MASTER

Market design of Dutch electricity in carbon-neutral energy scenarios of 2050

Alternatives to the market design to make the energy system both affordable and reliable for investors and end-users

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by

E.M. van Klink

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Preface

2020 - the year of a global pandemic, brain surgery and the finalisation of my master's degree with this piece of paper lying in front of you. A rollercoaster would be a suitable term, in which I am currently riding back to the docking station. It has been a year of keeping a physical distance from friends and family but at the same time keeping them close at heart. A year with uncertainties and insecurities regarding the future but also working hard on achieving the master's title and keeping it together. It has been eye-opening to recognise what is important, and what is not. It has provided insights on who I want to be, what I want to achieve but also on what is most valuable in life.

This thesis aims at providing insights into the financial effects of the implementation of carbon-neutral energy scenarios. The energy transition is an important challenge society needs to face in the upcoming decades. This transition is complex and affects social, technological, political and economic aspects. During both my bachelor and master, I have recognised my passion for this interdisciplinary challenge. In my further career, I will definitely continue working on this subject.

I could have never been where I am right now without the help and love of many different people. First of all, I'd like to thank Aart and Floor for their devotion to the subject, for the never-ending ideas and improvements, and for sticking to the core. Second, I'd like to thank everyone for giving love, sending postcards and keeping me on my feet when times were tough. Additionally, I'd like to thank everyone with whom I'd endless (interesting) discussions on this specific subject but also any other subject regarding the energy transition, such as my colleagues at Berenschot, Cyriel and Sam.

Enjoy!

Liesbeth van Klink

Utrecht, 24 December 2020

Abstract

For achieving the objectives of the Climate Agreement, four carbon-neutral energy scenarios for 2050 have been defined by Berenschot. These scenarios are established in the Energy Transition Model and describe the four boundaries of the future energy system. The implementation of high integration of variable renewable energy sources (VRES) affects the system on multiple levels. This study aims at exposing the challenges occurring on a financial level, and defining alternatives to counter these effects. Two challenges are examined, the 'missing money problem' and the 'merit order effect'. The first challenge focuses on the investment climate of back-up generators, whereas the second aims at the financial feasibility of VRES. The main research question of the study is: *Which alternatives are required to make the financial market design of electricity achievable and reliable for a carbon-neutral scenario in 2050 and beyond?*

To answer the research question, multiple steps have been taken. First, the four scenarios are modelled in an optimisation model, KyPF, to provide insights on the behaviour of the electricity market within the current market design. Second, the output of the KyPF model, together with insights from the Energy Transition Model, is used to calculate the extent of the 'missing money problem' and the 'merit order effect' in the four scenarios. Third, alternatives based on relevant literature and reviews with experts have been gathered. The alternatives aim at establishing an achievable and reliable system, and the effects of these alternatives on the system are discussed.

The output of the KyPF model shows that electricity pricing in 2050 will be two to three times higher and more volatile compared to the reference year, 2017. Additionally, the 'merit order effect' and 'missing money problem' occur in all four scenarios. The results show that there is a need for alternative market designs. The literature review, in combination with reviews with experts, has resulted in four alternative market designs: Capacity mechanisms, VRES subsidies, virtual dispatchable producers and nodal pricing. Moreover, multiple alternatives have been combined into a new alternative, the Nord Pool system case.

The results show that the current market design is not suitable for the transition towards a carbon-neutral energy system. Multiple alternatives for the market design have been proposed in this study and the effects have been discussed. Combining alternatives is needed to establish the required effect on the system at multiple levels. However, a new or updated model is required to validate the effects of the proposed alternatives. This is necessary to determine the optimal combination of market design alternatives to establish an achievable and reliable carbon-neutral energy system.

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1. Introduction

Since July 2004 the Dutch electricity market has been deregulated. The main objectives of the deregulation were to increase the efficiency of electricity markets and to lower electricity prices for end-users. Currently, a new transition has begun in the electricity system. As part of the Paris Agreement, the Netherlands has committed to several climate-related objectives, among which reducing CO_2 emissions. This implies altering the energy system towards a higher level of integration of renewable energy sources. Berenschot has created four different carbon-neutral energy scenarios for 2050 in the Energy Transition Model. This scenario study is part of the project 'Integrale Infrastructuurverkenning 2030-2050' that has been executed in collaboration with DSOs, Ministry of Economic Affairs and Climate policy, industry and energy companies regarding the Paris agreement. These four scenarios are seen as the boundaries of the future energy system between which the real future system will develop. These scenarios will form the basis in which challenges in future market design will be defined.

This study describes a major transition in the socio-technical domain. The reliability of electricity has become crucial for both society and the overall economy of the country. Moreover, the transition requires a change in both infrastructure and lifestyle. End-users will have an increasing role in the electricity market caused by demand-response and 'scarcity' pricing. The role of TSOs, DSOs and electricity suppliers in the market might alter as well, depending on the future market design. A change in the financial aspect of the electricity market should also be practically feasible and therefore, electrical as well as mechanical engineering is needed to alter the system. Additionally, the government has a strong role in guiding the transition on a yet to be specified regulatory level. Both the market design and stakeholders will have a crucial role in how and whether the transition towards a 100% carbon-neutral scenario with intermittent resources develops. This study requires competence in scientific disciplines and examination of existing theories to understand the multidisciplinary challenge as well as the ability to translate the outcomes of the quantitative analysis to recommendations for alternatives.

1.1 Problem statement

An electricity market functions well when the price signals support efficient short-term operation and provide sufficient investment incentives for all required generation capacity in the long term. In a future electricity market with a high level of variable renewable energy sources (VRES), the current market design may no longer work. Many studies have focused on the technical and functional side of the implementation of VRES, but not on how to make the implementation feasible and affordable for investors. First, there might be an investment problem for wind and solar projects. Both these sources have a high CAPEX and low OPEX, meaning that the initial investments are high, but the operational costs are relatively low. This is in stark contrast to the conventional energy sources, which have a high OPEX due to the costs of the required fuel, affecting the marginal price. The current market design is based on marginal pricing, meaning that generators will be dispatched based on their variable operating and maintenance costs. With high integration of VRES, with low marginal costs, this leads to an unsuitable climate for investors. This is referred to in the literature as the 'merit order effect'. The other challenge is the so-called 'missing money problem'. Back-up capacity is needed to establish a reliable system since demand and supply should always be balanced to have a stable frequency and power quality. Since this back-up capacity is rarely used, investments will not be cost-effective nor efficient. Therefore, the question arises how the market design can be altered to govern future electricity systems.

The challenges and possible solutions for future renewable energy markets are embedded in different literature streams. There is ongoing research in the field of governmental regulation and incentives to 'tweak' the current electricity market, financial research regarding a different tariff system for energy based on other types of 'network' products and risk management, and electrical engineering research regarding the practical implications. This research aims to provide possible alternatives for the market design to keep the system sustainable, affordable and reliable.

1.2 Study objectives

This study aims to assess the effects of the implementation of a high level of VRES in the current market design and to explore the effects of alternatives in the current market design.

The main research question this study focuses on and its sub-questions are:
Which alternatives are required to make the financial market design of electricity achievable and reliable for a carbon-neutral scenario in 2050 and beyond?

Which leads to the following sub-questions:

- *How will electricity prices behave in 2050 considering four different carbon-neutral electricity scenarios based on the Energy Transition Model under current market conditions?*
- *How are the 'missing money problem' and 'merit order effect' exposed by the electricity prices based on the scenarios of the Energy Transition Model?*
- *Which alternatives to the current market design, mentioned in relevant literature, can be applied to carbon-neutral electricity scenarios?*
- *What are the influences of the defined alternatives on the 'missing money problem' and 'merit order effect' in the electricity pricing model?*

The first sub-question addresses how the pricing mechanism of the current market design is influenced by the implementation of a high level of VRES. It is expected that the prices have a higher fluctuation and many hours will have lower pricing because of the absence of marginal costs of VRES. The second sub-question aims at how this change in electricity pricing influences the market functioning and results in investment challenges. The third and fourth sub-questions address relevant alternative market designs and the impact of these design alternatives in solving the challenges as defined in the second sub-question. Together, the four sub-questions will be used to answer the main research question.

2. Literature review

This section provides an overview of existing literature in the field. To define required alternatives in the current market design, it is essential to have a grip on the criteria and working mechanisms of a well-functioning market design. Subsection 2.1 describes the prerequisites of a market design, rationale for the deregulation of the electricity market and the current market functioning. In Subsection 2.2 the influence of a high level of variable renewable energy sources (VRES) on the market functioning is described. Subsection 2.3 reviews the theories and models in the literature that provide alternative options for establishing a market design with a high level of VRES within the aforementioned prerequisites.

2.1 Principles of electricity market design

This study defines market design as 'the set of arrangements which govern how market actors generate, trade, supply and consume electricity and use the electricity infrastructure' as in (Hu, et al., 2018). In general, a market-oriented system is preferred by economists, compared to a regulated market system, since liberalized markets are conceived as competitive, fair and transparent (Sioshansi, 2008). However, electricity markets cannot be completely liberalized because of the existence of a natural monopoly in transport and distribution and the primary necessity of electricity supply. Therefore, the electricity market will always need some level of regulation to prevent the abuse of market power and adhere to the Dutch criteria of maintaining a non-discriminatory, affordable, secure and reliable electricity supply. Additionally, there is a technical requirement of having power balance at every instance meaning that generation and demand must always be in balance.

Since July 2004 the Dutch wholesale market and retail competition have been liberalized. The objectives of this restructuring were mainly to create larger markets, promote trade to reduce the overall costs, to achieve equality among customers and to increase operational efficiency (IEA, 2016). Moreover, this market-oriented system makes pricing arrangements more realistic and protects end-users against opportunism. The limited amount of government interventions also leads to less political controversies and discussions on governmental powers (Gómez-Ibáñez, 2003).

Not only national criteria for electricity supply should be adhered to, but also the European energy policy framework should be considered. Since 2019, an update for this framework named 'Clean energy for all Europeans package' has been implemented to establish clean, secure and affordable energy supplies for all Europeans while promoting fair competition. The new framework, which allows electricity to move more freely across borders, establishes a secure supply and stimulates investments in electricity production. Additionally, a new limit has been set for electricity producers to receive state-driven additional revenues through capacity mechanisms, to maintain fair markets in the different states (European Commission, 2020). State-driven compensations could lead to unfair cross-border pricing due to uneven investment climates. This might lead to inefficient placement of generators.

In the current market design, marginal pricing determines the price for electricity in the system, directed by the merit order of generation as seen in Figure 1. This means that the production with the lowest marginal cost is brought first to the market, ascending to the one with the highest costs. The price is formed on the marginal price of the last generator needed to satisfy the demand; all forms of electricity production will have this uniform selling price. This market price is used in the day-ahead market (DAM) and used as a reference price in forward, intraday, and balancing markets (Hogan, 2017).

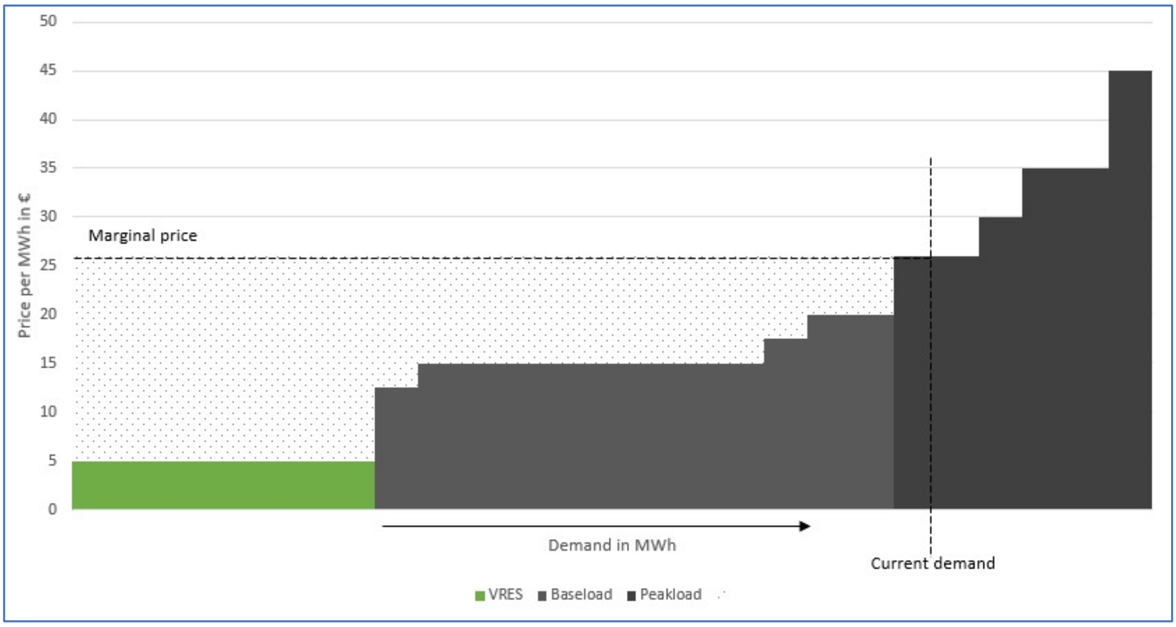

Figure 1: Merit order of limited VRES, baseload and peak load electricity production

In Figure 2, the different building blocks of the electricity markets are shown. The DAM is the most important market in the current market design and sets the reference price for the other markets. This market plans for and estimates the electricity needs for the upcoming day. For more granular control, the intra-day and balancing market can compensate the difference between the expected electricity requirements from the day-ahead and the actual demand. Electricity can also be bought on the forward markets with a mid-term contract to mitigate risks by setting fixed prices. On the long term, PPAs can be used for mitigating long-term risks. These PPAs are mainly used for investments in VRES, causing the VRES to have a stable investment climate.

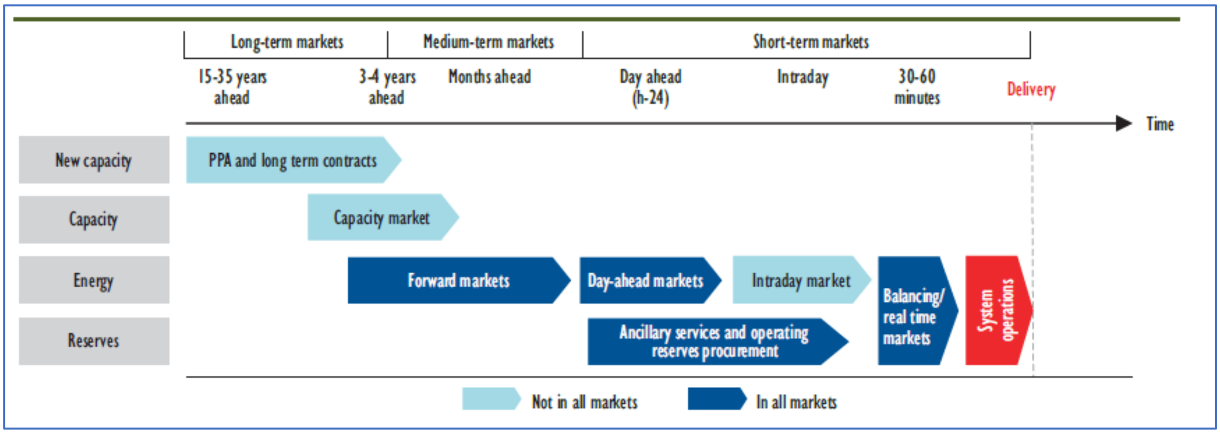

Figure 2: Overview of different building blocks of electricity markets (IEA, 2016).

Electricity generators use insights from marginal pricing data to form their business model based on their technical and financial characteristics. Baseload generators operate at relatively low marginal prices with a high amount of full load hours, while more expensive back-up capacity can operate flexibly at peak demands. The day-ahead market prices result in the cost-efficient allocation of production resources and additionally sends signals to long-term investments in capacity (Hu, et al., 2018). If prices rise, there is a signal for scarcity in the system, indicating possibilities for investments in new capacity and providing income for reserve power plants. If prices decrease, less efficient generators might have to be shut down since they cannot operate profitably anymore. The price signals, therefore, result in a natural drive for efficiency increases and capacity investments.

For non-renewable generators, the operational expenditures (OPEX) mainly drive energy prices (Garcia-Barberena, et al., 2014). These are primarily related to the costs of fossil fuel, such as carbon, gas, or oil. When investing in a non-renewable generator, the future costs of fossil fuels and electricity selling prices are therefore critical. OPEX-driven electricity pricing fits with the current market design of marginal pricing both for short term optimization and long-term investment possibilities. Moreover, a conventional power system strongly adheres to the market design criteria since it consists of uni-directional power flows and is dispatchable, resulting in a reliable system.

2.2 Influence of a high level of VRES on market design

VRES such as solar and wind energy, have different characteristics compared to non-renewable energy sources. In contrast to non-renewable energy sources, VRES do not provide predictable and steerable electricity generation due to the dependence on weather conditions. Additionally, VRES are strongly CAPEX-driven meaning that the capital costs of building VRES are high, whereas the operational costs are limited due to the absence of fuel costs and lower maintenance costs. In a system with a limited amount of VRES related to conventional sources, this does not cause challenges since there are enough conventional generators that can balance the system and set a market price in the marginal pricing system. However, in a system with a high level of VRES, two challenges arise.

First, a high level of VRES will suppress market prices because of the marginal pricing system. VRES have low marginal prices and are non-flexible, causing reduced market prices when the integration of VRES increases (Hu, et al., 2018); (AFRY, 2020). This is usually referred to as the 'merit order effect', also sometimes called the 'cannibalization effect', and is a strong barrier for realizing a sustainable energy system (Djorup, et al., 2018). The effect of VRES integration on the marginal pricing system can be seen in Figure 3.

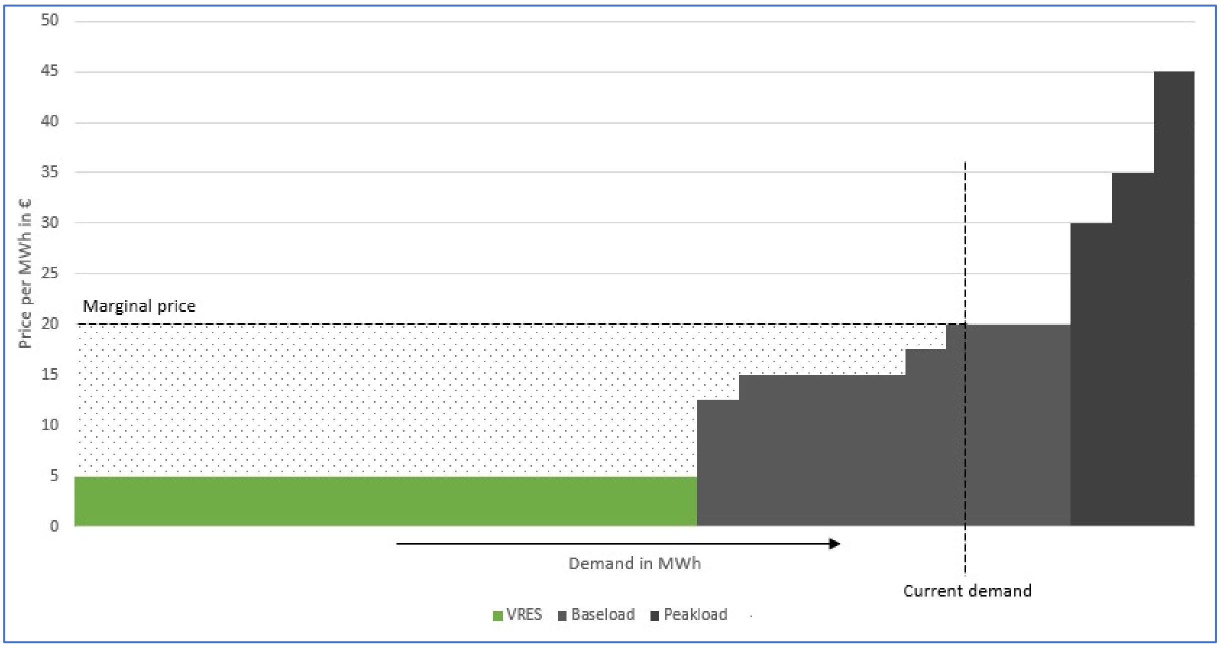

Figure 3: The effect of an increase in VRES on the merit order

This effect increases with the level of VRES in the system since the hours in which generators with a marginal price are required will decrease. The lower market prices result in a negative market signal towards investors and therefore endangers business cases for VRES investment. The negative market signals can be countered by government intervention to assure profits and stimulate investments in VRES. However, investment incentives are inconsistent with a market-oriented system and create market distortions (Hu, et al., 2018). Incentives might counter the effect of market signals and lower the drive for efficient and cost-effective allocation of production. Not only does this cause market inefficiencies, but also policy uncertainties arise from altering regulations which create an unpleasant investment-climate for VRES (Nelson, et al., 2015).

Since VRES are dependent on weather conditions, back-up capacity, and electricity storage is required for hours in which VRES cannot meet the electricity demand (Joskow, 2018). Back-up generators are minimally used since the marginal price of the back-up generators is high and will be placed at the top of the merit order, on the right side in Figure 3. This limits the number of hours that back-up generators can run and, therefore causes investment challenges. To stimulate investments in these back-up generators, the market prices will have to be extremely high during the limited operating hours. A similar situation holds for long term electricity storage that is required in periods in which no VRES is produced for several days. However, extremely high pricing is undesirable for electricity consumers and affects the affordability of electricity supply (Joskow, 2019). The spikes in market prices will likely result in government intervention through price capping. Therefore, the 'missing money problem' arises, meaning that the forecasted yearly revenue from generation is not adequate for capital investments for required back-up and long term storage at the high-end of the merit order, and thus distorts the long-term market equilibrium (Newbery, 2016).

Additionally to back-up generators and long-term storage, different types of highly flexible short term electricity storage will play an essential role in a sustainable energy system (Newbery, et al., 2018); (Lüth, et al., 2018). Short term electricity storage is meant to manage intraday demand and supply fluctuations. In the current market design, the dispatchable grid-scale batteries are part of the merit order and obtain revenues by withdrawing electricity from the system at low hourly prices and injecting electricity at high hourly prices. This revenue stream should be sufficient to provide for the high CAPEX of the short-term storage. However, when there are timeframes in which the supply and demand can be balanced entirely by VRES and batteries, the market price will approach zero across the whole timeframe. Therefore, the business case of grid-scale batteries will be impaired by both an increase in batteries and a strong increase in the level of VRES. A similar challenge as mentioned for VRES might therefore arise for short term electricity shortage in which the revenue stream is not sufficient to provide for the high CAPEX and investment for the required short-term electricity storage will be hindered.

2.3 Theories and models for a VRES-based market design

There are different theories and models in the current literature based on establishing a VRES-based market design which fits within the European and national criteria while dealing with the stated challenges of 'missing money problem' and the 'merit order effect'. Most of these theories take a system-wide approach of regulations, technology and markets. Other theories focus on the specific challenges without regarding the system-wide perspective. For this study both the specific challenges as the system-wide perspectives are relevant.

A contemplated solution for the 'missing money problem' is the introduction of capacity mechanisms. Capacity mechanisms are state-driven measures that provide additional revenue to generators for the availability of electricity. This creates revenue based on the electricity which a generator commits to have available at some point in the future next to the market pricing of the electricity produced. This mechanism encourages investments in back-up capacity to meet demands at all times. This form of government intervention additionally implies the requirement of market surveillance. Without surveillance, market power can easily be abused to simulate scarcity to receive funding for non-required capacity (Newbery, et al., 2018). Another challenge for capacity mechanisms is the use of state aid which should comply with the European Guidelines on State aid for environmental protection and energy 2014-2020 (EEAG) since it may cause unfair cross-border market prices (European Commission, 2016). In the latest European energy policy framework, the limit for electricity producers for receiving revenues through capacity mechanisms has been increased to stimulate investments (European Commission, 2020).

Delft University of Technology has established a framework with a system-wide perspective on the correlation between the different possible regulations that influence the economic efficiency of the market design (de Vries & Verzijlbergh, 2018). They promote a system integration approach between countries, levels of the electricity system and markets with different time scales to optimize regulation. The study focuses on four areas: system adequacy, network investment, short-term market design, and congestion management of the electricity sector. Flexibility options with different energy carriers, such as power-to-heat and power-to-Hydrogen, are not considered. The study states that the need for a capacity mechanism is largely dependent on expected revenues from generators in both short-term markets as balancing markets. Introducing a capacity mechanism might also influence an increase in revenues for VRES and have cross-border effects. It should be guarded that a capacity mechanism mainly focuses on long-term effects and not only short-term challenges. Moreover, a capacity mechanism should encourage developments that can stabilize prices and aim to decline the necessity of the mechanism. Additionally, all policy instruments should align with national missions for energy and sustainability. A challenge with VRES is coping with the variability and unpredictability of the sources. Both options of either punishing VRES for forecasting errors or to completely remove balancing responsibilities are undesirable. Therefore, VRES should have full balancing responsibilities but also benefit from providing balancing service. The key challenge is to establish more flexibility in the system, reflect technical aspects in regulations and change regulations with a system integration approach. Currently, flexibility is steered at minimizing operating costs, this might lead to paradoxical situations in which batteries are used to prevent start-up and ramp-down costs of generators by keeping the generators in production while not being necessary (Verzijlbergh, et al., 2017). Changes in the market design should create more price-elasticity since this will stabilize the system. A pan-European 'supergrid' might also cause this effect.

A 2018 study by Newbery et al. has a relatively similar view on altering the market design. The ideal market design is a complete market in which all services and products are effectively priced (Newbery, et al., 2018). Capacity mechanisms are required but do need strong market surveillance to prevent the abuse of market power. Moreover, price signals and regulated network tariffs should be introduced to reflect the complete value of the electricity service. The idea of creating more price-elasticity in the system to stabilize the electricity system is similar. However, in contrast to the aforementioned study by Verzijlbergh and de Vries, this study aims at nodal prices for establishing more fair and balanced pricing. So, instead of expanding the system price across a pan-European system, the study aims at making price areas smaller. Additionally, the study states that there should be different contractual relationships between electricity consumers and retailers. These contracts should focus on the long term and close-by generation, to provide a more stable investment climate.

A Danish study focusing mainly on the investment challenge of wind energy, also mentions the need for long term contracts in financing wind energy projects (Djorup, et al., 2018). The switch to long term contracts is needed since VRES mainly have long-term costs, due to the high CAPEX, instead of short-term costs. Additionally, the study states that electricity end-users should pay for the full cost of energy supply, instead of solely the marginal costs to tackle the challenge posed by the ‘merit order effect’. A market-redesign is not in the scope of this study.

A Dutch study of Utrecht University has a different perspective on solving the challenge of VRES business cases (Hu, et al., 2018). First, the study recognizes the need for a nodal pricing system similar to the study by Newbery et al. Additionally, some changes should be made to the intraday and balancing market. The time resolution of the intraday market should become smaller, the closure time later, and the auctions should be discrete instead of working with a ”pay-as-bid” price settlement to prevent varying prices within the same delivery time. These adjustments will make the market design more suitable for VRES. Moreover, steps are taken to increase the integration of VRES such as increasing the price cap of scarcity to the value of lost load (VOLL) and increasing CO_2 prices. The study also supports capacity mechanisms. Another change that should be made in creating a level playing field for all market participants. The objective is to encourage VRES to join the balancing market to be able to receive potential revenues from this market. This idea is rather similar to the balancing responsibilities challenge described by de Vries and Verzijlbergh. The study also recognizes the alterations that should be made to the balancing market to make it more suitable for VRES, such as a later closure time and a higher time resolution.

In a study by Joskow, many of the above perspectives are also mentioned (Joskow, 2019). The starting point of this study is the current market design which the study aims to reform to accommodate the characteristics of VRES. First, he recognizes the importance of price sensitivity and willingness to pay on the demand side. This can be done by integrating retail prices with wholesale market prices. Second, to prevent the ‘missing money problem’ of back-up capacities, the study suggests to either increase the scarcity prices to the VOLL or to introduce capacity mechanisms. However, increasing scarcity prices while simultaneously integrating retail and wholesale market prices might create market power abuse since scarcity prices could become extremely high. Scarcity price capping is therefore needed. Third, the study emphasizes the importance of investment stimulation of electricity storage. Storage can provide different services and could obtain different revenue streams. The first and most important revenue stream is energy arbitrage in which storage obtains revenue by moving energy from cheap to more expensive hours, this is based on the merit order. Moreover, storage can obtain revenue by providing peak capacity, frequency regulation, hold off-network investments and provide back-up power. The main question is whether these revenues are large enough to attract investments in storage and how these revenues can be increased by, for instance, capacity payments. Another concern is the lack of long-term contracts in the current system which are required for VRES such as mentioned in the studies by Newbery et al. and Djorup et al. To tackle this, the study suggests a separate market for long-term contracts that align with policy goals.

Different solutions have been opted in the literature to tackle the challenges of the 'merit order effect' and 'missing money problem' while regarding the criteria of a well-functioning market design. In Figure 4, an overview of the different proposed solutions for each study is shown.

	Capacity mechanisms	Nodal pricing	Long-term contracts for VRES (PPAs)	Pan-European supergrid	Altering Intraday / balancing market for VRES	Increase price sensitivity	Revenue for flex from ancillary services
Newbery et al.	✓	✓	✓	–	–	–	–
De Vries & Verzijlberg	✓	–	–	✓	✓	–	–
Djorup et al.	–	–	✓	–	–	–	–
Hu et al.	✓	✓	–	–	✓	–	–
Joskow	✓	–	✓	–	–	✓	✓

Figure 4: Overview of the stands of the different authors on the different market alternatives

These expected challenges and the proposed solutions will be validated with the electricity prices model for the scenarios of 2050 in the *Results*. In the final chapter, alternatives for the market design, based on the literature and results, will be identified and discussed.

3. Description of the four scenarios

The study examines the influence of high-level VRES energy systems on the market design and therefore, input data from an established study has been used. Berenschot, in collaboration with Kalavasta, has created four different carbon-neutral energy scenarios for 2050 in the Energy Transition Model. The scenarios are integral and include all sectors and energy carriers. The scenario study is part of the project 'Integrale Infrastructuurverkenning 2030-2050' that has been executed in collaboration with DSOs, the Ministry of Economic Affairs and Climate Policy, industry, and energy-related companies regarding the Paris agreement. These four scenarios are seen as the boundaries of the future energy system between which the real future system will develop. These scenarios will form the basis for which challenges in future market design will be defined. In this chapter, a description will be given, and an overview will be provided of the electricity systems as described in the four scenarios. Each scenario has a geographically-set focus on how the energy transition is governed.

3.1 Regional governance

In this scenario, the governance of the energy transition is mainly led by local and regional authorities. The national goal is to be completely self-sustainable, regions are not necessarily autonomous, but do control as much as possible within their region. Because of this local and regional focus, citizens are well-aware of sustainable initiatives and results. This causes a change in lifestyle and a buyer-power to push industries to become sustainable. Additionally, the energy-intensive industry shrinks because of the change in behaviour for both inhabitants and industries. Since this scenario aims at being self-sustainable, there is a relatively high level of short-term and long-term back-up capacity. For the short-term, batteries from EVs will be used, whereas for the long-term green hydrogen will be used.

3.2 National governance

The national government will be leading the energy transition in this scenario. The government will pursue a self-sustainable and circular national energy system. Since the governance is on a national basis, the number of local initiatives from citizens and companies will be reduced in comparison to the regional governance scenario. Risks of large-scale projects will be hedged by the national government, causing an increase in large scale wind parks and a national hydrogen infrastructure. The government steers the industry by obliging to electrify and become circular, while also hedging risks. Therefore, the industry will barely grow in this scenario. Similar to the regional governance scenario, there is a relatively high level of short-term and long-term back-up capacity to secure national self-sustainability.

3.3 European CO_2 governance

In this scenario, European-wide CO_2 taxes will be implemented. These taxes will be applied to all sectors in contrast to the current ETS. Since the taxes will be rapidly increased towards 2050, causing the rate of the energy transition to be directly correlated to the rise in CO_2

taxes. Investments in sustainable projects and initiatives will be done based on the financial benefits compared to non-sustainable options including CO_2 taxes. This causes not only investments in completely sustainable projects, but also in hybrid and CCS solutions. The yields of the taxes will be compensated at the European borders to secure the European market position. Additionally, the involved sectors will receive subsidies for sustainable investments causing a stable growth for industries. Until 2050, gas with CCS will be utilized, and this will also be used in back-up generators.

3.4 International governance

This scenario aims at a global market with global climate policies. The Netherlands will not be self-sustainable in this scenario and will be dependent on import. A European infrastructure for energy carriers will be established and international trade relations will thrive. The Netherlands will focus on a knowledge-economy and invest in sustainable projects which are competitive in international markets. Citizens and companies will focus on the development of new technologies. There is a high diversity in energy carriers. This will be seen in both industries as transport in which different fuels will be used next to the electrification.

3.5 Overview of the electricity system in the four scenarios

As described above, the scenario study includes the integrated energy system with all energy carriers, but only the electricity system is used in this study. Therefore, a graphical overview of the characteristics regarding the electricity system as defined in the four scenarios will be shown.

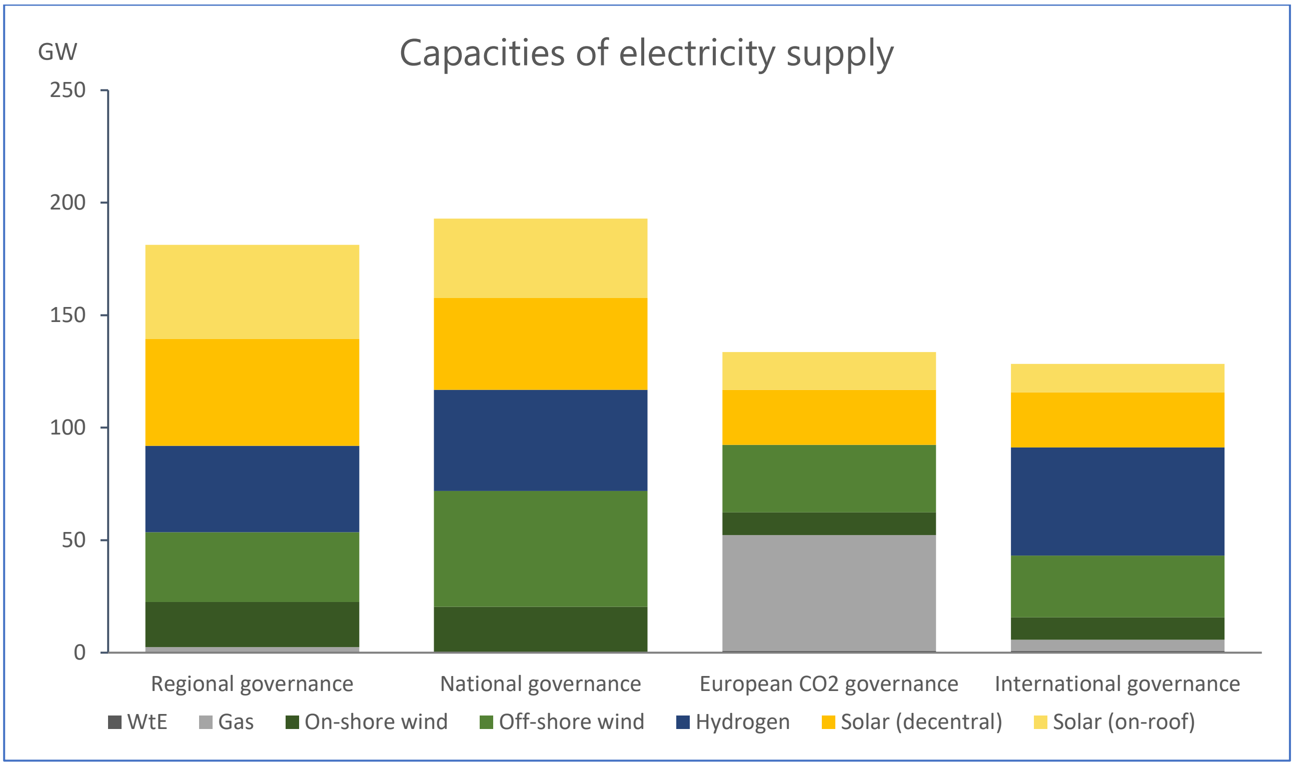

Figure 5: Capacities in Gigawatts of electricity producers in each scenario

Complying to the storyline of each scenario as described above, capacities for each type of producer have been determined. As seen in Figure 5, the regional and national governance scenarios have the highest capacities of renewable electricity supply in their system. This is caused by the high electrification and objective of self-sustainability in these scenarios. In the regional governance scenario, the focus is on solar energy, whereas the national governance scenario includes more wind. This is because the regional scenario aims at local initiatives from citizens and companies, whereas in the national scenario the risks of the wind parks are hedged by the government. The Hydrogen used in the national and regional scenario is green.

The European CO_2 and international governance scenarios have a limited amount of renewable energy capacity compared to the regional and national scenarios. In the European CO_2 scenario, the focus is on gas generators (with and without CCS) since these will financially outweigh more investment in wind and solar capacity. Additionally, this scenario does not contain a Hydrogen-based generator for the electricity system. The international governance scenario has a mix of electricity supply. The Hydrogen power plants mostly run on (blue) Hydrogen from the international market.

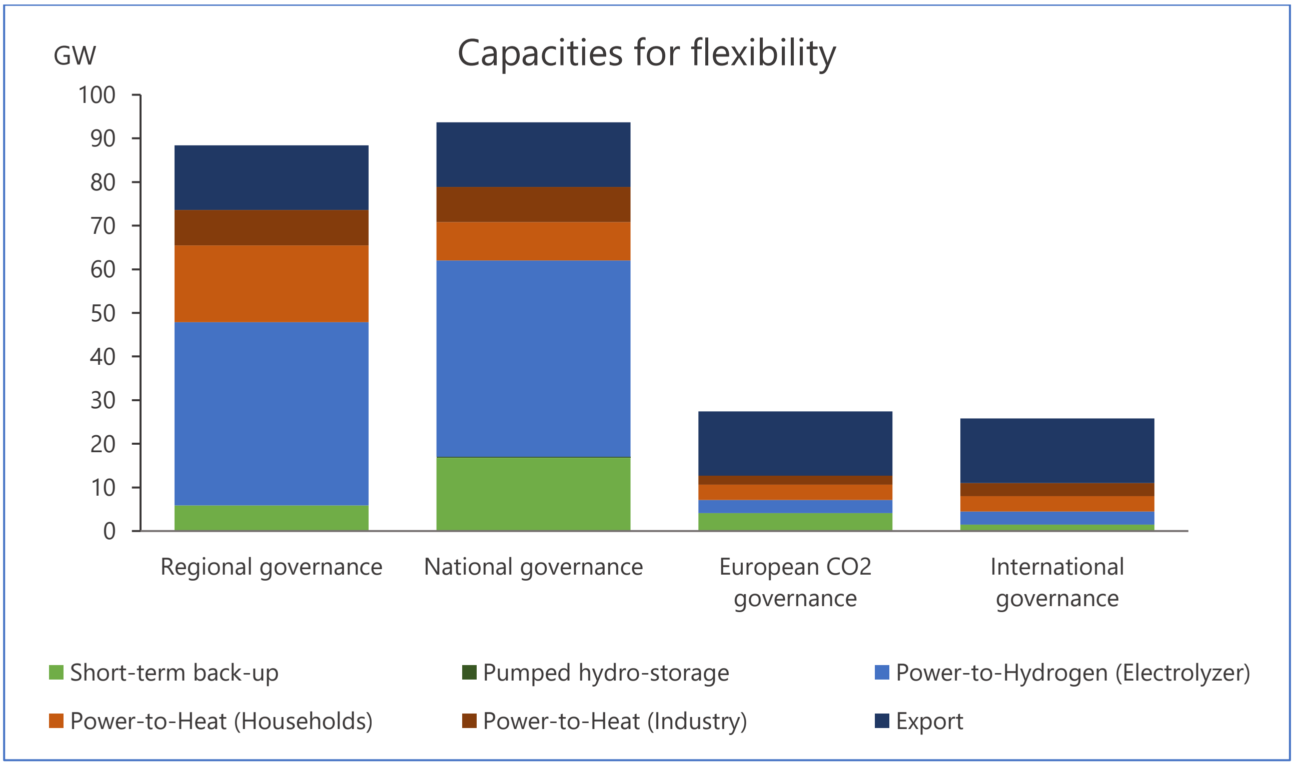

Figure 6: Capacities in Gigawatts for flexibility in each scenario

As seen in Figure 6, different types of flexibility are used in the four scenarios. The regional and national governance scenarios have the highest amount of flexibility available. This complies with the storylines in being self-sustainable on a national level in these two scenarios. The European CO_2 and international governance scenarios have less flexible capacity in the system since the amount of VRES is less than in the other two scenarios, and in the systems can rely on international markets for the availability of resources for the back-up generators. The short-term back-up capacity in the scenarios mostly comes from the availability of batteries of EVs. The Power-to-Hydrogen that can be seen in the figure is partly used for Hydrogen for transport and industry, and partly for Hydrogen for power as long-term back-up capacity. The Power-to-Heat is only converted in situations with electricity excesses in the system. The export capacity is always available in the model.

Hydrogen has an important role in the four scenarios, not only in the electricity market but also for industry and transport. Since the use of Hydrogen is a relatively new technique, major aspects should still be developed. For example, the optimal way of transportation and a market for Hydrogen has not be defined yet. Hydrogen will become an important energy carrier in sustainable energy systems, causing it to become a valuable asset for a country. Additionally, the generation of green Hydrogen depends on the generation of VRES. These insights show the need for storage both for weather and seasonal balancing, but also as a strategic reserve. The size of these storages largely depends on the weather circumstances within the modelled year. For electricity, the Hydrogen plants provide flexibility and balance to the market. Since most of the electricity used in the electrolyzers is from VRES, the Hydrogen plants can be seen as large battery systems. The role in the system is however not to provide balance on a daily scale, but focus on the back-up capacity and balance on the seasonal scale. Since the Netherlands does not have pumped hydro-storage to provide seasonal storage, this role of Hydrogen plants is crucial for a reliable and stable electricity system. Overall, the use of Hydrogen in a sustainable energy system is significant but also new and uncertain.

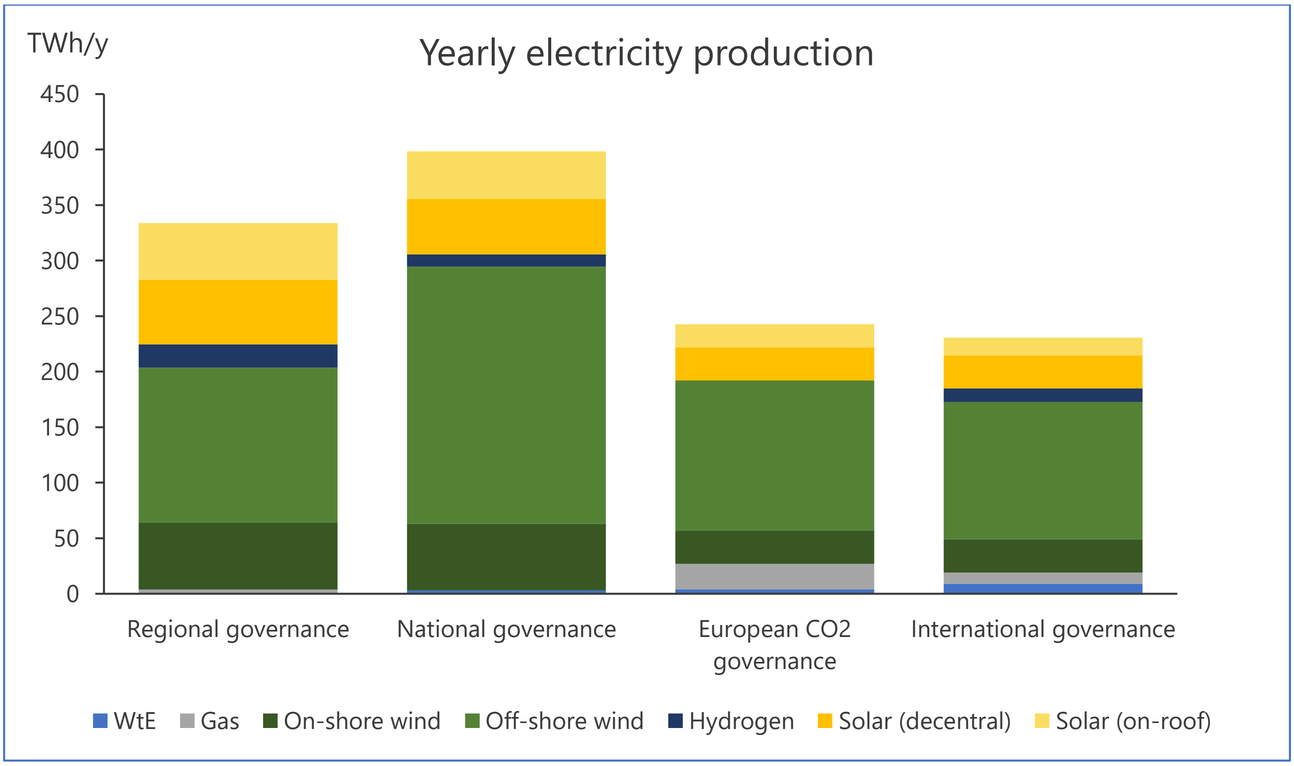

Figure 7: Yearly electricity production in Terawatt-hours in each scenario

In Figure 7, the yearly electricity production per type of producer is shown. This figure shows that each of the scenarios strongly relies on renewable electricity supply. Especially off-shore wind has a strong impact on all scenarios. Some of the electricity produced by off-shore wind will be used in the Power to Hydrogen conversion for industry and transport demand.

These four scenarios will be simulated in the KyPF model as described in the *Methodology*. Choices made within each of the four scenarios are validated during Berenschot's scenario study and will not be subject to change in this study.

4. Methodology

This chapter provides an overview of the chosen methods to answer the research question posed in the study. The study uses a mixed-method, consisting of four parts as shown in Figure 8. In the first step, input data is gathered from the four scenarios as established by Berenschot and Kalavasta and the Energy Transition Model (ETM) is examined. In the second step, simulations in KyPF are run based on the input gathered from the four scenarios. Required data not available in the first step is gathered from different sources. Based on the KyPF model, the behaviour of the electricity prices in 2050 based on the current market design is determined. Third, business case calculations are done to define the extent of the two challenges in the four scenarios. In the fourth step, alternatives to the market design are defined based on the extent of the two challenges. In this step, literature and reviews from experts in this field have been used to validate the alternatives and define the effects. In the following paragraphs, the four steps will be discussed in detail.

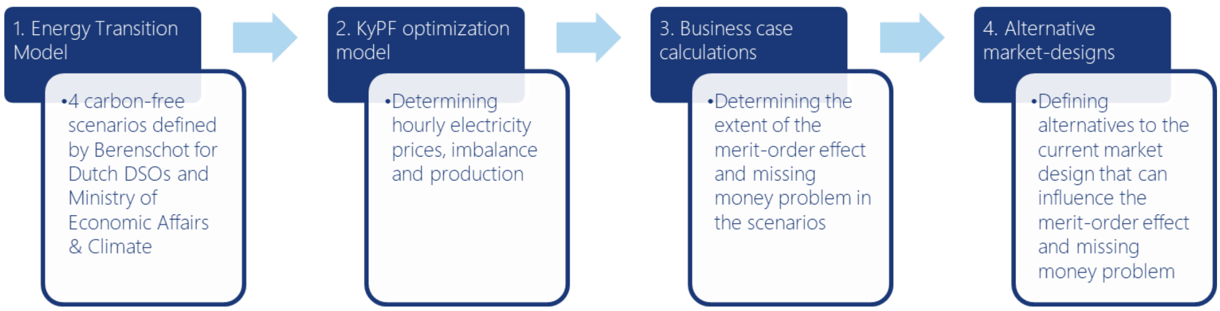

Figure 8: Overview of the different components of the study

4.1 Energy Transition Model

4.1.1 Model description

The four energy scenarios as described in the previous chapter, have been established in the Energy Transition Model (ETM) developed by Quintel Intelligence. The ETM is open-source and publicly available, this strengthens the quality and makes it accessible for future research. The references to the four scenarios used within this study can be found in Table 1. The ETM quantifies an hourly balance of supply and demand based on the total available capacities, flexibility, power-to-X and detailed demand curves.

Scenario	ETM-link
Regional governance	https://pro.energytransitionmodel.com/scenarios/606411
National governance	https://pro.energytransitionmodel.com/scenarios/606415
European CO_2 governance	https://pro.energytransitionmodel.com/scenarios/606418
International governance	https://pro.energytransitionmodel.com/scenarios/606388

Table 1: References to the used scenarios from the ETM

The ETM is suited for generating demand curves and balancing this with required supply capacities but does not accurately define the financial specifics of the electricity market nor the influence of neighbouring countries. The ETM assumes the import and export capacity to always be available and has no optimal dispatch of energy supply. Additionally, hourly electricity price curves cannot be accurately calculated within the ETM.

This study uses the ETM as a primary data source for defining the four scenarios. The data extracted from the ETM is used in the next step as input data for the KyPF model.

4.2 KyPF optimization model

4.2.1 Model description

To predict accurate hourly electricity pricing for the four scenarios, a commercially available simulation model by KYOS, called KyPF, will be used. Performing simulation research fits with this study because of the multi-level and complex character of sociotechnical transitions (Papachristos, 2019). The KyPF model is an iterative model used by different entities to predict electricity prices. In the model, individual powerplants are dispatched with the main objective of maximizing their earnings and have an optimal economic dispatch given the market prices and their cost structure. Additionally, the iterations aim to minimize the imbalance of the system and use the available cross-border capacity to have power flows from low-price to high-price markets. The modelling is based on four input variables: Hourly residual load curves, powerplant data, hourly fuel curves, and interconnection capacities. In the next paragraph, the steps for converting the primary data from the ETM into input variables for the KyPF model will be described. The model has been used before by Berenschot and has shown to be an accurate prediction model for the current market design based upon a merit order approach.

An overview of the different steps that are needed to model the four scenarios in KyPF, is provided in Figure 9. In the next paragraphs, each of the required steps is described in detail.

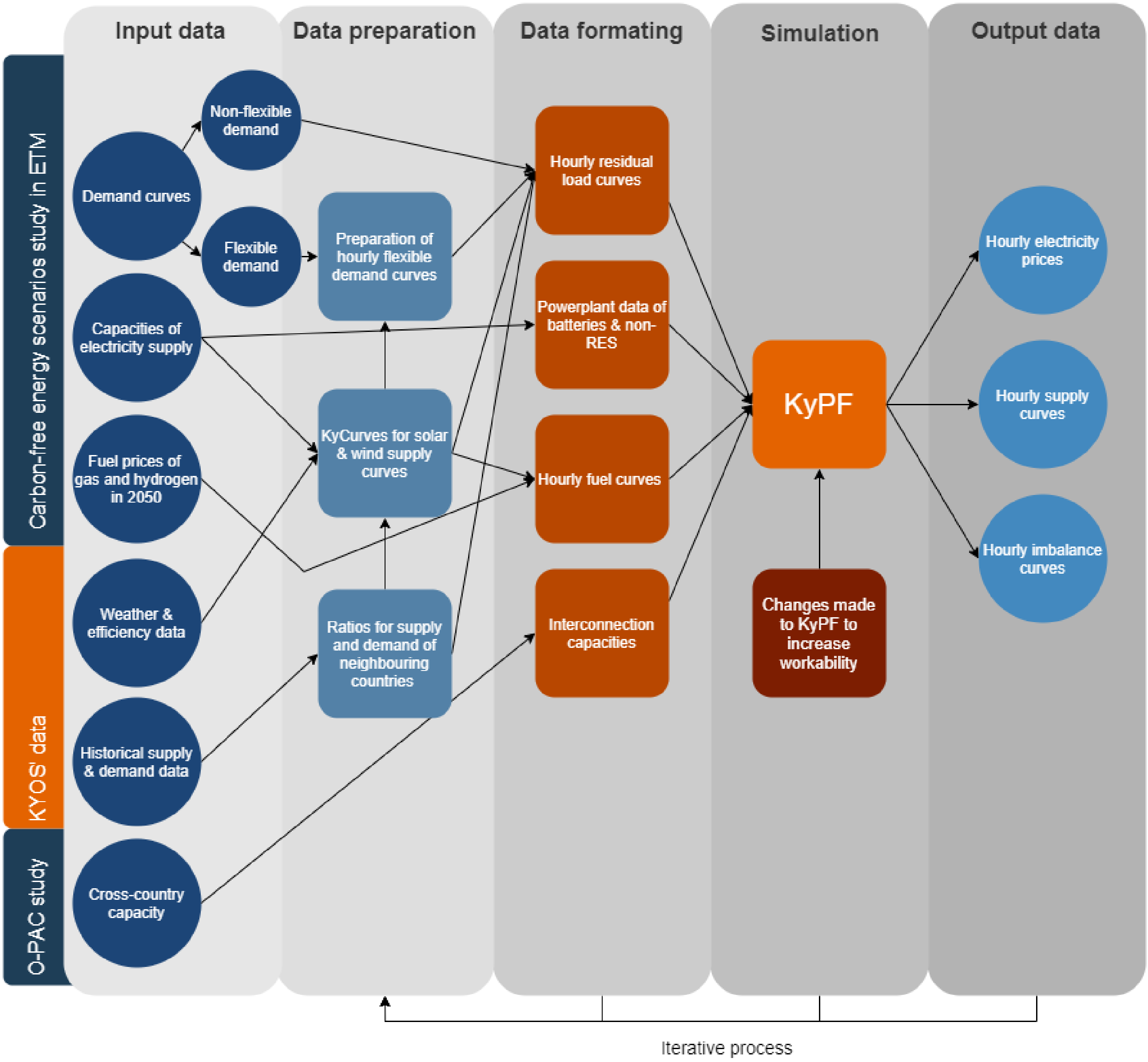

Figure 9: Overview of the iterative process for running the four scenarios in the KyPF model, based upon the different data sources

4.2.2 Input Data

First, different data elements have been gathered from a variety of sources as seen in Figure 9. These data elements form the basis of the simulation study and have been gathered from primary sources. In this subchapter, an overview of each data element is given including the source. In Table 2 can be seen that three data sources have been used. To accurately simulate the four scenarios of the ETM in KyPF, this study aims at using data from the ETM as a primary source. However, not all the required input variables can be found in the ETM. Therefore, data from the ETM has been complemented with data from KYOS' database and the O-PAC study. The O-PAC study has defined specific interconnection capacities based on another study done in KyPF.

Source	Element	Description
ETM	Demand Curves	The demand curves can be extracted from the ETM website and contain a detailed collection of hourly demand curves for different categories. In KyPF the residual load of the system as a whole is required. Therefore, the different demand curves from the ETM have been grouped into flexible and non-flexible demands. An extra step has been added in the data preparation for the flexible demand, which requires the division. This division is required to run the peakshaving algorithm, as explained in the next paragraph.
	Supply Curves of Solar and Wind	The supply curves of solar and wind can be extracted from the ETM based on hourly curves for solar on-roof for households, solar on-roof for buildings, large-scale solar, off-shore wind and on-shore wind.
	Capacities of non-renewable Electricity Supply	This can be extracted from the ETM and contains the characteristics of the different generators and batteries. The data includes the installed capacities per category, as can be seen in detail in *Chapter 3*.
	Fuel prices for 2050	The fuel prices for the different fossil fuels have been simulated in KyPF based on a fixed price that can be extracted from the ETM. The price curves have been fixed on a single, non-volatile price since there are no predictions available for 2050 in the current data sources.
KYOS	Weather and Efficiency	To predict the solar and wind curves for 2050, KyCurve requires input data from a reference year. This data is already available in KyCurve and for this study 2017 has been used as the reference year, in compliance with the reference year used in the O-PAC study and the KyCurve curves.
	Historical Demand Data	KyPF contains data for a set of reference years that can be used to form predictive curves for the future. For this dataset the same reference year, 2017, has been used.
O-PAC study	Cross-Country Capacities	The ETM assumes in its model that import and export capacities are always and unlimitedly available. To provide more realism and depth to this study, the interconnection logic from the KyPF model has been used. Input for the interconnection capacities has been gathered from the O-PAC study (Berenschot, 2019).

Table 2: Description of the input data elements used in the study including the source.

4.2.3 Data Preparation

The different data elements have been validated and prepared for running the KyPF simulations. The different steps in this process have been outlined in this paragraph.

Data validation

The input data from the ETM has been validated and the supply and demand curves have been analysed with the use of descriptive statistics. To validate the correctness and plausibility of these curves, the statistical characteristics of each of the curves from one scenario are examined. Based on the outcomes of the descriptive statistics of the supply curves of the ETM, a cross-check has been done with supply curves from KYOS. Since the curves from KYOS showed a more realistic distribution of electricity supply throughout the year, the supply curves from the ETM have not been used in the rest of the study. An additional benefit of using supply curves from KYOS is the ability to generate these curves for neighbouring countries.

Flexible demand curves

This paragraph describes the steps that have been taken to consider the flexibility, as described in the four scenarios, for the KyPF model. First, the KyPF model does not support the integration of power-to-X. As an alternative, a peakshaving algorithm has been developed in Python. This algorithm shaves the required electricity for power-to-X as defined in the ETM from the demand curves. To optimise the peakshaving, an optimization function is iteratively run over the demand curve and demand is only shaved where the excess of electricity supply peaks. The maximum amount of peakshaving per hour has been limited to the capacities of power-to-X in each scenario as defined in the ETM. The peakshaving algorithm[1] is visualised in Figure 10. The peakshaving algorithm is designed to only consider the excess of supply without considering the hourly demand for power-to-X. The algorithm is therefore not realistic but creates the best approach given the available data.

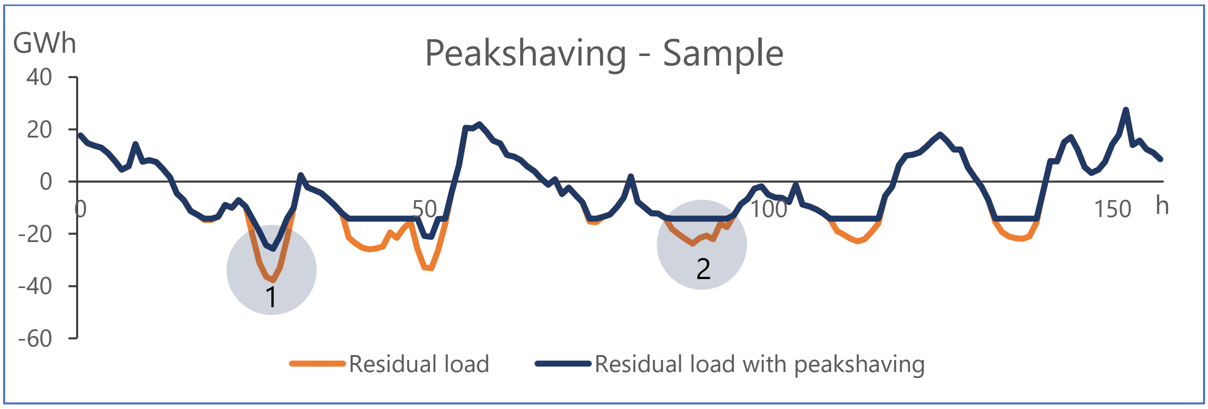

Figure 10: Sample of peakshaving the hourly residual load. In situation 1, the electricity excess exceeds the capacity for power-to-X. In situation 2, the curve is 'shaved' to the new baseline.

Second, flexibility regarding batteries, import and export have been removed from the demand curves, since this is separately simulated in KyPF. The batteries have been added to the powerplant files based on the capacities from the ETM. The KyPF model will try to optimally dispatch the batteries, together with the dispatchable generators. For the import and export capacities, the ETM assumes that these capacities are always available. The KyPF model improves upon this by also modelling the markets with which interconnections have been established. The available capacity is determined based on these models and provides an accurate representation of the availability of the interconnection capacities.

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[1] The algorithm is written in Python v2.7 and is publicly available at https://github.com/liesbethvklink/CurveAdjust/tree/master

Third, the required electricity for Hydrogen allocated to transport and industry has been removed from both the demand and the off-shore wind supply curves. The required electricity for Hydrogen has not been peakshaved, such as the other power-to-X, since it is likely that the demand for the electrolyzers is centrally required. In this way, the balance has been maintained in the system, and the demand for power-to-Hydrogen for industry and transport is not affecting the simulations. For the required Hydrogen as a powerplant fuel source, the same approach has been used. The KyPF model does not support a relationship between the electrolyzers and Hydrogen powerplants. Multiple options have been tested, but none have led to a workable solution. Therefore, the electricity required for the electrolyzers has been removed in the same way as for transport and industry demand. This is further discussed in the discussion.

KyCurves

Since the ETM VRES supply curves have shown to be less realistic than the ones from KYOS, as will be described in *paragraph 5.1,* solar and wind supply curves generated by KyCurves have been used in the study. KyCurves is a product of KYOS, which establishes supply curves based on historical data and the influence of additional capacity on the current supply distribution. To keep the input variables of both models consistent, the capacity used in KyCurves has been chosen such that the produced electricity of solar and wind are equal to the total production as used in the ETM. Therefore, the resulting production is the same as in the scenario study in the ETM and only the distribution throughout the year has changed.

Neighbouring countries

For the neighbouring countries, Germany, France, Belgium and the United Kingdom, the inputs of the four scenarios have been adjusted following the ratios of the electricity demand in the reference year, 2017. To determine these ratios, historical demand data has been used from KYOS' database and the total electricity demand of each country has been compared to the total electricity demand of the Netherlands in 2017. For the total demand curves for 2050 for each country, the Dutch hourly demand curves of each scenario for 2050 have been multiplied by this ratio. The demand curves used in neighbouring countries, therefore, have the same yearly distribution as the Netherlands. This has been done since the study in the ETM has not established demand curves for the neighbouring countries in different scenarios. Using different studies for each separate country would not match with the study in the ETM and establishing hourly demand curves matching the characteristics used in the ETM is outside the scope of this study. The supply curves for each country have been made separately with KyCurves to include the distinct weather conditions in the different countries. For the capacities of batteries and generators, the same ratio has been used for the hourly demand curves.

4.2.4 Data formatting

The KyPF model needs specific input files to run the model, therefore the prepared data needs to be formatted. This subchapter describes how the different input files have been created.

Hourly residual load curves

The residual demand is defined as the total electricity demand in megawatt-hour excluding the supply generated by variable renewable resources. The solar and wind supply curves have been subtracted from the demand curves to calculate the hourly residual demand curves for each country in every scenario. These curves, in combination with the peakshaving as performed in the data preparation step, results in hourly demand curves that can be both positive and negative, indicating demand that cannot be fulfilled by VRES and excess energy produced by the VRES. In total five different curves per scenario have been produced, one for each of the countries that have been included in the simulations.

Power plant data of batteries and dispatchable energy sources

Dispatchable energy sources and batteries are used in the different scenarios to provide electricity when VRES cannot meet demand. The power plant input files have been made such that the capacities of the electricity generators correspond with the capacities in the ETM. Additionally, efficiency, cold start costs, and variable operational and maintenance (VOM) costs have been added based on existing data in KYOS' database. Also, the capacity, volume, VOM costs and efficiency of batteries have been included from the ETM. For the neighbouring countries, the capacities have been adjusted considering the calculated electricity demand ratio and added to the power plant data in the same manner as the Dutch generators and batteries. Together, this results in four power plant files, one per scenario, including the powerplants for all five countries.

Hourly fuel price curves

The hourly fuel price curves are based on price data from the ETM. The price curves have been made with fixed, constant prices since there is no prediction of the price trends in 2050. For each commodity used, a curve has been made. When different scenarios use the same commodity, the same hourly fuel price curves have been used. This enables the cross-scenario comparison.

Interconnection capacities

Interconnection capacities can be set in the model itself and have been kept the same as in the O-PAC study. For this study, interconnections have been set up according to the matrix shown in Table 3.

To \ From	NL	FR	DE	BE	GB
NL	-	0	4000	2500	2000
FR	0	-	4000	3000	0
DE	4000	4000	-	1000	0
BE	2500	3000	1000	-	0
GB	2000	0	0	0	-

Table 3: Matrix of the different capacities in MW that have been defined for the interconnections

4.2.5 Simulations

Based on the input files the different simulations have been run in the KyPF model. For each simulation, the output has been validated and checked, regarding the hourly imbalance, pricing, dispatched supply and integration of VRES in combination with batteries. The validation has focused on looking for outliers that could indicate a potential issue. Besides, the results have been cross-referenced with the ETM and output from the O-PAC study to validate the results. Based on the output validation, changes to the input files have been made and tested. The changes mostly consisted of alterations on the structure of the powerplant files, as well as the flexible demand curves. The input files have been continuously adjusted to make the scenarios more realistic. This has been done for the neighbouring countries as well as the Dutch market. This has been an iterative process and led to the results.

Besides the changes to the input files, modifications to the KyPF model have been made, based on the results and validation of the different runs. The KyPF model has been designed for running short term predictions based on a low integration of VRES. The model had to be altered on three main aspects.

In the initial version of the model, batteries were modelled to start at full volume and end empty by the end of the simulation. This resulted in an unfair distribution and added non-existent electricity to the market. Therefore, a change has been made so the batteries either start and end empty, or start and end fully charged. This has been added to the powerplant files based on a random function to simulate a realistic scenario.

Besides the batteries, the model was set to start each iteration with a starting price of zero. This works in the current situation, where integrations of VRES and batteries are minimal, but resulted in a false optimum in the pricing mechanism when integrations of VRES and batteries increased. This led to a high imbalance in the system since the batteries did not work as intended. In collaboration with engineers of KYOS, several tests have been done to reduce this effect. In the end, increasing the starting price for each iteration resulted in a better performing pricing optimization and lower imbalance.

Additionally, the number of iterations in the KyPF model has been increased to improve the optimization mechanisms of the model. The KYOS model uses three phases in the iterative process, for which the last focuses on the optimization of imbalance in the system. Increasing the total number of iterations resulted in a lower hourly imbalance and improved the dispatched supply in combination with the batteries.

Since KyPF is a proprietary model, owned by KYOS, the changes have been made by their engineers. All changes have been extensively tested and discussed in collaboration with KYOS. In addition to the changes made, extensive discussions have been conducted with KYOS to define the optimal way of integrating Hydrogen/electrolyzer powerplants. Multiple tests have been run, but since there is no way of linking Hydrogen powerplants to the electrolyzers in an efficient manner, no changes to the KyPF software have been made.

4.2.6 Output data

With these input curves and variables, the KyPF model generates different outputs, of which hourly production, electricity pricing and imbalance curves for each scenario form the basis of the further analysis. These curves have been used to determine the behaviour of the electricity prices, how and on what degree the 'missing money problem' and the 'merit order effect' occurs, and provide insights on how the market design should be altered to be well-functioning with high levels of VRES integration.

4.3 Quantitative analysis: Business case calculations

In the quantitative data analysis, the outputs from the KyPF model are used to evaluate the challenges occurring in the current market design. The analysis also focuses on the behaviour of the electricity prices and provides reasoning to the challenges. This analysis focuses on answering the first and second sub-question of the study. For the analysis, the hourly electricity supply, market price and imbalance curves have been used. These curves have been created with and without the influence of interconnection capacities to neighbouring countries.

First, price-duration curves, boxplots, and average daily production curves have been made for each scenario. The price-duration curves show the sorted price and the range of hours in which the system has a certain price. Therefore, the curves should provide insights on price stability and distribution. The price-duration curves of the simulations including neighbouring countries show the effect of interconnection capacity on the electricity price distribution. In addition to the price-duration curves, the volatility of the price curves in the different scenarios has been calculated and is shown in boxplots. The results from these curves and boxplots will be used to answer the first sub-question by providing knowledge on the behaviour of electricity prices in 2050. Additionally, the price-duration curves will be matched with the hourly supply curves to provide insights on the distribution of prices per type of producer and the effects of the 'merit order effect' and 'missing money problem' on the system in each scenario.

Second, average daily supply curves will be made for each type of producer to provide a better understanding of the price distribution. These curves show how the prices evolve in each system and provide knowledge on the financial situation of each type of producer. Special attention will be given to batteries in the scenarios since the KyPF model has not been designed for a high level of battery integration. To measure the effects of dispatchable powerplants on the market prices, a Pearson correlation has been used. This provides insights into the correlation between the type of producer and market price.

Third, relevant costs for each type of producer are gathered based on the inputs from the ETM. Together with electricity prices, financial feasibility is determined. Additionally, the business cases will be cross-referenced with the average electricity prices of the reference year (2017) to comply with the criteria of affordability of electricity. Finally, a third business case is created where the net profit for the entire system is zero. This balances the system and exposes the distribution of profit throughout the system. All three financial analyses will be used to expose the impact of the 'merit order effect' and 'missing money problem' in the four scenarios as an answer to the second sub-question and input to the qualitative analysis.

4.4 Qualitative analysis: Alternative market designs

The results from the quantitative analysis in combination with the insights from the literature review and validation from experts are used to provide reasoning to answer the third and fourth sub-question of the study. In the quantitative analysis, the impact of the high level of VRES integration on the system and the causality of the challenges will be exposed. These quantitative results will be used to provide reasoning on how alternatives on the current market design, mentioned in literature and by experts, have an impact on the 'merit order effect' and 'missing money problem'. To evaluate these effects, first, the alternatives as shown in the literature review will be examined and reasoning to the impacts of these directions will be provided. Second, more detailed insights based on the quantitative analysis will be gathered from reviews with experts. The reviews with the experts and the alternatives from the literature will be combined to provide an answer to the fourth sub-question. The alternatives can be used as input for a new market design that can accommodate a high integration of VRES.

5. Results

As described in the method, this chapter will provide results of the quantitative and qualitative analysis to answer the research question and corresponding sub-questions. Before providing results of the analyses, data validation of the hourly curves of demand and supply that are used as input data will be provided.

5.1 Data validation

For the modelling in KyPF, different data is required for the supply, demand and available capacity. Since the study tries to model the four scenarios, the input data is primarily extracted from the ETM. The validation of this input data is described in this paragraph.

First, the hourly supply curves of VRES have been examined. The ETM provides curves for solar, off-shore wind and on-shore wind energy. The curves have been slightly altered to model an increase in efficiency over the upcoming years. While validating the curves, it was noticed that the solar curves did not reach a minimum of 0 MWh. Due to day-night rhythm, it would be expected that the solar curves would be 0 MWh at night time. Therefore, the ETM solar curves have been compared to historical data and curves provided by KYOS. In Figure 11, the percentual average solar supply curves are shown for the three data sources.

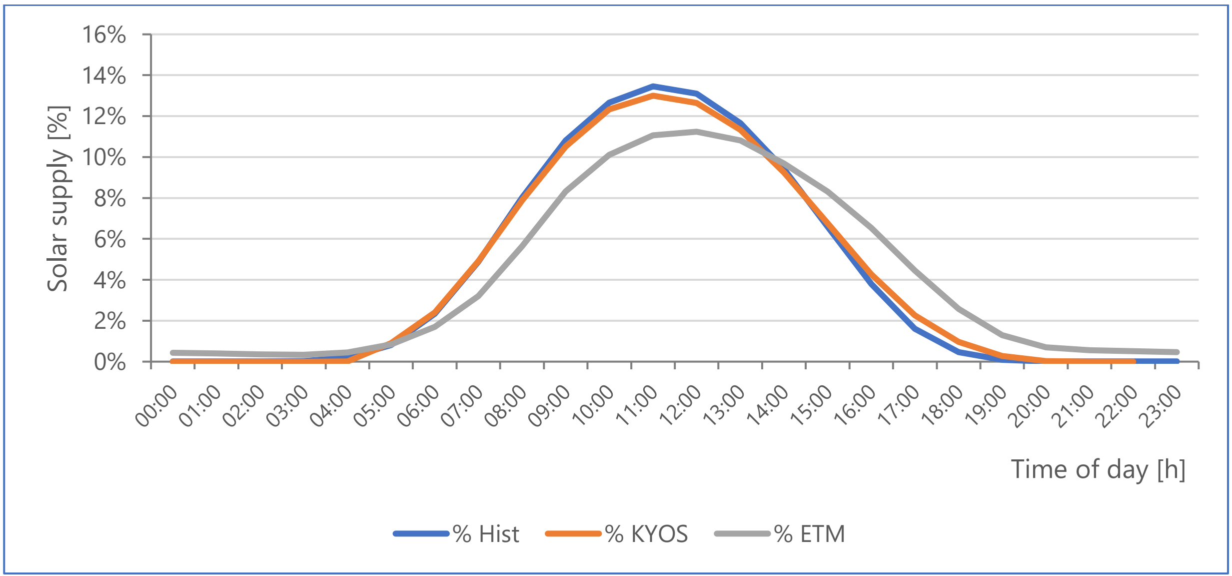

Figure 11: The average, percentual division of solar production in the Netherlands throughout the year (TU Delft, 2020).

In the figure can be seen that the solar supply curves of the ETM do not match with historical data. The curves as provided by KYOS, KyCurves, seem to have a better match. Since the day-night rhythm will not alter in the upcoming thirty years, the solar curves are expected to remain similar to historical data. The increase in efficiency will not affect the distribution, but on the total supply[2]. Therefore, the curves as provided by KYOS have been used in the modelling. To establish the efficiency increase, the total supply has been matched with the total supply as defined in the four scenarios.

The validation of the wind supply curves is more complex than the solar supply curves since the supply largely depends on the location and height of the wind turbines. The supply curves of the ETM and KYOS have been examined, but no abnormalities have been found. Since the solar curves of KYOS have been used, also the wind curves of KYOS are used in the model. This is done to have similar time scales and to maintain data integrity.

Second, the demand curves from KYOS and the ETM have been examined. In KYOS, the demand curves are based on historical data. The total demand can be increased but the distribution throughout the day and year is fixed. The four scenarios in the ETM provide demand curves on a detailed scale, considering the electrification and change in behaviour for 2050. In these curves are, for example, the introduction of (hybrid) heat pumps and electric vehicles included. These considerations provide more detailed insights into the demand curves for 2050, also considering the differences in behaviour in the four scenarios. Therefore, this study has chosen to use the demand curves of ETM in the modelling.

All other input data has been extracted from the ETM which links its parameters to scientific literature. Since this study aims at modelling the insights of the four scenarios as determined in the ETM, these parameters have not been additionally validated nor altered.

5.2 Quantitative analysis

5.2.1 Behaviour of electricity prices

The goal of this paragraph is to provide an answer to the behaviour of the prices of the four scenarios regarding the current market design. To expose the high-over distribution of prices, price-duration curves have been made. These curves show how many hours a year, a certain price is set in each scenario. In Figure 12, these curves can be seen for each scenario, with and without the influence of neighbouring countries, and for the reference year 2017.

[2] Based on these findings, changes to the ETM have been made to resolve the issue of not reaching 0 MWh during night time.

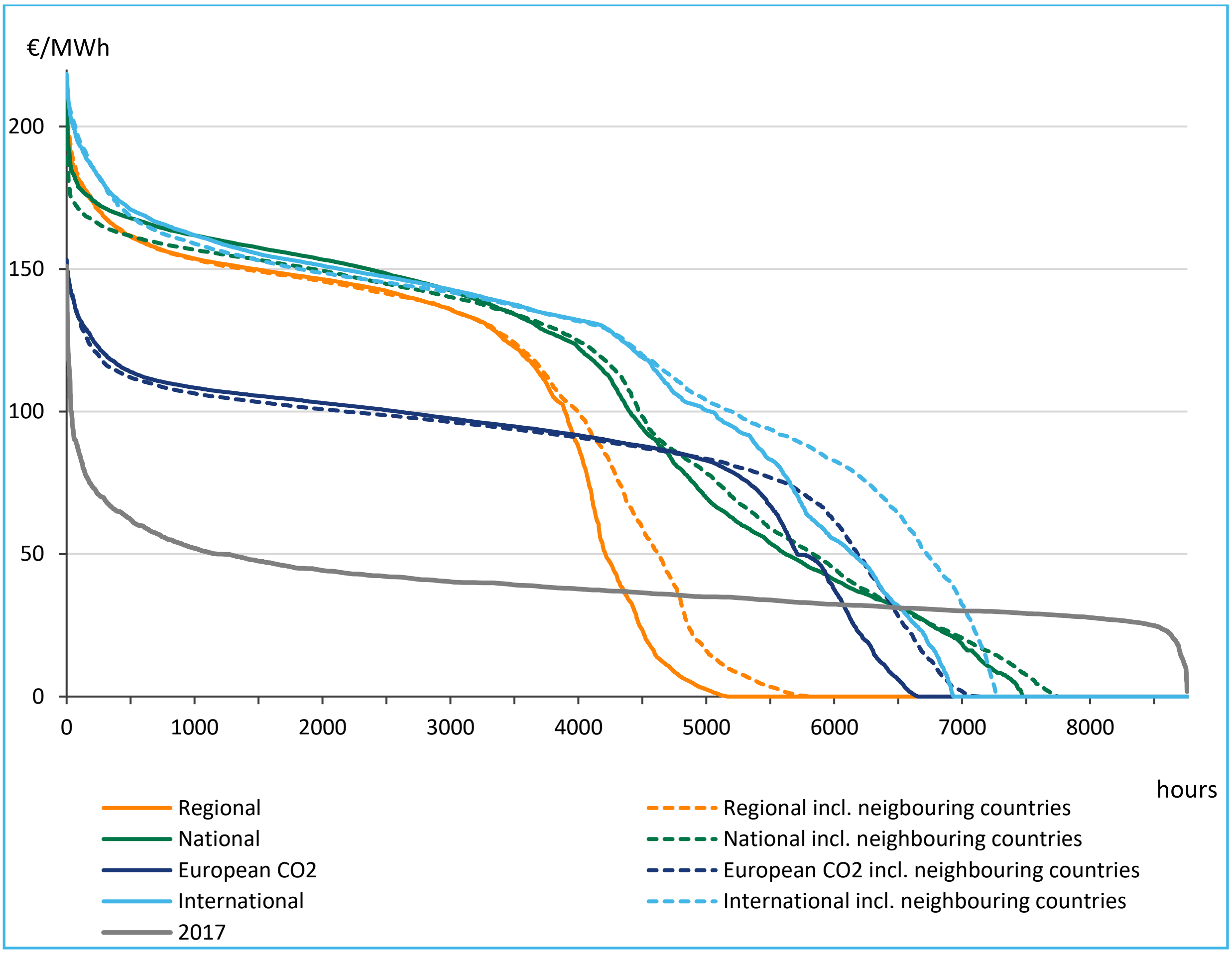

Figure 12: Price-duration curves of the four scenarios, with and without the influence of neighbouring countries, and reference scenario of the year 2017

In the figure can be seen that the average price in all of the four scenarios is significantly higher than in the reference year. Additionally, the price differences throughout the year are greater. The effect of the interconnections with neighbouring countries is similar in the scenarios: The prices on the high-end tend to be lower and on the low-end tend to be higher. The European CO_2 scenario does not include electricity from Hydrogen plants, and therefore has lower prices on the high-end of the price ranges. The regional governance scenario has the most hours with zero prices. The European CO_2 and international scenarios experience a similar price drop. The price drop in the national scenario is less steep than in the other scenarios because of the high influence of batteries in this scenario.

For the remaining figures in this chapter, scenarios including the influence of neighbouring countries have been used. This is done to reduce the number of figures in the text and keep an overview of the most valuable results. The scenarios including neighbouring countries are more realistic for the future system and prevent focusing on unrealistic problems on the high- and low-end that will already be solved by integrating the system with neighbouring countries.

In addition to the yearly spread in prices, the volatility of prices in each scenario has been examined. The volatility of prices provides insights into the stability and dynamics of the market. In Figure 13, boxplots can be seen of the monthly price distribution per scenario, including the reference year.

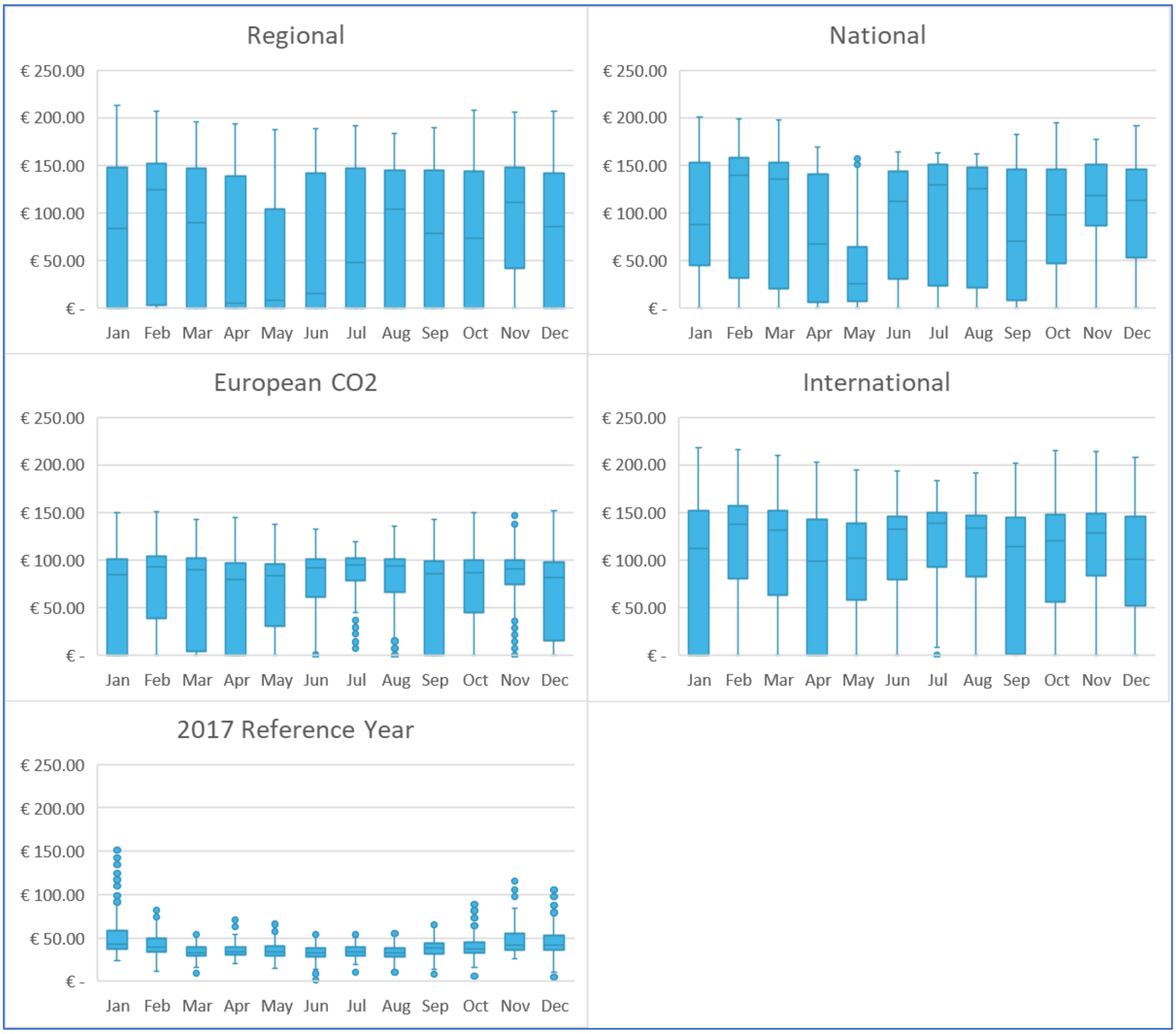

Figure 13: Boxplots of the distribution of market prices per month, per scenario

The boxplots in Figure 13 clearly show that the spread in prices is far greater in the four scenarios of 2050 than they were in the reference year. This demonstrates that not only the difference between the high-end and low-end prices are greater, but the volatility is also higher. This shows that the market will be difficult to predict and dynamic. Especially the regional scenario has a high volatility additionally to the great difference in prices, which is shown in Figure 12 via the slope and spread of the curve. The European scenario has the lowest prices, the least differences and the smallest volatility of the four scenarios.

To examine where these differences are coming from, the four scenarios will be examined on a more detailed level. Therefore, the prices will be split per energy source to show which energy source is in which part of the price-duration curves. These price distributions can be seen in Figure 14.

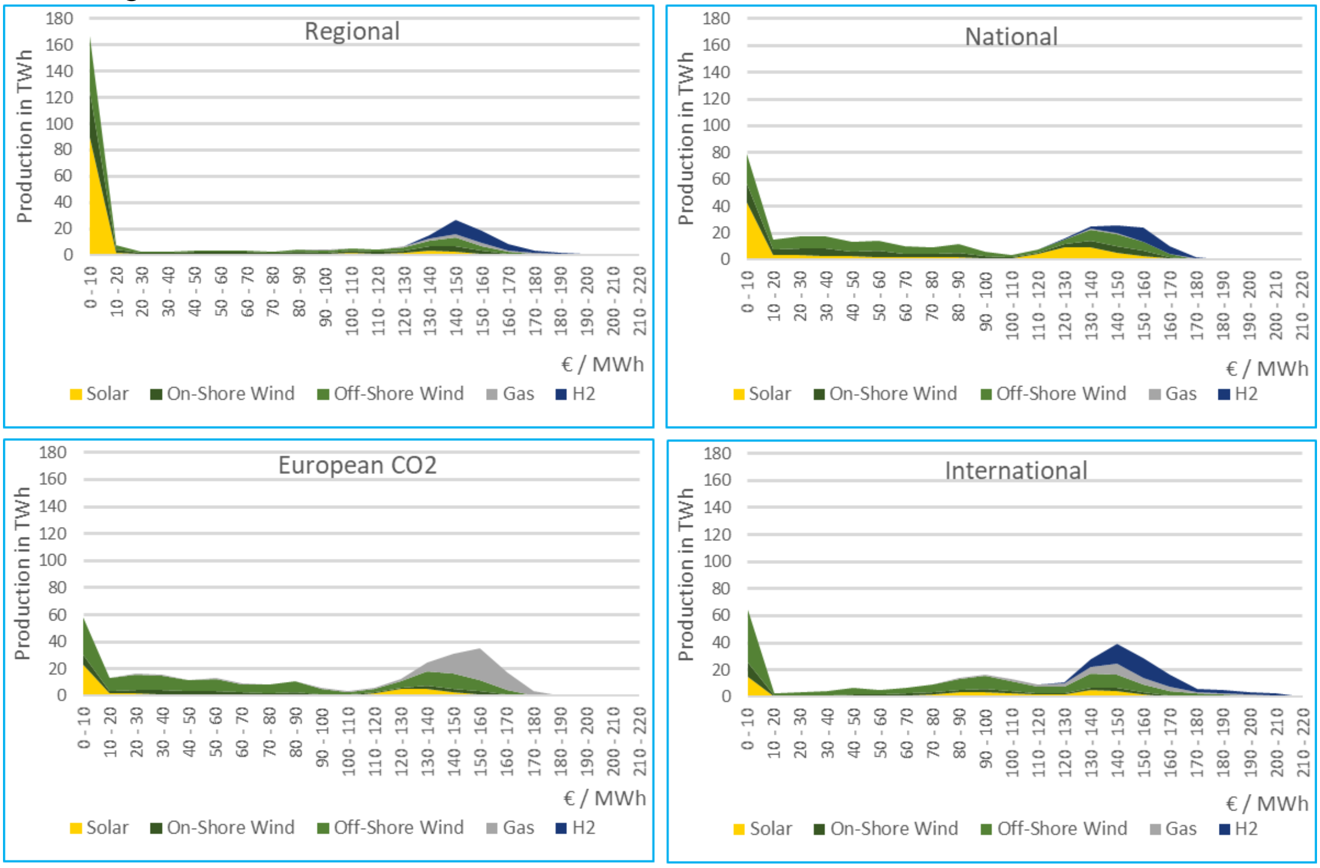

Figure 14: Distribution of energy production, per energy source, grouped by price [€/MWh] (stacked)
The total generation per energy source is shown, distributed along the x-axis by the price.

The graphs show the grouped values of prices per energy source with a €10/MWh interval. The intervals run between 0 €/MWh and 220 €/MWh. The different price duration curves clearly show the spread in prices per MWh per technology. For all scenarios, it is clearly shown that VRES (solar and wind) are largely situated in the lower pricing bands. H_2 and gas are more spaced towards the higher pricing spectrum. The regional scenario is most affected by this difference and 78% of the produced electricity by solar is sold for prices between €0 and €10 per MWh.

This paragraph has shown the behaviour of the electricity prices based on the four scenarios of the ETM. In general, the average prices are higher, the spread in prices is wider, the volatility is higher, and the distribution is unevenly spread across the energy sources. VRES are often priced for zero or near to zero €/MWh, whereas the gas and Hydrogen powerplants have higher prices compared to the reference year. This is interesting for the business cases and the allocation of money throughout the system. This will be discussed in the next paragraph in which an answer will be provided to possible challenges that arise due to the uneven distribution and widespread of prices. The high volatility in prices affects market dynamics and financial stability. This will be further discussed regarding possible alternatives to the current market design.

5.2.2 Challenges exposed by the behaviour of electricity prices

The goal of this paragraph is to provide an answer to the origins of the pricing and how the financial situations of the different technologies are affected by this. To complement the analysis, business cases for each scenario have been added based on both the 2050 prices as well as the prices of the reference year. This will show whether, and in what way, the current market design will be affected by the 'missing money problem' and the 'merit order effect' in 2050.

The previous paragraph has shown that the scenarios of 2050 will be having high volatility and widespread in the distribution of prices. The increased amount of VRES seems to be driving the prices down, whereas the Hydrogen and gas plants seem to be driving the prices up. To examine how this influences the business cases for each energy source, it should be known when the production of each source takes place and how this affects the distribution of prices per source. In Figure 15, an average production day of each season is shown for every scenario.

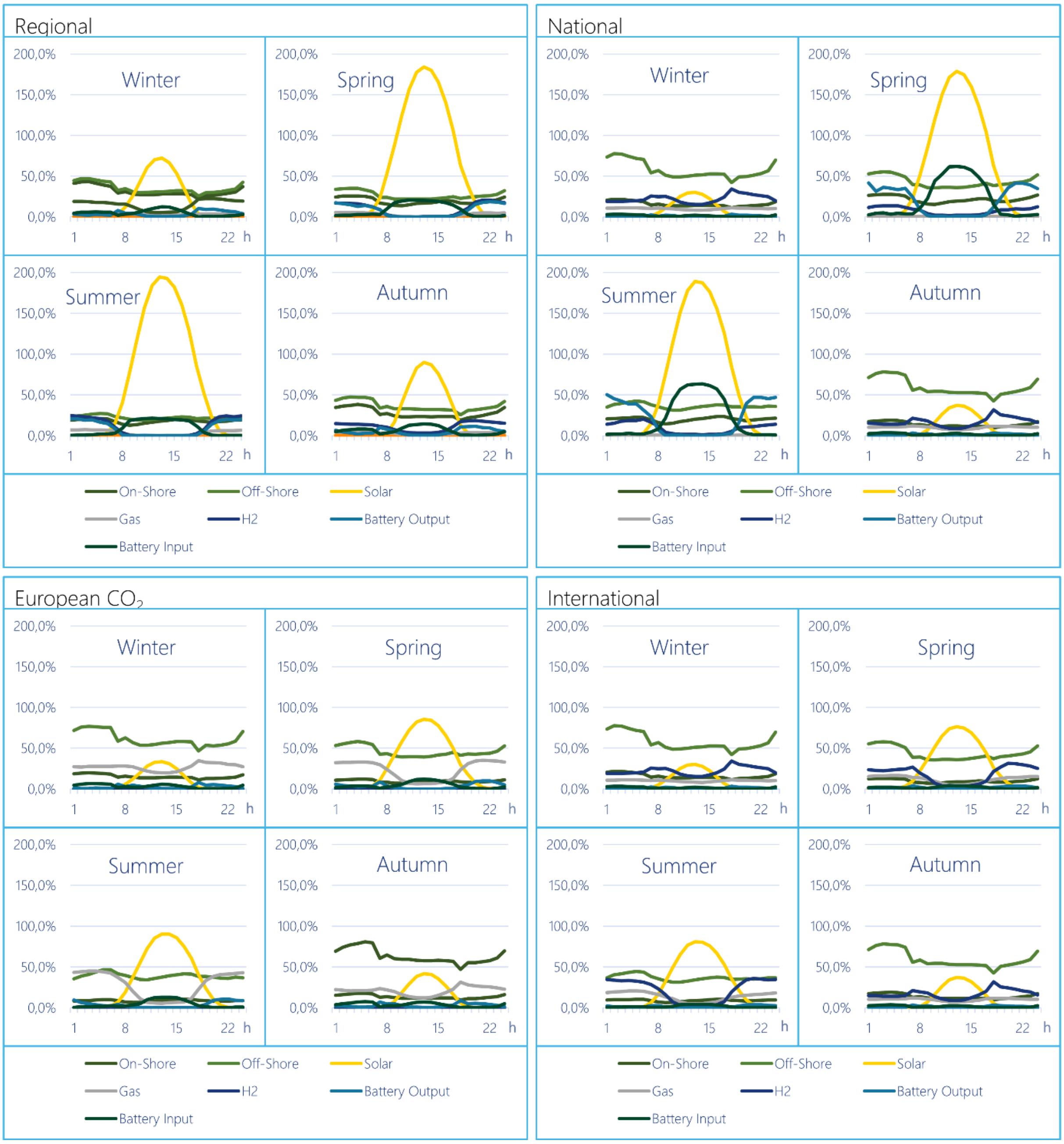

Figure 15: Distribution of produced electricity for an average day in each season based on the total hourly demand

The graphs of Figure 15 shows the hourly production set against the hourly demand. This shows that for each of the scenarios the production for off-shore and on-shore wind is, on a seasonal level, relatively stable throughout the day. Solar adheres to the normal distribution curve and corresponds with the daily solar radiation. Gas and Hydrogen tend to have a lower production at times when solar is at a peak. This is due to VRES covering the total demand during these hours.

Lastly, the batteries are split out into the intake and output curves. The batteries try to optimize the intake and output regarding the electricity prices. Therefore, they tend to fill during the VRES peak hours when prices are low and output during peak demand hours when the prices are high. This is most clearly shown in the winter seasons where solar does not meet the morning and evening peaks.

To show the distribution differences for solar, off-shore and on-shore wind in the four scenarios, production-duration curves of VRES have been made as shown in Figure 16.

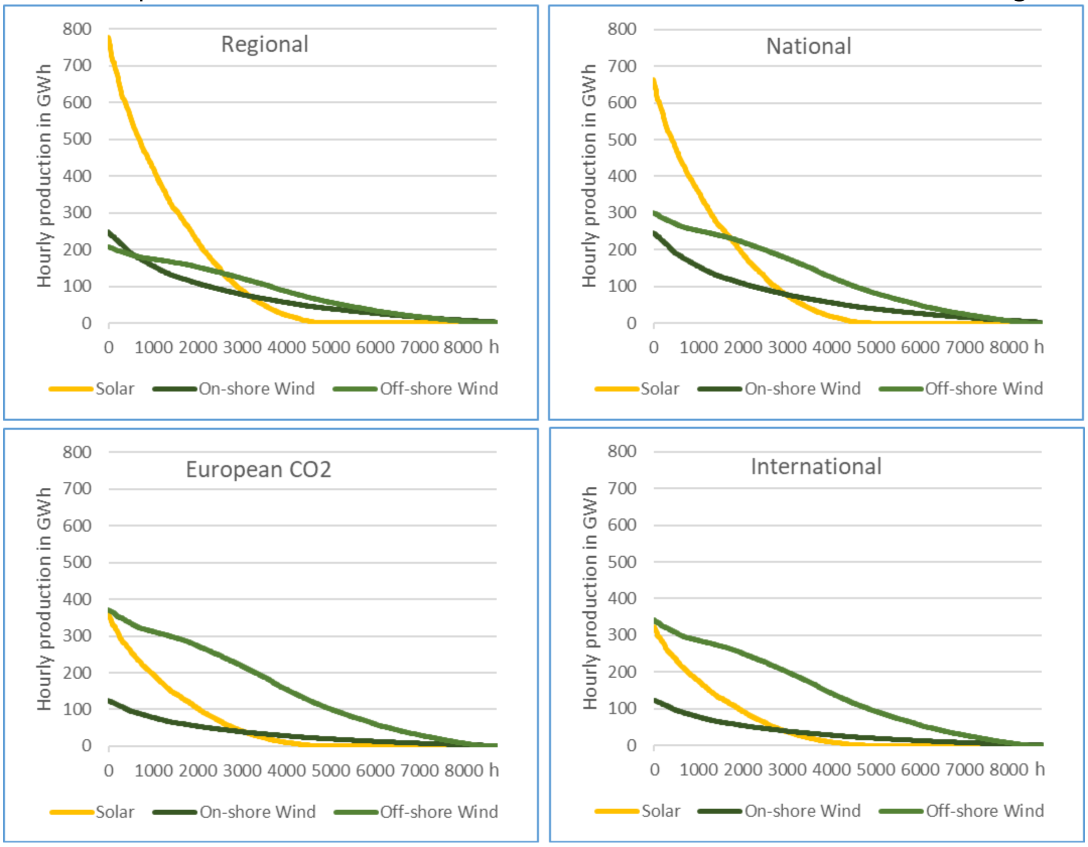

Figure 16: Production-duration graphs for VRES in the four scenarios (non-stacked)

The graphs in Figure 16 again show how off-shore and on-shore wind is more equally distributed throughout the year in comparison to solar energy. Additionally, it can be seen that the regional and national scenarios have a higher integration of VRES. This means that these scenarios are more affected by the 'merit order effect'.

To map the correlation between the hourly energy price and the production of the different energy sources, a Pearson correlation matrix has been calculated. The results can be seen in Table 4.

Energy Source	Regional	National	European CO_2	International
Solar	-0.511	-0.397	-0.301	-0.330
On-shore Wind	-0.483	-0.514	-0.633	-0.614
Off-shore Wind	-0.480	-0.545	-0.664	-0.652
Gas	0.932	0.821	0.712	0.919
H_2	0.715	0.679	N/A	0.691
Battery In	-0.644	-0.504	-0.605	-0.679
Battery Out	0.596	0.300	0.478	0.452

Table 4: Pearson correlation of the system price per scenario with the production of the different energy sources.

Table 4 shows that the production of electricity from gas powerplants has the highest correlation with the system price. This is mainly caused by the working mechanism of the model. Since Hydrogen and gas powerplants are the only commodities with a marginal price the system price is highly dependent on these energy sources. Gas plants have a lower marginal price, placing them before Hydrogen plants in the merit order. The impact of this will be discussed further in the discussion. Each of the VRES, have a negative correlation with the electricity price, showing that when the percentage of VRES in the system rises, the price lowers. For batteries, it holds that the battery intake has a negative correlation with the system price, whereas battery output has a positive correlation with the system price. Since batteries are an outlying category, they do not produce electricity but rather 'move' electricity throughout the hours of the day, it is relevant to dive deeper in the working mechanism of batteries in the scenarios.

Batteries gain profit by the price differences between intake and output of electricity, minus the efficiency rates and the costs of the battery. It is therewith important to expose at what average prices the batteries sell and buy electricity in the different scenarios. When price differences in a system are higher, batteries automatically gain higher profits. Moreover, the amount of capacity in the system also influences the average profit of the batteries. If the amount of batteries is overly dimensioned, the profits of individual batteries will drop. In a real-world scenario, the number of batteries will be determined by a market system of demand and supply. However, the scenarios from the ETM have not calculated the hourly financial situation of each of the scenarios. Therefore, the battery capacity in the system might not be optimal.

In Table 5, the input and output prices of the batteries are shown. It can be seen that the difference between the input and output prices is the highest in the regional scenario, whereas it is the lowest in the European CO_2 scenario. The effects of the deltas will be further discussed in the cost-benefit analyses.

Batteries input/output	Regional	National	European CO_2	International
Input	€ 17.13	€ 45.01	€ 33.42	€ 48.92
Output	€ 129.37	€ 120.03	€ 101.12	€ 144.70
Delta	€ +112.24	€ +75.02	€ +67.70	€ +95.78

Table 5: The average input and output prices with the delta for the batteries per scenario in €/MWh

Additionally to the price differences batteries profit from, there should be determined which energy source provides most of the electricity of the batteries' input, this can be seen in Figure 17.

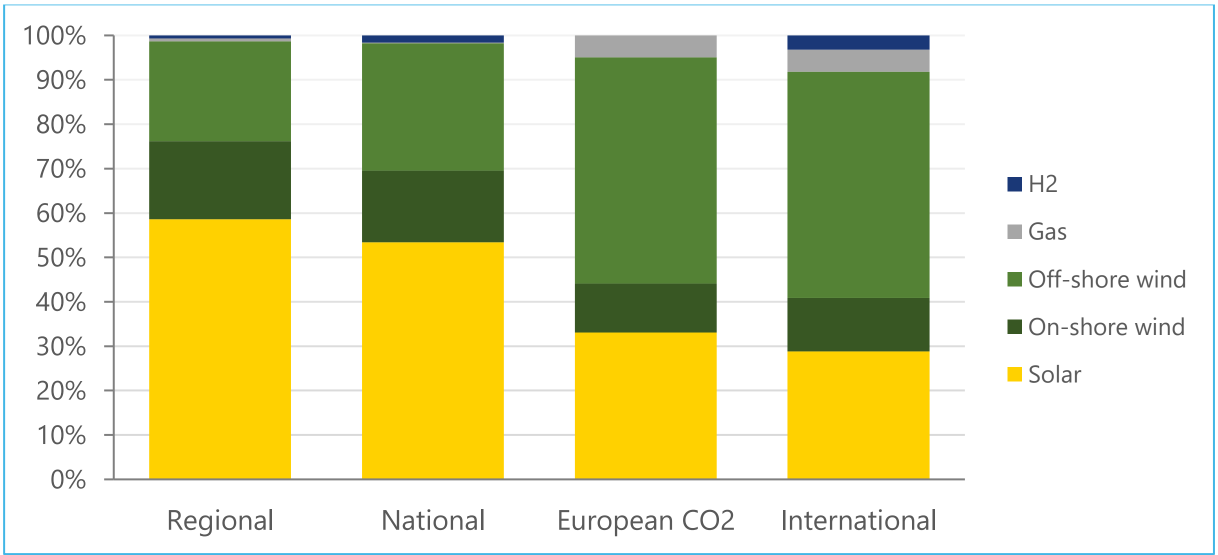

Figure 17: Intake of electricity of batteries per energy source in percentages of total intake

The intake as shown in the figure is determined by dividing a battery's intake, by ratio, over the energy producers for any given hour. This is done on a system-wide scale, the actual intake for each battery cannot be determined based on the KyPF output. In the figure can be seen that most of the electricity in batteries is provided by either solar or off-shore wind. This means, that based on the prices gathered in Table 5, these energy sources sell their electricity at a low price to the batteries at hours of peak supply. The batteries sell the electricity to the system at peak demand. Due to the inability of VRES to steer their supply, batteries gain profit. This is beneficial for the technical stability of the system in which the batteries provide stability as a service, but might add to the challenge of the 'merit order effect'. Therefore, it should be determined whether the financials of the systems are in balance and whether the business cases of each of the energy sources are positive.

Cost-benefit analyses

In the current energy system, the energy sources are OPEX-driven. This means that the initial costs are low, and the operational costs are high. In the four scenarios, this is the case for the Hydrogen and gas plants. The financial risks for investing in such a plant are depending on the commodity prices and the estimated production hours. If a plant can produce base-load electricity, the hourly profits can be lower than when operating as a back-up plant. For VRES, the initial investment costs are high, they are CAPEX-driven. Before investing in these technologies, it is therefore important to consider the financial risks and estimate the return on investment. Figure 18 shows the division in OPEX and CAPEX costs in the four scenarios.

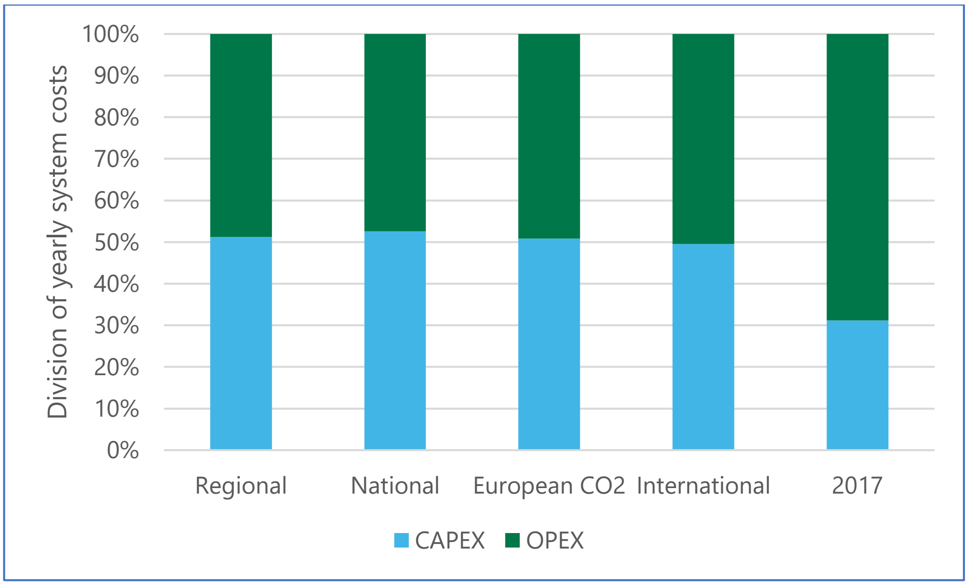

Figure 18: Division OPEX and CAPEX costs of the four scenarios

The figure shows that the four scenarios are more skewed to CAPEX, whereas the reference year is more skewed towards OPEX. Therefore, the electricity markets must provide a stable base to reduce financial risks for investors.

Cost-benefit analyses

To expose the extent to which the 'merit order effect' and the 'missing money problem' occur, financial cost-benefit analyses have been made. First, an analysis based on electricity prices as produced by the KyPF model has been created. This indicates the effects on the system without changing the current market design. However, the average market prices are two to three times higher than in the reference year. This affects the affordability of electricity for end-users. Therefore, a second cost-benefit analysis has been made in which the average prices are the same as in the reference year, but the distribution of prices is kept the same as in the initial analysis. In this analysis, the overall profit of the system is negative and shows that the prices should rise to make carbon-neutral energy scenarios feasible. In the third cost-benefit analysis, the net profit of the system per scenario is kept at zero. In this analysis, the distribution of profits throughout the different electricity suppliers is clearly defined. This shows which challenges should be tackled through alternative market designs. In the next paragraphs, the three analyses will be explained in detail and the effects on the system will be discussed.

Cost-benefit analysis based on 2050 prices

In the graphs below, the financial analysis of the different scenarios is shown based on the prices as determined by the KyPF model for 2050.

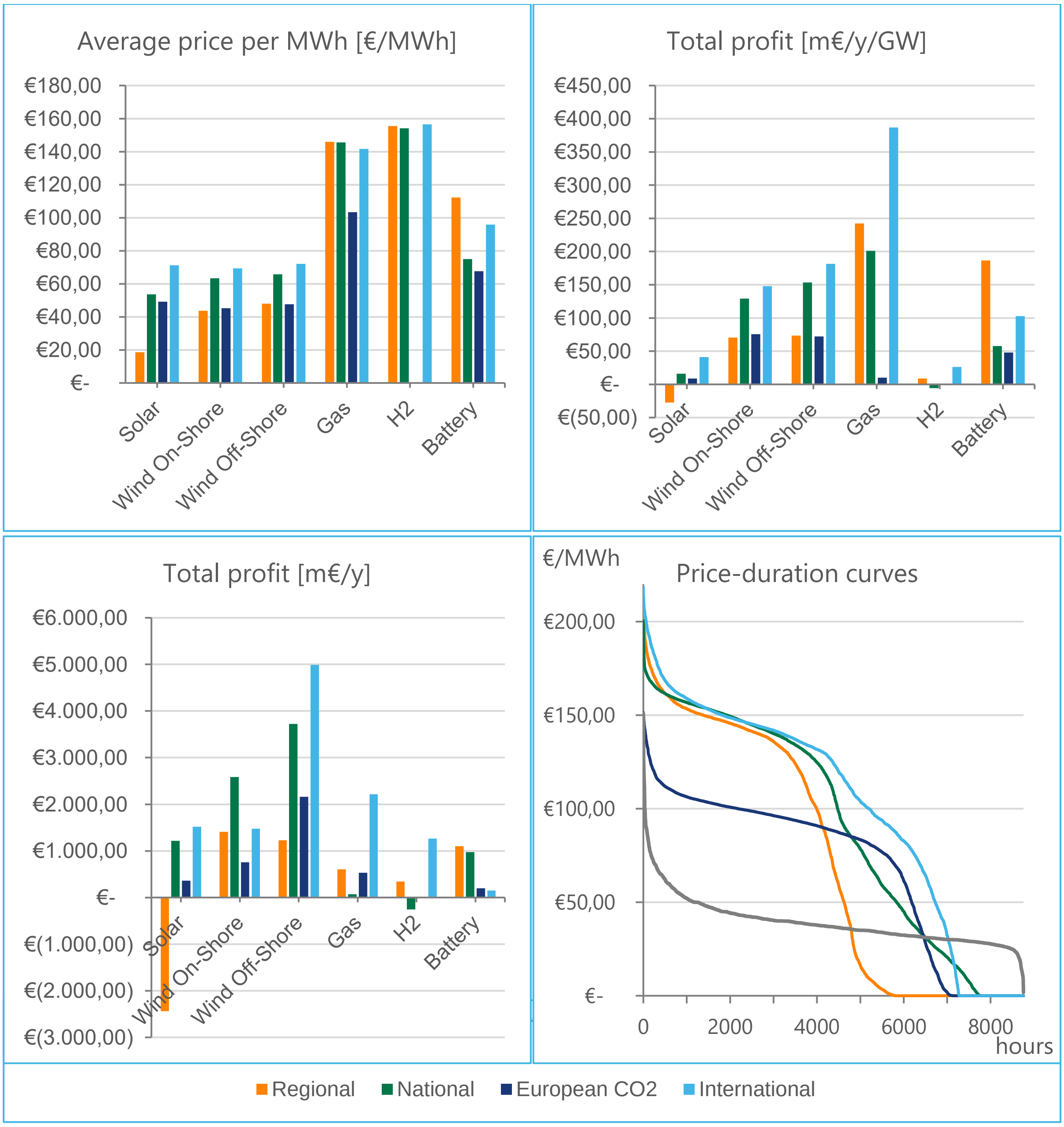

Figure 19: Financial analysis of the scenarios based on the 2050 prices of the KyPF model.

In the top-left graph, the average price per MWh per energy source is shown. In this figure can be seen that the prices for VRES are in the low range, batteries in the mid-range and gas and Hydrogen in the high range. The regional scenario has the highest amount of solar energy, causing the average price of solar energy, and the other VRES, to drop. The European CO_2 scenario has the lowest prices for most of the sources. This is caused by the absence of Hydrogen plants in this scenario. The electricity generated by Hydrogen plants has a high marginal price, causing the market price to increase at instances at which the hydrogen plants operate.

In the top-right graph, the profit of the energy sources per gigawatt is shown. It can be seen that most of the energy sources will be profitable in these circumstances. Challenges (almost) occur for solar energy, Hydrogen plants, and gas plants in the European CO_2 scenario. In the regional scenario, solar energy is not profitable. The regional scenario has the highest amount of solar energy, causing a high amount of zero priced hours as shown in Figure 12, Figure 14 and Figure 15. In the other scenarios, solar energy also has a tight business case but is profitable. The profit of gas plants in the European CO_2 scenario stands out in comparison to gas in the other scenarios. This is caused by the absence of Hydrogen plants in this scenario. In the other scenarios, the Hydrogen plants have a back-up function and limited full-load hours. Since the European CO_2 scenario does not have Hydrogen plants for this function, gas plants have this function. Therefore, a high capacity of these plants is needed, causing a low number of full-load hours. The Hydrogen plants of the other three scenarios, experience this same challenge.

In the bottom-left graph, the profit of the energy sources in total is shown. In this graph, the financial impact on the system can be seen. Regarding the circumstances of the model, solar in the regional scenario and Hydrogen plants in the national scenario need financial support in some manner. This reflects the challenges of the 'merit order effect' and the 'missing money problem', causing challenges on both the (far) low and high range of electricity prices.

In the bottom-right graph, the price-duration curves of the four scenarios are shown again. Regarding the other three graphs, it can be seen how the distribution of electricity prices throughout the year influences the financial situation of the energy sources. Additionally, it is noticeable how much the average electricity prices increase in 2050 compared to the prices in 2017.

So, as seen in the graphs, financial challenges for the system (almost) occur at the low range and high range of the system prices. Overall, the system is mostly profitable but has high electricity prices compared to the reference scenario. The question is whether this is desirable for the affordability of the system, which is one of the prerequisites of electricity markets. Therefore, another cost-benefit analysis with the same distribution and costs has been made, but the prices have been lowered to match the average price of the reference year.

Cost-benefit analysis based on 2017 pricing

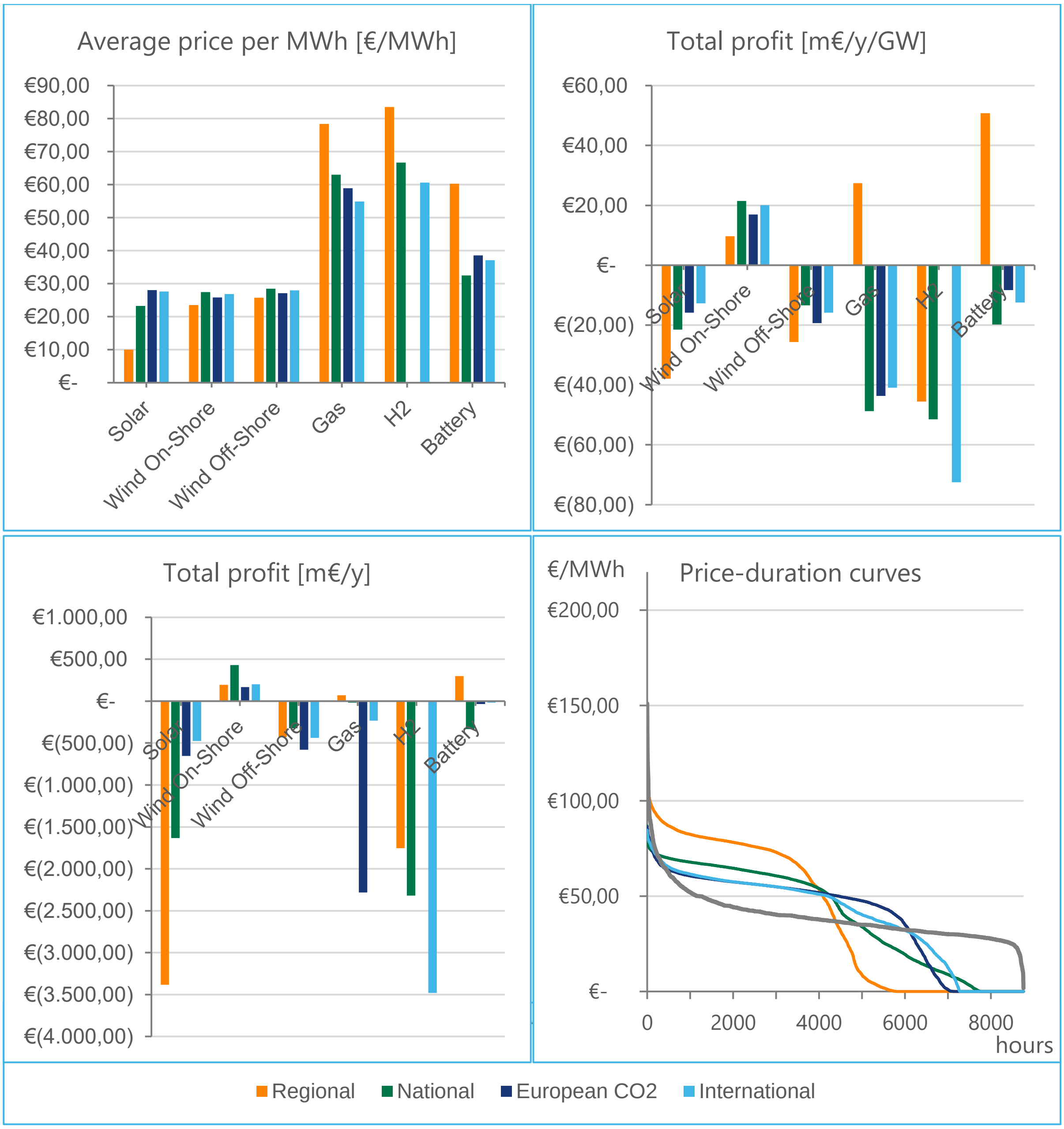

Figure 20: Financial analysis of the scenarios based on average prices of 2017

To determine the effect on the system when prices are more affordable for end-users, average prices of the reference year have been used. The distribution of prices has been kept the same as determined in the KyPF model, as can be seen in the bottom-right graph. Therefore, the price per MWh also becomes proportionally lower, as seen in the top-left graph.

The effect of lowering the average electricity prices on the financial feasibility can be seen in the top-right and bottom-left graph. Most of the energy sources have a negative business case with these lower prices. There are three exceptions to that: on-shore wind in all scenarios, gas plants in the regional scenario and batteries in the regional scenario. As seen in

Figure 15 and Figure 16, on-shore and off-shore wind are more equally distributed throughout the year and have a higher amount of full-load hours compared to solar energy. This positively influences the business case. Additionally, the costs for installing off-shore wind are higher than for on-shore wind. Therefore, the business cases for on-shore wind are financially positive, whereas the business cases for off-shore wind and solar are negative.

The regional scenario has the most negative business cases for solar and off-shore wind. This is caused by the high integration of solar energy in this scenario. The gas plants and batteries profit from this high integration. The batteries profit from the large difference in zero priced hours and highly-priced hours. The capacity of gas plants is limited, causing a high number of full-load hours with high prices.

Since the system as a whole is highly unprofitable with average market-prices similar to the reference scenario, and the high prices as determined by the model are undesirable, an additional cost-benefit analysis is made. In this analysis, break-even points are determined at which the profit of the system within a scenario is net-zero.

Cost-benefit analysis based on balanced system prices

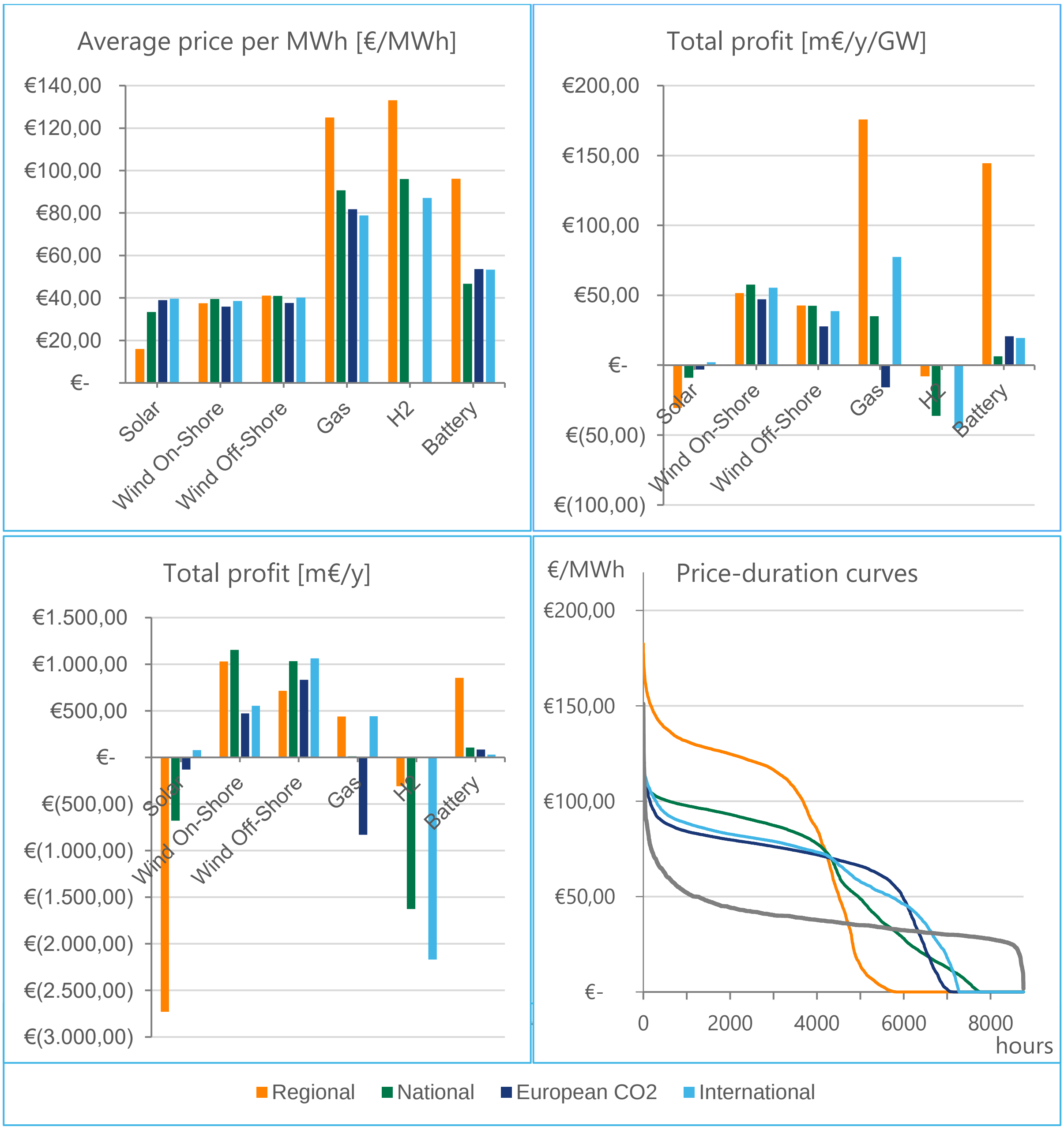

Figure 21: Financial analysis of the scenarios based on balanced system prices

In this cost-benefit analysis, the net profit of the system within one scenario is zero. Therefore, the distribution of money throughout the different energy sources are clearly shown. Additionally, the average electricity prices of the break-even points are calculated. These can be seen in the following Table 6.

[€/MWh]	Cost-benefit analysis I (based on 2050 prices of KyPF model)	Cost-benefit analysis II (based on reference year, 2017)	Cost-benefit analysis III (based on a system's profit of net-zero)
Regional	73.17	39.31	62.76
National	90.83	39.31	56.59
European CO_2	68.96	39.31	54.58
International	101.49	39.31	56.50

Table 6: Average electricity prices in the four scenarios considering the different cost-benefit analyses

Overall, the average market prices should increase compared to the reference year to have a financially balanced system, but not as much as determined in the KyPF model. With these balanced prices, the 'merit order effect' and 'missing money problem' are clearly shown in all scenarios. Additionally, each scenario has its own challenges related to the focus points in the scenario.

The regional scenario needs the highest average electricity prices for the net-zero profit. This is caused by the high integration of solar energy in this scenario. The difference between high and low prices is highest in this scenario, causing the batteries to have the best business case. The Hydrogen plants have the least negative business case compared to the other scenarios. This is caused by the relatively high number of full-load hours and high electricity prices.

The European CO_2 scenario does not include Hydrogen plants. This causes the average electricity price to be the lowest. This absence also causes the business case of gas plants to be worse compared to the other scenarios. Since gas plants are used as back-up capacity in this scenario, the total amount of capacity is relatively high and the number of full-load hours low. Additionally, the marginal price of Hydrogen does not drive up the prices of the system, causing the business case of gas to be negative.

The national and international scenario are rather similar. They both include a high amount of Hydrogen plants and have a similar balanced system price. The difference between the scenarios is the dependency on neighbouring countries. In the national scenario, this dependency is limited. Therefore, there is a high amount of batteries in this scenario and the Hydrogen plants are coupled to electrolyzers. The international scenario has a limited amount of batteries and depends on Hydrogen from neighbouring countries. The high amount of batteries in the national scenario causes the business case of these batteries to become less positive compared to the other scenarios. The high dependency on Hydrogen in the international scenario causes the Hydrogen plants to have the most negative business case.

So, the 'merit order effect' and the 'missing money problem' are seen in all four scenarios, in which the severeness depends on the focus point of the scenarios. Therefore, a different compensation structure is required for the energy sources to make the electricity market affordable, fair and reliable for investors. In the next paragraph, new market designs and incremental solutions will be discussed.

5.3 Qualitative analysis

The previous paragraph showed that both the 'merit order effect' as the 'missing money problem' occurs in all four scenarios for 2050. Especially the balanced cost-benefit analysis shows how the revenue streams are unequally distributed across the system. Additionally, the prices within the system are two to three times higher than in the reference year and the volatility rises as well. The electricity market is becoming less stable than it used to be. This is caused by the effects of the changes regarding the Climate Agreement on the rising gas prices and the higher percentage of renewable resources. These factors affect the investors' climate within the field. The electricity market is dynamic, and the rate of change is high, the behaviour of the market is therefore difficult to predict. This can cause undesirable effects on investments within the market.

The following paragraphs outline possible alternatives for the current market design. The alternatives discussed are: Capacity mechanisms, VRES subsidies, virtual dispatchable producers, and nodal pricing. Finally, a combination of alternatives will be discussed in the Nord-pool system case. For each alternative, the influence on different stakeholders, challenges and level of government regulation will be discussed. All alternatives should comply with an affordable, sustainable and reliable energy system. The conclusions and effects have been gathered from insights of the model, reviews with experts and literature review.

5.3.1 Possible alternatives and their influences on the electricity system

Figure 22, illustrates the effects of the different options for altering the market design. In the paragraphs below, the alternatives and effects within the four scenarios are discussed in detail.

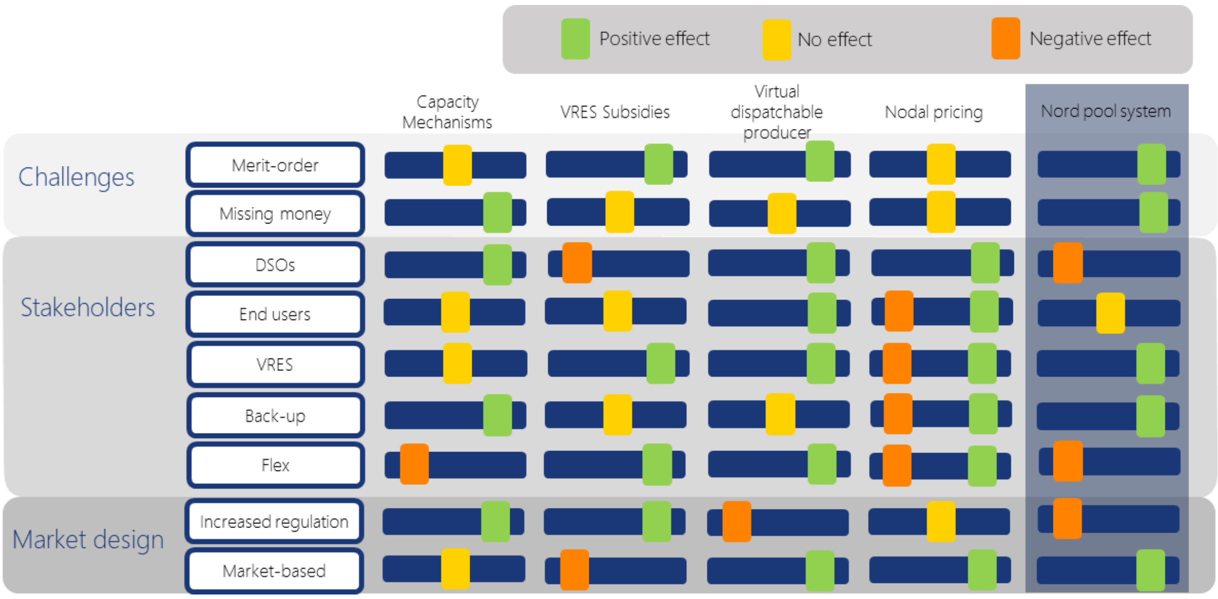

Figure 22: Overview of the effects of alternatives in the current market design

Forward Capacity Market (capacity mechanisms)

Several studies suggest the implementation of capacity mechanisms as a solution for the 'missing money problem'. (Newbery, et al., 2018); (Hu, et al., 2018); (de Vries & Verzijlbergh, 2018); (Joskow, 2019). Capacity mechanisms are a group of mechanisms designed to provide an extra revenue stream additional to the energy-only market. Capacity mechanisms help overcome the 'missing money problem' of the back-up generators caused by the low number of full-load hours. These mechanisms can either be price-based or quantity-based. A price-based mechanism might result in inefficient investments in back-up generators, because of a high level of government regulation. In general, a market-oriented system is preferred by economists, compared to a regulated market system, since liberalized markets are conceived as competitive, fair and transparent (Sioshansi, 2008). Quantity-based mechanisms can either be decentralized or centralized. These are also referred to as Forward Capacity Markets. Since the goal of a carbon-neutral energy system is a top-down objective of the national government and European Union, a centralized mechanism seems most suitable. For large consumers, decentralized mechanisms can also be applicable since they will provide incentives to avoid high peak demands.

In all four scenarios, additional revenue is required for the back-up generators as could be seen in Figure 21. In the regional, national and international scenario, Hydrogen plants have a negative business case. In the European CO_2 scenario, gas plants have a negative business case. The Hydrogen plants in the national and international scenario are most affected by the 'missing money problem'. This is caused by the high dependency on Hydrogen in these scenarios. In the national scenario, the Hydrogen required is produced within the country, whereas in the international scenario the production of Hydrogen is dependent on neighbouring countries. Both Hydrogen and gas are important, strategic assets for a country. Therefore, it is required to have a certain level of government regulation to establish a stable and reliable market for these assets. Centralized mechanisms are most suitable to guarantee these requirements.

In Figure 22, the effect of a centralized forward capacity market can be seen. The effects within the system should be minimal by design, this means that the additional revenue stream should not negatively affect the current market design. The merit order is not affected causing no effects on the VRES and flex capacity. The proposed solution does directly affect the 'missing money problem'. The back-up capacity receives an additional revenue stream, besides the energy-only market. For the DSOs, this also has a positive effect since back-up is guaranteed and the risks of outages will be minimized. This also positively affects the social acceptation for a system with high VRES integration. The downside of this solution is the risk of misusing capacity mechanisms by simulating scarcity. This should be prevented by implementing price signals that focus on long-term effects and decline the necessity of the mechanism.

Without government regulation, capacity mechanisms will not work. In a market-driven system, energy production by a back-up generator can be seen as an option, such as in a financial market. When building a back-up generator, options can be sold to parties unwilling to pay for high peak prices for electricity. This would work in a stable market system where stakeholders can get used to, but this is not the case due to the high market volatility and the significant financial changes in the system (den Ouden, 2020). This increased volatility could last due to the high level of VRES. Therefore, government regulation is required. Regarding this regulation, several constraints can be determined. First, capacity mechanisms should comply with European regulations (EEAG) to prevent unfair cross-border market prices. Second, high electricity prices should not be capped, and the market-oriented system should be maintained as much possible. High prices might affect the affordability and stability of the market system, but capping prices has a large effect on the market-oriented system. In times of scarcity, prices will rise, causing large consumers to sell their options to the market. If prices would be capped, the incentives of responding to market scarcities are minimized, causing challenges in stabilizing the market. So, price signals within the market should be maintained and be used to steer capacity mechanism policies. Additionally, the simulation of scarcity should be prevented, and the market-oriented system should be the primary focus. Therefore, back-up capacity should always operate on the market with a long-term vision and capacity mechanisms should only be used to stabilize the market and not fundamentally finance it.

VRES subsidies

Capacity mechanisms solve the problem on the high-end of the market prices for back-up generators. A similar approach can be implemented for the low-end, where subsidies can be provided for VRES. These subsidies will provide the hourly price difference to make investments in VRES viable. The differences between capacity mechanisms and VRES subsidies are; the number of hours requiring compensation, the objective, and the effect on the system. First, the number of hours in which VRES subsidies are necessary, outweigh the hours for capacity mechanisms. Besides, by stimulating investments in VRES in this manner, the hours requiring support will only increase. As Verzijlbergh et al. (2017) stated, state-driven compensations should be an intermediate solution for stabilizing the market and not be a long-term financing solution. This type of subsidy does not fit in this vision and will have a large effect on market signals. Second, the objective of VRES subsidies and capacity mechanisms differs. Capacity mechanisms are used for back-up generators to maintain a reliable energy system, whereas VRES subsidies are implemented to achieve national climate targets. Because of the large number of hours and the different objective, undesirable effects on the market signals occur.

The effect on the system is based on this reduction of current market signals. In a liberalized market, prices drop when supply is high, causing suppliers to reduce the amount of electricity generated. However, when implementing VRES subsidies, the suppliers of VRES will not have an incentive of reducing the amount of electricity supplied since they receive a compensation per mega-watthour, which is not completely dependent on the hourly electricity price. An additional effect is that the hourly electricity prices might drop towards negative prices. This can however be prevented by setting limitations to the hourly compensation. DSOs are negatively affected by the absence of incentives to respond to market signals since this might result in network congestion. Especially in a scenario with high amounts of solar energy without demand-response, the effects on congestion can be high. For short-term flexibility, such as batteries, the effects of VRES subsidies are beneficial to their business case. The number of hours with low prices will increase, causing the price differences as well. Additionally, innovation will be less stimulated since there are fewer financial incentives to optimize efficiency.

In the balanced cost-benefit analyses of the four scenarios, VRES subsidies are required for solar energy in the regional, national and European CO_2 scenario. The widespread and larger number of full-load hours prevent the necessity of subsidies for on- and off-shore wind energy. However, a case study by AFRY states that investments in off-shore wind will not be feasible without intervention because of the high material risks (AFRY, 2020).

Virtual partly-dispatchable producer

VRES, especially solar energy in the four scenarios, experience challenges based on the 'merit order effect' and therefore will not be able to exist without financial support. On the other hand, batteries have a (strong) business case in the scenarios. However, the business case of batteries exists because of the integration of VRES. Batteries profit from a high difference in buying and selling prices. The implementation of VRES enlarges the price difference by lowering the market prices for a significant number of hours. Especially in the regional scenario, this effect is clearly shown for batteries and solar, as seen in Figure 14. The dependency of VRES on back-up capacity, either long-term or short-term, is also shown in a report of AFRY and a letter of the Nederlandse WindEnergie Associatie (NWEA) to the Ministry of Economics and Climate Affairs (AFRY, 2020); (Hylkema, 2020). Since batteries cannot be profitable without VRES and the other way around, the two can be virtually coupled to stimulate investments in both. In a real case scenario, this would mean that large-scale batteries are virtually connected to solar-PV fields and on-shore wind. Physically coupling the batteries to a specific solar-PV field will be less efficient, since that will make the system less flexible. From a network perspective, physical coupling lowers the flexibility but also decreases network congestion. In a virtually coupled system, the producer can (to some extent) react to demand in the market system and therefore provide higher bids. The virtual producer can spread the generated electricity over multiple hours. In this way, the 'merit order effect' will be reduced, since not all VRES electricity is put on the market in the same instance.

To realize this new type of producer, different aspects should be considered. The electricity provided by the VRES should be sold to the batteries through long-term contracts such as PPAs. This is also suggested by multiple researchers (Newbery, et al., 2018); (Djorup, et al., 2018); (Joskow, 2019). These long-term contracts are required by both parties to create a suitable investment climate with minimized risks. Additionally, the intraday market should be altered for this new type of producer. Therefore, the time resolution of the intraday market should become smaller and the closure time later as stated by Hu et al (2018). Newbery et al. (2018) and Luth et al. (2018) also refer to the significance of altering the market to make it more suitable for short-term electricity storage and VRES.

Since the generated electricity is spread more equally throughout the day, the market will become more stable. Additionally, the coupling will provide incentives for both VRES and battery investments. The market signals will work better with this coupling since a higher amount of VRES will not have a negative effect on the business case of VRES. Therefore, no additional regulation is required. The investment in both VRES and batteries are however large and CAPEX-driven. From a financial perspective, it is therefore debatable whether investing in both these techniques is the most optimal solution. In the four scenarios, the battery capacity is provided by electric vehicles through vehicle-to-grid. Since the scenarios assume that the adoption of electric vehicles is high, this capacity is already available. In this way, a different, decentralized battery system can be created in which the vehicles' owners are compensated for the usage of the batteries through aggregators. With a different compensation structure, the end-users should be compensated for lowering peak supply and demands, causing net congestion to be minimized. Both the DSOs and end-users can profit from this system. A decentralized battery system has the downside of adding more stakeholders and complexity to the concept.

Nodal pricing

To maintain fairness and balance in the electricity market with the rising integration of VRES, different authors also recognize the relevance of nodal pricing (Hu, et al., 2018); (Newbery, 2016). With this system, price areas become smaller and are highly based on the transmission capacity between the different nodes. This influences the geographical distribution of supply and demand. Given that suppliers are receiving revenues, independently of their location, the network is saturated with the inefficient placement of supplies. In a nodal pricing system, the coupling of location and pricing would lower the network congestion by optimizing placements of future generation. Additionally, end-users experience a larger effect when responding to local electricity demand and supply, which increases price sensitivity. Investments in large-scale industry with high demands can be made on a suitable location in the network. Therefore, electricity supply and batteries will be realized at optimized locations. Price sensitivity and network availability will be considered more in this system. To accomplish the benefits of this system, the price areas need to be small enough to stimulate demand-response but should be large enough to operate efficiently and fair.

Different studies into the effects of nodal pricing state that such a system increases social welfare. This is mainly caused by lower overall electricity prices, efficient dispatch, and for better use of the electricity network. However, the Target Electricity Model (TEM) does not encourage nodal pricing and the system is not implemented in Europe. End-users can have unfair electricity costs based on the location of their network connection (D-Cision & Ecorys, 2019). Additionally, investments in electricity supply will experience higher risks. The report does state that in a market with possible capacity shortages, nodal pricing might become more relevant.

The exact effect of nodal pricing on the four simulated scenarios is difficult to predict since the scenario study does not include the exact locations of the generators, and price areas are not included in the KyPF model. In the next step of Berenschot's scenario study, the exact locations of VRES will be determined. In this study, the effect of nodal pricing would be relevant to consider since network costs are a major component of electricity pricing. Since the effects of nodal pricing on the stakeholders are largely dependent on the location within the system, the effects can either be positive or negative. For the DSOs, this system will have a positive effect since the transport and network capacity are considered to a greater degree. This decreases network congestions. In a recent study on the impacts of the four scenarios on the Province Overijssel, the network capacity was shown to be insufficient in all scenarios (Westerveld, 2020). The consideration of location and network capacity on VRES might have some challenges in a densely populated country as The Netherlands. Especially for offshore wind, this might have a negative impact since demand is not geographically close to the supply. Therefore, it should be considered to what degree linking the location of supply to demand is desirable within the socio-technical environment. Currently, for example, the cables to the off-shore wind parks are governmentally subsidized (Algemene Rekenkamer, 2018). In a nodal pricing system, the market will determine the best locations and most optimal network positions. Future research should define the effects of market-based nodal pricing, and establish the criteria of this alternative market design.

The Nord Pool system case

Each of the four provided alternatives is not optimal and has its drawbacks. Therefore, a combination of different aspects has been linked to ideas from the Scandinavian Nord Pool system. This system could provide a solution to the challenges posed by a high integration of VRES as shown in the four scenarios. For establishing this new market design, different expert interviews have been held and the used literature has been reviewed (Honkapuro, 2020); (den Ouden, 2020); (de Jong, 2020). In these interviews, some general concepts have been determined such as the inefficiency of a small area focus, the necessity of specific and directed government intervention, and the strong need for balance in a future market.

Implementing a high integration of VRES in Scandinavian countries is less challenging than in the Netherlands due to the high amount of pumped hydro-storage in Norway. This type of storage provides a high balance capacity, causing a relatively stable electricity market.
With the increased integration of VRES, these types of balancing capacity will play a crucial role in stabilizing the market. Establishing a stable electricity market in the Netherlands with high integration of VRES requires a high amount of short-term and long-term storage. The Nord Pool system has this covered by utilizing pumped hydro-storage, which is an inexpensive form of flexibility that can be used both in the short- and long-term. The Netherlands cannot implement this type of storage and must therefore resort to alternatives

such as batteries and Hydrogen storage. The drawback of these types of storage is that they require high investment costs and are expensive to operate. Additionally, the 'missing money problem' and 'merit order effect' occur as shown in the cost-benefit analyses. Therefore, this alternative to the market design aims at imitating the Nord Pool system to mitigate these two challenges. To accomplish this, the focus should be on the long-term and short-term market. In the long-term market, PPAs can be implemented for the integration of VRES, and capacity mechanisms can be used for back-up capacity. The need for PPAs is also recognized by Invest-NL, which states that there is enough capital available, but demand reallocated to match with the supply (Invest-NL, 2020). In the short-term market, balance will be provided to the system. The different markets are visualized in Figure 23. In this proposed system, the focus will be on the long-term, balancing, and intra-day markets, as shown in the orange circles. Currently, the day-ahead market (DAM) is used as the primary reference market for all other markets.

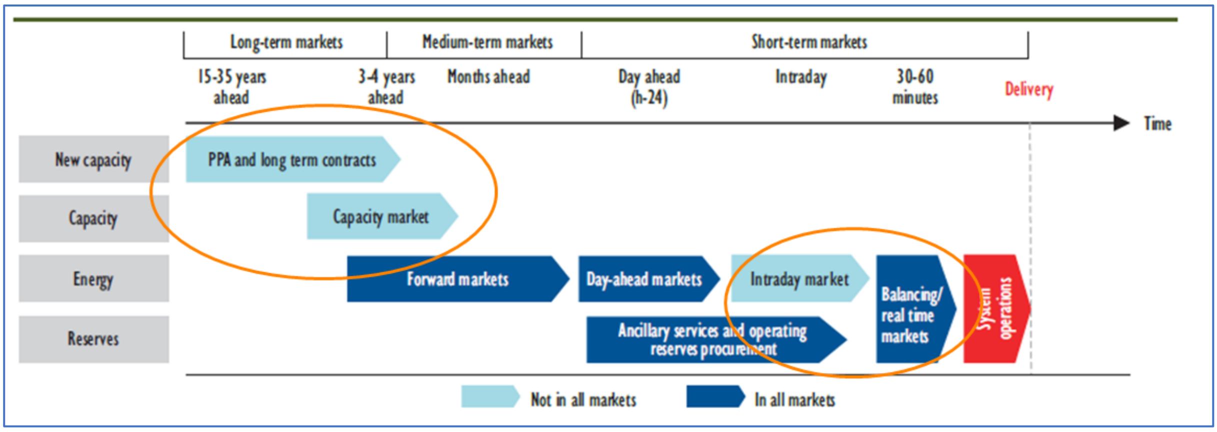

Figure 23: Overview of different building blocks of electricity markets. The orange circles show the focus of the Nord Pool case system (IEA, 2016).

The current DAM will become less relevant due to these changes, causing smaller liquidity on this market (Spodniak, et al., 2019). This might cause gaming in the DAM because of the limited number of players. Additional regulation would therefore be required, which might further destabilize the DAM. The challenges in creating large amounts of storage capacity and the prevention of gaming can be tackled by implementing a pan-European 'supergrid' as suggested by de Vries & Verzijlbergh (2018). By increasing the interconnection capacity across different countries, flexibility will be introduced due to the partial non-simultaneous demand and supply. This effect could also be seen in Figure 12 in which the price-duration curves with and without the integration of neighbouring countries is shown. The figure shows how the national electricity market is becoming more stable when connecting it to neighbouring countries. This effect will increase with growing transmission capacity.

In Figure 22, the effects of the Nord Pool system case on the different stakeholders are shown. For the different DSOs, the effect is negative since the load on the infrastructure will increase. The demand-response is not locally oriented but has an international scope, which increases the total flow of electricity in the network. The DSOs are tasked with improving the infrastructure and maintaining the reliability of the network, which could form a challenge. For VRES and back-up, there is a positive effect since the 'missing money problem' and the 'merit order effect' are addressed. This provides financial investment security to these suppliers. For short-term flexibility, the system creates a negative impact. Since the overall electricity prices are more balanced, the price differences are lowered causing fewer revenues for batteries. Additionally, interconnection capacity partly negates the necessity of battery capacity.

The proposed system is a good example of how the different alternatives might fit together into a market design that can scale to a high integration of VRES. However, this proposed system has its challenges. First, the increased interconnection capacity across Europe requires a robust infrastructure. Currently, our infrastructure is not suitable for this system and will need large investments to succeed. This causes technical, geographical, and political challenges. To manage these cross-border challenges additional research into the effects of a 'supergrid' should be conducted. Besides the challenges that arise during the implementation, this system also creates a higher dependency on other countries. The reliability of the system could therefore be compromised by political conflicts. Especially for the International scenario, in which there is already a high dependency on the import of Hydrogen, this might become a challenge.

Summary

In summary, these potential alternatives to the market design could provide a basis for a new market design which is suitable for a high integration of VRES. All alternatives are mentioned in relevant literature and have been discussed with several experts within the field. However, this is not a complete list of all possible alternatives but aims at the most prominent options. Besides the different components, the paragraph also provides a perspective on a combination of alternatives that can form a new market design. When looking at Figure 22, each of the alternatives has their benefits and drawbacks which need to be considered. The choice of picking the most suitable alternatives highly depends on technological, social and political aspects. Both in Berenschot's scenario study and, for example, TNO's scenarios, assumptions have been made on people's behaviour, technological innovation and degrees of regulation (Scheepers, et al., 2020). This highly influences the direction of the alternatives on the market design. In the discussion, the effects of the model, scenarios and alternatives will be further discussed.

6. Discussion

The objective of this study was to assess the effects of a high level of VRES integration on the current electricity market, and which market alternatives are required to mitigate these effects. To do so, this study has used the KyPF model in combination with the four scenarios defined by Berenschot. The results from this model have been combined with financial cost-benefit analyses to expose the extent of the 'merit order effect' and 'missing money problem' in the scenarios. Based on the outcomes, reviews with experts and relevant literature have been combined to propose alternatives to the market design. These alternatives focus on specific challenges that arise from the KyPF model and the cost-benefit analyses. This research highlights the need for alternatives to the market design and provides novel results from the KyPF model.

The results show that the current market design is not suited for carbon-neutral scenarios with high integrations of VRES. In the simulations, hourly electricity prices have tripled, the volatility has increased, and the revenues per generation type is not equally distributed. Moreover, the financial inequalities in the system on both the high- and low-end of the merit order show the effects of high VRES integration in the current market design. The 'missing money problem' and 'merit order effect' are reflected by the results and the market will need to be altered to manage these effects. This is also in line with the results from different studies as shown in the *Literature review*. Hu et al. (2018) state that the current electricity markets in Europe seem incapable of delivering the correct price signals when VRES integration increases. While the outcomes of the different studies suggest that the market design should be altered, this study adds to the existing knowledge by using a novel model for predicting the effects in detail. This level of detail clearly shows the effects and can correlate the data with the predictions and results from the various studies.

In the next paragraphs, the different steps in this study will be discussed. Each step includes its own choices and limitations, affecting the final output. Based on these limitations, suggestions for future research will be provided.

6.1 Scenarios by Berenschot

A key limitation of this research is the usage of the four scenarios by Berenschot. Whilst they provide a good understanding of the effects, the scenarios are taken to the extreme to showcase the 'four corners' of the playing field. This has the drawback that all results based on these scenarios will magnify the flaws and might not give an accurate representation.
As the four scenarios are only the first step in the long-term exploration of energy scenarios, new insights can be used to further refine the setup for the KyPF model. In this first step, the limits of the network are not considered. Therefore, network congestion and the effects of nodal pricing cannot be determined. Whilst these limitations might affect the exact results,

the modelling of the initial scenarios do expose which challenges will occur in the current market design.

For the design of the four scenarios, only currently available technologies have been used in the ETM. This has been done to mitigate any false predictions for the future. Nonetheless, an estimation has been made on the increase in efficiency for the current supply and usage of electricity. In the case of solar energy, efficiency increases are predicted for the future. However, the ETM was not able to accommodate this variable. Therefore, the number of full-load hours have been increased to simulate this efficiency increase. As mentioned in the *Data validation*, this study has chosen to not use the solar curves provided by the ETM since these altered curves included some peculiar effects. Therefore, solar supply curves from KYOS have been used. To include the efficiency increase in this study, the total capacity (in GWs) has been increased to reach an identical electricity output (in GWh). The demand curves as established in the ETM have been used in the modelling. These demand curves are an extensive set of data based on different types of end-users and consider behavioural changes in usage as defined in the four scenarios. However, the output of the modelling is depending on these demand curves, as they are a crucial part of the model. Improvements to these demand curves can provide a more realistic model but have been left out of scope for this study.

Another drawback based on the ETM is the type of electricity flexibility that can be implemented in the model. As shown in the *Description of the four scenarios*, the scenarios only use vehicle-to-grid (V2G) for short-term electricity flexibility. Other technologies such as O-PAC or large-scale battery systems have not been used. This affects the financial feasibility of the scenarios since the scenarios assume that the V2G capacity will not require additional investments. Additionally, other short-term back-up capacities might have a different effect on the balance within the scenarios. The scenario study is a first step for the long-term exploration into a carbon-neutral future in which the financial aspects have not been explored in detail. Additionally, the ETM is not suitable for determining hourly electricity prices. Therefore, this study has used the KyPF model to examine the financial effects of the four scenarios in more detail.

6.2 KyPF

The KyPF model has been used to define hourly production and price curves based on the four scenarios. KyPF is an optimization model currently used to predict the future electricity market based on the current market design. The model has never been used for predictions as far in the future as required in this study. Therefore, the high integration of VRES and flexibility has been challenging to simulate, since this has not been optimized within the model. For VRES, a limitation of the model is that the supply is subtracted from the demand curves before the optimization, this results in the residual load curve. The effect of only using the residual curve in the optimisation is that the VRES cannot be curtailed based on the demand. Since this study aims at researching the ‘merit order effect’, the inability of curtailing

VRES might cause this effect to be enlarged. On the other hand, this study aims at exploring the effects of the four scenarios. These scenarios have not been optimized based on detailed costs yet. Therefore, the inability of curtailing VRES might provide interesting insights into the effects of the four scenarios on the system.

Another challenge within the KyPF optimization were the long-term and short-term flexibility options as defined in the scenarios. The Power-to-X flexibility options have been peakshaved before the optimization model as shown in the

Data Preparation since the KyPF model is not able to integrate non-electricity flexibility in the model. This peakshaving has been done through an external algorithm in Python on the moments where the surplus of supply in the residual load is highest. This is not completely realistic since, for example, power-to-heat might not be necessary at times with high solar supplies. Another challenge in modelling flexibility within the KyPF was the integration of electrolyzers in the model. The electrolyzers provide Hydrogen for the Hydrogen plants by using electricity from the market. From a modelling perspective, this causes a large, inefficient 'battery' since both steps have an efficiency of respectively ~80% and ~60%. First, this has been simulated in the KyPF by implementing battery capacities with an efficiency of about 48% (80% * 60%). This did not provide reliable output for the system, since the KyPF model would not use this 'battery' system since the overall efficiency was too low and the operating costs too high. This caused high amounts of imbalance in the system. As a second option, simulations have been done with the Hydrogen plants partly as battery systems and partly as 'normal' Hydrogen plants. This still did not work since the system would only use the plants and not the battery systems, causing the imbalance still to be too high. Lastly, the electricity required for the electrolyzers has been subtracted before the KyPF model by lowering the electricity supply of off-shore wind. Off-shore wind was specifically chosen for this since it would be feasible that in the future parts of the off-shore wind supply will be used in electrolyzers for both industry and electricity demand. The demand for electricity used in electrolyzers is fixed when subtracting it before the KyPF model. The supply of electricity by the Hydrogen can however not be fixed since this depends on the optimization within the model. To balance the amount of electricity needed for the electrolyzers and the amount of electricity generated by the Hydrogen plants, different parameters have been altered. These changes could however not provide an outcome in which the electricity required and used was in balance. Therefore, the scenarios with electrolyzers use more electricity from Hydrogen plants than available. The total costs for Hydrogen plants will therefore be higher than suggested in the KyPF model.

For short-term flexibility, challenges mainly occurred in the national scenario which has the highest amount of battery capacity. At first, the batteries were modelled as full at the beginning of an analysis period, and empty at the end. This caused false capacity in the system. Therefore, an alteration in the model has been made that caused the batteries to be either full or empty at the beginning and end of the modelling period. This made sure that the state of the individual batteries was equal at the beginning and end of the period.

Second, the hourly price within KyPF started at 0 €/MWh, however, this caused issues for the batteries. In periods with solely VRES supply and batteries output, the price in the system remained 0, causing the batteries to not operate. This has been partly mitigated by setting the 'starting' price above 0. With this alteration, the batteries still did not work as expected. At hours in which gas or Hydrogen plants were needed to cover the demand, all batteries tended to provide electricity to the system. This is caused by the working mechanism of the model, in which the total revenues are optimized. At hours in which gas and Hydrogen plants were not required, the system price as set by the batteries would be a relative price based on the electricity intake, efficiency and operational costs of the batteries. This price would be lower than the marginal price of the gas and Hydrogen plants, causing an inefficient 'switching' of the battery output and supply by gas and Hydrogen plants. This would not be realistic in a real-world scenario because of the market system and regulation. It, however, raises the question of whether batteries at this scale might require additional regulation to prevent gaming in the market. In the current version of the KyPF model, an alteration has been made to limit this switching. This updated version has not been used for this study.

Besides the limitations, the KyPF model has given a good indication of the challenges that arise when high levels of VRES are integrated into the current market design.

6.3 Financial analysis

The study presents cost-benefit analyses based on the parameters from the four scenarios and the results from the KyPF model. Both have been combined to show how the 'merit order effect' and 'missing money problem' will be exposed in the four scenarios. The hourly price and production curves have been used from the KyPF model. Parameters for operational, maintenance and investment costs have been gathered from the four scenarios as established in the ETM. The parameter extraction has some limitations. Foremost, the ETM uses a lot of parameters for which the exact definition and allocation is not always clear. Since this study only uses the electricity-related aspects, and for example not heating networks, it is challenging to derive the exact costs. Due to this ambiguity, several assumptions had to be made, causing the financial analyses to not be completely accurate. This also holds for network costs. Since the first step of the scenario study does not define the exact locations of supply within the network, it is difficult to predict network costs. The ETM does use scientific literature for the estimation of financial and technological parameters.

The financial risks have not been considered in the financial analyses. This has been left out due to the high uncertainty of such a parameter over the next thirty years. Also, not including such a parameter keeps the analyses simpler. A review of the used method for the financial analyses has not been compared to relevant literature in the field. This could have increased the quality of the cost-benefit analyses and validated the outcomes. Additionally, non-numerical aspects such as investors' behaviour could also have been added, such as in a report by the CE Delft and University of Utrecht (Otte & Hers, 2019). This could have affected the presented outcomes since the investment feasibility could have been affected by such a behavioural analysis.

Overall, the cost-benefit analyses provide an overview of the challenges that will occur in carbon-neutral energy scenarios. The exact numbers from the financial analyses can however not be used for future research since the analyses are a rough estimation and not specific.

6.4 Alternative market designs

As the final step in this study, potential market alternatives have been defined based on the different outcomes. The results from the ETM, KyPF model and the financial analyses provide an overview of the extent and allocation of the challenges occurring in the four scenarios. These challenges have been linked to relevant literature and reviews with experts to establish alternatives to the current market design. The alternatives that have been suggested, provide an overview of the currently known possibilities. This study has tried to create a complete set of potential alternatives by cross-referencing relevant authors within the articles used. Additionally, reviews from experts have been used to cover possible knowledge gaps in the literature review, by tackling international based research and knowledge from non-scientific articles. The alternatives as described in current literature and by the experts have therefore been used in this study. However, there might be different suggestions or directions that are not covered in this study. A more extensive literature review or interview-based research could shrink this knowledge gap.

Besides the concept saturation, a limitation of this research is that the proposed alternatives to the market design have only been theoretically examined. Both the ETM and KyPF models were not suited for modelling alternatives to the market design. The ETM model balances supply and demand without the integration of an electricity market, whereas the KyPF model uses the current market design and optimizes for maximum revenues per source based on this design. Additionally, the theoretical examination of the effects of each alteration is challenging due to the high number of stakeholders and parameters. The scenarios consider electricity markets for 2050, it is therewith impossible to recognize all changes that will occur in the upcoming thirty years influencing the electricity market.

6.5 Future research

Future research can be done on the different steps within this study. First, a study can be done on models that work more optimally with high integration of flexibility options. Both the ETM and KyPF models have limitations when integrating flexibility options in the models. To determine the exact effects of flexibility within the electricity system, an extensive study should be done with a different or optimized model for this particular aspect. In several articles and reports, the relevance of flexibility within a carbon-neutral energy scenario is recognized. Therefore, a detailed study on the exact effects of flexibility on the network congestion, investment climate of VRES, the stability of the electricity market, and social behaviour can be a valuable asset to scientific literature.

Second, an extensive, systematic review should be done on possible market alternatives. Not only scientific articles should be analysed in this study, but also non-scientific reports should be considered. Since market alternatives affect society and the investment climate, case studies and opinions from market experts are relevant. In theory, for example, investments in off-shore wind parks without subsidies might be achievable, however, this might not always be recognized in practice by investors. It is, therefore, crucial to have a strong connection with the field when conducting more extensive research on market alternatives.

Moreover, future research into this subject could benefit from an interdisciplinary model for market alternatives. This model could be used to validate the different proposed solutions as provided within this study. The challenges for establishing a model is the requirement to incorporate the different stakeholders and perspectives. These aspects are all connected and influence the direction of the future electricity markets. Therefore, the model in future research should include financial, political, social and technological views.

Climate change is one of the largest challenge society has to face in the upcoming years. The objective of the Climate Agreement regarding establishing carbon-neutral energy scenarios is therefore an important challenge. As seen in this study, the integration of a high level of VRES brings along disruptions to the current stability of the electricity market. Future research on the extent of the challenges and possible alternatives are critical in achieving the targets set by the Climate Agreement.

7. Conclusion

In this research, the effects of the implementation of high VRES integration in the current market design are examined, and alternatives to the market design are proposed. To define the effects, four scenarios established by Berenschot in the Energy Transition Model have been used. These scenarios describe the four boundaries of the future energy scenario of 2050, based on different governance structures. The four scenarios have been modelled in an optimisation model, KyPF, to provide insights to the pricing behaviour in 2050 with the current market design. As a next step, the output of the KyPF model has been used to define the extent of the 'merit order effect' and 'missing money problem' in the four scenarios through cost-benefit analyses. Based on the results of the KyPF model and cost-benefit analyses, alternatives to the market design have been gathered from relevant literature and reviews with experts.

The results of the KyPF model provide an answer on the first sub-question of this study: *"How will electricity prices behave in 2050 based on four different carbon-neutral electricity scenarios based on the Energy Transition Model under current market conditions?"*. The hourly price and production curves provide an overview of the behaviour of the electricity prices in the system under the current market design. The curves indicate that the overall electricity prices will be two to three times higher and more volatile than in the reference year. Based on these results, in combination with the parameters extracted from the Energy Transition Model, financial cost-benefit analyses have been calculated to answer the second sub-question: *"How are the 'missing money problem' and 'merit order effect' exposed by the electricity prices based on the scenarios of Energy Transition Model?"*. The outcomes of the financial cost-benefit analyses show that there are financial inequalities which pose challenges on both the high- and low-end of the merit order. These challenges show how the 'missing money problem' arises for the back-up generators, as well as the 'merit order effect' that is shown for VRES. Both challenges imply that the current market design will not be suitable for the implementation of carbon-neutral scenarios due to an undesirable investment climate. This hinders the realisation of a carbon-neutral electricity system. To overcome these challenges, different alternatives to the market design have been proposed to answer the third sub-question: *"Which alternatives to the current market design, mentioned in relevant literature, can be applied to carbon-neutral electricity scenarios?"*. This study has gathered four alternatives: Capacity mechanisms, VRES subsidies, virtual dispatchable producers and nodal pricing. These alternatives have been cross-referenced with relevant literature and expert interviews to provide enough scientific merit. Last, the effects of these alternatives have been discussed. This answers the final sub-question: *"What are the influences of the defined alternatives on the 'missing money problem' and 'merit order effect' in the electricity pricing model?"*. The combined results of the sub-questions can be used to answer the main research question of this study: "*Which alternatives are required to make the financial market design of electricity achievable and reliable for a carbon-neutral scenario in 2050 and beyond?"*.

The proposed alternatives have been discussed in detail and the effects have been evaluated. Moreover, a combination of multiple alternatives, called the Nord Pool system case, has been opted to achieve a larger effect solving multiple challenges. A combination of alternatives is not only feasible but is required to maintain the reliability and affordability of a future electricity market. This study concludes that the alternatives are promising, but lack scientific validation and can only be theoretically examined. More research into the effects of market design alternatives is required and a model that is suited for validating the alternatives and flexibility is needed. This study does however clearly show the challenges occurring under the current market design and can form the basis for future research into the subject. Transitioning towards a carbon-neutral energy system is a major challenge which requires interdisciplinary and integrated research into social, political, financial and technological aspects. The urgency for change is high, and as presented by the study, the current market design is not ready for this transition.

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