

The table also shows whether variables change through time t. This means that a variable changes within a given year or scenario, but not variables that only vary by scenario. For example, the day-ahead price and wind speed vary on an hourly basis, but the installed capacity of wind turbines only varies by scenario.

Electricity supply			Electricity demand		
Offshore wind installed capacity	Coff,w	[MW]	Electricity demand total	ED,total,t	[MWh]
Onshore wind installed capacity	Con,w	[MW]	Electricity demand industry	ED,ind,t	[MWh]
Solar panels installed capacity	CPV	[MW]	Electricity demand agriculture	ED,agr,t	[MWh]
Nuclear power installed capacity	CNcl,	[MW]	Electricity demand dwellings	ED,dw,t	[MWh]
Fossil power installed capacity	CFossil	[MW]	Electricity demand mobility	ED,mob,t	[MWh]
Installed capacity Elsta Power	CElsta	[MW]	Electricity demand Cargil	ED,Cargil,t	[MWh]
Installed capacity Seasun B.V.	CSausun	[MW]	Electricity demand Eastman Ch.	ED,Eastman,t	[MWh]
Installed capacity Sloecentrale	CSloe	[MW]	Electricity demand Elsta Dow	ED,Dow,t	[MWh]
Total electricity prod. onshore wind	Eoff,w	[MWh]	Electricity demand Trinseo	ED,Trinseo,t	[MWh]
Total electricity prod. onshore wind	Eon,w	[MWh]	Electricity demand Yara	ED,Yara,t	[MWh]
Total electricity production PV	EPV	[MWh]	Electricity demand Z. Refinery	ED,ZR,t	[MWh]
Total electricity prod. nuclear power	ENcl	[MWh]	Electricity demand agriculture per year	ED,agr,y	[MWh]
Total electricity prod. by Elsta Power	EElsta	[MWh]	Electricity demand agr. per month	ED,agr,m	[MWh]
Total electricity production by Seasun	ESeasun	[MWh]	Electricity demand agriculture per day	ED,agr,d	[MWh]
Total electricity prod. by Sloecentrale	ESloe	[MWh]	Electricity demand dwellings total	ED,dw,t	[MWh]
Electricity production total	EPR,total,t	[MWh]	Electricity demand dw. natural gas	ED,dw,NG,t	[MWh]
Electricity production offshore wind	Eoff,w,t	[MWh]	Electricity demand dw. heat network	ED,dw,HN,t	[MWh]
Electricity production onshore wind	Eon,w,t	[MWh]	Electricity demand dw. heat pump	ED,dw,HP,t	[MWh]
Electricity production solar PV	EPV,t	[MWh]	Electricity demand cooking	ED,cooking,t	[MWh]
Electricity production nuclear power	ENcl,t	[MWh]	Electricity demand hot water	ED,water,t	[MWh]
Electricity production Elsta Power	EElsta,t	[MWh]	Electricity demand cooling	ED,cooling,t	[MWh]
Electricity production Seasun B.V.	ESeasun,t	[MWh]	Electricity demand mobility	ED,mob,t	[MWh]
Electricity production Sloecentrale	ESloe,t	[MWh]	Electricity demand electric vehicles	ED,vehicles,t	[MWh]
Power output total	PPR,total,t	[MW]	Electricity demand electric vans	ED,vans,t	[MWh]
Power output offshore wind	Poff,w,t	[MW]	Power demand total	PD,total,t	[MW]
Power output onshore wind	Pon,w,t	[MW]	Power demand Cargil	PD,Cargil,t	[MW]
Power output solar PV	PPV,t	[MW]	Power demand Eastman	PD,Eastman,t	[MW]
Power output nuclear power	PNcl,t	[MW]	Power demand Elsta Dow	PD,Dow,t	[MW]
Power output fossils	PFossil,t	[MW]	Power demand Trinseo	PD,Trinseo,t	[MW]
Power output Elsta Power	PElsta,t	[MW]	Power demand Yara	PD,Yara,t	[MW]
Power output Seasun B.V.	PSeasun,t	[MW]	Power demand Z. Refinery	PD,ZR,t	[MW]
Power output Sloecentrale	PSloe,t	[MW]	Power demand agriculture	PD,agr,t	[MW]
Minimum power output nuclear	PNcl,min	[MW]	Power demand dwellings base load	PD,dw,base,t	[MW]
Minimum power output turbine	Pturbine,min	[MW]	Power demand cooling	PD,cooling,t	[MW]
Maximum power output turbine	Pturbine,max	[MW]	Power demand cooking	PD,cooking,t	[MW]
Minimum windspeed for operating	vmin	[m/s]	Power demand heating	PD,heating,t	[MW]
Maximum windspeed for operating	vmax	[m/s]	Power demand hot water	PD,water	[MW]
Blade length	lblad	[m]	Power demand electric vehicle	PD,vehicle,t	[MW]
Power Coefficient	CP	[-]	Power demand electric van	PD,van,t	[MW]
Capacity factor	CF	[-]	Number of dwellings total	ndw,total	[-]
Generator efficiency	ηgenerator	[-]	Number of dwellings natural gas	ndw,NG	[-]
Gearbox efficiency	ηgearbox	[-]	Number of dwellings heat network	ndw,HN	[-]
Surface 1 solar panel	APV	[m2]	Number of dwellings heat pump	ndw,HP	[-]
Efficiency solar PV	ηPV	[-]	Number of natural gas dw. air-c.	ndw,NG,Airco	[-]
Correction factor solar PV	Fcorrection	[-]	Number of natural gas dw. cooking	ndw,NG,cooking	[-]
Average annual energy production	EPV,annual	[kWh]	Number of heat network dw. air-c.	ndw,HN,Airco	[-]
Number of solar panels	nPV	[-]	Number of heat network dw. cooking	ndw,HN,cooking	[-]
			Number of electric vehicles	nel,vehicles	[-]
			Number of electric vans	nel,vans	[-]

Table A.1: Overview variables - A

Economics					
Total costs carbon emissions	TCcarbon	[€]			
Total costs lost load	TClostload	[€]	Electricity storage		
Total production costs	TCproduct	[€]	UPHS charge capacity	Ccharge	[MW]
Total costs offshore wind	TCoff,w	[€]	UPHS discharge capacity	Cdischarge	[MW]
Total costs onshore wind	TCon,w	[€]	UPHS discharge rate	Pdischarge,t	[MW]
Total costs solar PV	TCPV	[€]	UPHS charge rate	Pcharge,t	[MW]
Total costs nuclear power	TCNcl	[€]	UPHS storage capacity	CUPHS	[MWh]
Total costs fossil power	TCFossil	[€]	UPHS charged electricity	EUPHS,t	[MWh]
Total costs Elsta Power	TCElsta	[€]			
Total costs Seasun B.V.	TCSeasun	[€]	Network		
Total costs Sloecentrale	TCSloe	[€]	Grid capacity	Cgrid	[MW]
Marginal costs offshore wind	MCoff,w	[€/MWh]	Electricity to the grid	E+distr,t	[MWh]
Marginal costs onshore wind	MCon,w	[€/MWh]	Electricity from the grid	E-distr,t	[MWh]
Marginal costs solar PV	MCPV	[€/MWh]	Power to the grid	P+distr,t	[MW]
Marginal costs nuclear power	MCNcl	[€/MWh]	Power from the grid	P-distr,t	[MW]
Marginal costs fossil power	MCFossil	[€/MWh]	Electricity shortage	Eshort,t	[MWh]
Value carbon emissions	Vcarbontax	[€/MWh]	Total electricity shortage	Eshortage,total	[MWh]
Value of lost load	Vlostload	[€/MWh]	Curtailment	Ecurt,t	[MWh]
Day-ahead price electricity	Vdaya-head,t	[€/MWh]	Total curtailment	Ecurt,total	[MWh]
Value of UPHS charge	Vcharge	[€]	Electricity import	Eimport,t	[MWh]
Value of UPHS discharge	Vdayahead,t	[€]	Electricity export	Eexport,t	[MWh]
Carbon emissions			Weather		
Carbon emissions of fossil power	CO2em,t	[CO2]	Density of the wind	ρwind	[kg/m3]
Carbon emissions of Elsta Power	CO2Elsta,t	[CO2]	Velocity of the wind	vwind,t	[m/s]
Carbon emissions of Seasun B.V.	CO2seasun,t	[CO2]	Global radiation	Rglobal,t	[kW/m2]
Carbon emissions of Sloecentrale	CO2Sloe,t	[CO2]	Outside temperature	Toutside	[˚C]
Carbon emissions of a natural gas plant	CO2NG	[CO2/MWh]			
Carbon emissions of a WKK plant	CO2WKK	[CO2/MWh]			
Time					
Timestep	t	[h]			
Timestep agriculture month	tagr,m	[mo]			
Timestep agriculture day	tagr,d	[h]			
Number of days per month	ndays,m	[-]			

Table A.2: Overview variables - B

A.3.1. Scenario development

Because the future will differ from the current situation scenario-development is an important part of the research. To what extent electrification will play a role in future society is however uncertain. Therefore, different scenarios need to be compiled and analysed both compared to the current situation and with each other, and in which UPHS does and does not play a role.

The variables and equations described in this chapter are representing a certain period of a specific scenario. The model is suitable for calculating a specific scenario for, the duration of a day, week, month, or year, for example. To compare scenarios with each other, the model should be used several times, with the input variables varying for each scenario.

Starting with the current situation data can be found for the years 2020 until 2025. For example, supply and demand but also current grid capacities and planned investments by TenneT in the short term. Scenarios from 2030 onwards require expectations of developments in power and demand, economic factors, and policy. Dividing expectations into different topics of mobility, agriculture, industry, and dwellings, in which subdivisions can be made subsequently, make the expectations specific.

A.3.2. Electricity distribution

Electricity distribution, or transmission, is the electricity that needs to be distributed over the grid within the electricity system of Zeeland due to electricity production or electricity demand. This is not a clear variable in the model as it presents an electricity flow between two nodes in the grid. This variable calculates the available grid capacity but depends on the grid capacity of a specific cable within the network. There may be differences between transmission and distribution capacities. As result there might be electricity shortages and curtailment. The formulas below need to be applied at every node within the system.

The electricity that can be distributed can be equal to the grid capacity at maximum. If more electricity needs to be distributed than possible than the difference is an electricity shortage or curtailment. Further, distribution cannot be negative, but to make clear in which direction electricity is flowing, 2 variables exist for electricity distribution. Electricity from the grid is labelled as negative, electricity to the grid is labelled as positive.

If $P_{+\text{distr},t} \leq C_{\text{grid}}$:

$$E_{+\text{distr},t} = P_{+\text{distr},t} \cdot t \tag{A.1}$$

$$E_{\text{curt},t} = 0 \tag{A.2}$$

where:

$P_{+\text{distr},t}$ Power to the grid [MW]
C_{grid} Grid capacity [MW]
$E_{+\text{distr},t}$ Electricity to the grid [MWh]
$E_{\text{curt},t}$ Curtailment [MWh]
t Timestep [h]

If $P_{+\text{distr},t} > C_{\text{grid}}$:

$$E_{+\text{distr},t} = C_{\text{grid}} \tag{A.3}$$

$$E_{\text{curt},t} = (P_{+\text{distr},t} \cdot t) - (C_{\text{grid}} \cdot t) \tag{A.4}$$

where:

$P_{+\text{distr},t}$ Power to the grid [MW]
C_{grid} Grid capacity [MW]
$E_{+\text{distr},t}$ Electricity to the grid [MWh]
$E_{\text{curt},t}$ Curtailment [MWh]
t Timestep [h]

If $P_{-\text{distr},t} \leq C_{\text{grid}}$:

$$E_{-\text{distr},t} = P_{-\text{distr},t} \cdot t \tag{A.5}$$

$$E_{\text{short},t} = 0 \tag{A.6}$$

where:

$P_{-\text{distr},t}$ Power from the grid [MW]
C_{grid} Grid capacity [MW]
$E_{-\text{distr},t}$ Electricity from the grid [MWh]
$E_{\text{short},t}$ Electricity shortage [MWh]
t Timestep [h]

If $P_{-\textbf{distr},t} > C_{\textbf{grid}}$:

$$E_{-\text{distr},t} = C_{\text{grid}} \tag{A.7}$$
$$E_{\text{short},t} = (P_{-\text{distr},t} \cdot t) - (C_{\text{grid}} \cdot t) \tag{A.8}$$

where:

$P_{-\text{distr},t}$ Power from the grid [MW]
C_{grid} Grid capacity [MW]
$E_{-\text{distr},t}$ Electricity from the grid [MWh]
$E_{\text{short},t}$ Electricity shortage [MWh]
t Timestep [h]

$$0 \leq E_{+\text{distr},t} \leq C_{\text{grid}} \cdot t \tag{A.9}$$
$$0 \leq E_{-\text{distr},t} \leq C_{\text{grid}} \cdot t \tag{A.10}$$

where:

$E_{+\text{distr},t}$ Electricity to the grid [MWh]
$E_{-\text{distr},t}$ Electricity from the grid [MWh]
C_{grid} Grid capacity [MW]
t Timestep [h]

The power that needs to be distributed to or from the grid depends on the total demand, total production, and charge or discharge of a certain storage technology. This differs per node.

$$P_{-\text{distr},t} = P_{D,\text{total},t} + P_{\text{charge},t} - P_{Pr,\text{total},t} - P_{\text{discharge},t} \tag{A.11}$$
$$P_{+\text{distr},t} = P_{Pr,\text{total},t} + P_{\text{discharge},t} - P_{D,\text{total},t} - P_{\text{charge},t} \tag{A.12}$$

where:

$P_{-\text{distr},t}$ Power from the grid [MW]
$P_{D,\text{total},t}$ Power demand total [MW]
$P_{\text{charge},t}$ UPHS charge rate [MW]
$P_{Pr,\text{total},t}$ Power production total [MW]
$P_{\text{discharge},t}$ UPHS discharge rate [MW]
$P_{+\text{distr},t}$ Power to the grid [MW]

Electricity can only flow in 1 direction between 2 nodes. So if there is power distribution from the grid it is not possible to distribute power to the grid.

$$P_{-\text{distr},t} \geq 0 \vee P_{+\text{distr},t} = 0 \tag{A.13}$$
$$P_{+\text{distr},t} \geq 0 \vee P_{-\text{distr},t} = 0 \tag{A.14}$$

where:

$P_{-\text{distr},t}$ Power from the grid [MW]
$P_{+\text{distr},t}$ Power to the grid [MW]

At the borders of the electricity system, thus from the last node inside the system to the first node outside the system, or from the first node outside the system to the last node inside the system, electricity distribution can be measured as import and export.

$$E_{\text{import},t} = P_{-\text{distr},t} \cdot t \tag{A.15}$$
$$E_{\text{export},t} = P_{+\text{distr},t} \cdot t \tag{A.16}$$

where:

$E_{\text{import},t}$ Electricity import [MWh]
$P_{-\text{distr},t}$ Power from the grid [MW]
t Timestep [h]
$E_{\text{export},t}$ Electricity export [MWh]
$P_{+\text{distr},t}$ Power to the grid [MW]

All the values of electricity import, electricity export, curtailment, and electricity shortages in a specific period can be summed up, which results in the total electricity import, total electricity export, total curtailment, and total electricity shortages in a specific area.

$$E_{\text{import}} = \sum_{t=a}^{b} P_{-\text{distr},t} \cdot t \tag{A.17}$$
$$E_{\text{export}} = \sum_{t=a}^{b} P_{+\text{distr},t} \cdot t \tag{A.18}$$
$$E_{\text{curtailment}} = \sum_{t=a}^{b} E_{\text{curt},t} \tag{A.19}$$
$$E_{\text{shortage}} = \sum_{t=a}^{b} E_{\text{short},t} \tag{A.20}$$

where:

E_{import} Total electricity import [MWh]
E_{export} Total electricity export [MWh]
$E_{\text{curtailment}}$ Total curtailment [MWh]
E_{shortage} Total electricity shortage [MWh]

A self-sufficient energy system, not dependent on other countries, is discussed a lot as the war between Russia and Ukraine resulted in the rise of energy prices. Therefore, interconnection with Belgium is not modelled in the first place, and the model have the limitation that it assumes that shortages of electricity can be imported all the time, independent of whether energy is available outside the system. Important to note, if there are multiple nodes where the modelled system can import and export energy, further distinction should be made in sub-codes of energy import and export variables. Otherwise, interpreting the results of the analysis will be more difficult.

A.3.3. Specification UPHS

The storage technology UPHS has both a charge- and discharge rate that determine how fast this asset charges or discharges at a certain moment. This can vary between not charging or not discharging to the maximum charge or discharge capacity.

$$0 \leq P_{\text{charge},t} \leq C_{\text{charge}} \tag{A.21}$$

$$0 \leq P_{\text{discharge},t} \leq C_{\text{discharge}} \tag{A.22}$$

where:

$P_{\text{charge},t}$ UPHS charge rate [MW]
C_{charge} UPHS charge capacity [MW]
$P_{\text{discharge},t}$ UPHS discharge rate [MW]
$C_{\text{discharge}}$ UPHS discharge capacity [MW]

The amount of charged electricity in UPHS at a certain moment is the summation of all electricity charged over time minus all electricity discharged in the same period. Additionally, the charged electricity in UPHS cannot be more than the storage capacity of UPHS and not less than zero.

$$E_{\text{UPHS},t} = \sum_{t=a}^{b} P_{\text{charge},t} \cdot t - \sum_{t=a}^{b} P_{\text{discharge},t} \cdot t \tag{A.23}$$

where:

$E_{\text{UPHS},t}$ UPHS charged electricity [MWh]
$P_{\text{charge},t}$ UPHS charge rate [MW]
$P_{\text{discharge},t}$ UPHS discharge rate [MW]
t Timestep [h]

$$0 \leq E_{\text{UPHS},t} \leq C_{\text{UPHS}} \tag{A.24}$$

$$\text{if } E_{\text{UPHS},t} = C_{\text{UPHS}}, \text{ then } E_{\text{charge}} = 0 \tag{A.25}$$

where:

$E_{\text{UPHS},t}$ UPHS charged electricity [MWh]
C_{UPHS} UPHS storage capacity [MWh]

A.3.4. Power output

The power output of offshore wind, onshore wind, solar panels, nuclear power, and fossil power can be determined by functions in which the input variables are considered. The sum of these power generators is the total power output.

$$P_{\text{Pr,total},t} = P_{\text{off,w},t} + P_{\text{on,w},t} + P_{\text{PV},t} + P_{\text{Ncl},t} + P_{\text{Fossil},t} \tag{A.26}$$

where:

$P_{\text{Pr,total},t}$ Power output total [MW]
$P_{\text{off,w},t}$ Power output offshore wind [MW]
$P_{\text{on,w},t}$ Power output onshore wind [MW]
$P_{\text{PV},t}$ Power output solar PV [MW]
$P_{\text{Ncl},t}$ Power output nuclear [MW]
$P_{\text{Fossil},t}$ Power output fossils [MW]

Offshore & onshore wind

To calculate the power output of a wind turbine, a dataset of the production of a specific wind farm can be used that results in reliable data including losses. From this, a dataset can be made per 1 [MW] and implemented in the computerised model and multiplied by the installed capacity.

If no dataset is available, the power output of wind turbines can be calculated using the formula, which results in a self-created dataset. Specifications can be found in technical data, and the data for wind speed at a specific location and height is available by KNMI.

If $v_{\text{min}} \leq v \leq v_{\text{max}}$:

$$P_{\text{off,w},t} = \frac{1}{2}\rho\pi r^2 C_P C_F v^3 \eta_{\text{Generator}}\eta_{\text{Gearbox}} 10^6 n_{\text{turbines,off}} \tag{A.27}$$

$$P_{\text{on,w},t} = \frac{1}{2}\rho\pi r^2 C_P C_F v^3 \eta_{\text{Generator}}\eta_{\text{Gearbox}} 10^6 n_{\text{turbines,on}} \tag{A.28}$$

where:

$P_{\text{off,w},t}$ Power output offshore wind [MW]
$P_{\text{on,w},t}$ Power output onshore wind [MW]
ρ Density of the wind [kg/m^3]
r Blade length [m]
C_P Power Coefficient [-]
C_F Capacity Factor [-]
v Velocity of the wind [m/s]
$\eta_{\text{Generator}}$ Generator efficiency [-]
η_{Gearbox} Gearbox efficiency [-]
v_{min} Minimum windspeed for operating [m/s]
v_{max} Maximum windspeed for operating [m/s]
$n_{\text{turbines,off}}$ Number of turbines offshore [-]
$n_{\text{turbines,on}}$ Number of turbines onshore [-]

Using the formula for the model also results in the need for production constraints related to wind speed. The velocity of the wind should have a certain value to run the wind turbine, which differs from turbine to turbine. Also, at certain values of the wind velocity the turbine needs to be switched off due to safety issues. These aspects are not relevant using a real dataset.

If $v < v_{\text{min}}$ or $v > v_{\text{max}}$:

$$P_{\text{w},t} = 0 \tag{A.29}$$

where:

$P_{\text{w},t}$ Power output offshore or onshore wind turbine [MW]
v Velocity of the wind [m/s]
v_{min} Minimum windspeed for operating [m/s]
v_{max} Maximum windspeed for operating [m/s]

$$P_{\text{turbine,min}} \leq P_{\text{off,w},t} \leq P_{\text{turbine,max}} \tag{A.30}$$

$$P_{\text{turbine,min}} \leq P_{\text{on,w},t} \leq P_{\text{turbine,max}} \tag{A.31}$$

where:

$P_{\text{turbine,min}}$ Minimum power output wind turbine [MW]
$P_{\text{off,w},t}$ Power output offshore wind [MW]
$P_{\text{on,w},t}$ Power output onshore wind [MW]
$P_{\text{turbine,max}}$ Maximum power output wind turbine [MW]

From the power output of a certain wind turbine or wind farm the electricity production in a certain period can be calculated. These results can be used for economic analysis for example and determining the electricity mix in certain scenarios.

$$E_{\text{off,w},t} = P_{\text{off,w},t} \cdot t \tag{A.32}$$

$$E_{\text{on,w},t} = P_{\text{on,w},t} \cdot t \tag{A.33}$$

$$E_{\text{off,w}} = \sum_{t=a}^{b} E_{\text{off,w},t} \tag{A.34}$$

$$E_{\text{on,w}} = \sum_{t=a}^{b} E_{\text{on,w},t} \tag{A.35}$$

where:

$E_{\text{off,w},t}$ Electricity production offshore wind [MWh]
$E_{\text{on,w},t}$ Electricity production onshore wind [MWh]
$P_{\text{off,w},t}$ Power output offshore wind [MW]
$P_{\text{on,w},t}$ Power output onshore wind [MW]
t Timestep [h]
$E_{\text{off,w}}$ Total electricity production offshore wind [MWh]
$E_{\text{on,w}}$ Total electricity production onshore wind [MWh]

Solar power

To calculate the power output of a solar panel, a dataset of the production of a specific solar field can be used that results in reliable data including losses. From this, a dataset can be made per 1 [MW] and implemented in the computerised model and multiplied by the installed capacity.

If no dataset is available, the power output of solar panels can be calculated using the formula, which results in a self-created dataset. Specifications can be found in technical data, and the data for global radiation at a specific location is available by KNMI. Involved variables are global radiation, surface of one solar panel, efficiency, and correction factor for the angle and gradient.

$$P_{\text{PV},t} = \frac{R_{\text{global},t}}{1000} \cdot A_{\text{PV}} \cdot n_{\text{PV}} \cdot \eta_{\text{pv}} \cdot F_{\text{correction}} \tag{A.36}$$

where:

$P_{\text{PV},t}$ Power output solar PV [MW]
$R_{\text{global},t}$ Global radiation [kW/m^2]
A_{PV} Surface area of 1 solar panel [m^2]
n_{PV} Number of solar panels [-]
η_{pv} Efficiency of solar PV [-]
$F_{\text{correction}}$ Correction factor for solar PV [-]

On average, solar panels have a surface of 1.65 [m2] per solar panel. Further, these have an efficiency of 0.25 [-], and the correction for angle and gradient can be set on 0.85 [-]. Solar panels have on yearly basis an energy output [kWh] that is equal to their capacity [kWh]. A solar panel of 370 [Wp] will produce around 370 [kWh] per year. This can be used for model validation. Global radiation data from KNMI is provided in [J/m2] per hour. This needs to be converted into [kW/m2]. This is equal to the original unit of [kWh/m2] as the model is based on an hourly basis.

$$R_{\text{global},t}[kW/m^2] = R_{\text{Global},t}[J/cm^2] \times \frac{1 \times 10^4}{3.6 \times 10^6} \times \frac{1}{1\text{ h}} \tag{A.37}$$

$$n_{\text{PV}} = \frac{C_{\text{PV}} \times 10^6}{E_{\text{PV,annual}}} \tag{A.38}$$

where:

n_{PV} Number of solar panels [-]
C_{PV} Solar panels installed capacity [MW]
$E_{\text{PV,annual}}$ Average annual energy production [Wp]

The equations above can be used to make a dataset representing for example the hourly power production of solar panels per 1 [MW] installed. Therefore, the number of solar panels needs to be calculated first, which is around 2,700 for 1 [MW], based on the average yearly power output. Multiplying this by the surface of solar panels [m2], the global radiation [kWh/m2], efficiency and correction of angle and gradient, the hourly power output per 1 [MW] installed solar capacity is calculated. This dataset can be used in the model and multiplied by the installed capacity.

From the power output of solar panels, the electricity production in a certain period can be calculated. These results can be used for economic analysis for example and determining the electricity mix in certain scenarios.

$$E_{\text{PV},t} = P_{\text{PV},t} \cdot t \tag{A.39}$$

where:

$E_{\text{PV},t}$ Electricity production solar PV [MWh]
$P_{\text{PV},t}$ Power output solar PV [MW]
t Timestep [h]

$$E_{\text{PV}} = \sum_{t=a}^{b} E_{\text{PV},t} \tag{A.40}$$

where:

E_{PV} Total electricity production solar PV [MWh]
$E_{\text{PV},t}$ Electricity production solar PV [MWh]

Nuclear power

The hourly power output [MWh] of a nuclear power plant is equal to the capacity [MW] if it is operating at its maximum. Similar to solar panels and wind turbines the total electricity production of a nuclear plant in a certain period is the sum of all the values of electricity production.

$$E_{\text{Ncl},t} = P_{\text{Ncl},t} \cdot t \tag{A.41}$$

where:

$E_{\text{Ncl},t}$ Electricity production nuclear power [MWh]
$P_{\text{Ncl},t}$ Power output nuclear [MW]
t Timestep [h]

$$E_{\text{Ncl}} = \sum_{t=a}^{b} E_{\text{Ncl},t} \tag{A.42}$$

where:

E_{Ncl} Total electricity production nuclear power [MWh]
$E_{\text{Ncl},t}$ Electricity production nuclear power [MWh]

The power output of a nuclear plant is preferably kept as constant as possible within a range of operating constraints, which are distinct from the technical constraints on more conventional power plants.

$$P_{\text{Ncl,min}} \leq P_{\text{Ncl},t} \leq C_{\text{Ncl}} \tag{A.43}$$

where:

$P_{\text{Ncl,min}}$ Minimum power output nuclear [MW]
$P_{\text{Ncl},t}$ Power output nuclear [MW]
C_{Ncl} Nuclear power installed capacity [MW]

Production can't be ramped up or down too quickly without causing a strain on the nuclear fuel rods and the reactor itself. Power changes in the reactor also involve significant temperature and radiation load changes that affect the lifespan. Maintenance of a nuclear power plant is complex and expensive due to the radioactive installation. Also, the requirements are much stricter than conventional power generators due to safety issues, and the tolerance for failures is lower. Therefore, it is assumed that the nuclear plant can ramp down to 90 [%] of its capacity. (Keeping the Balance, n.d.)

Fossil power

Fossil power generators are operating at the moment such as coal- and natural gas plants. In Zeeland there are 3 fossil power generators: Elsta Power, Seasun B.V., and Sloecentrale. These have their own operating capacities, located differently within the system. The total fossil power output is the sum of the power output of these power generators at a certain moment. The electricity production in a specific period of time can be calculated using the sum of all power outputs.

$$P_{\text{Fossil},t} = P_{\text{Elsta},t} + P_{\text{Seasun},t} + P_{\text{Sloe},t} \tag{A.44}$$

where:

$P_{\text{Fossil},t}$ Power output fossils [MW]
$P_{\text{Elsta},t}$ Power output Elsta Power [MW]
$P_{\text{Seasun},t}$ Power output Seasun B.V. [MW]
$P_{\text{Sloe},t}$ Power output Sloecentrale [MW]

$$E_{\text{Elsta},t} = P_{\text{Elsta},t} \cdot t \quad \text{(A.45)}$$
$$E_{\text{Seasun},t} = P_{\text{Seasun},t} \cdot t \quad \text{(A.46)}$$
$$E_{\text{Sloe},t} = P_{\text{Sloe},t} \cdot t \quad \text{(A.47)}$$

where:

$E_{\text{Elsta},t}$ Electricity production Elsta Power [MWh]
$E_{\text{Seasun},t}$ Electricity production Seasun B.V. [MWh]
$E_{\text{Sloe},t}$ Electricity production Sloecentrale [MWh]
$P_{\text{Elsta},t}$ Power output Elsta Power [MW]
$P_{\text{Seasun},t}$ Power output Seasun B.V. [MW]
$P_{\text{Sloe},t}$ Power output Sloecentrale [MW]
t Timestep [h]

$$E_{\text{Elsta}} = \sum_{t=a}^{b} E_{\text{Elsta},t} \quad \text{(A.48)}$$
$$E_{\text{Seasun}} = \sum_{t=a}^{b} E_{\text{Seasun},t} \quad \text{(A.49)}$$
$$E_{\text{Sloe}} = \sum_{t=a}^{b} E_{\text{Sloe},t} \quad \text{(A.50)}$$

where:

E_{Elsta} Total electricity production by Elsta Power [MWh]
E_{Seasun} Total electricity production by Seasun B.V. [MWh]
E_{Sloe} Total electricity production by Sloecentrale [MWh]
$E_{\text{Elsta},t}$ Electricity production Elsta Power [MWh]
$E_{\text{Seasun},t}$ Electricity production Seasun B.V. [MWh]
$E_{\text{Sloe},t}$ Electricity production Sloecentrale [MWh]

Fossil power generators that are using natural gas, heat, or coal, can ramp up and ramp down more easily than a nuclear power plant. Therefore, no constraints are necessary.

$$P_{\text{Fossil},t} \geq 0 \quad \text{(A.51)}$$

where:

$P_{\text{Fossil},t}$ Power output fossils [MW]

$$0 \leq P_{\text{Elsta},t} \leq C_{\text{Elsta}} \quad \text{(A.52)}$$

where:

$P_{\text{Elsta},t}$ Power output Elsta Power [MW]
C_{Elsta} Installed capacity Elsta Power [MW]

$$0 \leq P_{\text{Seasun},t} \leq C_{\text{Seasun}} \tag{A.53}$$

where:

$P_{\text{Seasun},t}$ Power output Seasun B.V. [MW]
C_{Seasun} Installed capacity Seasun B.V. [MW]

$$0 \leq P_{\text{Sloecentrale},t} \leq C_{\text{Sloecentrale}} \tag{A.54}$$

where:

$P_{\text{Sloecentrale},t}$ Power output Sloecentrale [MW]
$C_{\text{Sloecentrale}}$ Installed capacity Sloecentrale [MW]

The power output of the different fossil power generators depends on the market outcome and can vary between 0 and their maximum. The market outcome depends on the model used. Results based on emissions are likely to be different from those based on marginal costs. An optimisation model may look for the solution that is most beneficial and feasible. By giving constraints to, for example, electricity distribution and linking marginal costs and emissions to power generators, the model will look for the best solution. One comparison that the model can make, considering the use of fossil power generators, is that when the day-ahead price is higher than the production costs of fossil power generators, and there is still transmission capacity available on the grid, and a storage capacity like UPHS is already full, electricity is then transmitted to the Dutch high-voltage grid. These equations are mathematical not included in this report because software such as Linny-R already have these. Implementing all the equations described in this report will result in such conditions by the software itself.

A.3.5. Demand profiles

Electricity demand can be dived into electricity demand for industries, agriculture, dwellings, and mobility. The so-called electricity demand profiles differ between these sectors. In general, the profiles of the industry and mobility are more-less constant throughout the year. The energy demand of agriculture and buildings however may differ through the year because of seasonal patterns. Additionally, buildings, agriculture and mobility have different profiles throughout the day. The use of air-conditioning, heat pumps, electric cooking, and charging electric vehicles will determine the energy profiles of the built environment, agriculture, and mobility throughout the day. This also depends on how these sectors will be carbon neutral in the future.

$$E_{\text{D,total},t} = E_{\text{D,ind},t} + E_{\text{D,agr},t} + E_{\text{D,dw},t} + E_{\text{D,mob},t} \tag{A.55}$$

where:

$E_{\text{D,total},t}$ Electricity demand total [MWh]
$E_{\text{D,ind},t}$ Electricity demand industry [MWh]
$E_{\text{D,agr},t}$ Electricity demand agriculture [MWh]
$E_{\text{D,dw},t}$ Electricity demand dwellings [MWh]
$E_{\text{D,mob},t}$ Electricity demand mobility [MWh]

$$E_{\text{D,ind},t} \geq 0 \tag{A.56}$$
$$E_{\text{D,agr},t} \geq 0 \tag{A.57}$$
$$E_{\text{D,dw},t} \geq 0 \tag{A.58}$$
$$E_{\text{D,mob},t} \geq 0 \tag{A.59}$$

where:

$E_{\text{D,ind},t}$ Electricity demand industry [MWh]
$E_{\text{D,agr},t}$ Electricity demand agriculture [MWh]
$E_{\text{D,dw},t}$ Electricity demand dwellings [MWh]
$E_{\text{D,mob},t}$ Electricity demand mobility [MWh]

Electricity demand industry

CE Delft mentions that most electrification technologies for industry have mostly a flat pattern (Frans Rooijers et al., 2020) with a peak demand of 1,25 times the average demand. There might be an opportunity that electrolysers can provide flexibility in case of surpluses by solar and wind power (Frans Rooijers et al., 2020). It should be noted that in case of up and downsizing the industry as commissioned by a grid operator will have additional costs. Also, a report of the Schelde Delta Regio shows that demand and supply can be matched, with a base load of 1 [GW].

The calculations in the model within this research however assume that the electricity demand is constant throughout the day and the year, as this will probably give the highest production for the industry. The industry may be able to use more electricity to produce backup hydrogen for example, but that should work in theory in the same way as any other storage supplier. The equations provided can be used to calculate the hourly electricity demand, and hence the electrical power demand of the industries. From the spatial analysis in Zeeland the total annual power demand is known.

$$E_{\text{D,ind},t} = E_{\text{D,Cargil},t} + E_{\text{D,Eastm},t} + E_{\text{D,Dow},t} + E_{\text{D,Trins},t} + E_{\text{D,Yara},t} + E_{\text{D,ZR},t} \tag{A.60}$$

where:

$E_{\text{D,ind},t}$ Electricity demand industry [MWh]
$E_{\text{D,Cargil},t}$ Electricity demand Cargil [MWh]
$E_{\text{D,Eastm},t}$ Electricity demand Eastman Chemical [MWh]
$E_{\text{D,Dow},t}$ Electricity demand Elsta Dow [MWh]
$E_{\text{D,Trins},t}$ Electricity demand Trinseo [MWh]
$E_{\text{D,Yara},t}$ Electricity demand Yara [MWh]
$E_{\text{D,ZR},t}$ Electricity demand Zeeland Refinery [MWh]

$$E_{\text{D,ind},t} \geq 0 \tag{A.61}$$

where:

$E_{\text{D,ind},t}$ Electricity demand industry [MWh]

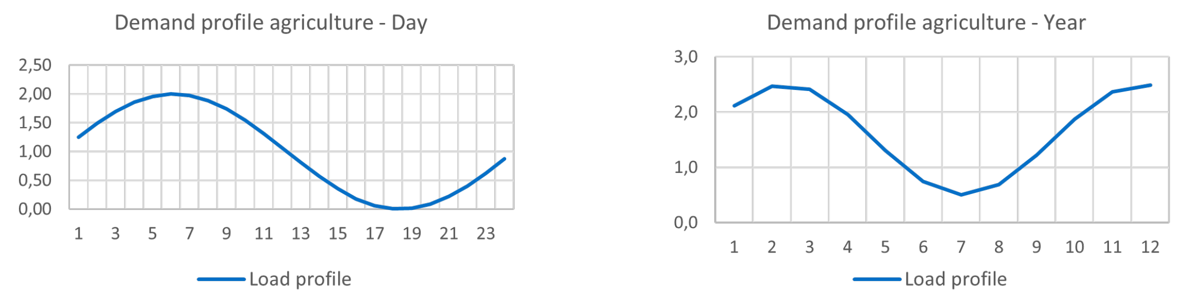
$$E_{\text{D,Cargil},t} = P_{\text{D,Cargil},t} \cdot t \tag{A.62}$$
$$E_{\text{D,Eastm},t} = P_{\text{D,Eastm},t} \cdot t \tag{A.63}$$
$$E_{\text{D,Dow},t} = P_{\text{D,Dow},t} \cdot t \tag{A.64}$$
$$E_{\text{D,Trins},t} = P_{\text{D,Trins},t} \cdot t \tag{A.65}$$
$$E_{\text{D,Yara},t} = P_{\text{D,Yara},t} \cdot t \tag{A.66}$$
$$E_{\text{D,ZR},t} = P_{\text{D,ZR},t} \cdot t \tag{A.67}$$

where:

$E_{\text{D,Cargil},t}$ Electricity demand Cargil [MWh]
$E_{\text{D,Eastm},t}$ Electricity demand Eastman Chemical [MWh]
$E_{\text{D,Dow},t}$ Electricity demand Elsta Dow [MWh]
$E_{\text{D,Trins},t}$ Electricity demand Trinseo [MWh]
$E_{\text{D,Yara},t}$ Electricity demand Yara [MWh]
$E_{\text{D,ZR},t}$ Electricity demand Zeeland Refinery [MWh]
$P_{\text{D,Cargil},t}$ Power demand Cargil [MW]
$P_{\text{D,Eastm},t}$ Power demand Eastman Chemical [MW]
$P_{\text{D,Dow},t}$ Power demand Elsta Dow [MW]
$P_{\text{D,Trins},t}$ Power demand Trinseo [MW]
$P_{\text{D,Yara},t}$ Power demand Yara [MW]
$P_{\text{D,ZR},t}$ Power demand Zeeland Refinery [MW]
t Timestep [h]

Electricity demand agriculture

CE Delft mentions that 80 [%] of the electricity demand in the agriculture sector is used for lighting and that 80 [%] of the electricity is used during the night especially between September to April (Frans Rooijers et al., 2020). This implies a fluctuating profile both through the day and year. The daily and yearly demand profiles of the agricultural sector can therefore be simulated by a sinus function with the lowest value of 0 on the y-axis representing the load. The sinus functions is transformed a bit so that these have similar characteristics according to the research of CE Delft (Frans Rooijers et al., 2020). The results in the graphs below are providing the shape of the daily profile in time steps of 1 hour, and the yearly demand profile in time steps of 1 month.



(a) Demand profile agriculture, day

(b) Demand profile agriculture, month

Figure A.4: Demand profiles for agriculture

From the functions described below a dataset can be made that represents the demand pattern of agriculture with a yearly demand of 1 [PJ] for example. This dataset can then be multiplied by the real demand of certain agricultural clusters, as presented in the analysis of Zeeland.

$$E_{\text{D,agr},t} = P_{\text{D,agr},t} \cdot t \tag{A.68}$$

where:

$E_{\text{D,agr},t}$ Electricity demand agriculture [MWh]
$P_{\text{D,agr},t}$ Power demand agriculture [MW]
t Timestep [h]

$$E_{\text{D,agr},t} \geq 0 \tag{A.69}$$

where:

$E_{\text{D,agr},t}$ Electricity demand agriculture [MWh]

The total demand of agricultural companies is known. Using the sinus functions the hourly electricity demand, and thus the hourly power output, can be determined. To calculate the hourly demand, first the monthly demand need to be calculated. This is the share in electricity demand per month multiplied by the yearly electricity demand. The share in electricity demand per month can be calculated using the sum of all the values of the 24 time steps of the sinus function which is 20.15.

$$E_{\text{D,agr,m}} = \frac{\sin\left(\frac{t_{\text{agr,m}}}{1.5}\right) + 1.5}{20.15} \cdot E_{\text{D,agr,y}} \tag{A.70}$$

where:

$E_{\text{D,agr,m}}$ Electricity demand agriculture per month [MWh]
$t_{\text{agr,m}}$ Timestep agriculture month [mo]
$E_{\text{D,agr,y}}$ Electricity demand agriculture per year [MWh]

$1 \leq t_{\text{agr,m}} \leq 12$
$E_{\text{D,agr,m}}$ Electricity demand agriculture per month [MWh]
$t_{\text{agr,m}}$ Timestep agriculture month [mo]
$E_{\text{D,agr,y}}$ Electricity demand agriculture per year [MWh]

The daily electricity demand from agriculture is calculated by dividing the monthly demand by the number of days in the month. Here the simplification is made that every day in a certain month has the same electricity demand.

$$E_{\text{D,agr,d}} = \frac{E_{\text{D,agr,m}}}{n_{\text{days,m}}} \tag{A.71}$$

where:

$E_{\text{D,agr,d}}$ Electricity demand agriculture per day [MWh]
$E_{\text{D,agr,m}}$ Electricity demand agriculture per month [MWh]
$n_{\text{days,m}}$ Number of days per month [-]

From the daily electricity demand in a certain month the hourly electricity demand, and thus the hourly power demand of the agricultural sector, can be determined. This follows the same concept of using a sinus function and calculating the share of every hour within a day. The sum of the values of the function of 24 timesteps is 23.97.

$$E_{\text{D,agr,t}} = \frac{\sin\left(\frac{t_{\text{agr,d}}}{3.9}\right) + 1}{23.97} \cdot E_{\text{D,agr,d}} \tag{A.72}$$

where:

$E_{\text{D,agr,t}}$ Electricity demand agriculture [MWh]
$t_{\text{agr,d}}$ Timestep agriculture day [h]
$E_{\text{D,agr,d}}$ Electricity demand agriculture per day [MWh]

$$1 \leq t_{\text{agr,d}} \leq 24 \tag{A.73}$$

where:

$t_{\text{agr,d}}$ Timestep agriculture day [h]

Electricity demand dwellings

The electrical load profile of dwellings can be divided into several parts. First, there is a basic electricity load profile of the houses that will be heated by natural gas or heated by a heat network. A certain share of these will have electric cooking resulting in demand peaks especially in the early morning and in the end of the afternoon and early evening. Another share of the houses will have air-conditioning due to rising temperatures in the summer. This also results in a higher electricity consumption profile in the summer. There are also houses that are all-electric, both newly constructed and adapted, and have a similar profile to the basic load profile but the load is higher and is fluctuating more.

$$E_{\text{D,dw},t} = E_{\text{D,dw,NG},t} + E_{\text{D,dw,HN},t} + E_{\text{D,dw,HP},t} \tag{A.74}$$

where:

$E_{\text{D,dw},t}$ Electricity demand dwellings [MWh]
$E_{\text{D,dw,NG},t}$ Electricity demand dwellings natural gas [MWh]
$E_{\text{D,dw,HN},t}$ Electricity demand dwellings heat network [MWh]
$E_{\text{D,dw,HP},t}$ Electricity demand dwellings heat pump [MWh]

$$E_{\text{D,dw,NG},t} \geq 0 \tag{A.75}$$
$$E_{\text{D,dw,HN},t} \geq 0 \tag{A.76}$$
$$E_{\text{D,dw,HP},t} \geq 0 \tag{A.77}$$

where:

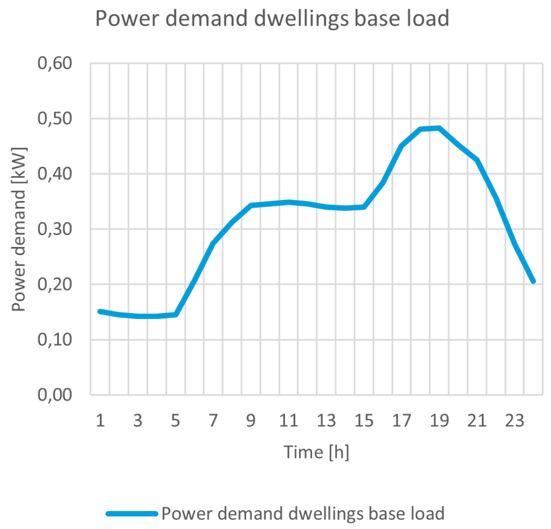
$E_{\text{D,dw,NG},t}$ Electricity demand dwellings natural gas [MWh]
$E_{\text{D,dw,HN},t}$ Electricity demand dwellings heat network [MWh]
$E_{\text{D,dw,HP},t}$ Electricity demand dwellings heat pump [MWh]

$$n_{\text{dw,total}} = n_{\text{dw,NG}} + n_{\text{dw,HN}} + n_{\text{dw,HP}} \tag{A.78}$$

where:

$n_{\text{dw,total}}$ Number of dwellings total [-]
$n_{\text{dw,NG}}$ Number of dwellings natural gas [-]
$n_{\text{dw,HN}}$ Number of dwellings heat network [-]
$n_{\text{dw,HP}}$ Number of dwellings heat pump [-]

The Vereniging Nederlandse Energie Data Uitwisseling (NEDU) has data available regarding load profiles, based on smart-meter data of more than 3 million households from the year 2016 (Kewo et al., 2020). The load profile indicated by Kewo et al., given in the share per hour [%], can be used as the base load profile which is kind of equal throughout the year.



Graph 7 Power demand dwellings base load per dwelling

Figure A.5: Power demand dwellings base load

On average, a household used 6.77 [kWh] per day based on the yearly electricity use of 2,499 [kWh] in 2021. This represents mostly electronic devices and domestic appliances but varies a bit through the year. June for instance have a share of a bit less than 8.0 [%] while January on the other hand has a share of 9.0 [%] (Kewo et al., 2020). Including the number of days per month, the average electricity use per day for electronic devices and domestic appliances can be determined from the yearly consumption and monthly share. Multiplying this with the hourly power demand share for dwellings, the hourly basic electricity load throughout the year can be calculated.

The base load power demand as mentioned in the equations below can, after conversion from [kW] to [MW], be taken from the graph below as this graph represents the basic load profile per dwelling.

Season	Seasonal share [-]	Montly share [-]
Winter	0.26	0.09
Spring	0.25	0.08
Summer	0.25	0.08
Autumn	0.24	0.08

Table A.3: Seasonal differences in basic power demand

$$E_{\text{D,dw,NG},t} = \left(P_{\text{D,dw,base},t} \cdot n_{\text{dw,NG}} + P_{\text{D,cooling},t} \cdot n_{\text{dw,NG,Airco}} + P_{\text{D,cooking},t} \cdot n_{\text{dw,NG,cooking}}\right) \cdot t \tag{A.79}$$

where:

$E_{\text{D,dw,NG},t}$ Electricity demand dwellings natural gas [MWh]
$P_{\text{D,dw,base},t}$ Power demand dwellings base load [MW]
$n_{\text{dw,NG}}$ Number of dwellings natural gas [-]
$P_{\text{D,cooling},t}$ Power demand cooling [MW]
$n_{\text{dw,NG,Airco}}$ Number of natural gas dwellings air-conditioning [-]
$P_{\text{D,cooking},t}$ Power demand cooking [MW]
$n_{\text{dw,NG,cooking}}$ Number of natural gas dwellings cooking [-]
t Timestep [h]

$$E_{\text{D,dw,HN},t} = (P_{\text{D,dw,base},t} \cdot n_{\text{dw,HN}} + P_{\text{D,cooling},t} \cdot n_{\text{dw,HN,Airco}} + P_{\text{D,cooking},t} \cdot n_{\text{dw,HN,cooking}}) \cdot t \tag{A.80}$$

where:

$E_{\text{D,dw,HN},t}$ Electricity demand dwellings heat network [MWh]
$P_{\text{D,dw,base},t}$ Power demand dwellings base load [MW]
$n_{\text{dw,HN}}$ Number of dwellings heat network [-]
$P_{\text{D,cooling},t}$ Power demand cooling [MW]
$n_{\text{dw,HN,Airco}}$ Number of heat network dwellings air-conditioning [-]
$P_{\text{D,cooking},t}$ Power demand cooking [MW]
$n_{\text{dw,HN,cooking}}$ Number of heat network dwellings cooking [-]
t Timestep [h]

Houses that have a heat pump will have a different electricity consumption profile than houses using natural gas or heat due to additional demand for heating, production of hot water, and electric cooking. The electricity demand of all-electric houses consists therefore of the demand for heating, the production of hot water, and cooking, additional to the base load of electrical devices.

$$E_{\text{D,dw,HP},t} = (P_{\text{D,dw,base},t} + P_{\text{D,heating},t} + P_{\text{D,water},t} + P_{\text{D,cooking},t} + P_{\text{D,cooling},t}) \cdot n_{\text{dw,HP}} \cdot t \tag{A.81}$$

where:

$E_{\text{D,dw,HP},t}$ Power demand dwellings heat pump [MWh]
$P_{\text{D,dw,base},t}$ Power demand dwellings base load [MW]
$P_{\text{D,heating},t}$ Power demand heating [MW]
$P_{\text{D,water},t}$ Power demand hot water [MW]
$P_{\text{D,cooking},t}$ Power demand cooking [MW]
$P_{\text{D,cooling},t}$ Power demand cooling [MW]
$n_{\text{dw,HP}}$ Number of dwellings heat pump [-]
t Timestep [h]

$$n_{\text{dw,NG}} \geq 0 \tag{A.82}$$

$$n_{\text{dw,HN}} \geq 0 \tag{A.83}$$

$$n_{\text{dw,HP}} \geq 0 \tag{A.84}$$

$$n_{\text{dw,NG,Airco}} \geq 0 \tag{A.85}$$

$$n_{\text{dw,NG,cooking}} \geq 0 \tag{A.86}$$

$$n_{\text{dw,HN,Airco}} \geq 0 \tag{A.87}$$

$$n_{\text{dw,HN,cooking}} \geq 0 \tag{A.88}$$

where:

$n_{\text{dw,NG}}$ Number of dwellings natural gas [-]
$n_{\text{dw,HN}}$ Number of dwellings heat network [-]
$n_{\text{dw,HP}}$ Number of dwellings heat pump [-]
$n_{\text{dw,NG,Airco}}$ Number of natural gas dwellings air-conditioning [-]
$n_{\text{dw,NG,cooking}}$ Number of natural gas dwellings cooking [-]
$n_{\text{dw,HN,Airco}}$ Number of heat network dwellings air-conditioning [-]
$n_{\text{dw,HN,cooking}}$ Number of heat network dwellings cooking [-]

$$P_{\text{D,dw,base},t} \geq 0 \tag{A.89}$$

$$P_{\text{D,heating},t} \geq 0 \tag{A.90}$$

$$P_{\text{D,water},t} \geq 0 \tag{A.91}$$

$$P_{\text{D,cooking},t} \geq 0 \tag{A.92}$$

$$P_{\text{D,cooling},t} \geq 0 \tag{A.93}$$

where:

$P_{\text{D,dw,base},t}$ Power demand dwellings base load [MW]
$P_{\text{D,heating},t}$ Power demand heating [MW]
$P_{\text{D,water},t}$ Power demand hot water [MW]
$P_{\text{D,cooking},t}$ Power demand cooking [MW]
$P_{\text{D,cooling},t}$ Power demand cooling [MW]

The so-called graaddagen method can be used to determine the share of electricity demand for heating by heat pumps per month and day (Huurcommissie, 2022). This method is used for determining the natural gas demand and considers the time of the year as the outside temperature varies through the year. This method includes however the hot water profile, as natural gas is normally used for heating water as well (Timme van Melle et al., 2015). Therefore, the profile based on the graaddagen method is corrected by subtracting the hot water profile. These differ from each other in reality. The hot water profile is taken from Quintel (Dataset Manager, n.d.). Ecofys described the power demand profile for electrical cooking (Timme van Melle et al., 2015). The results of the power demand profiles for heating, production of hot water, and cooking are provided in the graph below.

$$E_{\text{D,cooking},t} = P_{\text{D,cooking},t} \cdot t \tag{A.94}$$

where:

$E_{\text{D,cooking},t}$ Electricity demand cooking [MWh]
$P_{\text{D,cooking},t}$ Power demand cooking [MW]
t Timestep [h]

$$E_{\text{D,water},t} = P_{\text{D,water},t} \cdot t \tag{A.95}$$

where:

$E_{\text{D,water},t}$ Electricity demand hot water [MWh]
$P_{\text{D,water},t}$ Power demand hot water [MW]
t Timestep [h]

Month	Graaddagen	Share [-]
January	499	0.18
February	423	0.15
March	360	0.13
April	272	0.10
May	169	0.06
June	24	0.01
July	11	0.00
August	30	0.01
September	54	0.02
October	199	0.07
November	350	0.12
December	430	0.15

Table A.4: Overview n ”graaddagen” per month

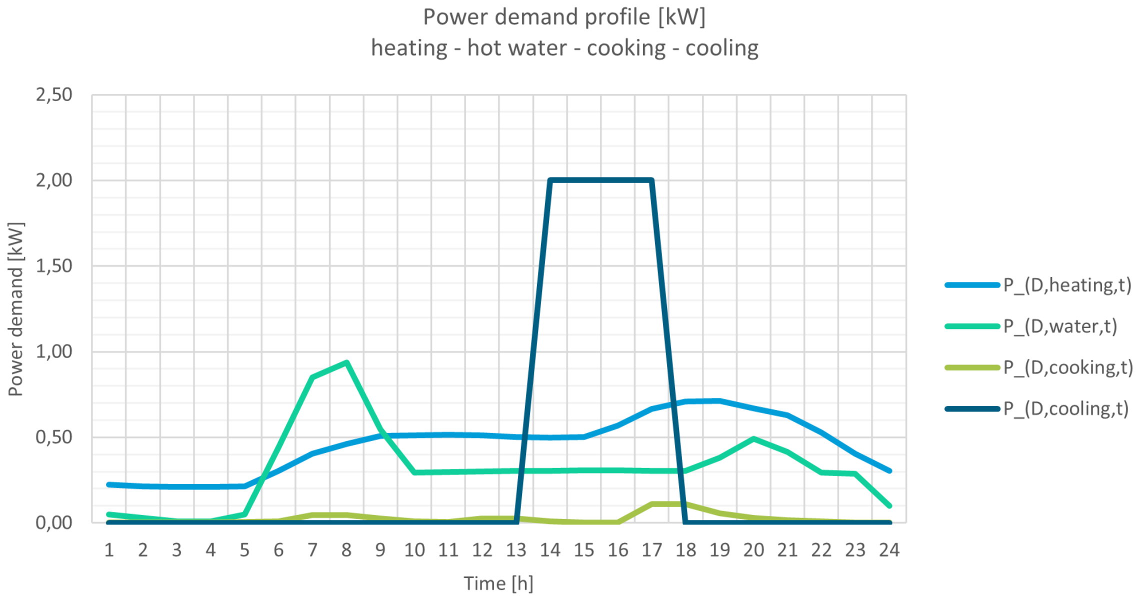


Figure A.6: Power demand profiles heating, hot water, cooking, cooling

CE Delft expects a 65 [%] market share of electric cooking in 2030, and 80 [%] in 2050. It can be assumed that all newly constructed and adapted houses to all-electric will have electric cooking. This is less than the expected market share in 2030, thus a part of the houses that are still heated by natural gas or connected to a heat network will also have electric cooking. Therefore, electric cooking is part of the power demand formulas for houses that are connected to the natural gas network and heat network, and all-electric houses.

Air-conditioning is included in the functions because this will result in higher energy demand for several hours a day during warm days in summer.

$$E_{\text{D,cooling},t} = P_{\text{D,cooling},t} \cdot t \tag{A.96}$$

where:

$E_{\text{D,cooling},t}$ Electricity demand cooling [MWh]
$P_{\text{D,cooling},t}$ Power demand cooling [MW]
t Timestep [h]

$$\text{if } T_{\text{outside}} > 23 \implies P_{\text{D,cooling},t} > 0 \tag{A.97}$$

where:

T_{outside} Outside temperature [°C]
$P_{\text{D,cooling},t}$ Power demand cooling [MW]

$$\text{if } T_{\text{outside}} \leq 23 \implies P_{\text{D,cooling},t} = 0 \tag{A.98}$$

where:

T_{outside} Outside temperature [°C]
$P_{\text{D,cooling},t}$ Power demand cooling [MW]

Some electric cars will be charged at home, but this is excluded from the load profiles of dwellings as these are included in the mobility part of the electrical demand.

Electricity demand mobility

The electricity demand of mobility consists of the electricity demand of electric vehicles and electric vans. It is assumed that heavy transportation such as trucks will use hydrogen. The charging of electric bikes and the remaining modalities are excluded from the model.

$$E_{\text{D,mob,t}} = E_{\text{D,vehicles,t}} + E_{\text{D,vans,t}} \tag{A.99}$$

where:

$E_{\text{D,mob,t}} =$ Electricity demand mobility [MWh]
$E_{\text{D,vehicles,t}} =$ Electricity demand electric vehicles [MWh]
$E_{\text{D,vans,t}} =$ Electricity demand electric vans [MWh]

The electricity load profile of electric vehicles and electric vans is visualised by CE Delft, based on 1.9 million electric vehicles and 115,000 electric vans as the objective of the Klimaatakkoord (Frans Rooijers et al., 2020). The load profile of electric vehicles repeats itself from Monday to Friday but has a different character on Saturday and Sunday as a result of less car use during the weekend. The peak demands are mostly in the early morning when people go to work and at the end of the afternoon when people are coming home. Electric vans have a similar pattern as in that it repeats itself during the week and deviates on weekends. Vans will charge mostly during the night but also in the early morning and around noon, so the pattern differs per day between passenger cars and vans.

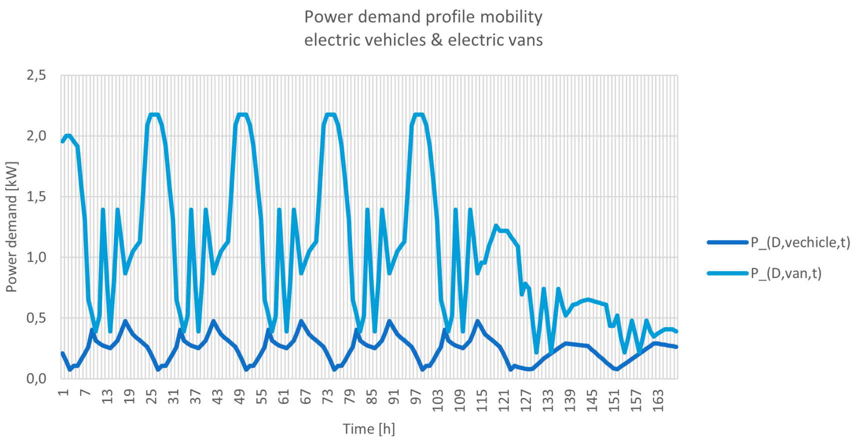


Figure A.7: Enter Caption

The deviation of vans sets in as early as Friday. Additionally, the power demand of a single van is greater than the power demand of an electric passenger car. The load profiles are given in the graph below and include charging at home, charging in public, charging at work and fast charging and can be translated into a profile that reflects the expected number of electric vehicles and electric vans in Zeeland. The electricity demand can be calculated by the power demand multiplied by the time and number of electrical modalities.

$$E_{\text{D,vechicles},t} = P_{\text{D,vechicle},t} \cdot t \cdot n_{\text{el.vehicles}} \tag{A.100}$$

where:

$E_{\text{D,vechicles},t}$ Electricity demand electric vehicles [MWh]
$P_{\text{D,vechicle},t}$ Power demand electric vehicle [MW]
$n_{\text{el.vehicles}}$ Number of electric vehicles [-]
t Timestep [h]

$$E_{\text{D,vans},t} = P_{\text{D,van},t} \cdot t \cdot n_{\text{el.vans}} \tag{A.101}$$

where:

$E_{\text{D,vans},t}$ Electricity demand electric vans [MWh]
$P_{\text{D,van},t}$ Power demand electric van [MW]
$n_{\text{el.vans}}$ Number of electric vans [-]
t Timestep [h]

$$P_{\text{D,vechicle},t}, P_{\text{D,van},t} \geq 0 \tag{A.102}$$

where:

$P_{\text{D,vechicle},t}$ Power demand electric vehicle [MW]
$P_{\text{D,van},t}$ Power demand electric van [MW]

$$n_{\text{el.vehicles}}, n_{\text{el.vans}} \geq 0 \tag{A.103}$$

where:

$n_{\text{el.vehicles}}$ Number of electric vehicles [-]
$n_{\text{el.vans}}$ Number of electric vans [-]

A.3.6. Emissions

As a result of electricity generation by fossil power plants, CO2 emissions are released. Evaluating the added social value of UPHS, the CO2 emissions saved need to be calculated for the different scenarios. For each type of power plant numbers are available on how many tonnes of CO2 are released by the production of 1 [MWh]. The total carbon emissions at a certain moment, as result of electricity production by fossil power, is the sum of the carbon emissions emitted at that moment by the different fossil power generators. These are Elsta, Seasun B.V., and Sloecentrale.

$$\text{CO}2, \text{em}, t = \text{CO}2, \text{Elsta}, t + \text{CO}2, \text{Seasun}, t + \text{CO}2, \text{Sloe}, t \tag{A.104}$$

Where:

$\text{CO}2, \text{em}, t$ Carbon emissions of fossil power [CO2]
$\text{CO}2, \text{Elsta}, t$ Carbon emissions of Elsta Power [CO2]
$\text{CO}2, \text{Seasun}, t$ Carbon emissions of Seasun B.V. [CO2]
$\text{CO}2, \text{Sloe}, t$ Carbon emissions of Sloecentrale [CO2]

The carbon emissions per fossil generator can be calculated by multiplying the electricity generation by the carbon emission rate per produced energy unit. Therefore, the power output of the power geneator need to be multiplied by the duration of the timestep.

$$\text{CO}_{2(\text{Elsta},t)} = P_{(\text{Elsta},t)} \cdot t \cdot \text{CO}_{2\text{NG}} \tag{A.105}$$

Where:

$\text{CO}_{2(\text{Elsta},t)}$ = Carbon emissions of Elsta Power [CO_2]
$P_{(\text{Elsta},t)}$ = Power output Elsta Power [MW]
t = timestep [h]
$\text{CO}_{2\text{NG}}$ = Carbon emissions of a natural gas plant [CO_2/MWh]

$$\text{CO}_{2(\text{Seasun},t)} = P_{(\text{Seasun},t)} \cdot t \cdot \text{CO}_{2\text{WKK}} \tag{A.106}$$

Where:

$\text{CO}_{2(\text{Seasun},t)}$ = Carbon emissions of Seasun B.V. [CO_2]
$P_{(\text{Seasun},t)}$ = Power output Seasun B.V. [MW]
t = timestep [h]
$\text{CO}_{2\text{WKK}}$ = Carbon emissions of a WKK plant [CO_2/MWh]

$$\text{CO}_{2(\text{Sloe},t)} = P_{(\text{Sloe},t)} \cdot t \cdot \text{CO}_{2\text{NG}} \tag{A.107}$$

Where:

$$\text{CO}_{2(\text{Sloe},t)} = \text{Carbon emissions of Sloecentrale [CO}_2\text{]}$$
$$P_{(\text{Sloe},t)} = \text{Power output Sloecentrale [MW]}$$
$$t = \text{timestep [h]}$$
$$\text{CO}_{2\text{NG}} = \text{Carbon emissions of a natural gas plant [CO}_2\text{/MWh]}$$

It can be assumed that the carbon emissions of a natural gas plant is equal to 0.37 [CO2/MWh], and the carbon emissions of a WKK is equal to 0.38 [CO2/MWh].

A.3.7. Economics

Whether certain generators will produce electricity or not goes along with economic factors. Currently, the main determinants are marginal costs and the day-ahead price. However, for the added value of UPHS, it is interesting to also look at the difference in costs for CO2 emissions and not being able to supply a certain amount of energy. As for a business case that fits the current market, the value of electricity at the time of charging and discharging can be looked at, and how that compares with previous investments. The table below shows the assumed marginal costs and will be explained next.

System costs	Value per unit
Solar PV	1 [€/MWh]
Onshore wind	1 [€/MWh]
Offshore wind	2 [€/MWh]
Nuclear power	15 [€/MWh]
Seasun B.V.	30 [€/MWh]
Sloecentrale	60 [€/MWh]
Elsta Power	60 [€/MWh]
Curtailment	150 [€/MWh]
Electricity shortages	68,887 [€/MWh]
Import	Day ahead [€/MWh]
Export	Day ahead [MWh]
Carbon emissions	80 [€/ton]

Table A.5: Overview system costs, value per unit

Marginal costs & production costs

Every power generator has certain marginal costs. These are the costs of one additional product. Marginal costs for wind turbines and solar farms are low because they do not require fuels. The marginal cost of nuclear power is already somewhat higher because of the necessary raw materials uranium or thorium. In contrast, coal- and gas-fired power plants have much higher marginal costs because they use coal and natural gas. In reality this also include the CO2 price because of the emission rights. Because the only WKK installation within Zeeland's electricity system runs on residual heat, the marginal costs of this plant are again somewhat lower.

The total production costs are determined by the marginal costs multiplied by the electricity produced. The functions below describe the production costs of offshore wind power, onshore wind power, solar power, and fossil power. The production costs of fossil power consists of the sum of total costs of power produced by Elsta, Seasun, and Sloecentrale.

$$\text{TC}_{\text{Product}} = \text{TC}_{(\text{off,w})} + \text{TC}_{(\text{on,w})} + \text{TC}_{\text{PV}} + \text{TC}_{\text{Ncl}} + \text{TC}_{\text{Fossil}} \tag{A.108}$$

Where:

$$
\begin{aligned}
\text{TC}_{\text{Product}} &= \text{Total costs offshore wind [€]} \\
\text{TC}_{\text{(off,w)}} &= \text{Total costs offshore wind [€]} \\
\text{TC}_{\text{(on,w)}} &= \text{Total costs onshore wind [€]} \\
\text{TC}_{\text{PV}} &= \text{Total costs solar PV [€]} \\
\text{TC}_{\text{Ncl}} &= \text{Total costs nuclear power [€]} \\
\text{TC}_{\text{Fossil}} &= \text{Total costs fossil power [€]}
\end{aligned}
$$

$$\text{TC}_{\text{(off,w)}} = \text{MC}_{\text{(off,w)}} \cdot E_{\text{(off,w)}} \tag{A.109}$$

Where:

$$
\begin{aligned}
\text{TC}_{\text{(off,w)}} &= \text{Total costs offshore wind [€]} \\
\text{MC}_{\text{(off,w)}} &= \text{Marginal costs offshore wind [€/MWh]} \\
E_{\text{(off,w)}} &= \text{Total electricity production offshore wind [MWh]}
\end{aligned}
$$

$$\text{TC}_{\text{(on,w)}} = \text{MC}_{\text{(on,w)}} \cdot E_{\text{(on,w)}} \tag{A.110}$$

Where:

$$
\begin{aligned}
\text{TC}_{\text{(on,w)}} &= \text{Total costs onshore wind [€]} \\
\text{MC}_{\text{(on,w)}} &= \text{Marginal costs onshore wind [€/MWh]} \\
E_{\text{(on,w)}} &= \text{Total electricity production onshore wind [MWh]}
\end{aligned}
$$

$$\text{TC}_{\text{PV}} = \text{MC}_{\text{PV}} \cdot E_{\text{(PV)}} \tag{A.111}$$

Where:

$$
\begin{aligned}
\text{TC}_{\text{PV}} &= \text{Total costs solar PV [€]} \\
\text{MC}_{\text{PV}} &= \text{Marginal costs solar PV [€/MWh]} \\
E_{\text{(PV)}} &= \text{Total electricity production solar PV [MWh]}
\end{aligned}
$$

$$\text{TC}_{\text{Ncl}} = \text{MC}_{\text{Ncl}} \cdot E_{\text{(Ncl)}} \tag{A.112}$$

Where:

$$
\begin{aligned}
\text{TC}_{\text{Ncl}} &= \text{Total costs nuclear power [€]} \\
\text{MC}_{\text{Ncl}} &= \text{Marginal costs nuclear power [€/MWh]} \\
E_{\text{(Ncl)}} &= \text{Total electricity production nuclear power [MWh]}
\end{aligned}
$$

$$\text{TC}_{\text{Fossil}} = \text{TC}_{\text{Elsta}} + \text{TC}_{\text{Seasun}} + \text{TC}_{\text{Sloe}} \tag{A.113}$$

Where:

$$\begin{aligned}
\text{TC}_{\text{Fossil}} &= \text{Total costs fossil power [€]}\\
\text{TC}_{\text{Elsta}} &= \text{Total costs Elsta Power [€]}\\
\text{TC}_{\text{Seasun}} &= \text{Total costs Seasun B.V. [€]}\\
\text{TC}_{\text{Sloe}} &= \text{Total costs Sloecentrale [€]}
\end{aligned}$$

$$\text{TC}_{\text{Elsta}} = \text{MC}_{\text{Elsta}} \cdot E_{\text{(Elsta)}} \tag{A.114}$$

Where:

$$\begin{aligned}
\text{TC}_{\text{Elsta}} &= \text{Total costs Elsta power [€]}\\
\text{MC}_{\text{Elsta}} &= \text{Marginal costs Elsta power [€/MWh]}\\
E_{\text{(Elsta)}} &= \text{Total electricity production by Elsta Power [MWh]}
\end{aligned}$$

$$\text{TC}_{\text{Seasun}} = \text{MC}_{\text{Seasun}} \cdot E_{\text{(Seasun)}} \tag{A.115}$$

Where:

$$\begin{aligned}
\text{TC}_{\text{Seasun}} &= \text{Total costs Seasun B.V. [€]}\\
\text{MC}_{\text{Seasun}} &= \text{Marginal costs Seasun B.V. [€/MWh]}\\
E_{\text{(Seasun)}} &= \text{Total electricity production by Seasun B.V. [MWh]}
\end{aligned}$$

$$\text{TC}_{\text{Sloe}} = \text{MC}_{\text{Sloe}} \cdot E_{\text{Sloe}} \tag{A.116}$$

Where:

$$\begin{aligned}
\text{TC}_{\text{Sloe}} &= \text{Total costs Sloecentrale [€]}\\
\text{MC}_{\text{Sloe}} &= \text{Marginal costs Sloecentrale [€/MWh]}\\
E_{\text{Sloe}} &= \text{Total electricity production by Sloecentrale [MWh]}
\end{aligned}$$

Whether certain generators will produce electricity or not goes along with economic factors. Currently, the main determinants are marginal costs and the day-ahead price. However, for the added value of UPHS, it is interesting to also look at the difference in costs for CO2 emissions and not being able to supply a certain amount of energy. As for a business case that fits the current market, the value of electricity at the time of charging and discharging can be looked at, and how that compares with previous investments.

Day-ahead

The day-ahead price varies through the day, week, and year, and is determined by the intersection of power supply and power demand at national level. The simplest way to do this is to use a dataset of ENTSOE. It is important that the year this dataset comes from matches the year the wind data and global radiation comes from. Because these are related to each other in reality. At times of high wind speeds or solar radiation, the production of renewable energy increases and therefore the day-ahead price decreases. The demand datasets already consider seasonal and daily variations. Datasets from the same year for wind speed, global radiation, and the day-ahead price will sufficiently mimic reality.

Furthermore, it is worth noting that to model the current situation, a dataset of the day-ahead price of the Netherlands for an entire year must be adopted. Because Zeeland supplies more electricity than it demands in reality. However, when compiling an experiment looking at a regional market model, a model in which the energy price is determined at the regional level is required. Therefore, a function should be compiled in which the energy price is determined based on energy demand and supply in the Zeeland.

Carbon dioxide tax

The costs for carbon emissions can be calculated by multiplying the value of carbon emissions with the emitted emissions in a certain period.

$$\text{TC}_{\text{Carbon}} = V_{\text{carbontax}} \cdot \text{CO}_{\text{2em}} \tag{A.117}$$

Where:

$$\begin{aligned} \text{TC}_{\text{Carbon}} &= \text{Total costs carbon emissions [€]} \\ V_{\text{carbontax}} &= \text{Value carbon emissions [€/tonCO}_2\text{]} \\ \text{CO}_{\text{2em}} &= \text{Carbon emissions [tonCO}_2\text{]} \end{aligned}$$

Value of lost load

The costs for lost load can be calculated by multiplying the value of lost load with the occurred lost load in a certain period.

$$\text{TC}_{\text{lostload}} = V_{\text{lostload}} \cdot E_{\text{Shortage}} \tag{A.118}$$

Where:

$$\begin{aligned} \text{TC}_{\text{lostload}} &= \text{Total costs lost load [€]} \\ V_{\text{lostload}} &= \text{Value of lost load [€/MWh]} \\ E_{\text{Shortage}} &= \text{Total electricity shortages [MWh]} \end{aligned}$$

Value of charge- and discharge

Charging and discharging of UPHS can be given a certain value by using the day-ahead price of charging and discharging at a certain moment. This can be used to evaluate a business case according to current market conditions.

$$V_{\text{charge}} = \sum_{t=a}^{b} \left(P_{\text{(charge,t)}} \cdot t \cdot V_{\text{(day-ahead,t)}}\right) \tag{A.119}$$

Where:

$$\begin{aligned} V_{\text{charge}} &= \text{Value of UPHS charge [€]} \\ P_{\text{(charge,t)}} &= \text{UPHS charge rate [MWh]} \\ t &= \text{Timestep [h]} \\ V_{\text{(day-ahead,t)}} &= \text{Day-ahead price electricity [€/MWh]} \end{aligned}$$

$$V_{\text{discharge}} = \sum_{t=a}^{b} \left(P_{\text{(discharge,t)}} \cdot t \cdot V_{\text{(day-ahead,t)}}\right) \tag{A.120}$$

Where:

$$\begin{aligned} V_{\text{discharge}} &= \text{Value of UPHS discharge [€]} \\ P_{\text{(discharge,t)}} &= \text{UPHS discharge rate [MWh]} \\ t &= \text{Timestep [h]} \\ V_{\text{(day-ahead,t)}} &= \text{Day-ahead price electricity [€/MWh]} \end{aligned}$$

A.4. Computational model

The modelling cycle is an iterative process that can be seen in the modelling process of this research as well. First, an Excel model is made to identify the variables and correlations and gain insight into model behaviour. Excel has some limitations when it comes to dynamic modelling and huge datasets as input. Therefore, the software Linny-R is used to develop a model that works dynamically with datasets, and in which scenario-development is easy to implement. Linny-R is a graphical specification language for mixed integer linear programming (MILP) problems, developed by Pieter Bots at TU Delft.

This chapter first describes how the input variables, internal variables, output variables, equations, and created datasets, as presented in the previous subchapter, are implemented in Linny-R. Subsequently, the model is validated by reflecting on the consistency between the conceptual model, operational model, and the developed model in Linny-R, and if the model outputs can be used to answer the research question. Then, the model is verified to be sure that the model is working correctly, by comparing model outputs and system behaviour with the real world. This also includes a sensitivity analysis.

A.4.1. Model development in Linny-R

As mentioned, Linny-R is a graphical specification language for MILP problems. It works with processes, products, and arrows. A product represents something that can be produced or consumed by a process, visualised by an oval. A process represents a transformation of some products into other products, visualised by a square. These processes need to be linked to at least one product. The arrows represent the link of a potential product flow and its direction. Using Linny-R, a model can be made that calculates different power flows in various directions within a system, taking into account the capacities of the power grid.

The capacities of the high-voltage grid in Zeeland are provided in the analysis of Zeeland. This data has to be used to build the model in Linny-R. Each station in the high-voltage grid has been given a place in the model using so-called products, named energy hubs or nodes and labelled with the name of the area. In an energy hub, both electricity is produced, and electricity is required by for example industries and dwellings. A node on the other hand is a place where only energy is demanded. In reality, the nodes and hubs are connected with cables, and therefore in the model with arrows. The arrows indicate the possibility of a product flow of electricity.

The model is structured following the geographical layout of Zeeland. However, a simplification was made in the model by merging the municipalities of Kapelle, Goes, Noord Beveland, Schouwen-Duiveland and Tholen as one subarea. This area is labelled as the remaining part of Zeeland. The Westerschelde flows horizontally between Borssele and Terneuzen. Further, Rilland is the only place where electricity can get out of the system, and all electricity surpluses below the Westerschelde nees to be transmitted through the cable from Terneuzen to Borssele.

The maximum amount of current that can flow in one direction at a time, is for each cable specified. Current can flow from A to B or from B to A, but not from A to B and B to A at the same time, and taking the maximum transmissions capacity into account. Therefore, an additional process step has been made to each connection between nodes and energy hubs.

From energy hub A, for ample Rilland, electricity can flow towards energy B, for example, the Dutch transmission grid. Electricity can also flow from B to A. To model these directions two processes are made, for each cable one process. The upper process in the figure represents the transmission from the Dutch grid to Rilland, and the lower process represents the transmission from Rilland to the Durch grid. By bounding both processes by setting the upper bounds equal to the maximum capacity, the capacity constraint of this cable is implemented. In the example between Rilland and the Dutch transmission grid the maximum capacity is 1645 [MVA]. This is equal to 1645 [MW].

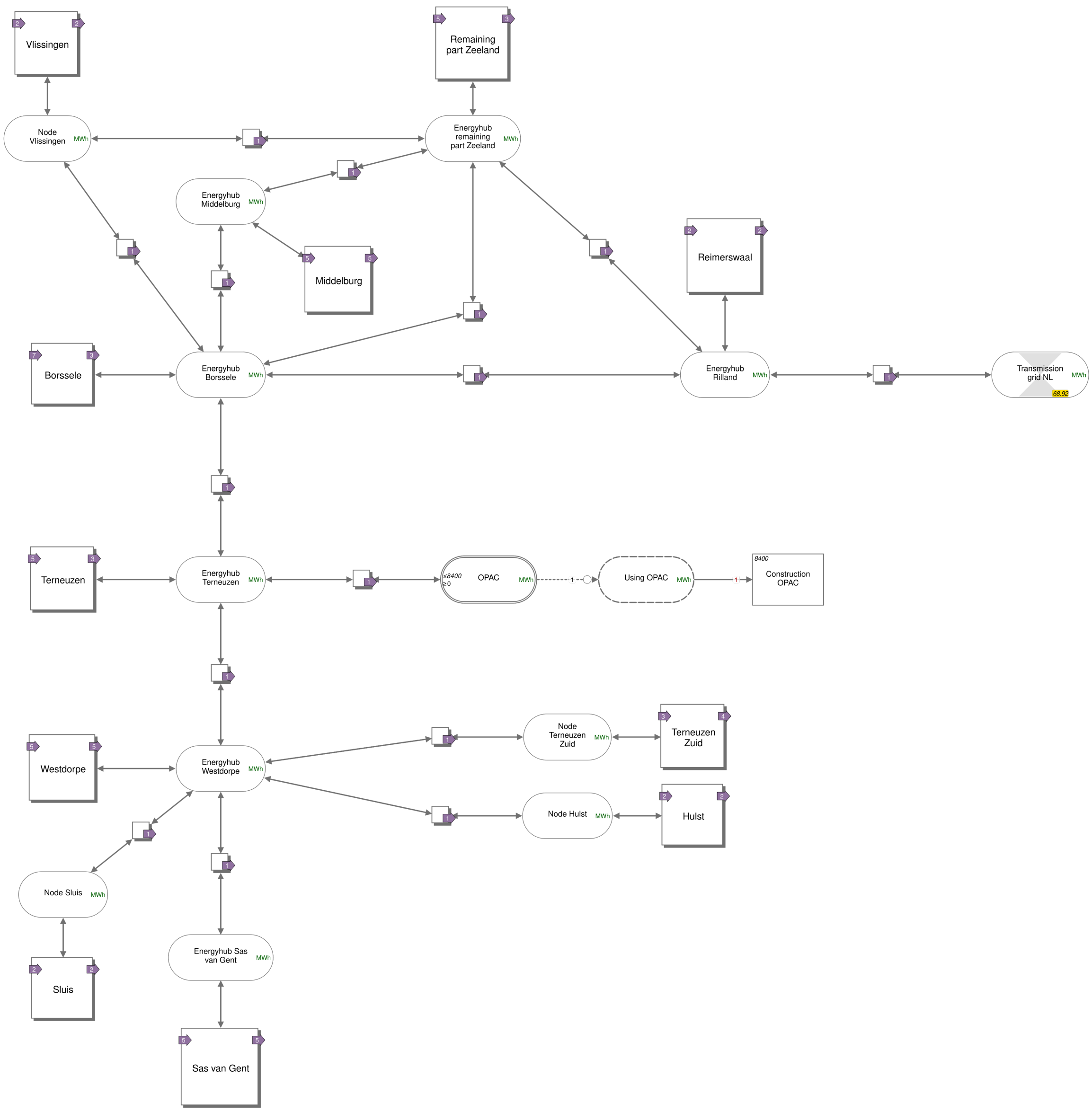


Figure A.8: Impression model in Linny-R

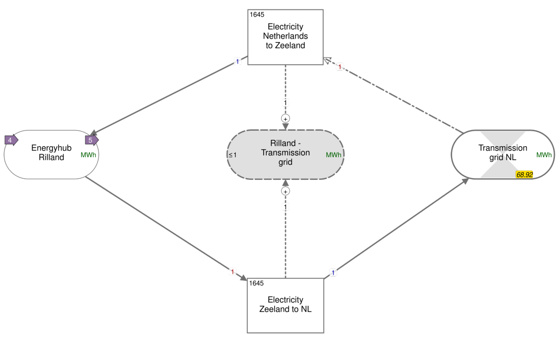


Figure A.9: Modelling of grid constraints

Subsequently, it has been implemented that electricity can only flow in one direction. This has been done using the grey data product in the middle. A data product only measures information thus no physical power passes through this. A data arrow has been drawn from both cable processes to the data product. A + sign in the flow is given here. This data arrow indicates that if the flow through the cable is greater than 0, the value of the data arrow equals the number 1, regardless of how large the flow is. If no current flows through the cable, i.e. the process, then the data flow is equal to 0. The data product consumes these values of 0 or 1 from the cable process. Subsequently, the data product is given the constraint that it cannot be greater than 1. In other words, the sum of both data arrows together may not be greater than 1. This results in a single flow between these locations because electricity in both directions will bring the data product to 2 which is not allowed by the model.

Clusters represent a group of processes, visualised by squares with shadows behind them. These are used to keep the model clear. So, within a cluster, electricity can be generated and used.

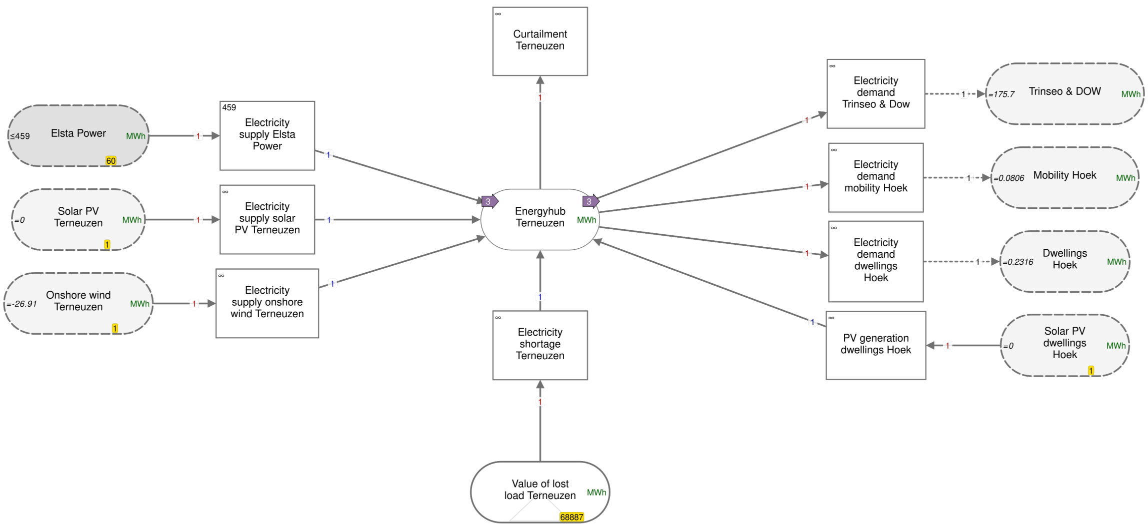


Figure A.10: Modelling energy hubs in Linny-R

The principle of the energy hub is that electricity generated enters the hub and the electricity required in that area leaves the hub. Within a cluster, structure is given by putting power generators on the left side and the sectors that require electricity on the right side. This is shown in the figure below. Furthermore, electricity can also enter the cluster from another energy hub through a cable as described earlier on. This happens when the hub itself does not produce enough electricity. Conversely, electricity can also leave the energy hub to another hub. This happens when there is an electricity surplus.

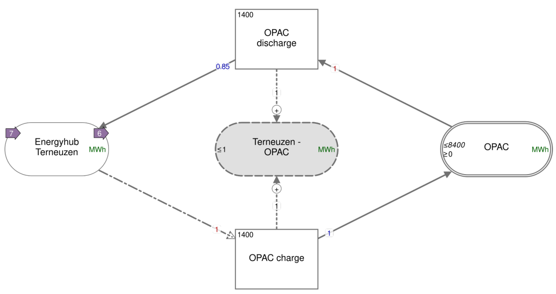


Figure A.11: Modelling of UPHS in Linny-R

As described, there are constraints in the model such as the maximum capacity of the grid. There are also other constraints to get the desired output variables. Therefore, the minimum output from renewable sources, the lower bound, must equal the electricity that could be generated at that time. In other words, electricity from renewable sources is produced regardless of grid capacity. If there is no enough grid capacity to distribute surpluses of electricity to other parts of Zeeland, the residual electricity can leave the energy hub through the curtailment process within that hub. Every hub has this process, and the values of these processes can be summed up, site-specifically and in total, at a specific time but also over an entire period. This enables the possibility of measuring curtailment location specifically and time-based. In contrast, electricity shortages may also occur. If there is insufficient electricity production within an energy hub, and the grid cannot feed in the required amount of electricity due to grid constraints, electricity can still enter the hub through the electricity shortage process. This is however linked to the value of lost load product. This means however that when electricity is taken from this process, the costs of value of lost load come over as well. This is similar to the marginal costs of wind turbines and a natural gas plant for example, and the day-ahead price of electricity from the Dutch grid, but the value of lost load is significantly higher than these. Therefore, the model will only use lost load if there is no other opportunity. In the real world, industries are being asked to scale down their activities and get paid by the value of lost load per energy quantity. This is a compensation for not being able to operate.

In terms of electricity production, the model also includes that electricity is produced by solar PV owned by households. In the model, this has been placed on the right side within the cluster, below the electricity demand of dwellings. In reality, the electricity demand of dwellings is the residual electricity demand, which is the remaining demand after all produced electricity by their solar panels are used by the dwellings themselves. On the other hand, dwellings can therefore feed electricity back to the grid when the electricity produced exceeds their electricity demand.

Further, the production of electricity from onshore wind turbines and large-scale solar PV is done proportionally by surface ratio. The production of wind and solar power is therefore more divided equally. This ratio is different in the real world. Currently, below the Westerschelde there are mainly large-scale solar PV installations while there are mainly onshore wind turbines above the Westerschelde. It is uncertain how the construction of wind turbines and solar PV will develop in the future. These developments are dependent on landowners and technological developments for example, and the regulation associated with these in terms of distance to residential areas for example. To maintain consistency, and to properly examine the impact of UPHS, the model assumes a distribution of turbines and solar PV by surface and increases in ratio in the scenarios towards 2030, 2040, and 2050.

Offshore wind farms are all connected to the energy hub of Borssle, where also a new nuclear power plant may be built. The location of fossil power generators such as Elsta Power and Sloecentrale are site-specific.

Considering the location of UPHS, UPHS is modelled in Terneuzen. Therefore, a link is made from the installation UPHS to the energy hub Terneuzen. The representation of UPHS in the model of Linny-R is shown in the figure below. Important to note is that UPHS can only charge or discharge at a specific moment. In other words, electricity can only flows in one direction, which is similar to how the grid is modelled. The processes however are different because there are no cable processes but charge and discharge processes. The upper process represents the discharge process, and the lower process represents the charging process. The constraints are the charge and discharge capacities in stead of grid capacities. Furthermore, the efficiency of UPHS need to be taken into account which is 85 %. Therefore, one link is given a rate of 0.85.

A.4.2. Model validation

Subsequently, the model is validated by reflecting on the consistency between the conceptual model, operational model, and the developed model in Linny-R, and if the model outputs can be used to answer the research question.

Because of the iterative process of this research, the steps within the modelling cycle are consistent with each other. The visualization of the conceptual model was finalized after the electricity system analysis was performed. The correlations between variables and the established equations were finalized after the model was set up in linny-R, and this model was validated and verified for desired output and system behaviour. Adjustments in later steps were thus incorporated into earlier steps.

The model should be suitable for determining the value of UPHS within the electricity system of Zeeland. Therefore, the model should be able to simulate a simplified version of the electricity system of Zeeland and present the behaviour of electricity flows within the system in different scenarios over a period of time.

Regarding technical aspects, the model has to give insight into electricity surpluses, shortages, curtailment, lost load, import, and export quantities, both at specific locations and certain moments, but also as Zeeland as a whole over a while. These output variables can be used to assess for example the system efficiency and reliability of the power grid, but also any necessary reinforcements can be made more specific. By comparing scenarios in which UPHS does and does not play a role, the difference in these variables can be calculated, and therefore the added value of UPHS in technical terms. Network reinforcements and lost load can then be expressed as an economic factor for example.

The social added value in UPHS lies in, for example, that perhaps fewer grid reinforcements are needed, or other forms of energy storage that involve other negative impacts on public spaces and residents. So, the economic and technical output can be used to describe the social added value. The added value of UPHS is also in reducing emissions. These are therefore also part of the output variables. A related economic export variable is the cost of emission allowances in different price scenarios. This is to give an idea of scale.

Furthermore, it is also relevant for investors to know whether a revenue model is viable. For this reason, according to the current market principle, the day-ahead price is linked to UPHS charging and discharging through comparisons. The difference in this gives the earnings over a certain period. This can then be used to draw up a business case.

In summary, the model is mainly suitable for generating technical output variables, which can then be used to determine the economic and social value of UPHS. It should be emphasised here that the aim of the study is about the long-term social added value of UPHS. This cannot be measured directly from the model because the model simulates the electricity system of Zeeland. However, the model is suitable for answering the research question because it is needed to answer the research question more broadly. To determine the social added value, the technical and economic added value is required. The model is also suitable because it provides insight into system behaviour through the year, thus adding value over studies that only come up with summations of installed renewable capacities, energy production, and necessary flex capacity. The behaviour of UPHS in different seasons, on average, but also in extreme situations can therefore be evaluated.

A.4.3. Model verification

The model is verified to be sure that the model is working correctly, by comparing model outputs and system behaviour with the real world. Also, a sensitivity analysis is conducted to gain more insight into the behaviour of variables and the impact of change in some variables on the model outputs and thus conclusions. The model is verified by analysing the model outputs of the current situation first. Therefore, the data output of the whole modelling year 2025 is analysed. Sometimes, specific time ranges are used to show the differences throughout the year and to point out details. Some scenarios of 2030, 2040 and 2050 are also used for the model verification, as UPHS operates under circumstances of energy surpluses, which is less the case in 2025.

First, the basic principles of electricity demand, electricity supply, and economics will be verified. After this, correlations between the elements in the model are analysed and described according to the relevant parameters that determine the added value of UPHS. This needs to be consistent with the causal loop diagram.

Market conditions

As described earlier on, the day-ahead price in the model is not a function of the global radiation, velocity of the wind, and demand, but a real dataset. There is a correlation between these variables in reality, and therefore data for solar and wind production and the day-ahead price is taken from the same year which is 2019. The assumption is made that this sufficiently relates to reality because higher global radiation and higher velocity of the wind result in lower electricity prices. Since the data is from the same year, the correlation should be visible.

It is difficult to prove the correlation because the day-ahead price depends on the amount of installed capacity and real power output in the Netherlands. At the national level, the installed capacity of wind turbines was 4.5 GW, and the installed capacity of solar PV was 6.8 GW in 2019, thus the ratio was about 3:2. In Zeeland the ratio is completely different. The installed solar PV capacity in Zeeland in 2025 will be about 373 MW, and the installed wind turbine capacity was about 1,327 MW, a ratio of 1:4. Further, this does not indicate the real power output, because the degree of velocity of the wind has a significant impact on the power output due to the third-power function of wind turbines. This indicates that especially at higher wind speeds the price has to drop. The correlation between the power output of solar PV however is more linear with the global radiation. Also, a 10 MW wind turbine can actually deliver a power output of 10 MW, but a 10 MWp solar-PV installation can deliver a power output of 4.2 MW at maximum according to the global radiation in 2019. In summary, the day-ahead price in the model will have to go up more linearly with global solar radiation, and more in exponential form with an increase in wind speed. Because of the ratio of installed capacity of wind and solar, as well as the potential power output, the effect of solar and wind on the day-ahead price is in the same order of magnitude. Therefore, a graph is made from the day-ahead price, global radiation, and velocity of the wind. To determine if there is a correlation between weather and the day-ahead price in the model, the datasets of windspeed and solar radiation are stacked in a graph.

A graph from January is presented. In the first week of January, relatively higher peaks in the day ahead price are there, while there is relatively lower wind speed and solar radiation. The last week of January, the day ahead price drops, when the wind speed and solar radiation increase.

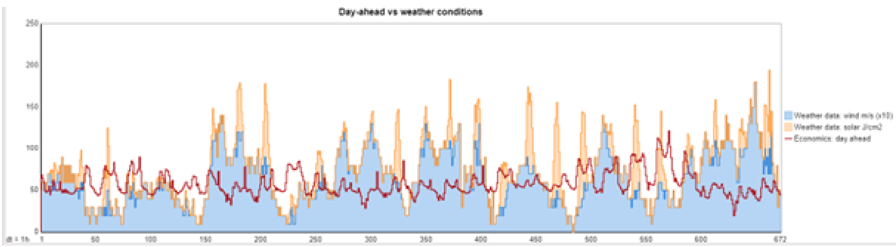


Figure A.12: Solar radiation and velocity of the wind in January

A graph is also made from the current situation in. It can be seen that the price drops when the solar radiation increases. From hour 4800 until hour 4850 of the year, which is in the middle of June, the wind speed increases as well a bit, resulting in a further decrease in the day-ahead price.

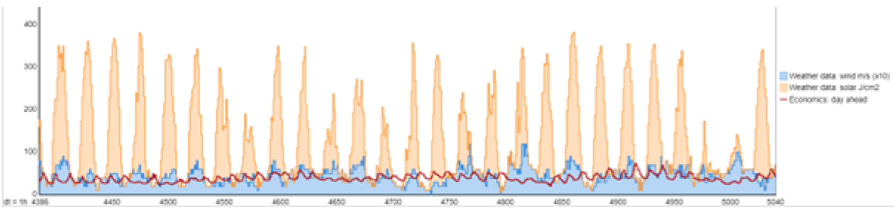


Figure A.13: Correlation weather circumstances and day ahead price

Based on the reasoning and observations made above, it can be concluded that the behaviour of the day-ahead price matches the global radiation and the velocity of the wind in the model. Despite there being no actual correlation between these variables in the model through equations, the model does mimic this correlation.

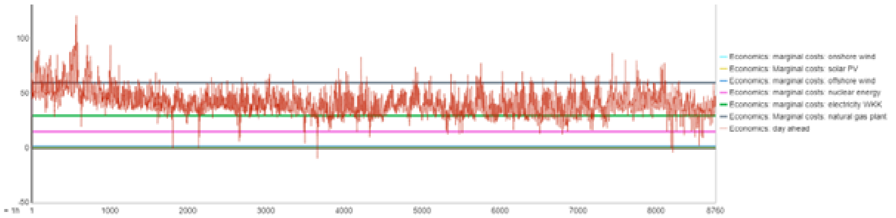


Figure A.14: Day ahead price and marginal costs

According to the principle of the energy market, power from wind and solar power generators will be supplied to the market as soon as there is a certain wind speed or solar radiation because wind and solar power generators have the lowest marginal costs. The dispatch order is then followed by nuclear power generators, and after fossil power generators. The graph shows the marginal costs of all type of power generators in Zeeland and the day-ahead price over the year.

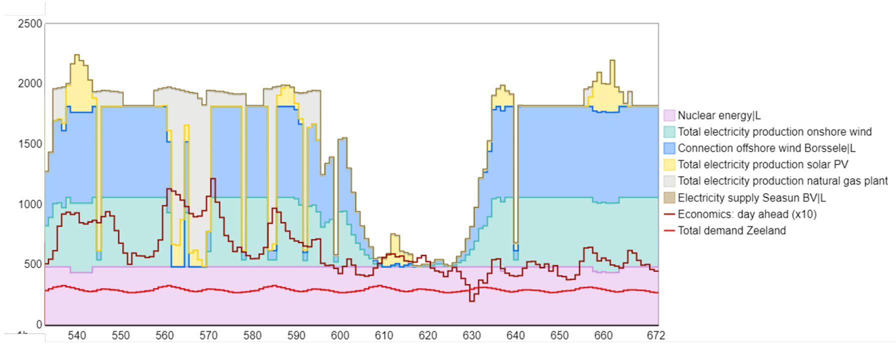


Figure A.15: Impression merit order

The graph shows the energy production of Zeeland in the first month of the year. Nuclear power has been operating this entire period. This makes sense because nuclear power has low marginal costs but also little flexibility in scaling up and down. From the figure can also be seen that when fossil power generators are delivering power the day-ahead price increase or is higher than average in that period, and when fossil power generators are not operating the day-ahead price is lower than the average day-ahead price in that period.

Power supply

The power supply is first analysed at whether the weather conditions correspond to the production of renewable energy, thus the production by wind turbines and solar panels. The profile of global radiation should match the profile of electricity from solar panels, and the profile of wind speed should match the profile of electricity from wind turbines.

For the global radiation on an hourly basis, a dataset of the location Vlissingen (KNMI, n.d.-b) from the year 2019 is chosen, as this is central in the area to analyse. In Zeeland in 2022, a total of 109 MW is installed of which 43 [%] on roofs and 56 [%] on fields. (RvO, 2023). For the current situation, the numbers of 2025 are used which results in 373 [MW] solar PV in total. This corresponds with policy and future developments.

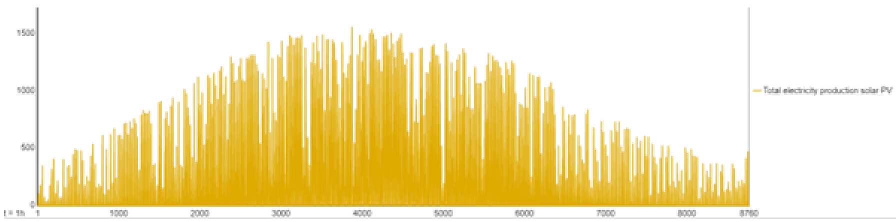


Figure A.16: Power production by solar PV

The graph shows the overall behaviour of electricity production from solar PV over the year. It can be seen that the production is less during winter, but increases from January until August, and then decreases towards December.

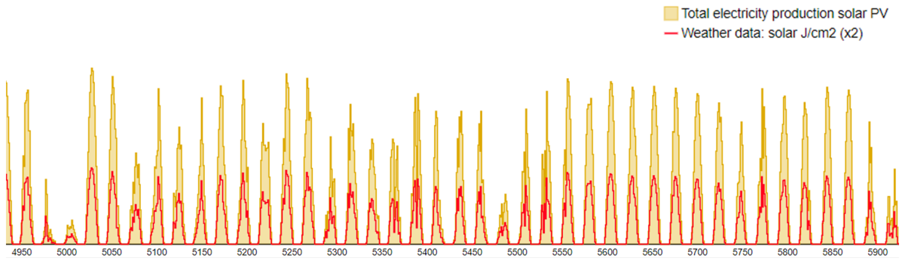


Figure A.17: Solar radiation and power production by solar PV

The graph shows that when global solar radiation increases, electricity from solar panels also increases. When there is no solar radiation, no electricity is produced from solar panels either. This is also explained by the fact that global radiation in the model is linked to electricity production from solar panels. The behaviour of electricity from solar panels matches the expectations because electricity is generated during the day and not at night. Furthermore, the electricity production in summer is higher than electricity production in winter.

A dataset of the production of Windpark Koegorspolder is used as input for the power production by wind (The Windpower, n.d.) (admin_pondera, 2023). This wind farm has an installed capacity of 2 [MW] thus the dataset is divided by 2.0 to create a dataset based on an installed capacity of 1 [MW]. This dataset is used for both onshore and offshore wind, and in the model multiplied by the expected development factor according to policy and future developments.

The graph shows the electricity production profile from wind turbines. This is fluctuating through the whole year. However, the frequency is somewhat lower in summer than in winter. The maximum amount produced, just under 600 MW of power supply for onshore turbines in Zeeland in 2020, is due to the maximum production capacity of turbines.

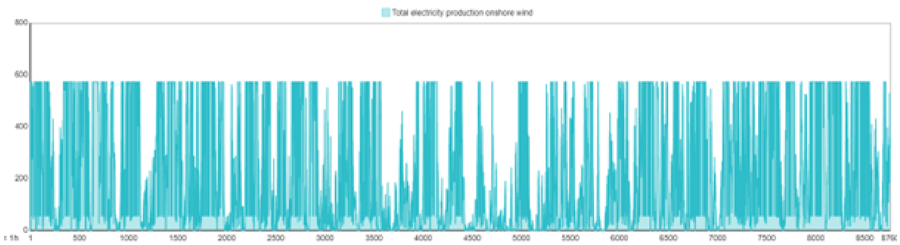


Figure A.18: Power production onshore wind

The correlation between wind speed and electricity production from wind turbines is more difficult to establish, and the graph shows these profiles. The expectation that the two profiles correspond is not quite correct. At certain times, this expectation is correct for example at hour 5300 of the year. However, at hour 5100 of the year the wind speed increases but there is little or no electricity production from wind turbines. However, the two profiles do follow each other's pattern, which may imply a delay in production data. Also, at hours 5500 and 5850 of the year, for example, the two profiles have similarities in pattern. It could be that the wind farm was not on at certain times, but a more logical explanation is that wind speed varies by location and altitude. The wind farm dataset is from the Koegorspolder near Terneuzen, while the wind dataset is from Vlissingen. The actual electricity production for both solar and wind will vary by location within Zeeland. It is assumed that the model does what it is supposed to do, because all data used is from the same year, the profiles are largely similar, minor differences can be explained, and the model correctly shows the expected behaviour of solar and wind production.

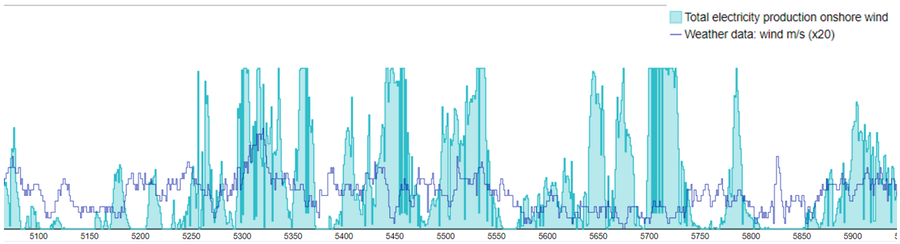


Figure A.19: Power production wind turbines and velocity of the wind

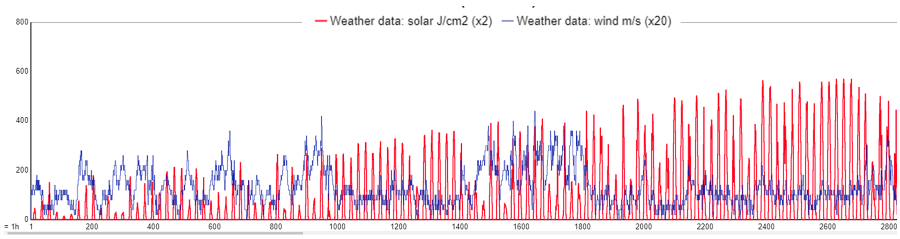


Figure A.20: Solar radiation and velocity of the wind

The simultaneity of wind speed and solar intensity is also considered. These are mostly alternating in the real world. This is also the case in the model. At times of higher wind speeds, for example in the beginning of the year, global solar radiation is low. When solar radiation increases, the wind speed decreases. This alternation is clear from hour 1400 to 1600 for example. A drop in global radiation and higher wind speed in late February and the beginning of March. This indicates a cloudy day and corresponds to the time of year.

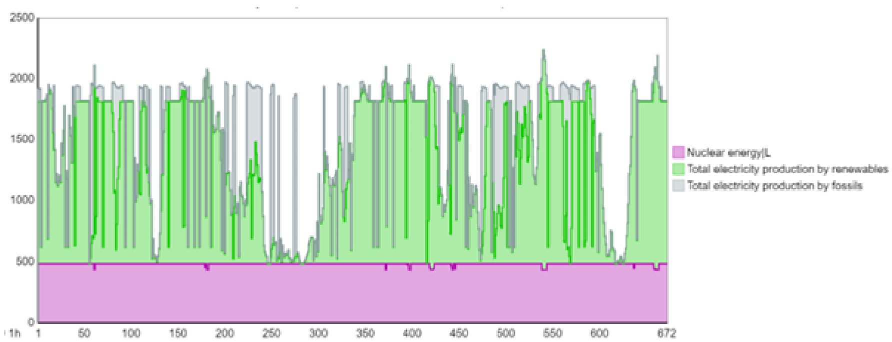


Figure A.21: Nuclear, renewables and fossils

Electricity is further produced by nuclear power and fossil power generators. Constraints are given to nuclear power as it can only scale up and down to a limited extent, and thus produces electricity at maximum capacity most of the time. Electricity from solar and wind turbines is modelled so that it goes into the grid, regardless of whether there is transmission capacity available or not. The production of electricity by nuclear power, renewables and fossil power generators in January is shown in the figure below. It can be seen that nuclear power is operating most of the time, followed by power from renewables, and that sometimes fossil power generators are operating as well.

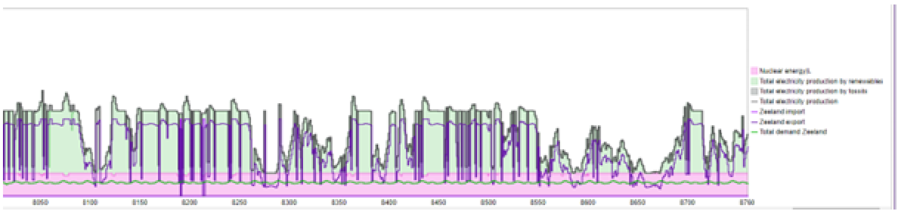


Figure A.22: Power production, import, export, and demand in January

The graph shows the electricity supply mix, import, export, and demand. It can be seen that the production exceeds demand a lot. This is caused by the constraints of nuclear power and that electricity from renewables always is putted into the grid. Further, the marginal costs of the power generators are most of the time lower than the day-ahead price as described earlier on. This results in the production of electricity by power generators in Zeeland because electricity surpluses can be traded on the market. This electricity generation will be transported to the Dutch electricity grid, but the model incorporates transportation capacities for power production by fossil fuels, thus there cannot be more electricity produced and transported than the transmission capacity. In reality, these power generators did offer energy to the market but are financially compensated for not producing with the balancing market. This financial compensation is not part of the model.

In summary, and according to the dispatch order as well, there is base load production of electricity by nuclear power, supplemented by wind and solar power generation if available. If the day-ahead price is higher than the marginal costs of fosil power plants, and there is still transmission capacity available, fossil power plants will operate. This is shown in the graph for the month December in the current situation. At hour 8100 of the year, there is a drop in renewable energy production and an increase in fossil power generation. And, when the electricity export is at maximum, which can be seen by the flat line that occurs with regularity slightly above 1500 [MW], there is no electricity production by fossil power generators.

Power demand

The industry has, with a flat pattern, a share of over 60 [%] in the electricity demand. The demand of agriculture, dwellings and mobility on the other hand has a fluctuating pattern throughout the day and year, as described earlier. Data from the analysis is used in the model and will therefore be reflected in this chapter.

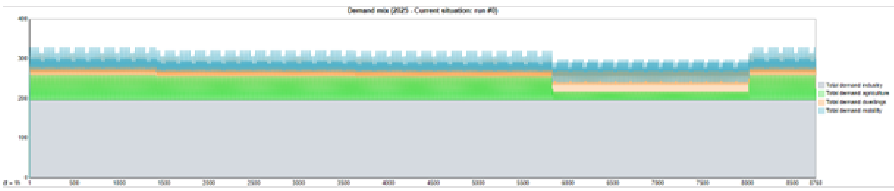


Figure A.23: Power demand industry, agriculture, dwellings, and mobility

The power demand for agriculture, industries, dwellings, and mobility for the current situation through the year is given in the graph above, and more specifically at the end of the year in graph below. The graphs show the variability of the energy demand mix over the year and day. The patterns are following the demand profiles, and it can be seen that the industry has the highest share in the demand mix, followed by agriculture, dwellings, and mobility.

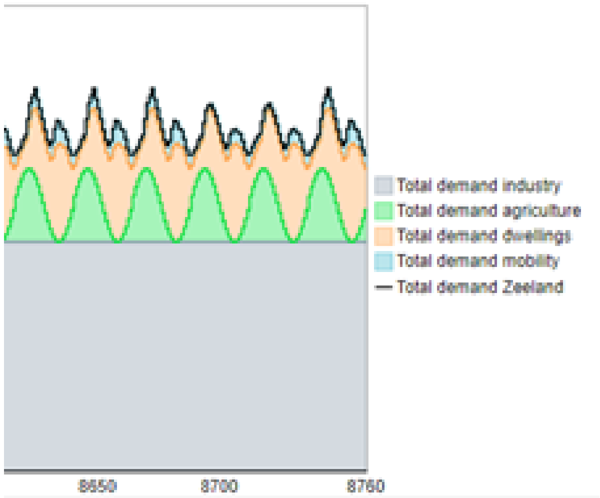


Figure A.24: Share industrial power demand and profiles

Data output of the model is further compared to the expectations of CE Delft for Zeeland in order to verify if the data input and output is correct. Because data input in the model is based on both the CE Delft and other reports to map industrial demand by company because location specific data is required for the analysis. The total industrial demand should match the expectations of the CE delft study.

Industrial power demand

Industrial companies have an annual electricity demand of 5 [PJ] in 2020, which is about 1.4 [TWh]. Assuming a flat pattern for the power demand over the year, the industrial sector will have a power demand of 158 [MW] in 2020 according to the CE Delft study. The industrial power demand in the model is compared with the industrial power demand of CE Delft, assuming a flat pattern over the year, thus 24 hours production per day all days of the year. The results are presented in the table below, that also shows the deviation of the power demand in the model to the average number of the CE Delft study. Both the scenarios of 2040 and 2050 are in the range of the expectations of CE Delft, but the expectations of the model are in 2020 and 2030 a bit higher. This may cause higher amounts of electricity import and less amounts of electricity export, because the industrial electricity demand is higher.

	2020	2030	2040	2050
Power demand CE Delft [MW]	158	190 – 317	(190 – 1,651)	190 – 2,986
Average demand CE Delft [MW]	158	254	921	1588
Power demand Model Linny-R [MW]	197	536	1043	1,239
Difference on average	+24[%]	+211[%]	+13[%]	-22[%]

Table A.6: Industrial power demand developments

Agricultural power demand

The analysis estimated sites that might be connected to a heat grid or go fully electrified. This also indicates a range; if a connection to the heat grid will not be realised, electrification may still take place. The model assumes that agricultural businesses in Zeeuws-Vlaanderen will be connected to a heat network and will therefore not be part of the electricity system. The other areas, all located in the remaining part Zeeland, have been given a range in the analysis in how far they will use electricity for the agricultural sector in the future. In the model, this range has been converted to scenarios for the agricultural sector in a low, medium and high-demand scenario. The dataset in Linny-R is given in electricity demand in [MW], per 1 [PJ]. The low-, medium-, and high-scenarios are therefore converted into a factor, based on the expectations described. The table shows the range of expected power demand in [TWh]. It can be seen that the numbers of the scenario's in Linny-R are corresponding the numbers of the CE Delft study.

	Scenario's in LinnyR			CE Delft
	Low [TWh]	Medium [TWh]	High [TWh]	CE Delft [TWh]
2020	0,22	0,22	0,22	0,22
2030	0,22	0,29	0,36	0,22
2040	0,24	0,36	0,47	0,36
2050	0,25	0,44	0,64	0,69

Table A.7: Agricultural power demand developments

From the analysis is known that the pattern differ through the day and through the year. To be sure that the model convert the datasets of different seasons, and using the correct factors, the datasets are plotted in a graph first to verify if the power output output of the model is correct.

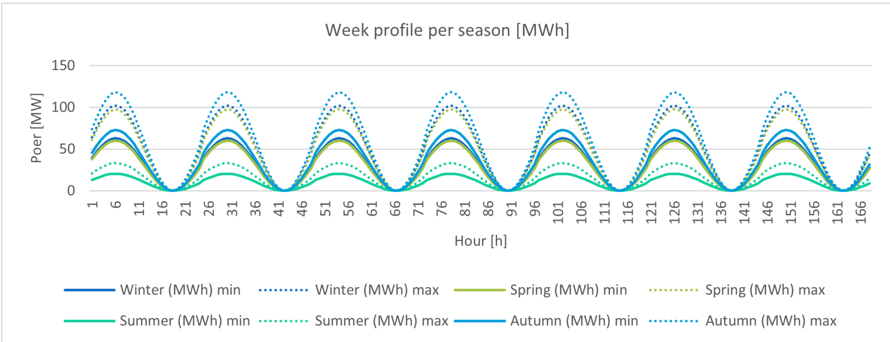


Figure A.25: Power demand profile agriculture

The electrical power demand profile of the agricultural sector, generated by the model in Linny-R, is shown in the figure. It can be seen that the demand varies through the day and year, and corresponds with the average numbers of the plotted datasets in the graph.

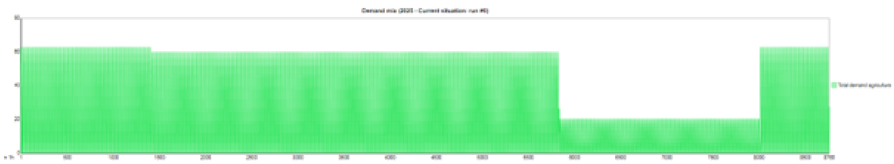


Figure A.26: Power demand agriculture throughout the year

There is however no gradual transition of the demand from season to season. This is an area of improvement for the model. This requires a function that fluctuates by day, but also through the year, with the values of the function decreasing from January to June and increasing again from June to December. As a result, the transitions from season to season are modelled less accurately.

Power demand built environment

CE Delft expects that the built environment will have an annual electricity demand of 5.13 to 6.40 [PJ] in 2050, compared to 4.87 [PJ] in 2020 (Sjoerd van der Niet et al., 2020). So the annual electricity demand may grow from 1.35 [TWh] in 2020 to 1.43 or 1.77 [TWh] in 2050. The model calculates however an electrical demand of 0,45 [TWh] in 2020, 0.68 [TWh] in 2030, 1.14 [TWh] in 2040, and 1.59 [TWh] in 2050. The calculated total electricity demand in the model suits the expectations of CE Delft in 2050, but the calculated electrical demand from 2020 until 2040 is lower. This may be the result of excluding public property, commercial property, and recreational property. According to the RES, the expected electrical demand of the biggest classification businesses is 0.33 [TWh] in 2020. This includes grocery stores, restaurants, commercial properties, hospitals, retail companies, and recreational property. Office buildings are not mentioned here and may cause an additional electrical demand of 18.9 [GWh] per year, based on 300,000 [m2] (M.V. Zuidema et al., 2012) and an average electricity consumption of 63 [kWh/m2] (Milieubarometer, 2022). The sum of missing demand of office buildings and the biggest businesses is 0.35 [TWh]. Thus there is still a gap of 0.55 [TWh] in the electrical demand. CE Delft have used the electrical demand of dwellings from the year 2016, and this study used the average electrical demand of 2020, which is 10 [%] lower than 2016. But using data from the year 2016, thus 171,896 households with an average electrical demand of 2,745 [kWh], results in a total electrical demand of 0.47 [TWh]. This is a bit higher than 0.45 [TWh] in 2020, based on 178,648 households with an average electrical demand of 2,499 [kWh]. This does however not explain the difference.

Assuming that the electrical demand of the built environment only includes dwellings, the expected annual electrical demand per dwelling by CE Delft will be between 5,958 [kWh] and 7,375 [kWh] in 2050. The calculations in the model result in a total electricity demand of 6,625 [kWh] per year per household, including the additional electricity demand of newly constructed houses and the basic electricity load because of using electronic devices and domestic appliances. The assumptions in the model are mostly similar to the scenario of national leadership which results in a demand of 5,88 [PJ] or 1.63 [TWh] (Sjoerd van der Niet et al., 2020), and are therefore in the same order. It is however not sure to what extent CE Delft included the additional electricity demand of newly constructed houses.

In conclusion, the model does not include the electricity demand for public, commercial, and recreational property, resulting in that especially in the years towards 2040 the electricity demand of the built environment is lower in the model than in reality. The model therefore indicates higher export needs and less import needs until 2040, because less electricity is needed. For what the electricity is used for does not really make any difference in the model, because most buildings are connected to the medium- and low- voltage grid. From 2040, the electrical demand of dwellings in the model matches the expected electrical demand for the built environment by CE Delft.

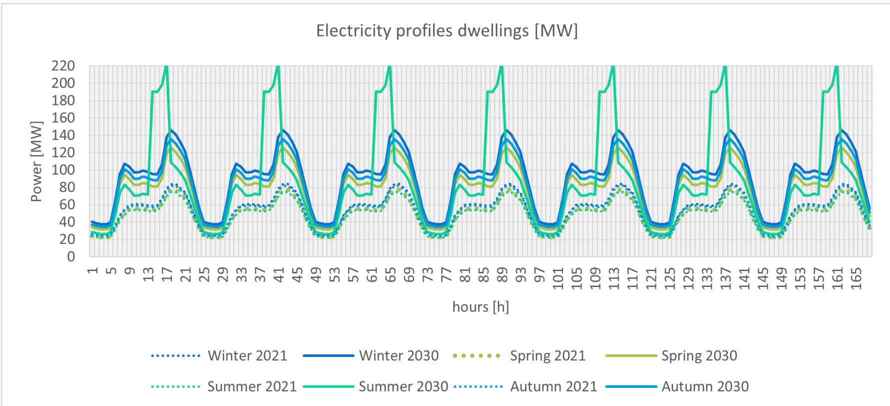


Figure A.27: Power demand profiles dwellings

The produced datasets that are based on growing numbers in houses to build newly, housed to be adapted towards all-electric, and the increase in air-conditioning, are plotted in the graph. The pattern of the demand profiles of future scenarios are changing a lot, compared to the pattern of the current power demand profile. This corresponds to the studies used by developing these datasets.

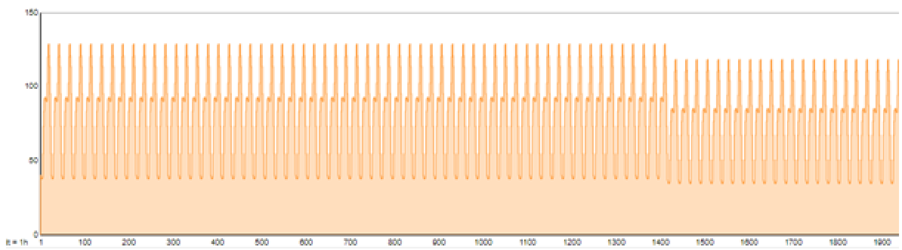


Figure A.28: Power demand dwellings throughout the year

The graph represents the power demand profile of dwellings in winter, and partly spring, in 2030, from the Linny-R model. This corresponds to the graph as the minimum winter values are both a bit below 50 MW, and the maximum winter values a bit below 150 [MW].

Power demand mobility

As described in the analysis, the electricity demand from the CE Delft study was supplemented with an expectation of the number of electric vans. This makes the electricity demand for mobility higher in Linny-R than the CE Delft study as shown in the table. The CE Delft study does not provide any expectations for the year 2040. Because the model in Linny-R works with scenarios for 2040, the expectations for 2030 and 2050 has been interpolated for the year 2040. The expected number of electric vehicles is multiplied by the electricity load profile of electric vehicles in the Netherlands, and the same is done for electric vans using the electrical load profile of electric vans. This results in electricity load profiles for electric vehicles and vans in Zeeland.

	Scenario's in LinnyR			CE Delft
	Low [TWh]	Medium [TWh]	High [TWh]	CE Delft [TWh]
2020	0,10	0,10	0,10	0,0
2030	0,26	0,33	0,38	0,28
2040	0,55	0,69	0,80	
2050	0,84	1,06	1,21	0,56 – 0,83

Table A.8: Power demand mobility developments

The datasets describing the load profiles of electric vehicles and electric vans are plotted in the graph. These profiles are describing the total load profiles on a weekly basis for the year 2030 and 2050. The sum of those, thus the total load profile, needs to be similar to the power demand of mobility in the model of Linny-R.

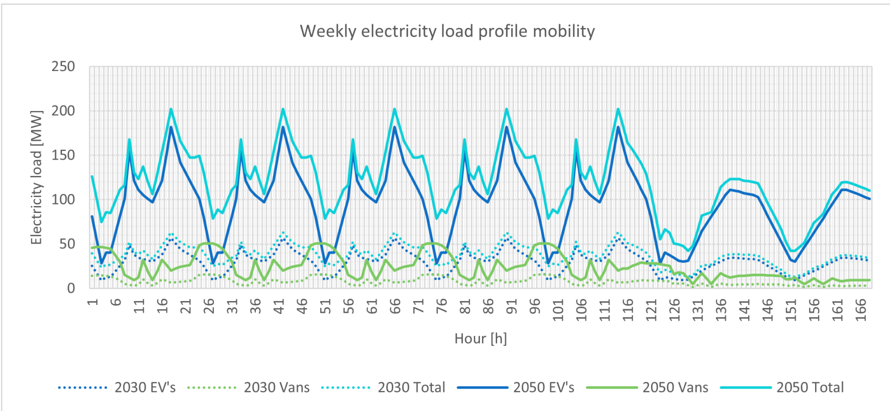


Figure A.29: Power demand profiles mobility

The graph represents the overall demand profile of mobility over a period of just over a month in the current situation. This clearly shows weekends, the two lower peaks that occur in between. The larger peaks represent weekdays. This is also to be expected with reality.

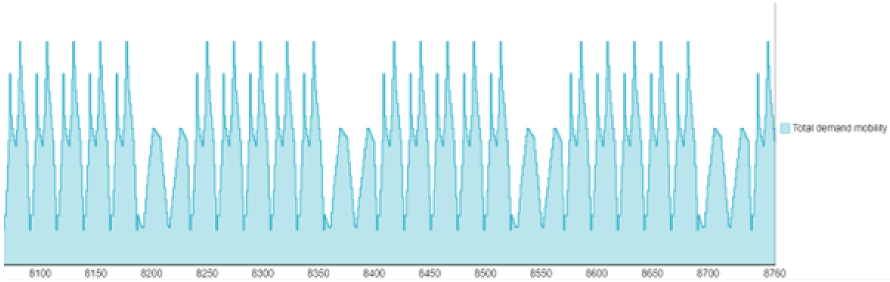


Figure A.30: Power demand mobility linny-R - A

In 2020, the impact of electric buses cannot be seen yet as the share in electric vans is very low. This is different for 2050 in which the shape on Friday is slightly different than the other weekdays. Also the power demand profile in the weekend differs a bit compared to the situation of 2020. The representation of the power demand of mobility in the model is therefore in line with the expectations from the analysis.

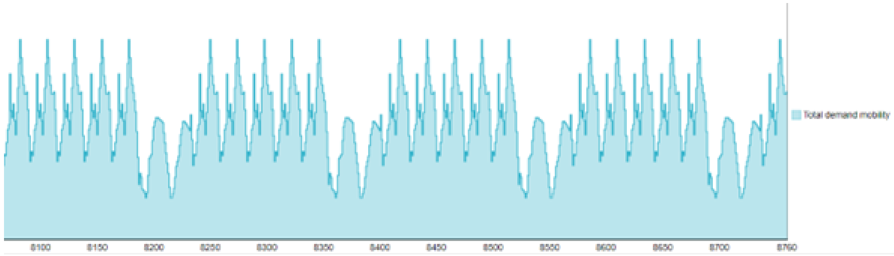


Figure A.31: Power demand mobility linny-R - B

Curtailment

Sometimes, the model shows extremely high numbers of curtailment. This happens during high electricity imports and very low day-ahead prices.

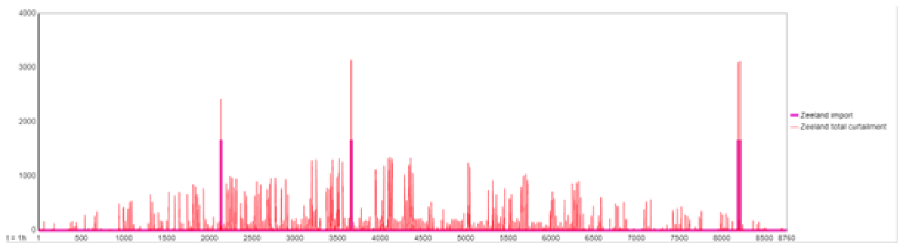


Figure A.32: Curtailment profile

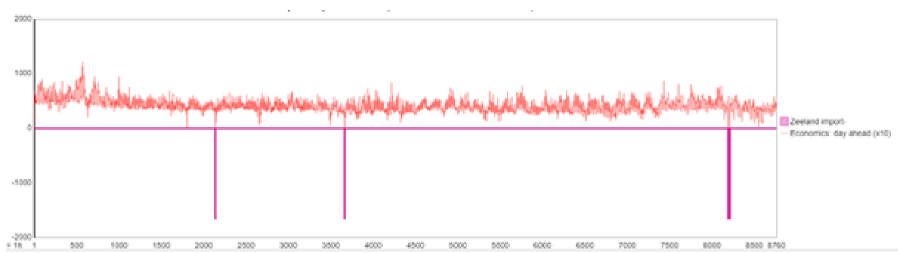


Figure A.33: Day ahead price versus curtailment

It might be that the model electricity imports from the Dutch grid because the day-ahead price is negative, and no economic value is given to curtailment in the model. The model may think that it can benefit from this situation because it receives money by importing electricity and transporting it away through curtailment does not cost any money. This only happens at the extreme values of curtailment.

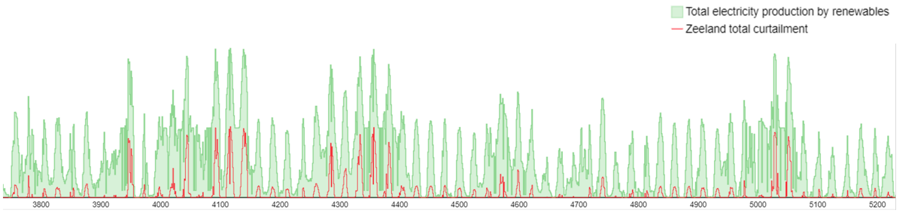


Figure A.34: Curtailment and renewable poewr generation

The pattern of curtailment follows the pattern of renewable power generation and is further in the same order. So, besides the extreme values of the day-ahead price the model behaves, in terms of curtailment, as it has to do according to the current electrical power system.

Electricity shortages

Electricity shortages hardly appear in the analysis results, but it appears in 2050 scenarios, due to the absence of renewable power generation and capacity constraints of the grid. From the graph it can be seen that electricity shortages occur mostly during the winter months. From the graphs of renewable power generation it can be concluded that the renewable power production is the highest in the summer and lowest in winter. Therefore the electricity shortages are less during summer months.

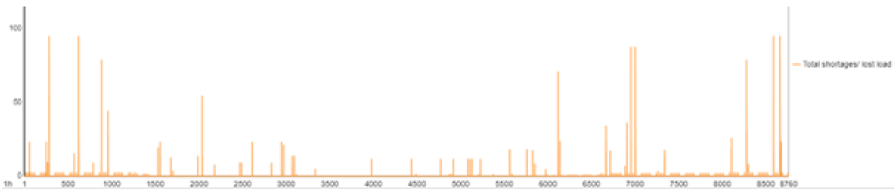


Figure A.35: Power shortages throughout the year

To dive further into system behaviour, from the graphs can be concluded that during electricity shortages, electricity is imported from the Dutch grid. The electricity imports are however at its maximum Both electricity import and electricity export clearly shows the boundary of 1645 [MW] in the graph. The remaining electricity demand concerns electrical shortage at a certain moment.

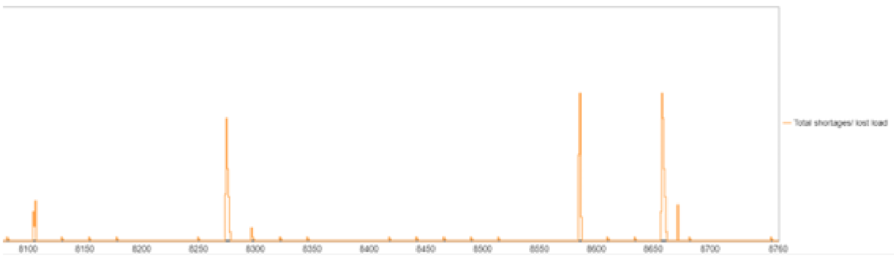


Figure A.36: Power shortages december

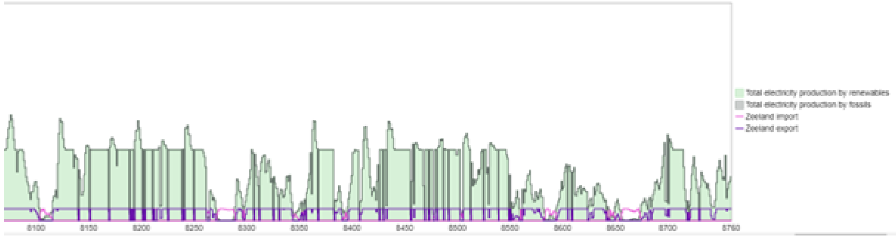


Figure A.37: Power production and export

The model shows the expected system behaviour of the real word, based on the observations above. No shortages are found in the scenarios of 2030 and 2040 that can be explained by the fact that the electrification of the industry for example, has accelerated.

Electricity import/ export

The graph presents the electricity export of Zeeland, and based on this, high amounts of electricity are transported to the Dutch high-voltage grid. This goes along with the power demand, marginal cost of power generators and the day-ahead price. Zeeland mainly exports energy over the year because the electricity demand of Zeeland is almost covered by only nuclear power, and both nuclear power and renewable power generators have capacity constraints. The day-ahead price is most of the time higher than the marginal costs of renewable power generators and nuclear power. Surpluses of electricity, as result of the operating nuclear plant, wind turbines and solar PV, are then transported to the Dutch high-voltage grid. Additional power is sometimes needed, but most of the time there is some renewable energy production by solar or wind or both, that covers demand completely. Surpluses of electricity are transported to the Dutch electricity grid, but to what extent depends on the market conditions at that time step.

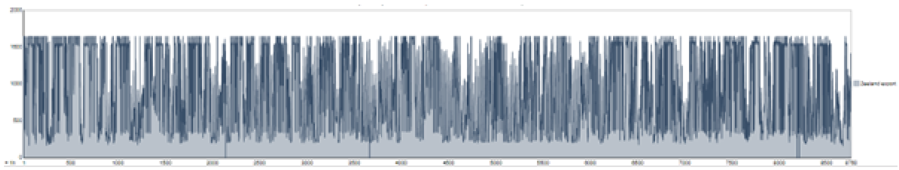


Figure A.38: Power export

If there are surpluses, first electricity from wind, solar and nuclear power will be transported to the grid. As described, a nuclear plant has operation constraints and need to produce. If there is still transmission capacity available, and the marginal costs of the fossil power generators is lower than the day-ahead price, fossil power generators will run and export energy to the Dutch energy grid. This electricity can for example be traded on the day-ahead or intraday-market.

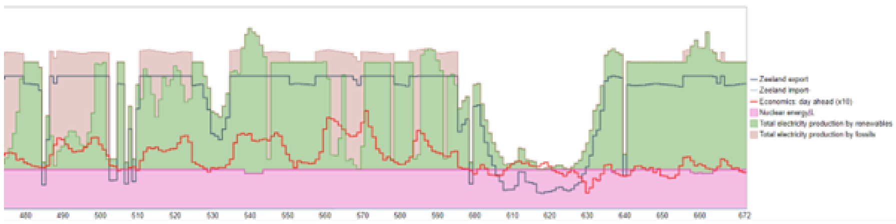


Figure A.39: Power surplusses and export

More specifically, the day-ahead price drops in the last week of January for example, which is shown in the graph. This result in no power production by fossil power generators, and the export drops to 210 [MW] instead of 1645 [MW] at maximum.

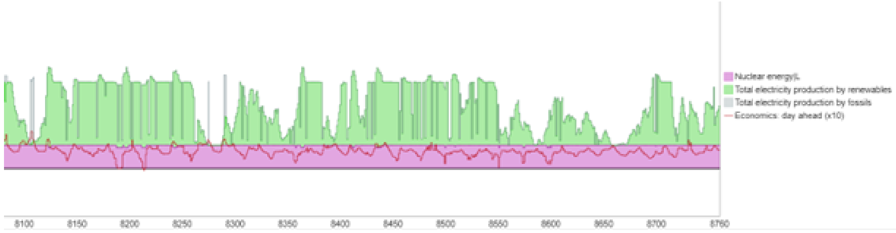


Figure A.40: Power production and day ahead

The day-ahead price may be lower than the marginal cost of nuclear power. This is shown in the graph. The nuclear plant then switches off as much as possible, and only renewable sources such as wind turbines and solar power generators are active. If needed, energy will be imported from the Dutch grid since this is the cheapest option. Otherwise, surpluses will be sold to the Dutch grid. Also, curtailment may still occur because certain cables in the grid are full, so not all renewable energy may be used.

UPHS behaviour

Regarding the behaviour of UPHS, the charging and discharging process and the stored electricity needs to be analysed. From the graph, it can be seen that UPHS mostly charges full and discharging empty. During the second half of January, however, UPHS holds electricity a bit longer.

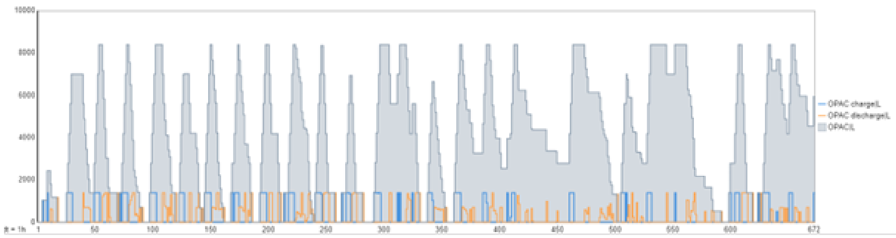


Figure A.41: Charge and discharging cycles of UPHS

The rate at which UPHS charges and discharges varies. This is because no constraints are given on the capacity of charging and discharging, allowing UPHS to behave as UPHS will in reality.

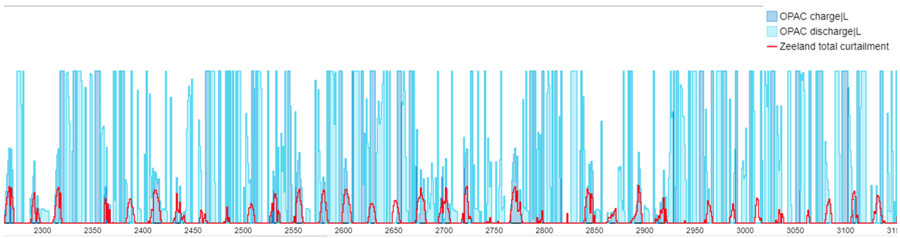


Figure A.42: Charge/discharge of UPHS and curtailment

The figure above shows that UPHS mostly charges during moments of curtailment. This also indicates that less electricity is curtailed as UPHS uses it.