Direct Trade PPA

Economic & Financial Benefits of a Direct Energy Contract With a Wind farm

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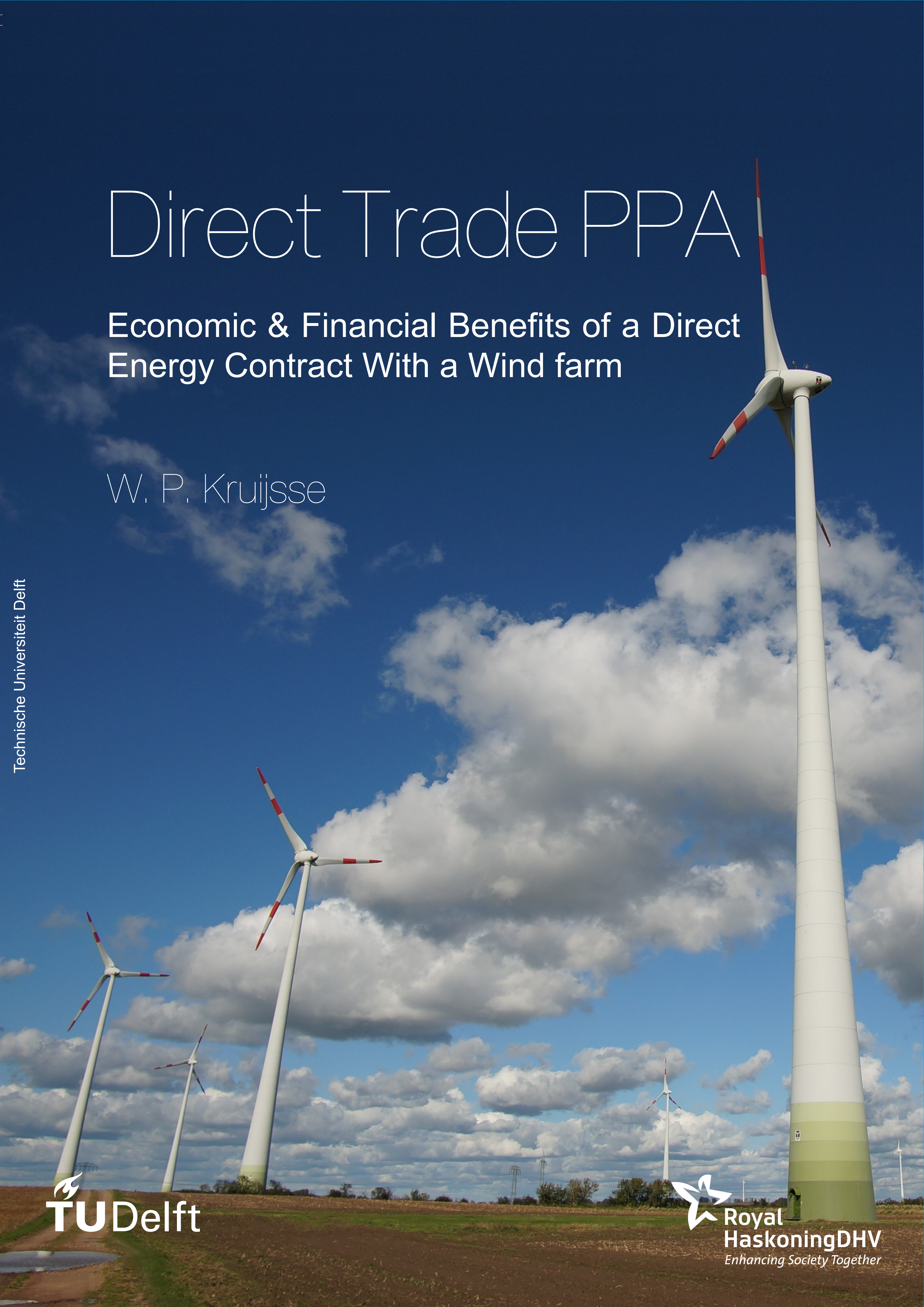

TU Delft

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Economic & Financial Benefits of a Direct Energy Contract With a Wind farm

by

W. P. Kruijsse

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Preface

In front of you lies my thesis about a new Power Purchase Agreement type called a direct trade PPA (a long-term energy contract). This research into the power contracts in the energy sector is executed to explore the economic and financial potential of this new energy contract in the light of the energy transition and investments in renewables in the Netherlands. This thesis is written in order to obtain my masters degree of the study Complex Systems Engineering & Management at TU Delft and part of my graduate internship at Royal HaskoningDHV (RHDHV). At this company I did my research in the period of February 2019 until August 2019.

In collaboration with Peter de Waard and Job Last from RHDHV and with the help of my TU Delft supervisors, Rudi Hakvoort and Aad Correljé, I have formulated my research topic. They all have helped me a lot to scope my research and explore the possible research options in the field of renewable energy. During my internship I joined a project to formulate a business case for a PPA contract for HaskoningDHV, this gave me insight in the energy sector and in how the contracts are formed in the field. During my research my supervisors, Job Last and Bastian Knoors, provided me with helpful feedback and made time to discuss my progress and gave suggestions to move on.

Hereby I want to thank my supervisors at RHDHV for the responsibility and trust they gave me to work on the business case and for the feedback and help they gave during the process. Moreover, I want to thank my supervisors of the TU Delft who made time for me to provide me with helpful feedback during the formulation of the proposal until the execution of the research and writing this thesis.

Additionally, I want to thank all the other colleagues at HaskoningDHV who gave input for my research and were always interested in my research and gave tips from their experiences. Last but not least, I want to thank my friends and family for the time they had to read my thesis and provide me with feedback, for the moral support during this thesis period and for the fun time to distract me from my research from time to time.

I hope you enjoy reading this report.

W. P. Kruijsse
Delft, August 5, 2019

Summary

In the Netherlands the share of renewable energy should be increased to reach the climate goals. Currently, many plans are made to design and construct wind farms, off-shore as well as on-shore. The investments for these wind farms are very high and therefore many investors are needed. The wind projects were often subsidised, but recently the Dutch government decided to tender wind projects without subsidy. In order to secure the investments in wind farms, the wind farm owners sell their power in long-term energy contracts in the form of a Power Purchase Agreement (PPA). In this contract both volume and price are defined, and it ensures a constant revenue stream for the wind farm owner and an insurance for the investors.

Until now only large corporates closed PPA contracts to obtain the ”garanties van oorsprong” (GVOs) and claim to be renewable. These corporates use PPA contracts as a hedge for the electricity price on the long-term and many of them want to become more sustainable by contracting renewable energy. The energy they get from the wind farms, has GVOs that show the origin of the power and are used as prove that this energy is produced with a renewable energy source. However, they keep only the GVOs and sell all the power to a utility or the energy market, so they do not bear the risks of this production. In this research a new type of a Power Purchase Agreement is proposed. This contract has a direct link between the corporate and the wind farm and transfers both power and GVOs to the corporate. The corporate contracts a part of the production and uses this directly for its demand without selling it all to a utility, like in traditional PPAs. In this construction, the corporate has a separate contract with a service provider to manage the surplus and shortages caused by the volatility of the wind resource.

The literature shows that very few is written about this direct trade PPA. The advantages and feasibility of this contract are not known. Additionally, there lacks a framework that gives insight in the service costs of the service provider, which results in a nontransparent cost structure of this party. Hence, the aim of this research is to analyse the effects of this contract in terms of economic efficiency and financial benefit. In this study two methods are used to approach this research question. First, an economic theory, the property rights theory, is applied to the energy sector to design an analytical framework. This framework helps to identify the transactions in this contract, the allocation of the risks and the economic incentives in this contract. This framework is used to compare the new PPA type to a traditional contract. Moreover, a financial model analyses the benefit of this PPA and compares the costs to a traditional contract. Furthermore, two experiments are done with a battery energy storage unit and a solar park to analyse the effect of those on the match between supply and demand. The hypothesis is that the better this match, the lower the service costs are, since less energy has to be managed by the service provider.

To conclude, a direct trade PPA does have financial benefit compared to a traditional contract. The savings are for the case of RHDHV around 4000 Euros in the advantage of the direct PPA, this a reduction of 2% on the total energy costs. The exact saving depends on the situation, but the new construction is competitive and in most cases beneficial compared to a traditional contract. Besides, the incentives of this new PPA are more efficient and have a positive effect on the match between supply and demand and on the investments in renewable energy. The direct link to the wind farm ensures more investments in wind compared to traditional contracts. The service provider has the incentive to maximise the match between supply and demand and reduce the imbalances in the grid. This incentive is weaker in the current energy market, where the retailer has an incentive to maximise the supply of energy to its consumers. Also, this research shows options to increase the match by using battery storage or additional solar capacity. This match can be improved up to 25% for a combination of solar and wind capacity. On the other hand, the battery shows a less promising result to reduce the surplus and shortages.

The next step is to further investigate this direct trade PPA with other model periods and more demand profiles of corporates. The results of this research are positive so this PPA type may be promoted to corporates that want to invest in renewables. The exact implications on the energy system in general, when this structure is rolled out on large scale, are to be explored further. Additionally, as this new contract structure is further implemented, a research can be done into the opportunities to make this contract type available to smaller consumers.

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Abbreviations

aFRR	Automatic Frequency Response Reserve.
BESS	Battery Energy Storage System.
BRP	Balance Responsible Party.
BSP	Balance Service Party.
CAPEX	Capital Expenditure.
CoSEM	Complex Systems Engineering & Management.
DER	Distributed Energy Resources.
DSO	Distribution System Operator.
ESCo	Energy Service Company.
ESS	Energy Storage System.
EV	Electric Vehicle.
FRR	Frequency Response Reserve.
GVO	Garantie van Oorsprong.
HV	High Voltage.
IPP	Independent Power Producer.
KNMI	Koninklijk Nederlands Meteorologisch Instituut.
LV	Low Voltage.
OPEX	Operational Expenditure.
PPA	Power Purchase Agreement.
PR	Property Rights.
PV	Photovoltaic.
RES	Renewable Energy Sources.
RHDHV	Royal HaskoningDHV.
SDE+	Stimulering Duurzame Energieproductie.
ToP	Time of Production.
ToU	Time of Use.
TSO	Transmission System Operator.
USEF	Universal Smart Energy Framework.
V2G	Vehicle-to-Grid.

1

Introduction

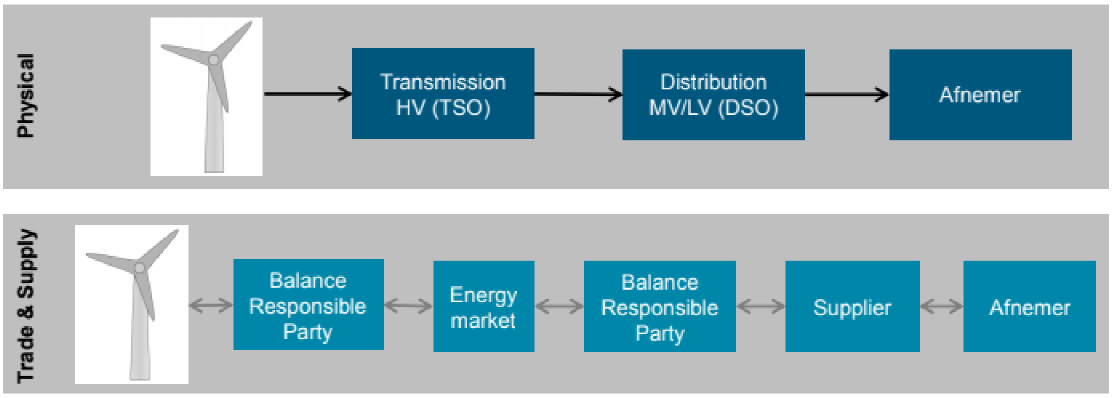
1.1. Background

The urgency to reduce the worlds carbon emission gets more and more clear to people and politicians in the world. Last year (2018) the climate top in Katowice discussed again all the measures and targets that countries need to set in order to implement the Paris Climate Agreement and keep the temperature rise under two degrees Celsius (COP24, 2018; Horowitz, 2015). One of the sectors in which this transition is important is the energy sector. The whole electricity demand needs to be generated in a sustainable way and the same for the heat demand. In the Netherlands the goals for the energy transition are described in the Energieagenda 2050 (Ministry of Economic Affairs and Climate Policy, 2016). It states the goals and measures to take in order to reduce the CO_2 emissions with 80 to 95%. The energy sector needs to be CO_2-neutral with more local energy production and it should have a strong electricity market and electricity supply. Moreover the amount of renewable energy needs to increase by 1GW per year for offshore wind. The goal is to generate 16% renewable energy in 2023. To reach these goals many countries build large wind parks in the sea or on land. These projects were in the beginning often subsidised, but recently more projects try to build the parks without subsidy (Greentech Media, 2018). This will force offshore wind operators to be innovative in the financing of their projects, influenced by the energy markets which will become more decentralised and declining energy price for wind (Julian Turner, 2018).

Power Purchase Agreements (PPAs) can offer a solution for this. These contracts are long-term energy contracts with a specified volume and price. In the US this contract form is very commonly used, and it is starting to be used more in Europe and Asia. The energy production in the US has been decentral organised for a longer period with a well-regulated PPA construction. The shift from centrally produced power to decentral is more recently evolving in the EU with the increasing penetration of renewables and increasing amount of wind farms. The amount of PPAs will grow in Europe as can be concluded from the volume of corporate PPAs that is tripled in 2016 compared to 2015 (Wind Europe, 2017).

The first reason parties are joining PPA contracts, is as a hedge for their electricity prices for a longer period and second, they want to become more sustainable by increasing the share of renewable energy in their energy contract (Julian Turner, 2018). The incentive for Independent Power Producers (IPPs) and utilities, who invest in wind farms and like to start a PPA contract, is a guaranteed off-take of their power so both volume and price are guaranteed. The result is a stable income from the energy they sell in the PPA contract and with this guarantee they can attract investors and cover their capital costs. This is in the basis the situation on PPA contracts. As described above, recently the market for PPA contracts develops and includes more corporates that sign PPA contracts. Slowly, also smaller players are developing collaborations and aggregate their demand to sign together a PPA. Especially in the Netherlands this construction has taken off since the power sector is fully unbundled and allows the producer to sign a contract with a customer without a utility. For example the Dutch Railways (NS) uses this construction for their energy demand. This construction is now used by large corporates who completely take off all the energy of a wind farm and use it in their offices and data centres, like Google

Figure 1.1: Physical power flow and the trade & supply chain



and AkzoNobel.

The downside of this construction is that the customers must carry the risks associated with the volatile production of the wind farm. If the customers demand is significantly larger than the total production there is no problem, but if customers want to use the production for their full primary demand they must deal with the fluctuations. Until now PPAs are mostly contracted by very large companies that have a demand way larger than the production and carry the fluctuations easily. Or they sell the energy directly to an energy provider and keep only the green certificates to 'greenwash' their energy.

A new PPA construction can be designed that combines multiple customers and sum their demand until the production level of the wind farm. In this way more parties can make a PPA deal with a wind farm and consume directly green energy from the wind farm. In this construction the customers use the power of the wind farm directly, instead of selling it to an energy provider and then buy it back from them to coop with the volatility. However, this construction is more complex than a regular PPA in terms of risk allocation, costs & revenues allocation and the match of demand & supply. In this construction the parties in the regular supply chain are bypassed and therefore also the balancing parties such as the retail companies & the energy market as can be seen in Figure 1.1. The customer on the right will have a direct relation with the wind farm on the left. The energy market and the balancing activities will be parallel to this and will manage the surplus and the shortage by trading or buffering power.

1.2. Relevance

This PPA construction is very relevant to current research and public debates in Europe. First, this construction can be compared with a microgrid or off-grid consumers, which are popular research topics. A microgrid can be defined as:

"a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode" (Ton and Smith, 2012).

From this definition three key elements of a microgrid can be identified: the system can be distinguished from the rest of the system with clear boundaries, the system is a single controllable entity and the system can connect and disconnect with the grid. This means that the microgrid can operate independent from the grid and from the traditional services of the utilities. The direct PPA agreement is on some aspects comparable to a microgrid. This construction has distributed generation in the form of a wind farm, the balancing of supply and demand can be done by batteries and the energy contract is without the use of traditional services from the utilities. The main aspect is that this construction is a step into more independency on the grid and the traditional energy suppliers. This aspect is also the main element of microgrids. The microgrids are described extensively in the literature on the technical functionality and operation, however the economics and policy implications lack. This study can contribute to the research into the economic implications. (Hirsch et al., 2018; Mariam et al., 2016;

Shuaixun Chen et al., 2012; Zhao et al., 2013).

A second relevant point, is the design of off-grid systems by combining wind, PV and storage (Jian et al., 2011). Developments in Australia and the US show this; users are disconnecting from the grid since PV power has reached grid parity and the prices for battery systems are declining (Khalilpour and Vassallo, 2015). It is interesting to see if it is beneficial to be self-supportive in power or that the grid is still needed for the times when Distributed Energy Resources (DER) are not available. A study showed that the PV capacity and the battery capacity should be very high to reach independency of the grid and even in that case it is not 100% independent in the whole year (Khalilpour and Vassallo, 2015). The PV/battery systems still have to rely on the grid, but it could decrease the purchase from the utility. A direct PPA construction with buffering is also not able to be completely independent, but it could reduce the purchase of energy from the grid. This study will look into these buffering options and can show what the benefits are for this system and to what degree the system is independent of the grid. So this study is relevant for the development of microgrids and consumers that look into the possibilities to go off-grid.

A third aspect that shows the relevance of this study, is the public debate about green energy and green certificates. These certificates show that certain energy is produced by renewable sources. In the Netherlands these are called Garantie van Oorsprong (GVO), these are guarantees that show the origin of the produced energy (WISE, 2015). However, the problem with these Garanties van Oorsprong (GVOs) is that these certificates can be traded internationally, which means that the GVOs of excess energy from for example Norway are used in the Netherlands as compensation for the grey energy. These certificates do not increase the physical amount of renewable energy in the Netherlands, despite the fact that more ‘green’ energy is used by consumers (Mulder and Zomer, 2016). This direct trade PPA also has GVOs, but these are directly traceable to the wind farm in the Netherlands and show to the consumer that the energy is produced in the Netherlands in a sustainable way. And thus offers a possible solution for the amount of renewable energy in the Netherlands.

Lastly, a point of relevance of this study is that very few research is done into the economics of balancing services from utilities. These companies match the supply and demand by using their large portfolio of various generation sources. The demand curve is dampened by the large number of customers and the production side can be adjusted to increase or decrease the production. The costs for these activities are not transparent but are included in the service costs of a utility. This study will try to analyse the cost components of this balancing activity, in order to make an estimate for the price of this service. This is very relevant knowledge for microgrids and off-grid consumers who have to match their DER with their demand for which they can contract this balancing service.

1.3. Problem Statement

In the current situation the energy market and the prices of the energy providers are not completely transparent. As described in the previous section the unbundling and the movement to more decentral energy production give rise to more initiatives that want to be independent from the grid and reduce the role of the retailer. The problem is that the costs for the services are not transparent, so customers cannot make the comparison between the costs for using the services of a retailer and the costs for doing these tasks themselves. The price for matching the supply and demand should be made more transparent with a specification of the cost components. Second, a framework lacks that describes the relations between the parties in a direct trade PPA agreement. The responsibilities, the power flows and the financial flows are not clearly allocated. Third, there is no data of the advantages of a direct PPA agreement. Is this construction feasible in the current electricity market? Is it more efficient for the system as a whole? And more importantly, is it beneficial for society? These three problems are present in the energy sector and should be looked into. The impact on society and the energy system will be discussed later in chapter 7.

These problems require the knowledge of both the technical characteristics and the economical and institutional characteristics of the energy sector. That is why this subject fits very well in the program for which this research is executed. This research proposal is written as part of the master program Complex Systems Engineering & Management (Complex Systems Engineering & Management (CoSEM)) at TU Delft. This topic contains both institutional, technical and economical aspects which are aspects that are central in this master program. The energy system can be seen as a complex system with a lot of parties involved with their own perspective on the problems in the system and with their specific roles & responsibilities. Moreover, the technical aspects of electricity and the rules in use in the electricity market will add more complexity to this system.

1.4. Objective & Research Questions

The objective of this research is to include the above-mentioned aspects and come up with a design for a new type of power purchase agreement and analyse the effects of these agreements in terms of economic efficiency and financial benefit. The expected outcome is an analytical framework describing the economic incentives in the energy sector with a direct PPA contract and a financial analysis on the benefits of this contract compared to a traditional energy contract. This financial analysis is supported by a modelling approach on the power production of a wind turbine and the trade of the energy surplus & shortages on the electricity markets. This gives insight in the energy costs and the balancing costs of matching supply and demand. Moreover, experiments are done into the effect of solar production and battery storage on the balancing costs.

This research paper will investigate this new PPA construction with a consortium of customers that contract power directly from a wind farm. This structure is explained and visualised in chapter 2. An institutional framework is designed to facilitate the role divisions in this construction and the allocation of risks and costs & benefits. This institutional design also makes an analysis of the property rights between all the actors. These rights will be used to determine the price components of the balancing services. These price components will be used in a model to analyse the match of supply and demand with the possibility of trading & buffering surplus or shortage. The following research question is central in this research:

"What are the economic & financial effects of a direct PPA on the energy sector by using a property rights theory approach?"

The sub questions are:

1. What are the actors involved in a direct trading PPA contract and what transactions are present in this construction?
2. What are the risks and cost components of these transactions and how are these applied to a direct trade PPA?
3. What are the effects on the economic incentives of the actors in the energy sector by using direct PPA contracts with a balancing service provider?
4. What is the financial benefit of a direct trade PPA compared to a traditional contract?
5. What is the effect of energy storage and solar production on the financial benefit of direct PPA?

1.5. Methodology

In this research two methods are used to come to an answer of the main research question. First, the property rights theory will be applied to the energy sector and second, a modelling study is executed to support the theory with empirical results.

The property rights theory is a well-known theory in the field of land markets and land reforms. The theoretical framework is used to describe the working of economic theories and institutional change. The property rights theory is an analytical framework that analyses the transactions in an economic environment and it can decompose these transactions to get insights in the components that are traded. It gives an integrated view on complex transactions and it analyses the incentives of the actors and the economic efficiency of the market. Furthermore, the modelling method is used to quantify the effect of a direct PPA and compare this with the results of the property rights analysis. The model is designed using the modelling software Microsoft Excel. Additionally, the software tools Python and R-studio are used respectively to clean the data and to visualise the results.

In the energy sector this PR theory is applied on the gas sector by (Hallack and Vazquez, 2014; Goodman, 2010). In their paper an analytical framework is provided that splits the gas sector up in very small components, these can be used to describe the interactions and transactions in the gas network and transport, as well as the trade of the volume of gas. This method is very similar to the property rights theory that identifies transactions between actors and describes the components of that transaction. In the electricity sector this view on transactions and property rights theory is not quite known and applied. That is the reason why this research is using the property rights theory to develop an analytical framework and analyse the transactions in the electricity sector. A specific focus is on the transactions in the PPA contract and the balancing contract with a service provider. Additionally, this theory is applied because the theory focuses both on the network assets as well as variable costs of energy. In the energy sector a lot of studies are done into efficient networks and cost structures or into pricing of energy and trading structures. As stated above the integrated view on complex transactions is very fitted to the complex energy market. The analysis of the economic incentives of the involved actors and economic efficiency of the market can give interesting and new insights in the functioning of this market.

1.6. Research Strategy

In this research approach there is a combination of two research approaches. First an economic framework is applied to the energy sector to describe the transactions within the energy sector. Second, this analytical framework focuses on the direct PPA and analyses the transactions between the wind farm owner, consumer and service provider. In this structure the wind producer will sell its energy directly to the customer and cut out the retailer. However, the tasks of a retailer are still needed in another role. The retailer does not directly deliver the energy but can offer its services in the handling of the match between demand and supply. Third, the Property Rights (PR) theory can analyse what the risks are for a wind farm owner when it produces energy and wants to sell this. All these risks can be linked to a property rights element. These property right elements form the components of the transactions between the wind farm owner and the buyer. The same can be done for the service provider selling its balancing service. The risks for this service provider can be listed and the PR-elements identified. All these elements should be included in the contract between the service provider and a consumer for an efficient economic transaction. When the components are clear in this transaction it is more clear what exactly is traded and what determines the price for this transaction.

This analysis will be supported by a case study of a wind project between a wind farm ‘Ferrum’ in IJmuiden and a direct PPA with three companies among them Royal HaskoningDHV (Royal HaskoningDHV (RHDHV)). This case is an example of this new structure and gives empirical insights in the actors involved, their roles and responsibilities and in the financial implications of this new construction. It can be used to compare the total energy costs of a direct PPA and the conventional contract with a retailer.

In a model study the insights from the property rights framework can be used to give a motivation of the prices and numbers used in the model. This model will give a quantified analysis of the implementation of a direct trade PPA with a balancing service provider. The demand and production will be modelled and the costs for balancing the surplus & shortages will be calculated using an estimated balancing service price. Furthermore, the model is extended by adding different sizes of storage and adding solar production to execute two experiments. The first experiment includes a model extension with a battery storage which influences the surplus curve. The storage may have a positive influence on the shortage and surplus and will decrease the costs for buying extra power and will increase the income for selling the surplus at higher prices. A second experiment is done by adding an extra solar production park that may produce energy on other times in the year than wind and may complement the wind production curve. Again the effect on the match between supply and demand is researched. This gives insight in how the production and demand can be better matched and what the effect is on the costs for the service provider.

1.7. Thesis Outline

This thesis is structured according to the research questions formulated above and is visualised in Figure 1.2. Chapter 2 will give a theoretical background on the concepts that are discussed in this research, moreover it is supported by scientific papers to embed it in the literature. Chapter 3 discusses the structure of a direct PPA and consists of an actor analysis with their responsibilities and tasks. This analysis is used in chapter 4 to define the property rights for each transaction in this structure. The property rights are created for the transactions that are not defined in literature already. The result is a framework with an allocation of the property rights, the allocation can be financially compared with the results of the model. In chapter 5 the models are conceptualised and implemented in an Excel model. The model is run in different scenarios: the base case, a buffering scenario and a scenario with solar energy production. The results of these runs are presented in chapter 6 and the corresponding research question is answered. The results of the model and the experiments are discussed in chapter 7 and finally in chapter 8 a conclusion is drawn, answering the main research question and giving recommendations for further research.

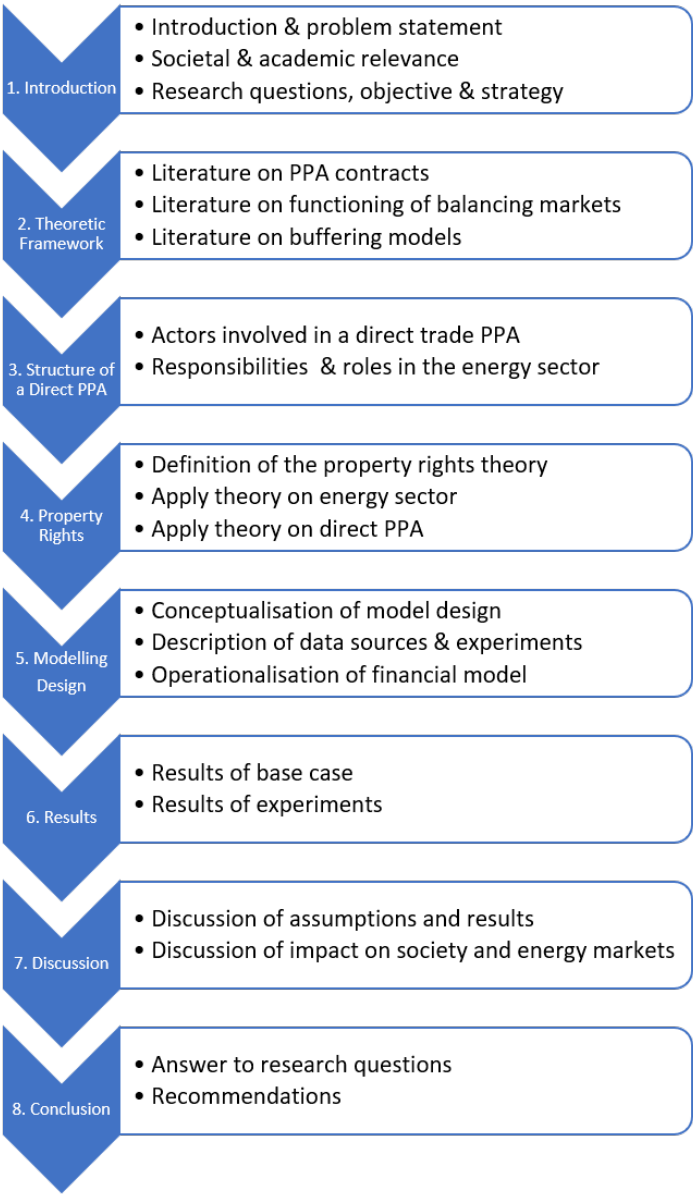


Figure 1.2: Structure of the report

2

Theoretic Framework

In this chapter a literature review is done to see what is already written about PPA contracts in general and specific on direct trade PPA contracts. Moreover, the trading markets in the energy sector are described to create a good understanding on which markets there are and how they relate to each other. Lastly, the literature on battery storage systems is analysed to gain insight in the technology and the models that are already designed. The concepts discussed in this chapter are the foundation for the property rights analysis and the modelling study in the next chapters.

2.1. What is a PPA and What Types Are There?

Dingenen and Reid (2018) have made an analysis of several countries around the world on how PPA energy contracts are implemented. A PPA contract is an energy contract between a buyer and a producer to trade power on a long-term basis. There is a distinction between an energy contract between a retailer and generator and an energy contract between a corporate and a generator or wind farm. This first type can be seen as a traditional PPA and the second type is called a corporate PPA. This contract is, as the name says, a contract with a corporate and a generator. This corporate PPA can be further decomposed into three types: the sleeved PPA, the virtual PPA and the direct trade PPA. This last type is a new type and is central in this research. Below these PPA types will be described in a separate paragraph.

2.1.1. Sleeved PPA

A sleeved PPA construction consist of two contracts, this is shown in Figure 2.1. In the first contract the energy from the wind farm is sold to the corporate. But the corporate does not need all the produced energy at all times so the corporate has a second contract with a utility. In this contract all the produced energy is sold to the utility, the energy is 'sleeved by the utility'. This is done to balance the power with

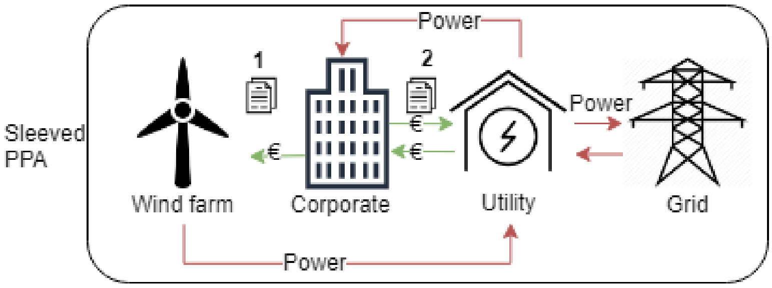


Figure 2.1: Sleeved PPA construction: power flow through the utility, GVOs flow to the corporate in a direct contract with the wind farm

the grid. The corporate in the end is supplied by the utility with the energy it needs at the moment of consumption. The price for the energy is determined by the price of the PPA and the costs of the utility for sleeving the energy. This sleeved PPA is a way for corporates to buy GVOs from a wind farm without having to manage all the power of the wind farm. The corporate can compensate its full demand with the credits it gets from the wind farm.

2.1.2. Virtual PPA

The virtual PPA is mainly used in the USA and is similar to the sleeved PPA. The difference is that there are three contracts in a virtual PPA as is illustrated in Figure 2.2. First, the wind farm and utility have a PPA in which power is traded, second, the utility has a contract with the corporate to supply the power, third, the corporate has a contract with the wind farm for a fixed strike price. The reason why this is called a virtual PPA is because the corporate does not have an energy contract with the wind farm directly. This energy contract is between the wind farm and the utility. The corporate does have a contract with the wind farm in which they settle the difference between the strike price and the market price. This contract is used as a hedge for the corporate to have a stable long-term energy price. The corporate is still supplied by the utility with power and GVOs, they do not have a contract like the sleeved PPA in which they contract the GVOs themselves.

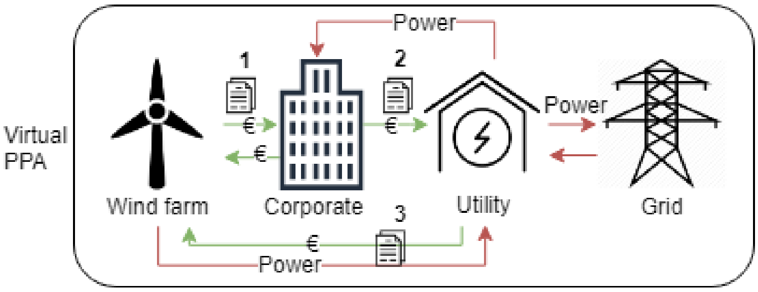


Figure 2.2: Virtual PPA construction: power flow and GVO flow through the utility, no direct power contract with corporate and wind farm

2.1.3. Direct Trade PPA

A direct trade PPA is a new construction that has some similarities with the sleeved PPA. In a direct trade PPA the corporate has a power contract with the wind farm. In this direct trade the customer and the wind operator must bear the risk related to the volatility of the wind turbines instead of the market or a utility which functions as buffer and balancing medium. The corporate uses the power when it is produced and has a separate contract in which they trade the surplus and shortage of energy. This contract is with a service provider who offers services to corporate and consumer to manage the surplus and shortages by trading this on the energy markets. The difference with a utility is that they do not own generators or have long term contracts with them. They are mainly focused on the short-term balancing and administrative service to submit for example the programs to the Transmission System Operator (TSO). In the literature there is only little research conducted on the structure of direct trading of wind energy. In Figure 2.3 this direct trade structure is visualised.

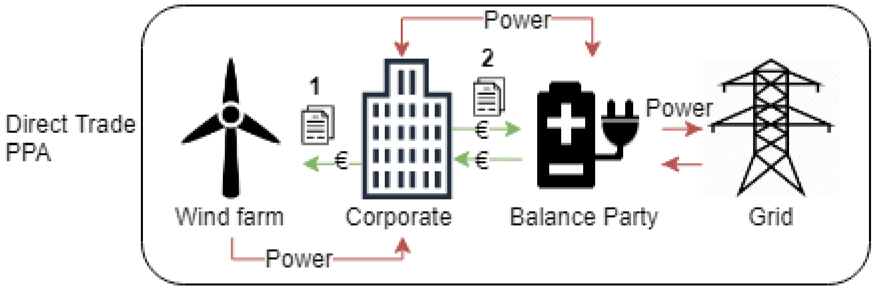


Figure 2.3: Direct Trade PPA construction: power flow and GVO flow through the corporate in a direct contract with the wind farm

2.1.4. Application of PPA types

In the Netherlands the sleeved PPA is more developing because of the high degree of unbundling of the energy sector. This situation makes it possible to make a direct contract between a corporate and a generator without needing a utility (Dingenen and Reid, 2018). This is an important aspect for the direct trading agreement which will be discussed in this research. The generator has a transport agreement with the grid operator to feed in its power into the grid and the corporate can transfer its program responsibility to a trading or balancing party. This construction is used by various companies in the Netherlands e.g. Google, Dutch Railways (NS), Philips, AkzoNobel and DSM. However, all these companies have a high demand in which the wind power is only a small share of their demand. They use a sleeved PPA instead of a direct trade PPA. The situation in which the full demand of a corporate is supplied by a wind farm and in which the finance stream and the power stream is directly with the customers, is still an uncultivated area and is a knowledge gap in the literature.

The development in the market for corporate PPAs is slowly maturing and small buyers are entering this market. This is a hopefully development since “there are only so many companies like Google or Walmart that can buy hundreds of megawatts at a time. Developers need to figure out ways to execute deals with smaller buyers, or they will get left behind” according to Matt Langley, vice president of finance and origination at Infinity Renewables (Rotatori and Zanchi, 2017).

The first large aggregated wind power PPA project was developed by MIT and received a lot of attention. In the end of 2016 this university joined two local partners to aggregate their demand and together set up a PPA contract with a large solar farm ‘Summit Farm’ in North Carolina. This 60 MW farm produces 146 GWh and will make up a large part in greening the grid. This aggregated PPA needs four components: a utility as a natural aggregator, a developer of the wind or solar farm, an investor that can bear the risks and split the production in parts and customers that contract parts of the production. By aggregating their demand they capture benefits that they could not negotiate solely, and this large solar farm would not have been developed (Massachusetts Institute of Technology, 2016). This was a showcase for others to clear the way to more PPA contracts with multiple parties aggregating their demand.

In general, PPA contracts are very important as is stipulated by Kann (2009) stating the fact that a PPA is important in ensuring a long-term contract to cover most of the expected output. This will clear the way for the wind farm owner to obtain investors for the wind turbines. Salci and Jenkins (2018) have done a research into independent power producers (IPP) that own a grid-connected wind farm. They identify three key players in this construction: the IPP (owner of the wind farm), a public electric utility (consumer of energy) and the government (investor). In their financial and economic analysis, they conclude that the net present value in this project is only positive for the IPP since it gets a steady income to cover the investment costs. The electric utility has more risks involved because the price for the produced wind is fixed for a period of 20 years. This price must be lower than the current fossil fuel price and the projected prices of this fuel for the coming 20 years. The fossil fuel prices are very volatile and there is a chance that these will be below the agreed price of the wind energy. “Investing in a wind farm is simply paying now to avoid future oil purchases” (Salci and Jenkins, 2018).

Moreover, in the literature the risk that are involved in a PPA contract are analysed by Martins et al. (2011). The PPA contracts can reduce the risks for both parties and it contains agreements on the allocation of these risks. These risks can be used in the institutional design that is discussed in chapter 3.

In the current projects found in the literature, only the benefits of a hedge for the energy price and the revenues of the green certificates of the contracted wind power are considered. Both in the physical and virtual PPA only the price and the renewable energy credits (RECs) are traded and the energy is sold to the customer through a utility as is analysed by (Cory et al., 2008; Deloitte, 2017; Kent, 2016; Leung and Bailey, 2018). That is why this research has a focus on the direct trade PPA to investigate the uses of this type in which both power and GVOs are contracted by the corporate.

2.2. Balancing markets and prices

System Balance In order to trade electricity, the balance in these electricity markets needs to be managed. The characteristics of electricity demand the system to have at each point in time a total production equal to total consumption. This is done by a balance management system that ensures the security of supply through the continuous, real-time balancing of power demand and supply in order to stabilise the system frequency (van der Veen and Hakvoort, 2016). This frequency is a measure in the AC grid for the grid stability and should always be kept at 50 Hertz. If the system is out of balance this frequency changes, which deteriorate the power stability and quality and may trigger the disconnection of system components, and ultimately blackouts (van der Veen and Hakvoort, 2016).

Balancing Market Design In most energy systems the systems balance is maintained by the system operator, the Balance Responsible Parties (BRPs) and Balance Service Parties (BSPs). The BRPs are responsible for informing the grid operator of their planned electricity production, consumption and transport needs. Every generator and off-taker in the grid is obliged to have a contract with a BRP or be their own balance responsible party (TenneT, 2017). In general all small consumers are served by large energy providers which have contracts with large generators and trade energy on the markets. The system consists of three markets in which these parties act and trade energy in different time intervals. These markets are: the day-ahead market, the intraday market and the imbalance market. The day-ahead market also called the apx-market is the main market on which electricity is traded. All energy providers (BRPs) and energy producers (BSPs) plan their needed demand or estimated production in time slots of 15 minutes for a whole day. They place their bids on the market one day ahead and the system operator clears the market which results in a price for energy at every time of the day and the needed production at that time. Between the time of energy delivery and the apx clearing time, BRPs may want to trade some energy based on last minute changes in their demand or due to the weather forecasts. This can be done on the intraday market. However, this market is in the Netherlands quite small since it is introduced in 2017 and most of the last-minute corrections are done in the imbalance market. If the total generation and/or consumption of the BRPs deviates from their trade schedules, an energy imbalance occurs. This imbalance is settled against the imbalance price, which is based on the price for activating balancing reserves. The generators get compensation for generating extra energy and BRPs are penalised for their extra consumption (TenneT, 2017).

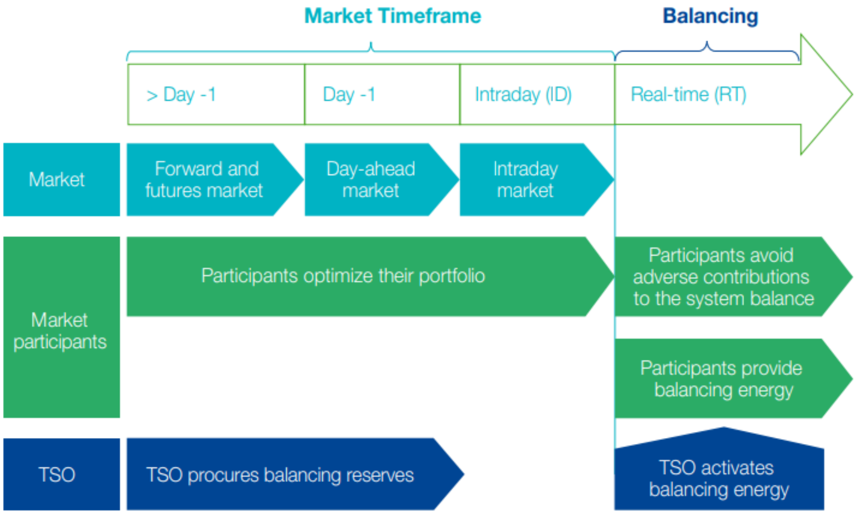


Figure 2.4: Market Timeframe and Balancing, (TenneT, 2017, p.4)

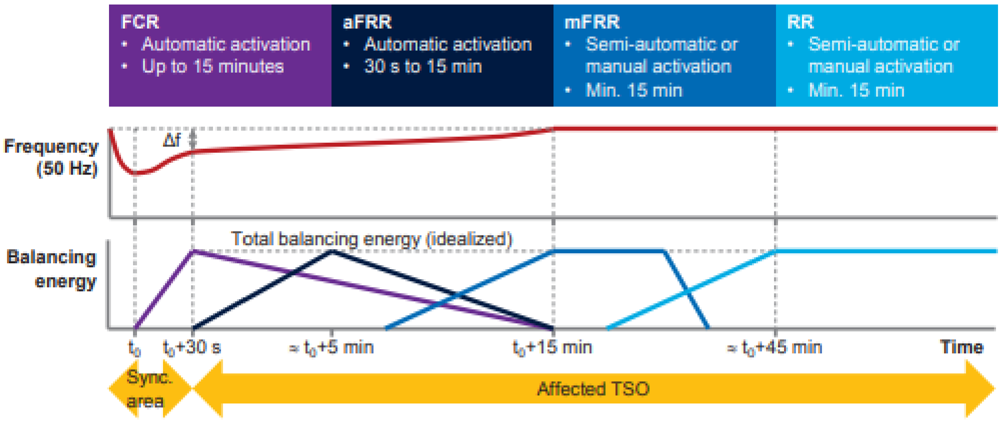


Figure 2.5: Balancing Market Reserves with activation time (ENTSOE, 2016, p.3)

Balancing Reserves The balancing reserves market is a separate market and is divided in primary reserve, secondary, third and fourth reserve. The primary reserve is called the Frequency Response Reserve (FRR) and is automatically activated to maintain the frequency of 50 Hz. The secondary reserve, called the Automatic Frequency Response Reserve (aFRR) is automatically activated within 30 seconds and it should last until 15 minutes. This reserve is used as a complementary compound to the FRR. The third and fourth reserve are manually activated and have an activation time of more than 15 minutes. These reserves are only used during maintenance of generators, during accidents or during seasonal peaks. All these balancing reserves are provided by the balancing service providers (BSPs) and are contracted by the system operator. The BSPs place bids on the balancing market and TenneT contracts the needed volume for a period ranging from a week until a year.

Imbalance Market In the imbalance market the imbalances are settled between all market parties as described above. The behavior of this market is very volatile, the balance is very sensitive and can easily flip between shortage or surplus. All BRPs influence this market and they can increase the imbalance or decrease the imbalance. If they contribute to decreasing the imbalance, by adjusting their production or demand, they can earn money, however if the balance tips they have to pay a fine for their extra production. This market mechanism attracts parties that want to earn money on this market by speculating. Especially with the increasing renewable energy production some BRPs can produce very cheap energy during windy and sunny times and they can store this energy in batteries. They can speculate on the imbalance market with this energy storage and even better, they can let TenneT contract them for the aFRR. In that case TenneT can control the storage of the BRP to settle the imbalances at a constant price for the BRP. This mechanism in the imbalance market has decreased the imbalance price in the energy system (TenneT, 2017, p.46). The imbalance market is very important for the producers of renewable energy, since this production is very hard to forecast exactly. A large part of this renewable energy is settled last minute when the real production is known. So for the business case of wind farms this has a high impact. This is further researched in the model that is made in chapter 5.

2.3. Models for buffering

In the direct PPA construction the power production and demand of the consortium need to be matched. This function is executed by the utility in conventional energy contracts, but this role is changing. The match between supply and demand can be made by trading or by buffering by parties themselves. This section will analyse the literature in this field.

Several studies are done into optimising the use of storage as buffer. In 2008 Wang did a study into determining the optimal size of a battery for buffering wind energy. The objective was to maximise the economic benefit compared to the costs of the battery. The benefit of the storage is maximised by dispatching the energy on the energy market (Choi and Kim, 2018). Another study focussed on a combination of solar and wind energy (Shuaixun Chen et al., 2012). This study designed a forecast model for wind speed and solar radiations, this was used for optimisation study on the size of a Battery Energy Storage System (BESS).

Two other studies also focus on this subject (Li et al., 2013; Wang et al., 2019), Li et al. performed a study on smoothing the curve of the Photovoltaic (PV) power and wind power in combination with a battery. The result was a decrease in fluctuation from a peak of max 50% to a peak of max 10%. Wang et al. (2019) used a multi-objective optimisation model to model wind, BESS and battery power. The model uses Time of Use (ToU) prices so the price is taken from the energy market at the moment of production or usage. The results are positive and show that the combination of the TOE price and the BESS can reduce the wind and BESS uncertainties and improve the electricity systems efficiency (Wang et al., 2019). The model used a combination of 200 MW wind, 50 MW BESS and 50 MW BESS, so a ratio of 4:1:1. Lastly, a study is done on the combination of solar, wind and battery storage by Muh and Tabet (2019) with a focus on the net present value calculations of these combinations. The results were similar to the above-mentioned studies.

In contrary to the studies on BESS with a dispatched storage, a study by Zhang et al. (2019) looked into the optimisation of a battery storage without selling electricity to the grid. The Energy Storage System (ESS) was only used for the consumers in the neighbourhood in providing them some benefits. Different battery types were compared on their efficiencies and prices. The polysulfide bromide (PSB) battery gave the best performance in terms of economic benefit due to the lower price, despite the lower efficiency of this battery type Zhang et al. (2019) Another storage method is the option of Electric Vehicle (EV) used as a buffer. A model is designed called ‘PowerFlex’ to model the EVs that are connected to the grid with a bidirectional power flow, called Vehicle-to-Grid (V2G)(CE Delft, 2016). This study was made to explore the situation of a 100% renewable energy system and calculates the total production of solar & wind and the amount of storage used.

Hernández-Torres et al. (2019) executed a study on a power system on an island. The problem on an island with a high percentage of RES is the instability of the grid, because there is not a very robust and extended interconnection infrastructure to handle the intermittency of the Renewable Energy Sources (RES). A BESS can be used to cope with the intermittency of these sources and increase the renewable energy percentage. This study is useful because it focusses on a wind farm that participates in the day-ahead market, just like the wind surplus from the wind farm in the PPA construction. This study uses a combination of Li-Ion batteries and H2/S2 batteries and a techno-economical analysis is made to determine the optimal size and combination of technology. A special focus is on the ageing models of storage devices, which is an important factor when using for example batteries of EVs. The model results are in favour of a system with a Li-Ion storage system, although the H2/S2 batteries looks promising (Hernández-Torres et al., 2019).

These studies show that battery storage is a really good option for buffering the energy of wind farms. Another point is that PV panels can be used to smooth the wind production, which is a point that can be further researched in the case of a direct PPA. Lastly, the PowerFlex model looks very promising in using EVs as a storage system.

3

Structure of a Direct PPA

In this chapter the structure of a direct PPA is further decomposed. The differences between the available PPA contracts are explained in the previous chapter. Here the actors are identified that play a role in a direct PPA, next the interests and view on the problem are analysed for every actor. Finally, their roles and responsibilities in the energy sector are described. This chapter will give an answer to the first research question: "*What are the actors involved in a direct trading PPA contract and what transactions are present in this construction?*"

3.1. Actors in the Direct PPA construction

In this section the landscape of the actors is identified and the relations between them. In the direct PPA structure there are seven main actors involved, these are seen in Table 3.1. The most important actors are the customer, the developer and owner of the wind farm and the service provider or retailer. These are analysed in detail in the next paragraphs.

Customer The customer in this construction is central. The customers have a wish to consume renewable energy and want to know the source of their energy. As discussed in the introduction the origin of renewable energy is not always clear due to the international market for GVOs. The energy in this construction can be directly linked to the company and even the brand can be printed on the turbines to strengthen this link. Furthermore, most importantly is the price the customer pays for the energy. In general, customers have a contract for a year with a fixed energy tariff. This results in very predictable energy costs for every year and it is very flexible, since they can change their contract or provider every year. The new situation is fixed for a period of 15 years, the lifetime of the wind farm. So this will result in a long-term reliability for the customer with a higher risk since the future is very uncertain. If the consumers or corporates are joined in a consortium then a solution for this can be an exit option in the consortium. This can be arranged between the members of the consortium in a consortium contract. If not, the consumer may discuss an exit option with the service provider.

Developer The developer is the initiator of the wind farm and will take care of the construction and funding. The developer is also the operator of the wind farm and will maintain the wind farm and is the owner of the produced energy. The main interest is to find enough funding at investors for the capital costs of the wind farm. Moreover, he wants to minimise the whole period of funding and construction in order to reduce the costs of this project. The difficulties for the developer are getting the permits from the governmental bodies, completing the funding and contracting parties for the produced energy. Ideally the developer wants to set up long-term off-take contracts to have a stable and predictable income and sales.

Service Provider The service provider is a new role and it provides energy services to the consortium members. This actor provides a service for balancing the demand and supply of the members and a service to act as a BRP on the behalf of the members. The role of BRP includes the forecast of the wind production and submit a program to the TSO with expected demand and supply. The power flow will not be adjusted, the energy is still transported from the generators to the High Voltage (HV) and Low Voltage (LV) grids to the consumers. The service provider ensures that there is extra energy bought at the energy market in case of less production than demand and it sells the surplus of the wind farm when demand is lower than production. The problem of the service provider is that it takes the risks of forecasting the production and trading on the energy market. However, they can include this risk in the price they ask to the members.

Table 3.1: Involved actors and interests

Actors	Role	Goal	Problem	Preferred Solution
Consumer	Consume energy	Low energy costs Green energy from NL	Long-term reliabilities	Exit option
Consortium	Aggregate consumers	Low (long-term) price Stable & predictable costs	Uncertainty energy prices	Small price bandwidth
Retailer	Supply Energy Balance Responsible Party	Customer relations Increase energy portfolio Forecast demand & production	Role decreases Forecast wind hard	Keep current situation
Service Provider	Match supply/demand Balance Responsible Party	Optimise trade & buffering of energy Forecast demand & production Increase contracted services	Risks in forecasting & trading	Flexibility at the producers or consumers
DSO	Manage distribution network	Reliable distribution network Connect every consumer	Congestion High investment network	Efficient matching
TSO	Manage transmission network	Reliable transmission network Sufficient capacity	Imbalances High investment network	Constant power infeed
Investors	Invest capital	High profit on investment Low risks long-term Sustainable investments	Forecast energy market uncertain	Guaranteed profit
Developer	Construct & operate wind farm	Sufficient funding Fast construction period	Funding Permits Contracts	Long-term take-off agreement

3.2. Roles & Responsibilities In the Energy Market

The roles and responsibilities can be best explained using the Universal Smart Energy Framework (USEF) (USEF, 2015). This is a framework that has multiple designs on how smart energy systems can be implemented. The roles in this framework are described to give a solid background on their responsibilities in the energy system. This lays the groundwork for the analysis using the property rights theory in the next chapter.

3.2.1. Producers, suppliers and balance responsible parties

The producers or generators currently ensure the provision of energy to the energy market. The energy production is on a central level and based on fossil fuels. The role of energy production is shifting to more decentral, so the role of the generators changes. The amount of central production will decrease, caused by the decentral production of consumers who become prosumers. The producers need to optimise their generation assets, so they can coop with the volatility of the renewable energy sources. This demands flexibility to reduce peak loads based on the user's demand profile and hence prevent the dispatch of less efficient and polluting generation units (USEF, 2015).

Suppliers currently provide energy to their end users whenever they need it. The supplier provides energy, measures the consumption and bills the end users. Moreover they act as the balance responsible party on behalf of their users to the system operator. The costs of the supplier to balance the demand of the users with the production is spread over a total volume of energy that is supplied to the consumers. However, since the end users become prosumers they produce more energy themselves at the costs of the energy supply from the retailer. The retailer should change their business model to a more service-based business model in which they provide services to their customers for balancing and flexibility. They can provide their customers with demand response devices influence the demand profiles to the available renewable energy sources such as the wind and sun. The users benefit from this by lower consumption, lower energy bills and environmental benefits. Another use of this demand respond devices is the data it gathers from the consumers on their consumption profile. This data can be used by the supplier to improve the prediction models of the demand portfolio. An accurate prediction model and algorithms give advantages in efficiently bidding on the energy markets and in efficiently making use of of the available flexibility to optimise their portfolio.

3.2.2. Distribution and transmission system operators

The Distribution System Operator (DSO) & Transmission System Operator (TSO) are the system operators who have the responsibility to ensure the energy flow from the producers to the consumers. They must guarantee a sufficient capacity which is always available. The electrical grids have a long technical lifetime with a long construction time. This infrastructure is very capital intensive and is well planned in advance. The costs of the grid are divided over all users of the grid, but to keep these costs acceptable the depreciation period is around 30 - 50 years. Currently the grid is very safe, reliable and stable, hence the new services should not have a negative impact on this. The new devices should be tested extensively before they are rolled out on large scale. In the Netherlands the system operators are rolling out smart meters to every household. These devices enable tariff differentiation, provide insight to the users and reduce the settlement costs. Only the last two functions are used now, a new tariff method is not implemented yet. The largest challenge for the system operators in the changing energy market is to manage the peaks in the grid caused by a high degree of decentral energy resources. The smart meters can help in this by providing flexibility to the system operators.

On a central level the TSO has to maintain the system balance. The TSO relies now on the flexibility from large, central generation units that are contracted to provide primary and secondary reserves. The increased share of renewables demands more flexibility, while at the same time the number of central generation units is decreasing due to the shift toward more decentral energy resources. This means that the flexibility pool is also decreasing. The TSO can keep existing generation capacity online as reserves, but the utilisation is relatively low which may results in higher prices. Another solution is to contract flexibility aggregators to provide balancing services or to build a strong transmission grid throughout Europe to cancel out imbalances in the system on European level. This requires more integration of the national grids and a flexibility market on which the flexibility is traded (USEF, 2015).

3.2.3. Prosumers

The consumers become more prosumers as they invest in their own generation assets e.g. solar panels on their roofs. They want to reduce their energy bills by making use of energy-efficient technologies or by insulating their houses. They want to make sure that these measures result in the expected savings, so they want insight into their energy bills, consumption and production (USEF, 2015). The prosumers can go one step further by participating actively in the energy market. They can provide flexibility by letting other parties control their devices in return for lower energy costs. Some prosumers will collaborate and develop energy communities in their neighbourhood, in which knowledge is shared and renewable energy production is promoted. As the energy transition progresses more consumers have electric cars that need to be charged at home. They plug in their EVs and do not care about the network that must transport that energy to the vehicle. The EV charging should be flexible and adapted to the energy market signals and the solar panel's generation profile. The small consumers are not aware of the functioning of the energy market and have no interest in the limitations of the existing market model. They want access to the system, use their assets whenever they want and buy and sell energy from anyone in the system. To achieve this, the involved parties should adapt their roles and responsibilities to a new energy system and they should develop relevant energy service.

3.2.4. Aggregators and energy service companies

In the new energy system a new role is introduced to provide the flexibility that is needed. This can be an aggregator that accumulates flexibility from demand-response resources owned by consumers or the industry. They can provide the flexibility to the market parties that are described above. The advantage of an aggregator is that the flexibility is not dependent on one consumer, eliminating the risk of non-delivery and providing reliable service. Also, the aggregator prevents the exposure of consumers to the risks involved in the energy market. Another role is the Energy Service Company (ESCo) which can provide ancillary energy services. This role is not directly linked to the energy and flexibility chain. The services are more general and can include the installation of solar panels, maintenance and operation of this equipment, provide demand response devices and provide information on energy saving measures. The roles of aggregator and ESCo can be combined in one business model or in separate roles.

3.2.5. Consortium

In this construction of a direct PPA the energy is contracted by the consortium from the wind farm. They contract the energy for a long period, for example 15 years, to guarantee the developer with a steady revenue and for the consortium to have a constant, low price for the future. The consortium is important because it aggregates the demand of the consumers and splits the risks among them. The consumers would not sign this contract themselves with their relatively small energy demand. The consortium can get a good price since it is larger and can take off the complete production of the plant which is attractive for the developer. The price for the PPA contract is in general depending on the apx prices, since the Stimulering Duurzame Energieproductie (SDE+) subsidy is also calculated with these prices in the Netherlands. This subsidy will compensate the wind farm for the profile factor of the wind which reduces the price for the wind energy sold on the market. The amount of the subsidy is determined by calculating the difference between the average energy price for wind energy and the national average price (Lensink and Van Zuijlen, 2015; Lensink, 2018). The implications for the consortium is that they do not have a fixed price for the contract period, but are dependent on the energy market prices. This is a risk for them and in order to reduce this they can negotiate a maximum and a minimum price to create a bandwidth for the price. If the market prices rise above this upper limit the price in the PPA is capped at the maximum price. The same for the case in which the market price drops under the minimum price. This situation is not very like to occur and is not very attractive for the consortium, since they can buy their energy for less on the market. The impact however is low because the prices are already very low so the difference on the total energy costs is minimal. This lower limit is more attractive for the wind farm to prevent negative prices, a situation in which the wind farm has to pay the consortium to take off energy.

3.3. Conclusion

From the actor analysis it becomes clear that there are three main roles in a direct PPA: the developer, the consumer and the service provider. The developer is the owner of the wind turbine and makes sure that there is financing and that the wind farm is built. The consumer can either be on its own or in a group of consumers or in a consortium and lead the negotiations with the developer to agree on a PPA agreement. The third role is for the service provider who has a contract with the consumer to deliver the required services to the consumer. Next to these actors, there are supporting actors like the financiers of the wind farm and the network operators on distribution and transmission level. But these are not directly involved in the PPA and do not have a direct link with the consumer. Important is to look at the goals, interests and preferred solutions of all actors to create understanding of the view of the actors on the case and make them feel important and involved.

The transactions between these actors are analysed and come down to two main transactions: the agreement on the PPA price and requirements between the developer and the consumer, secondly the transaction between the service provider and consumer to divide the risks between them in the service contract. Moreover, there are transactions between the developer and the investors, a transaction between the DSO/TSO and the service provider and transactions between the service provider and the energy markets.

4

Property Rights in the Energy Sector

In this chapter the second and third research questions are the object of study. First, the property rights theory in general is explained based on a literature review (section 4.1), second, the theory is applied to the energy sector (section 4.2). The framework that results from this section is used to focus on the transactions and allocation of PR in the direct trade PPA (section 4.3). This will give an answer the second question:" *What are the risks and cost components of these transactions and how are these applied in a direct trade PPA?*".
Furthermore, in section 4.4 the economic incentives in a PPA contract are identified and are linked to the property rights found in section 4.2. These incentives are compared to a regular contract to see if this new PPA structure has more economic efficiency. This will in the end answer question three: "*What are the effects on the economic incentives of the actors in the energy sector by using direct PPA contracts with a balancing service provider?"*. The relevance and added value of this theory will be discussed in chapter 7.

4.1. Property Rights Theory

4.1.1. Transactions costs

In the literature there are several definitions of transactions costs, these are identified by Musole (2009). It can be defined as *"the costs for bargaining, information measurement, supervision, enforcement and political action"* (Libecap, 1986). Furubotn and Richter (1997) define the transactions costs as *"search and information costs, bargaining and decision costs, and policing and enforcement costs"*. A few examples of transactions costs are identified by Furubotn and Richter: market transaction costs, result from the need for information and bargaining processes, managerial transaction costs, costs relating to organisational design and running an organisation, political transaction costs, costs related to a system's formal and informal political organisation and running a polity (Musole, 2009). The definitions depend on the theoretical perspective. The property rights theory for example defines transaction costs as *"costs of establishing and maintaining property rights"*. In all cases where property rights are formed, adjusted or weakened there are transaction costs (Allen, 1999). Another perspective is the neoclassical theory which defines transaction costs as *"costs resulting from the transfer of property rights"* (Musole, 2009). A remark from Allen (1999) on this is that this definition is only applicable to costs that arise between firms or individuals in the process of market exchange.

Now that the transaction costs are defined, let's look into what sources contribute to these costs. Five sources are identified by Musole (2009). The first source is the number and diversity of agents (Benham and Benham, 2001; Milgrom and Roberts, 1992; Wang, 2003; Webster and Lai, 2003; Williamson, 1985), second the complexity and value of rights exchanged (Webster and Lai, 2003), third policy factors (Coase, 1960; McCann and Easter, 2002), fourth natural difficulties in trading and legal factors (Demsetz, 1967) and lastly size and structure of the transaction (Stavins, 1995). *"In our real world, transaction costs determine property rights, ownership, the extent of trade, specialisation, and production. If transaction costs decrease, property rights will be more clearly defined, more goods and* *services will be traded, the benefits of specialisation will increase, and greater economic gains will be realised"*, (Benham and Benham, 1998).

4.1.2. Property rights

Transactions costs are as seen in the definition of Allen closely related to property rights. As with the variety of definitions of transaction, there is not one definition agreed upon in the literature. Cole and Grossman (2002) assume that there exist property rights in the legal sense and in the non-legal sense. In the legal sense they conform to legal definition, these are defined by the state and recognised by the law. Other rights are sanctioned by convention, e.g. customer relationships. Next to the legal definition, the focus is on economic rights which describe the ability of individuals to exercise their rights over an asset (Zhu, 2002, pg. 42). In general property rights are basically rights of ownership. It is about the rights people have to have or acquire over the use of a resource. The literature suggests that when property rights are not clearly defined, transaction costs rise, and market failures will result (Musole, 2009). Property rights can be seen as *'a bundle or a portion of rights to use a resource that is owned'*. These rights are always circumscribed by the prohibition of certain actions (Alchian, 1973). Property rights are not absolute and can be changed by individual's action (Barzel, 1997). The value of any good exchanged depends, ceteris paribus, on the bundle of property rights that is conveyed in the transaction (Furubotn and Pejovich, 1972). *"The roman law categorises the property rights in the right to use an asset (usus), the right to capture benefits from an asset (fructus), the right to change its form and substance (abusus) and the right to transfer all or some of the rights specified to others at a mutually agreed price (transfer)"* (Pejovich, 1990). If someone has the full bundle of property rights this property is seen as complete ownership, if not this person has partial ownership. Usus means the right to determine how an asset is used, fructus is the right to get the benefits from the use of an asset, abusus is the right to exclude others from usage and the benefits and also the right to transform the asset. For example if person B leases a house from person A, person B gets the usus and person A has the fructus, abusus and right to transfer. Person B can use the house but cannot change structural things of it or lease it further to others to obtain revenue neither can he transfer the usus to others since A and B have a contract.

4.1.3. Transactions and property rights

A transaction takes place when a good or a service is transferred across a technologically separable interface (Williamson, 1985). This means that a physical object or knowledge that is embodied in a physical sense, e.g. written text, has to be transferred. In the mechanical engineering sector if a machine does not run smoothly this can be due to friction between the parts in the machine. In the economy field this friction can be expressed in transaction costs. Do all the parties operate harmoniously, or are there frequent misunderstandings and conflicts that lead to delay, breakdowns, and other malfunctions (Musole, 2009)? If the transactions costs are high, the allocation of property rights is more critical since the transfer has more friction. In these cases the existing property rights arrangement has a big impact and enduring effects on the functioning of the system (Libecap, 1986).

4.1.4. Conclusion

It can be concluded that there is a link between property rights and the transaction costs which is also linked with the economic efficiency. However, the link of this economic efficiency is better explained if the effects of risk are incorporated in the model (Jaffe and Louziotis, 1996). In this article they argue that risk is also an important factor in this property rights model and influences the economic efficiency. Stronger property rights will reduce the involved risks and it will give certainty of receiving the future benefits of a bundle of rights. Especially in long-term investments this certainty is important, and it will give an incentive to developing markets for this in the longer term. These markets will inevitably contribute to greater incentives for economic efficiency, since the number of available goods increases which makes individuals and society better off (Musole, 2009).

Moreover, the property rights play a large role in the economic environment. This theory can be used to define the parameters for the use of scarce resources and associated rewards and costs to this can be assigned. This will result in incentives and time horizons for investments, production and exchange. The arrangement of the property rights affects the allocation of the resources and thus economic growth.

4.2. Allocation of Ownership in The Energy Sector

The property rights theory can be applied to the energy sector to analyse how the resources and assets are allocated and to see if the allocation is efficient in the new PPA construction. The energy sector is a very dynamic system and has undergone several structural changes over the years, under pressure of the European Union. The energy sector was at first a full monopoly with an integrated supply chain. This has developed to a fully unbundled system with competition on the generation side and on the supply side. This unbundled market has opportunities for market players to enter the market with new services and compete with the traditional retail companies (Hallack and Vazquez, 2014, pg.3-6). These services are described in the previous chapter and can be provided by aggregators or service companies. The impact on the energy sector and the markets will be analysed in this section using the property rights theory as described above in section 4.1. The focus is especially on the interaction between the aggregator and the consumers in the market of flexibility. The value proposition of this flexibility will be researched to determine the price components of flexibility for consumers and for suppliers of flexibility.

Electricity has several properties that are important in the allocation of property rights. It is produced at a certain time with a certain volume and also consumed on a certain time with a specific volume. Since electricity cannot be stored within the grid easily as with the gas grid, the total supply must be equal to the total demand on every time of the day. Another property is the right of transport of energy. The transport infrastructure is regulated and operated by TenneT in the Netherlands. This party will allocate the transport rights to all the other parties in the market. Moreover, there are technical properties of electricity that specify the voltage of the carrier, the voltage of the grid on which the carrier is transported, the location in the grid and the speed of the carrier which determines the current. All these properties are shown in Table 4.1.

If the ownership of an asset is split up, the previous owner loses its complete property rights and can transfer some of these to someone else. The right to capture the benefits of this assets is in general still with the 'owner' of the asset. In the energy sector the generators have full ownership of their generation assets and of the energy they produce. When they trade this energy they trade the full bundle of property rights to the market. A retailer who buys this energy from the market gets this full bundle of property rights and can provide it to its customers. The customer gets only partial ownership: he gets the right to use and to transform this electricity to other forms by using it in their home devices. However, the right to capture benefits is not transferred since the customer cannot sell the electricity to others and capture benefits from it. This right to capture benefits is still with the retailer. This is not very strange since the retailer carries the risks associated to the variable demand of the consumers and this property rights are an extra value proposition for them to include this risk in the transaction. Furthermore, in the energy chain the system operator (SO) also has the right to capture benefits on its transport assets. The SO integrates the risks of balancing the supply and demand and is rewarded for this by getting the right to capture benefit if the right to use is transferred to the generators and retailers.

4.2.1. Transfer property rights

A third aspect of the property rights allocation, is the right to transfer some or all of the property rights (Pejovich, 1990, p.27-28). In transactions not everyone is able or permitted to trade a property right to one another. In the land market or housing market a property can be sold to another if the seller has the full bundle of property rights. If not, the seller can transfer only a part of the property rights

Table 4.1: Properties of electricity: these are used to analyse and decompose the transactions in the energy sector

Electricity Properties	
Time of Production (ToP)	Volume
Origin of production (GVO)	Voltage
Transport Right	Speed
Time of Use (ToU)	Location
Current Owner	

bundle, for example by leasing or renting a property. In the electricity sector the right to transfer can be identified in the markets for energy. In these markets the electricity is traded by transferring the rights of usus, fructus and abusus. However, in the energy market design not everyone can trade electricity on the market. This is due to the unique characteristics for energy such as the required balance between supply and demand, as described in the previous chapter. In general, the market is organised by the system operator which collects the bids and offers of the energy providers and generators. The system operator requires every trader to be registered as a BRP and to submit a program of their energy usage every day. Moreover, the traders have to be company employees, have sufficient knowledge of energy systems and the bidding software and are financially cleared by a bank or by the European Clearing Customer (ECC) (EPEX Spot, 2019). The system operator and the market operator oblige traders to meet these demands in which they can obtain the rights to transfer their energy on the market to others and capture benefits. This is the case for the energy that is sold on the wholesale markets (day ahead, intra-day and imbalance markets). This means that generators, retailers and other BRPs can trade energy on the market and transfer the property rights. A consumer who gets energy supply from a retailer cannot transfer these rights on the market. Although, it is possible to trade energy directly to others in private contracts also called bilateral contracts. In these contracts usually large volumes of energy are traded on a long-term basis between one generator and one consumer. For this trading structure the parties have the right to transfer the property rights of the electricity, however they still have to contract a BRP to access the transport grid and submit the energy program.

4.2.2. Time dimension in right to use

The electricity on the transport network should always be in balance on every time of the day. This demands a new property right in the energy sector that specifies the time on which parties can produce or use energy in the system. This is included in the properties of electricity as can be seen in Table 4.1. The time of production and the time of consumption are labels of the energy that specify the time dimensions. Ideally, the total volume produced at each timestamp should at every time step be equal to the total volume consumed at each timestamp. This time dimension is important in every step in the supply chain and will be analysed step by step below.

First, the generators that produce electricity will closely monitor and control their generation plants on the amount of produced electricity. They are a BRP and submit their energy program to the TSO one day ahead. This program specifies exactly how much energy is expected to be produced at every time of the day. The generators trade their energy on the market and need to buy the right of transport from the TSO with the specification of volume and time of production.

Second, the energy provider on the other side of the market buys electricity from the generators. The energy they buy provides all their customers demand and they specify this in a program they send to the TSO. The time of consumption is very hard to predict exactly since the consumers are not controlled by the energy provider and use energy whenever they want. To coop with this uncertainty the providers aggregate the total demand of their customers so that the individual behaviour has less impact. Next to that they have a model that forecasts the demand which they use as a proxy for an average demand of a customer. The energy provider includes this demand pattern in an energy program with the time of consumption and the volumes and this is submitted to the TSO. The energy provider gets in return the right to transport the bought energy on the network to their customers.

Finally, the TSO checks whether the programs of the generators and the energy providers match with each other. If the total amount of produced energy at a time step is not equal to the total amount of consumed energy at that time step, they send a signal to the imbalance market to solve this mismatch.

4.2.3. Monitoring abuse

Since the electricity sector is very complex and a critical infrastructure for the society, the monitoring of abuse is very important. This monitoring task is reserved for the TSO. The TSO monitors the match between the actual situation on the grid and the programs of the generators and providers. They manage the imbalance settling and they manage the congestion on power lines when too much energy is flowing through a particular section in the network. The TSO is allowed to penalise the parties that not behave according to their submitted program. This penalty reflects the costs of the TSO to ramp up or ramp down assets to settle the imbalance.

In the light of property rights the TSO has the right of usus and fructus on the transport assets, the right to transfer the usage rights of this asset and the right of abusus of the network. Usus, fructus and the transfer of these are described above, in this section the abusus of the energy infrastructure will be analysed. The property right of 'abusus' means the right to change the form of an asset. The TSO checks whether the users of the network behave according to the rules and the property rights they have. The users don't have the right to change the form of the asset, in this case the network, so the TSO is checking if they behave according to that. The users in the energy sector can influence the balance of the network by using more energy or producing more energy than is specified in their program. This imbalance changes the network, resulting in destabilising the grid and in the worst-case cause blackouts. A blackout may occur when there is too much energy in the system, this energy is not stored in the grid and cause congestion in the network. In the case of too less energy in the system also a blackout can occur because devices connected to the grid do not have enough energy. The task of the TSO is thus to monitor this strategic behaviour and misuse of the property rights and can penalise users who do not comply with the rules.

The right of abusus is not allocated to the users of the network, since they do not have the ownership rights on this. However the users do have the ownership of the electricity they buy from the energy provider. So they can exert the right of abusus on their own energy. This happens when they use the electricity for their electrical devices, the energy is than transformed to another form for example power or heat. The generators do also have the right of abusus on the electricity they produce and transfer this right on the market. They do not use this right of abusus, although they do exert this right on the resources they use to produce the electricity. The conventional generators transform the energy of coal or gas to electricity in their plants, so that is also a right to transform an asset. The upcoming generators which produce renewable energy from the wind or the sun do not have the full ownership of this resource. They only have the right of use and the right to transform the resource to another form, in this case electricity.

At one place in the energy sector the property rights are not fully allocated. This is the case when users have their own DER and produce energy with it which they feed into the grid. They use the grid in a bi-directional way, without the need of submitting a program of their production. They will destabilise the infrastructure without the property rights of use, fructus and abusus on this asset of the SO. If this happens on a small scale with a limited volume the network can easily handle it, but with the energy transition in mind the amount of DERs is increasing rapidly and starts to have a significant impact on the grid. The property rights should be allocated in this case, this can be done by aggregators. They can, comparable to the situation of the retailer, aggregate the decentral production and integrate this in a portfolio to make this production more predictable. The portfolio they can in turn sell to the DSO which can better manage the congestion with it. More of this construction will be explained in section 4.3.

4.3. Allocation of Ownership & Energy Properties in a Direct PPA

In this section the focus is on the direct trade PPA construction. The risks for the involved actors are identified and these are linked to cost components and to the property rights elements. In this construction five actors are relevant: the wind farm owner, the consortium, the service provider, the flexibility supplier and the system operator. The direct PPA construction with the according property rights is shown in Figure 4.1. The transactions between the actors can be further specified by zooming on the energy properties that are transferred, these transactions are listed in Table 4.2. Lastly, the risks are identified and linked to the property rights elements, these are bundled in Table 4.3.

Table 4.2: Transactions in a direct trade PPA with the corresponding properties of electricity which are transferred

		Volume	Voltage	ToP	ToC	GVO	Location
Wind farm	Aggregator	X		X			X
Wind farm	Consumer	X				X	
Wind farm	TSO/DSO		X				X
Aggregator	TSO/DSO	X		X	X		X
Consumer	Aggregator	X			X	X	
Generator	Aggregator	X		X		X	X
Generator	TSO/DSO		X				X
Aggregator	E-market	X		X		X	

4.3.1. Wind Farm Owner

The wind farm owner has the full ownership on its assets and with these assets he produces electricity that can be traded to consumers. The energy is traded to a consumer in a PPA agreement and in this transaction the volume and the GVO is traded. The wind farm is still responsible for the voltage, the location and time of production. The traded property rights can be linked to the risks that a wind farm has and needs to integrate. The volume risk is linked to the energy that is produced from the wind farm and the GVO makes sure that the energy is labelled as green energy and is also a revenue stream for the wind farm. The voltage and time of production are still risk that remain and could be covered by a contract with another party. Moreover, there are extra costs not directly related to the production of the energy such as financial costs for the maintenance and financing of the turbine. These are covered by an extra margin added to the PPA price.

The first uncertainty, is the volume of the generated power, this is highly dependent on the weather, the location of the turbine and the technological efficiency. These factors make it difficult to determine exactly the operational hours per year of the turbine. The operational hours determine the revenue of the turbine and the return on investment. A second volume risk, is a failure of the turbine or required maintenance. The moments of failures are hard to predict and happen very spontaneous. The impact is quite high since the consumer depends on the power supply and the power production is forecast and submitted to the transmission operator. A third volume risk, is the short-term forecast of the wind production, this is quite good to model however there is always a small difference between forecast and actual production. This difference is to be traded on the imbalance market and the costs for this needs to be reflected by the volume risk factor. Lastly, the volume is affected by possible curtailment of the turbines. This means that the turbine is ramped down by turning the blades away from the wind. This may happen when there is an oversupply on the market and the prices are negative. The owner can initiate this to prevent extra costs or a TSO can pay the wind farm to ramp down to prevent congestion on the grid.

The allocation of these risk depend on the details of the PPA. In this direct PPA the uncertain production volume due to the forecast is for the consumer, the failure risk and the uncertain operational hours are for the wind farm. The wind farm only gets paid for the production of wind so this risk of non-production is for him. Lastly, the volume risk for curtailment is initially for the wind farmer but it can be controlled by an aggregator if both have an agreement.

Next there is a financial risk for the wind farm for the loans and other financial means required for construction and operation of the wind farm. This risk includes a possible adjustment of the interest rates he pays. Other more external risks are changing regulations in for example the tax legislation or the environment legislation. These risks are threats from outside and cannot be influenced. So these risks are not included in the transaction, they are shared risks. Although, most of them are for the wind farm as entrepreneurial risks and these are covered by the profit margin on the PPA price.

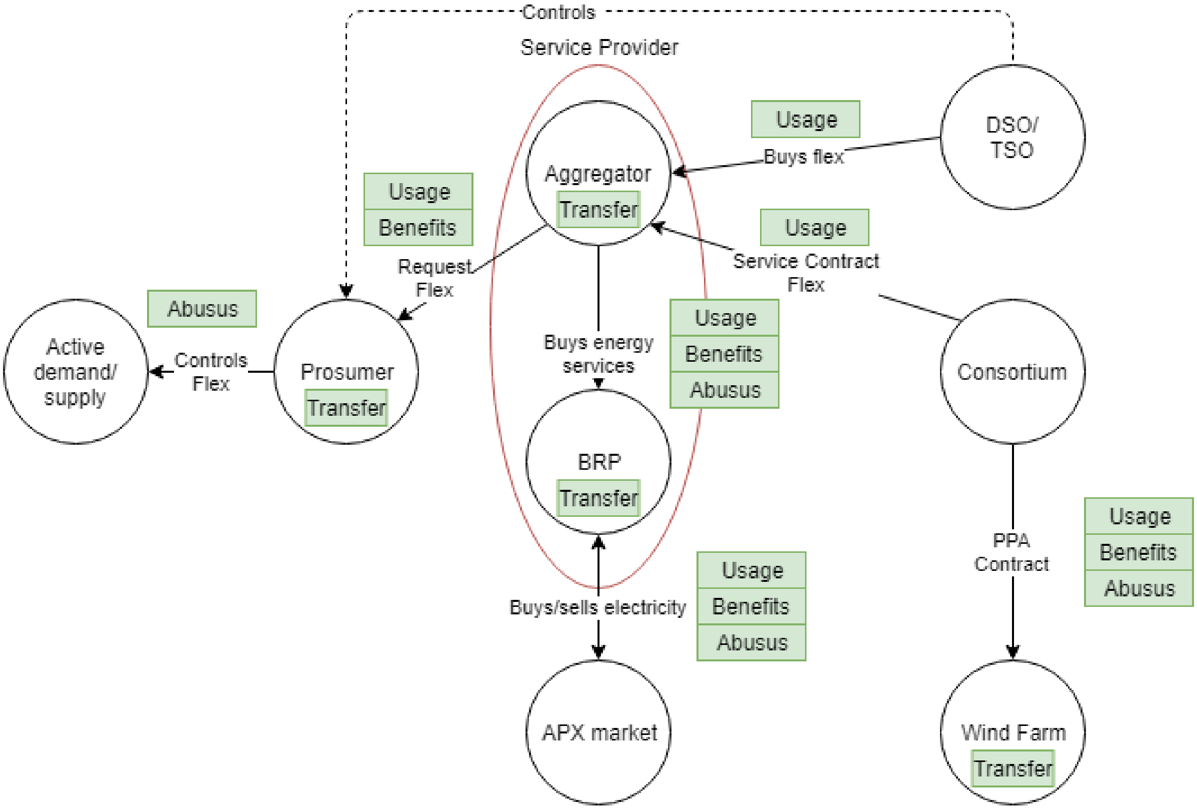


Figure 4.1: Overview of the transactions and property rights in an electricity market with a direct PPA construction

4.3.2. Consumer and Consortium

The energy from the wind farm is sold to the consumers that may be aggregated in a consortium or have an individual contract with the wind farm. The consumers also have risks that need to be covered in the PPA contract. The property rights they buy are the rights to use the energy, the right to benefit and the right to abuse or transform the energy. These rights are linked to the price risk and the volume risk of the consumer.

First, the price risk which is the main component of the energy contract. Consumers are mainly focused on the price they pay for their energy and only see benefits if the price of a new contract is lower or more stable and predictable than their current contract. The price for the energy is specified in the PPA contract, this can be a fixed price or a variable price with a floor and a cap. When the consumer buys the energy it buys the rights to use and the right to transform this energy from the wind farm. The price components consist of the GVO of the energy and the cost price for the energy depending on the SDE+ subsidy.

Second, the volume risk is a factor that influences the amount of energy that is traded. In a PPA contract the volume of generated energy is not constant due to the volatility of the wind. Most contracts allocate the volume risk to the consumer who has to buy all the generated power. In some cases there is also a minimum generation volume specified in the contract to reduce the risk for the consumer. At the same time the risk for the generator increases since the produced wind energy is not constant and may be below the minimum. That is why this minimum is not often used and if it is, the minimum is far below the average production level. Another uncertainty for volume is the failure of the turbine. In the contract they have to make agreements about the consequences and financial compensation for failures and non-delivery. The volume risk can be covered by a separate contract with an aggregator will take care of the weather forecast, program responsibility and the imbalance. The consumer is compensated for this risk by the value of the GVO and the energy which both can be traded against the market prices.

Thirdly, the consumer has risks for the availability of the wind, the security of supply and the risk of managing the surplus of the energy. The consumer can take these risks themselves and decrease their energy costs. However, the costs to coop with these risks are higher for a single consumer than for a service provider with more knowledge and experience with this. So that is why consumer allocate this risk with a service provider and pay them a service fee. In this transaction they contract the service provider and they can use the service of matching the time of production with the time of consumption. This service includes the supply of extra energy during low wind production or during failure of the turbine and it includes the trade of the surplus energy to the market. On this part of the energy flow the consumer trades its right to benefit to the service provider who can make a revenue with the surplus and cover their risks.

4.3.3. Service Provider and Aggregator

The service provider consists of two roles: the aggregator and the balance responsible party (BRP). The aggregator is the link between the suppliers of flexibility and the consumers of flexibility. The BRP manages the trade of energy on the market by selling the surplus and buying extra energy.

The aggregator literally aggregates the flexibility that is offered by other actors in the market. This flexibility portfolio can be traded to others who need flexibility to match their supply and demand. In the case of a direct PPA this aggregator can manage the surplus and the shortages of the wind energy from the consortium. The consortium buys in this case the right to use a flexibility option at a specific time with a specific volume.

The risks of aggregation are mainly determined by the time-dimension of the energy supply and demand. The aggregator has the risk of supply the flexibility to the consumer on the right time with the right volume, it has the risk of acquiring sufficient flexibility options and it has the risk of selling all the flexibility options. These risks are included in the flexibility price for selling and buying the flexibility options and are supported by the right to benefit that they buy from the prosumers and own on their flex portfolio. The risk to deliver the flex is included in the right to use which they sell to the consumers. The risk allocation is very effective, since the aggregator is the party in this construction that has the ability to act and reduce the costs of the mismatch. If the aggregator has clear rules and contracts with the other parties it can reduce it risks and costs. The incentive is in the right place to develop an efficient market.

Furthermore, if the aggregator wants to trade on the electricity market to buy extra energy or sell the production of its users, it needs to buy the market service from a BRP. In this transaction the aggregator buys the right to use the service from the BRP which has the right to transfer energy on the apx market. The BRP buys or sells energy from the apx market and gets the full property rights bundle including the usage, benefits and abusus. This energy can be sold to the aggregator by trading the full property rights bundle.

4.3.4. Flexibility Suppliers

First start with a definition of what flexibility is exactly. Flexibility can be defined as *’the ability and willingness of power consumers and producers to adapt their power demand and production’*(USEF, 2015). Flexibility is a product that determines the flow of electricity, the full ownership of the electricity is not transferred but only the right to use. A flexibility supplier can offer its flexibility to other users or to an aggregator. An example of a flexibility supplier is a prosumer, but it can also be a greenhouse company with a co-generation unit or a cold store operator. When a prosumer offers its flexibility it trades the right to use and right to benefit, but keeps the right of abusus on his own generation assets. The prosumer controls the flexibility options it has, such as solar panels, battery storage or smart devices. This flexibility they offer is restricted to a specific time period and with a certain volume. Next, the aggregator can aggregate all of the flex options from prosumers and create a flexibility portfolio.

The prosumer can offer its flexibility directly to a consumer without the facilitating role of the aggregator. However, this has an increased risk for both parties. When the provider of flexibility cannot deliver its option and do not keep their agreement, it may cause harm to the system if the consumer depends on this to keep the grid stable. The risk can be allocated to the aggregator who has a larger portfolio which serves as a buffer for these unplanned actions of users. The aggregator takes away the risk from the provider and from the consumer and guarantees a reliable service for flexibility. In return for this risk reduction for the supplier the right to benefit is traded to the aggregator.

The flexibility supplier obtains revenues in two ways: one is a compensation for the production costs of their DER and the other is a compensation for a part of their independence of using energy of their assets if the aggregator can control their devices. The production costs are covered by trading the right to use and the revenues from trading the right to benefit cover the costs for a decrease in freedom of energy usage.

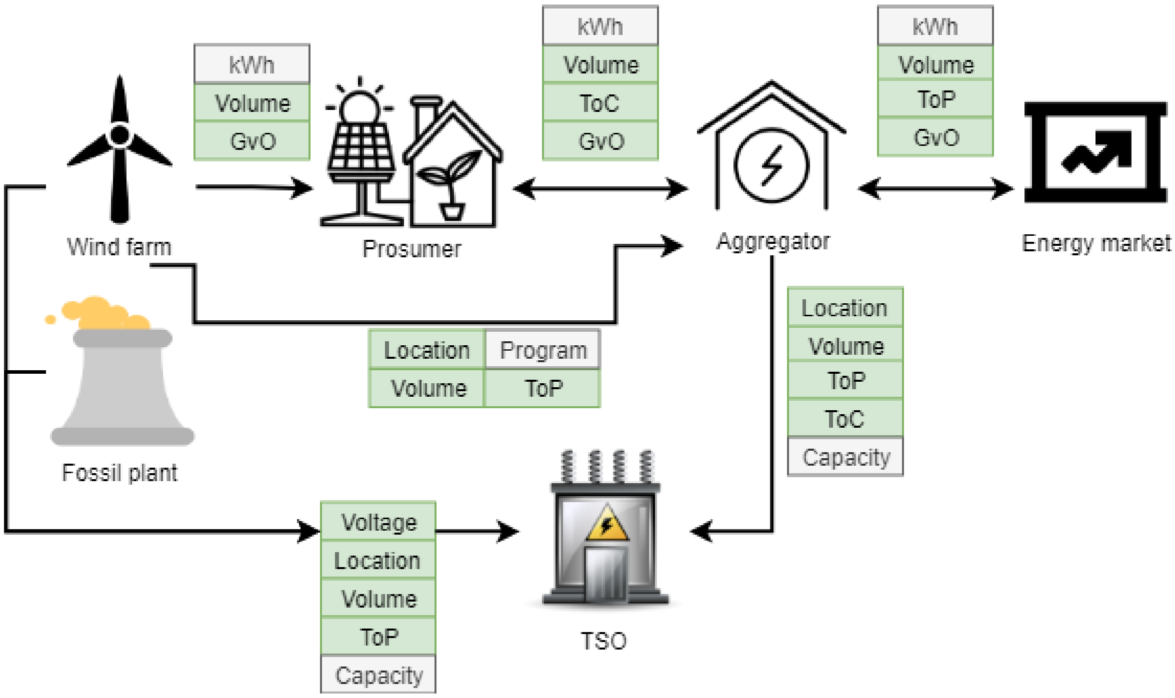


Figure 4.2: Property Rights allocation with properties of energy of a direct PPA construction

4.3.5. System Operators

The system operator is the monitor of the energy system. In this flexibility and direct trade construction it ensures that the property rights are not misused or that structures are abused. When someone offers flexibility they need to specify the volume and time of the extra production. Important is that the time of production is in balance with the time of consumption. This balance is monitored by the system operator, this can be a DSO or TSO depending on the size of the grid connection of the user. They can control the voltage on the transmission and distribution network and they coordinate the programs which includes the match between time of production and time of consumption. The TSO has transactions with the aggregator and with the wind farm to transfer the information about voltage, location of the feed-in and the time of production & time of consumption as shown in Table 4.2.

In this direct trade structure the right of abusus or right to transform an asset is allocated to the prosumers, the consumers, the DSO and the aggregator. The prosumer can transform its flexibility assets and the consumers can transform their electricity to other forms. The allocation of abusus property right is also illustrated in the figure above. One asset that is very likely to be abused is the distribution network. The prosumer can offer more flexibility than he can deliver or feeds in significant amounts of renewable energy in the grid that is not specified in a flexibility option. These things can deteriorate the grid and transform this asset. The DSO has the responsibility to monitor the grid and signal congestion or overuse of the grid. The DSO can act to solve this congestion and can analyse what the cause is and take measures to mitigate this. The aggregator also has a monitoring role to check if the users comply with the flexibility contracts. Users may only use this service within the specified time interval and with a certain volume. The violation of this can also be seen as misusing the rights of abusus.

The system operators have three cost components that cover their risks and operation costs, these are: grid investments, grid maintenance and congestion management. The main risk for the system operator is possible congestion or a malfunction in the transport network. The system operator reduces these risks by maintaining the grid, controlling the use of the grid by keeping the voltage on a safe level and investing in extra capacity if the flow through the network is running to its maximum. These costs are covered by the transfer rights that everyone must obtain in order to use the transport network. The congestion is reduced by buying usage rights on a flexibility portfolio from an aggregator or service provider.

Table 4.3: Identified risk in a direct PPA construction with their link to the property rights allocation

Actor	Risk	Contract	Cost component	Property Right
Wind Farm Owner	Negative prices	Minimum price or curtailment	Energy price [€/kWh]	Transform, Use
	Price that covers expenses	Minimum price	Energy price[€/kWh]	Transform, Use
	Commodity risk for market price & value of wind	Long-term contract	Inflation & NPV factor [%]	Benefit
	Volume risk	Contract as generated	Volume uncertainty factor [%]	Benefit
	Failure of turbine: blade failure/gearbox failure/fires	Operational hours	Volume uncertainty factor [%]	Benefit
	Curtailment	Contract as generated	Volume uncertainty factor [%]	Benefit
	Wind forecast uncertainty	Contract as generated	Volume uncertainty factor [%]	Benefit
	Interest rate on loans	Profit margin on price	Finance factor [%]	Benefit
	Change in tax legislation	Shared risk	-	-
	Environment legislation	Shared risk	-	-
	Failure of grid connection	Penalty clause	Grid tariff [€/kW]	Transfer
Consumer	Price risk	Maximum price	Energy price [€/kWh]	Transform, Use
	Uncertain wind prediction	Contract as generated	Volume uncertainty factor [%]	Benefit
	Failure of turbine	Contract as generated	Volume uncertainty factor [%]	Benefit
	Surplus of wind energy	Balance Service	Service price [€/kWh]	Use, Benefit
	Availability of wind energy	Balance Service	Service price [€/kWh]	Use
	Security of supply	Balance Service	Service price [€/kWh]	Use
DSO	Recover investments costs	Mandatory connection fee	Transport [tariff €/connection]	Transfer right
	Recover maintenance costs	Mandatory connection fee	Transport [tariff €/connection]	Transfer right
	Congestion	Flexibility contract	Flexibility price [€/kWh]	Usage right
Aggregator	Market risk sufficient supply of flex	-	Selling flex price [€/kWh]	Benefit right
	Market risk sufficient demand of flex	-	Buying flex price [€/kWh]	Benefit right
	Risk delivery flex	Direct Control / Penalty clause	Selling flex price [€/kWh]	Usage right
	Volume risk of wind production		Selling flex price [€/kWh]	Usage right
	Volume risk of consumers demand		Selling flex price [€/kWh]	Usage right
Flexibility supplier	Remunerate production costs DER	Minimum price	Selling price [€/kWh]	Usage right
	Reduced freedom of energy usage	Compensation fee	Selling price [€/kWh]	Benefit right

4.4. Incentives of Actors

The identified risks and property rights can be used to analyse the incentives of the actor and the allocation of these. The incentives are compared between the traditional energy contracts and the direct PPA contract. The economic incentives may be more efficient allocated resulting in a more efficient energy system and with potential economic benefits.

4.4.1. Incentives in direct PPA contract

Consumer:

1. Flexible demand
   ⇒ Lower price for PPA energy than service tariff of SP
2. Contract balancing partner
   ⇒ Uncertain volume/security of supply
3. Contract balancing responsible party
   ⇒ Need to sell surplus
4. Demand a predictable price or fixed price
   ⇒ Uncertain behaviour of market prices

Wind farm

1. Maximise operational hours
   ⇒ Production determines revenues
2. Close long-term contracts
   ⇒ Uncertain volume/security of supply
3. Minimise return on investment / demand minimum price
   ⇒ Uncertain value of wind in future
4. Maximise price of energy
   ⇒ Margin above the cost price is profit for the owner
5. Improve forecast of wind production
   ⇒ Uncertain wind production causes high imbalance costs and high financial risks

Aggregator/Service provider

1. Direct control of flexibility supply
   ⇒ Uncertain supply of flexibility
2. Analyse information of demand/production profiles
   ⇒ Uncertain volume and time of demand & supply
3. Variable price for flex depending on time of use
   ⇒ Coop with peak and off-peak demand & supply
4. Improve flexibility portfolio
   ⇒ Risk of sufficient demand & supply on every time of the day

Flexibility supplier

1. Produce more renewable energy
   ⇒ Increased benefit from flexibility compared to FIT tariff
2. Flexible demand (peak shaving/load shifting)
   ⇒ Save on energy bill by benefit of flex
3. Invest in controllable (smart)-devices
   ⇒ Benefit from offering flex

DSO

1. Minimise congestion
   ⇒ High impact of congestion on grid stability
2. Minimise grid reinforcements
   ⇒ Social cost-benefit analysis required for investments
3. Maintain grid
   ⇒ Penalties for disruptions of power flow
4. Support flexible use of grid
   ⇒ Capacity is not fully efficient used, only bottleneck in a few peak hours

4.4.2. Incentives in traditional energy contract

Consumer:

1. Inflexible demand
   ⇒ Flat tariff for time of use
2. Hold back from investing in DER
   ⇒ Validity of government support scheme is uncertain
   ⇒ Low benefits for feed-in, long ROI
3. Use energy when needed/no control of devices
   ⇒ Lack of knowledge of effects time of use of energy
   ⇒ No financial incentive, flat tariff during all hours of the day

Wind farm

1. Maximise operational hours
   ⇒ Production determines revenues
2. Close long-term contracts
   ⇒ Uncertain volume/security of supply
3. Minimise return on investment / demand minimum price
   ⇒ Uncertain value of wind in future
4. Maximise price of energy
   ⇒ Profit driven company
5. Improve forecast of wind production
   ⇒ Uncertain wind production causes high imbalance costs and high financial risks

Retailer

1. Efficient trading
   ⇒ Lower market price increases profit
2. Sell energy during peak hours
   ⇒ Peak hours generate more revenue
3. Increase size of portfolio (number of consumers)
   ⇒ Uncertain timing and volume of demand
   ⇒ Risk of mismatch forecast and realised demand and production
4. Sell large amount of energy (no incentive of energy savings)
   ⇒ More supply is more revenues

DSO

1. Minimise congestion
   ⇒ High impact of congestion on grid stability

2. Minimise grid reinforcements
   ⇒ Social cost-benefit analysis required for investments
3. Maintain grid
   ⇒ Penalties for disruptions of power flow
4. Support flexible use of grid
   ⇒ Capacity is not fully efficient used, only bottleneck in a few peak hours

4.4.3. Comparison Incentives

In the previous sections the incentives for the involved actors are identified and the underlying causes and risks are shown. It can be concluded from this analysis that the largest differences between these two contracts are related to the consumer and the energy supplier. The wind farm has the same incentives and goals since they also close a PPA in the traditional system, in that case with a retailer instead of directly with a large consumer. The same goes for the DSO whose incentives are supported by legislation and regulation. In both contract types the role of the DSO is to manage the grid and this incentive is not affected by the type of contract. The new contract type is however beneficial for the DSO since this contract gives incentives for the flexibility of consumer and the aggregator can offer services to the DSO to reduce the congestion.

The biggest differences between the incentives of the consumers are the awareness and flexibility of their demand. The consumers have a financial incentive to reduce their energy demand during the peak moments. The construction is more transparent for the consumer and the effect of the time of use of energy is more visible. They have a separate contract with a service provider or aggregator and pay them for their imbalances. These imbalances can be reduced by shifting their demand to the moments of high DER production, this gives a direct financial benefit and is a strong incentive to be flexible. These incentives lack in the traditional contracts in which the consumer pays a flat tariff for all the times of the day. Moreover, they pay only one tariff to the retailer and have no view on the imbalances they cause. The role of the retailer in the traditional contracts is very commercial and has an incentive to maximise the energy supply since this increases their revenues. Although, the trading of retailers is very efficient since they have an incentive to minimise the purchase of energy on the market and increase their profit with this. In the direct PPA contract the role of the retailer is split, only the balancing service of the retailer is relevant in this construction. That is why there are new parties in the market who focus only on this balancing service, these are called aggregators or service providers depending on the ability to trade on the market.

In the view of risks and property rights these differences can be explained by the increased risk that is allocated to the consumer. The consumer has several volume risks due to the volatile wind production. These risks force the consumer to coop with these effects and be more aware of them. The risks are integrated in a contract with a balance party and this creates the financial incentive of minimising the mismatch between wind production and demand. Another change in risk allocation is the balancing and flexibility risks of a retailer. These are now divided between the aggregators and the prosumers. In the traditional system these risks were integrated in the portfolio of the retailer, but now these risks are integrated in the flexibility market with aggregators, flexibility providers and consumers.

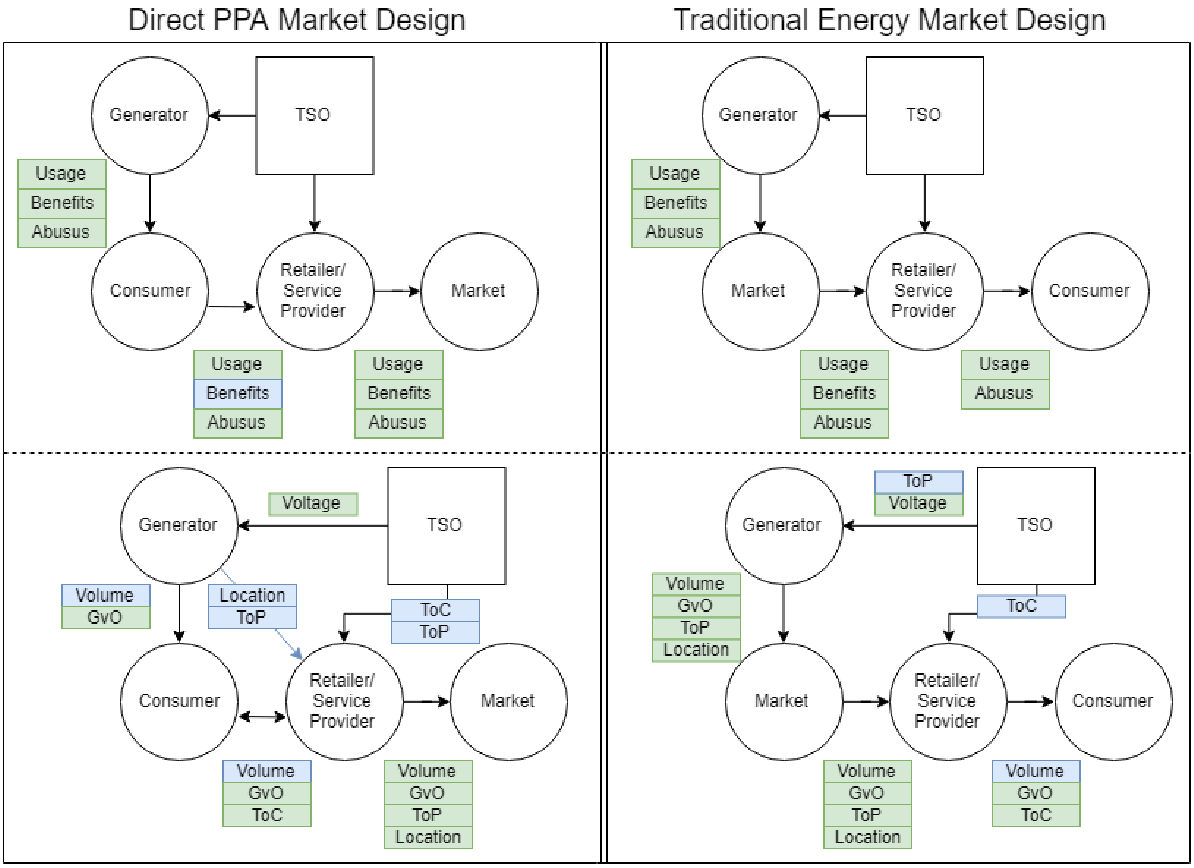
4.5. Conclusion

In this chapter the energy sector is analysed using the property rights theory. This analysis gives an insight in the energy sector and allocation of revenues, costs & benefits and risks. This allocation can be done by identifying the usus, fructus, abusus and transfer to get insight in the ownership of the energy. Another method is to analyse the allocation in more detail by specifying the properties of energy that are transferred. Both allocation methods are shown in Figure 4.3.

Ownership in a direct PPA The TSO/DSO has the ownership of the transport infrastructure and trade the right to use to the other market parties. These parties may use the grid as long as they do not damage or abuse the grid by causing large imbalances. The voltage and frequency must be stable at all time which means that the in-flow and out-flow of the grid should be equal. The ownership of the energy units itself is allocated based on the trade on the market and regulated by the market rules. Not all actors can transfer the property right, only those that have a license to be a balance responsible party. Those BRPs buy and sell energy on the market and deliver it to the consumers. The consumers cannot participate in the market on their own and so they cannot control what energy or from what origin they buy energy. In a direct PPA this is possible for the consumer since they have a private agreement with the generator and can choose to buy energy from a specific wind turbine. In conclusion, there are two large differences in this new PPA structure. First, the right to benefit is allocated to the consumer who now can obtain revenues from the energy by selling it to the SP. Second, the position of the consumer has changed and is now positioned in-between the producer and the retailer and has the right to use the service of the retailer/service provider. The physical flow of energy remains the same with the same allocation of property rights. Only the economic transactions differ between the consumer, the retailer/service provider and generator.

Energy properties in a direct PPA If we look at the properties of the energy that are transferred, the largest difference is the position of the consumer. On the left the consumer has a direct connection with the generator and on the right it is at the end of the chain with the market and retailer in-between. The consumer can decide what generator to contract and buy the power from him, but the volume is uncertain in the case of a wind farm. The consumer on the right is fully dependent on the retailer and cannot sell its power to the market. However the consumer has no volume risk since the retailer always provides the demand of the consumer. Another difference is seen in the way the programmes are submitted to the TSO with the Time of Use (ToU) and Time of Production (ToP). In the traditional contract the generator submits its program to the TSO, but in the direct PPA with a wind farm the service provider submits the ToP of the generator and the ToU of the consumer combined to the TSO. The consumer is responsible for this program in first instance, but they do not have the expertise for this and contract the service provider to do it for them. This has financial advantages since the service provider can optimise the bidding of the production in all the available markets and it has an incentive to do this because the profit on the balance costs is for them. The consumer can even take part in this profit if they agree on that in their contract.

Incentives & risks The incentives and risk allocation is also different. The retailer on the right has an incentive to maximise the energy delivery to their customers since they make more profit if their energy supply is increased. The volume risk of the uncertain demand and supply lies here at the retailer and the consumer pays for this in their tariff. Second, the retailer wants to increase their portfolio by increasing the number of customers in order to reduce the volume risk of the consumer. On the contrary, the service provider on the left does not have an incentive of a maximised supply since they only need to balance the demand and supply of the customer. Their service is not focused on the number of energy units, but on the balancing service. The consumer on the left has a volume risk of the wind supply and an incentive is created to adjust their demand on the availability of energy. They are more aware of this because the link between production and demand is more transparent. Moreover, this adjustment is financially attractive because the balancing costs are reduced. This incentive is not present in the traditional system since the energy price is fixed for every moment of consumption and the influence of their behaviour on the energy system is less visible. So the volume risk allocated to the consumer instead of the retailer has more benefits for the consumer, however they make costs for the balancing of their demand and supply. The more the consumer can reduce this imbalance, the more benefit remains for the consumer.



Direct PPA Market Design

Traditional Energy Market Design

Figure 4.3: Comparison of market designs of a traditional and direct PPA contract: on the first level the property right concepts and on the lower level the specification of energy properties transferred in the transaction

5

Modelling Design

In order to give a quantified result of the direct PPA contract a model is designed. This model calculates the costs for the energy contract and the service provider. First, the model conceptualisation is discussed in section 5.1, giving the model building blocks with the relations between them. Second, in section 5.2 the scenarios in the model are presented. Here the base case parameters and the key performance indicators are set. Moreover, the scenarios with battery energy storage and solar production are described. In section 5.3 the specific calculations in each model step are elaborated on. This shows the mathematical relations between the input data and the parameters in each scenario. Furthermore, in this section the data sources and the model configuration regarding the modelling period are listed and discussed.

5.1. Conceptualisation

In this section the relation between the input data, the parameters and the output data is shown. In Figure 5.1 the model strategy is visualised. In this figure five processes are shown: calculating wind production, surplus, buffering, trading costs and the total energy costs. The inputs are shown with parallelograms and the specific values of the parameters are listed in Appendix A.1

5.1.1. Wind Production

The wind production in this model is based on the wind project Ferrum situated in IJmuiden. This wind park will be constructed in 2019 and finalised in the beginning of 2020. The wind park consists of three 3 MW wind turbines that are owned by a large investor. The turbines are placed on the property of Tata steel very close to the coastline. The wind production of these turbines is mainly determined by the available wind and the average wind speed at that specific location. The average wind speeds are mapped by the RVO Nederland based on the data of Koninklijk Nederlands Meteorologisch Instituut (KNMI). This wind speed is dependent on the height of the turbines and the exact location. The turbines of Ferrum have a height of 85 meter which results in an average wind speed of 8.5 m/s.

The assumption made in the model to calculate the wind production is not exactly based on this average wind speed. The produced wind energy is calculated by using the total capacity of the wind farm and a capacity factor. This capacity factor is a measure for the power output of a wind turbine. It is based on the hourly wind speed data and on the power curves of a large database of wind turbines specified by type and location. The capacity factor is indirectly influenced by the wind speeds and downtime of the turbine, but all these variables are averaged out over the whole database of wind turbines. The capacity factor is not an exact proxy for the production of a specific wind turbine, but it is a good measure for a general turbine.

This average wind speed is also important for the subsidy from the government. This subsidy, named Stimulering Duurzame Energieproductie (SDE+), is a policy tool to stimulate the development of renew-

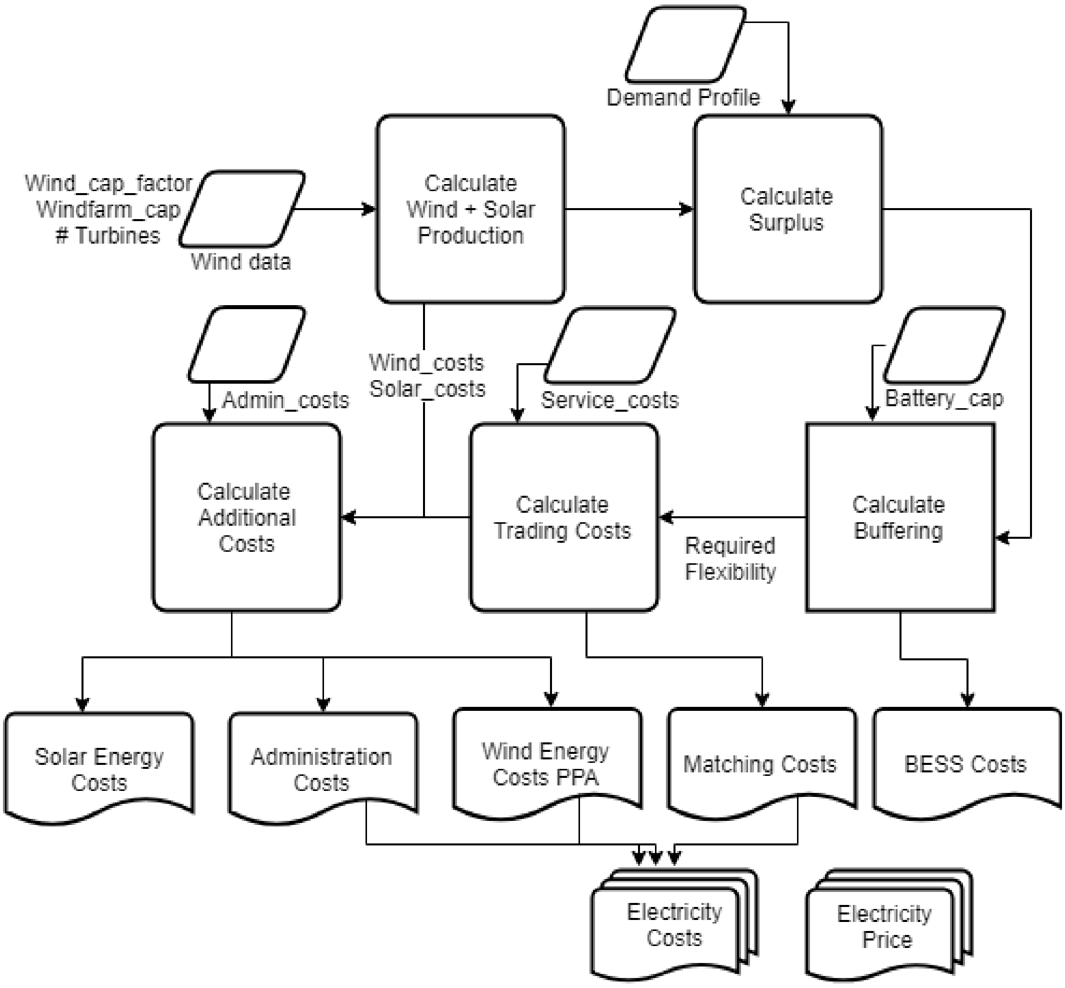


Figure 5.1: Model strategy of matching supply and demand & calculating total energy costs

able energy. In short, this subsidy is a compensation for the higher investment costs of renewables. The subsidy is calculated as the difference between the total investment costs and the market price. This subsidy is a guarantee for the owner of the renewable energy asset, in this case an onshore wind turbine, to ensure a stable return on investment. The SDE+has set for every Renewable Energy Sources (RES) a minimum tariff and a break-even tariff. This break-even tariff is calculated for every RES and ensures that the costs of the technology are returned in a reasonable time period, often 15 or 20 years. The amount of the subsidy to be received by the owner is calculated every year by comparing the actual average price received for the produced energy and the break-even tariff. The difference is compensated by the government with a minimum subsidy price determined by the minimum tariff. So this SDE+ ensures that the wind owner gets a constant price for the produced wind energy.

In the direct PPA agreement this SDE+ price is set as limit for the energy price paid by the consumers. The maximum price of the produced energy is set at the break-even tariff and the minimum price is set at the minimum tariff. The price of the PPA fluctuates between these limits depending on the apx market price. This market price is used in the SDE+ subsidy to determine the amount of subsidy paid. In the PPA contract this market price is also used to reduce the risks of the wind park owner. As the technology evolves the costs will reduce and the subsidy will be lowered, this is already the case for off-shore wind farms as stated in the introduction. A PPA with wind farm without subsidy has another structure in which a fixed price can be set instead of a price that fluctuates between the boundaries. This fixed price is high enough for the wind farm owner to return on its investments, but should also be markt competitive for the consumer.

5.1.2. Surplus

The surplus is the most important aspect in this direct PPA. The surplus is the result of a mismatch between the production of the wind farm and the demand of the consumer. Normally this mismatch is not an issue for the consumer since the electricity price is the same for every hour of the day, or it is separated in a peak and off-peak price. In this direct PPA this time of consumption is directly influencing the energy costs since this determines if cheap energy can be used from the wind turbine or more expensive energy from the energy market through the service provider.

This surplus is a simple calculation of the produced energy and the consumption in every hour. The demand profile that is used in the model is from Royal HaskoningDHV. This is a engineering and project management consultancy bureau of which 6 offices are included in the demand profile. This profile includes five connections with a capacity of 3x80A and a total demand of 3.5 MWh. The reason for a business profile over a small consumer profile is the larger demand of businesses that can take off a larger part of the wind farms capacity. The wind farm owner can contract a smaller number of businesses which is easier and has less administrative costs. The demand of consumers can also be aggregated and then contracted via a direct PPA, but this is another construction and falls outside the scope of this research. The focus in this model is the demand profile of businesses and in this case the demand profile of RHDHV.

5.1.3. Buffering

Buffering is the term for storing energy and using it on another time of the day. This buffering can be done using multiple technologies, but for electricity the most common is Battery Energy Storage System (BESS). This BESS technology is also used in this model to model the effects of buffering. BESS have the advantages that they can charge and discharge relatively fast with a high efficiency and the self-discharge is very low. The disadvantage is that the energy density is not very high compared to other storage systems such as compressed air, hydropower or hydrogen. The ratio volume/power is high and that is the reason why these units are often used as a short period storage of one or two days depending on the capacity.

Buffering can be used to store surplus energy and use this in moments of shortage when the demand is higher than the production. Another use of buffering is to speculate on the market by selling power on the market during high prices or by offering the storage to the aFRR and obtain revenue from the TSO when the stored energy is used to balance the system. The goal for which buffering is used in this model is as the first function, to use the energy only for self-consumption without dispatching it. This kind of buffering has an effect on the surplus curve and can affect the service costs if less surplus or shortage is to be managed by them. The effect of this buffering is modelled in the first experiment. The battery capacity is an input variable for this calculation step and this capacity is varied in this experiment. The effect of different storage capacities on the service costs is modelled.

5.1.4. Trading Costs

The surplus or shortage that is caused by the mismatch need to be managed by a service provider. The surplus is sold on the apx market against the corresponding apx price on that hour. If there is a shortage, extra energy is supplied by the service provider against a service cost. When the service provider manages the surplus and shortages, the revenues from selling the surplus and the costs for buying extra energy from the market are for the service provider. In regular balancing contracts the consumer pays a fee on the total amount of surplus and shortage to compensate for the costs of the service provider. The value of this fee is very uncertain and is determined by the market parties. In order to model the service costs the costs and benefits of trading on the energy markets are summed and the net costs are settled with the consumer. This assumption means that the consumer can also have negative service costs, although this is not very likely to occur. The energy directly consumed is not charged and so the consumer has an incentive to match its demand with the production. The price of the PPA is composed of the corresponding apx price at an hour and a profit margin for the wind owner. The margins for the service provider and the wind farm owner are included in the parameters list in appendix A.1.

An important notion here is that the energy can be traded on multiple markets in the Netherlands depending on the time ahead. The wind production is forecast by the service provider and this forecast energy is traded on the apx. However, the wind on the day itself can differ from the forecast resulting in a forecast error in the predictions. The mismatch between the prediction and actual production is traded on the imbalance market. The assumption in this model is that 80% of the wind power can be predicted and traded on the apx and the other 20% is traded on the imbalance market. This is supported by Milligan et al. (2009) who did research in the wind forecast errors. A single wind turbine has a larger error than a few wind parks or the full wind capacity of a country. A single wind turbine has a mean absolute error (MAE) of 5-7% for a two hour ahead forecast with an increased forecast error up to 20% for day-ahead forecasts. For larger parks this error is reduced. In Germany a large, single wind project has a forecast error of 10-15%, but this drops to only 5-7% for day-ahead forecast for the wind capacity of the whole country. So based on this, it is safe to assume that the single wind park with three turbines in this model has a forecast error of maximum 20%.

5.1.5. Total Energy Costs

The last step is the calculation of the total energy costs. The total energy costs consist in the current situation of one all-in price that includes the energy costs, the risks for imbalance, administration costs and transport costs. This new direct PPA contract includes only the price for the energy. The trading costs are separately modelled as described in the previous paragraph. The other cost components are included by using a constant parameter which is multiplied with the sum of the PPA costs and the trading costs. The administration component consists of the responsibilities of the retailers or service providers to estimate the production and demand and submit this in a program to the TSO and a part of this component is to cover the costs for measuring the energy use and billing. The transport costs are not included since these costs are constant and not dependent on the source of the energy. In the traditional contract and in the direct PPA the demand of the consumer is assumed to be constant, so the transport costs would not influence the result. In this last step also the costs for using the BESS and producing solar energy is included. The costs of BESS and solar production can be relatively high and should be included to see if the investment costs out-weight the possible savings on the service provider costs.

5.2. Scenarios

5.2.1. Base Case

In the base case the direct PPA contract is considered and the matching is fully managed by a service provider. The expectation is that roughly half of the wind production is directly consumed by the consumer and the other half need to be managed by the service provider. The cost structure for the service provider consists of a low price for the directly consumed power and a higher price for mismatch. These two prices determine the costs for the consumer. The costs for the PPA are determined by the market price and the margin of the wind farm owner. The assumption is that the consumer does not influence its demand, so the demand profile is not changed compared to the old situation with a traditional contract. The base case can be used to compare the energy costs of a direct PPA with a service provider with the energy costs of the traditional contract.

The key performance indicators for this case are listed in Table 5.1. The costs & benefits of the consumer, the service provider and the wind farm are the main KPIs. These indicators can be compared with the traditional contract and a direct PPA contract. The allocation of the costs is compared to the theoretical allocation based on the property rights theory. The hypothesis is that if an actor integrates more risks that the allocated costs are lowered. Next, the graphs of the surplus and the costs are used as KPIs to analyse the effect of the different contracts on these the matching and the total energy costs. In these graphs the behaviour of the production and demand can be seen and the effect on the matching costs.

Table 5.1: KPIs for base case

KPI	
Costs & benefit SP	Surplus curve & value
Costs & benefit consumer	Costs SP curve & value
Costs & benefit wind farm	Net total costs curve & value
Allocation of costs	

Table 5.2: Configuration of model runs for buffering scenario and solar production scenario

Scenario 2: Buffering	**Scenario 3: Solar Production**	
Battery capacity	**Solar Capacity**	**Wind Capacity**
0 MW	0 MW	1.8 MW
2 MW	0.6 MW	1.6 MW
4 MW	1.2 MW	1.4 MW
6 MW	1.8 MW	1.2 MW
8 MW	2.4 MW	1.0 MW

5.2.2. Buffering

In the buffering scenario a battery capacity is added to the model. This battery is, as described in the conceptualisation, used to temporarily store the surplus wind energy and use this during time of insufficient wind production. The hypothesis is that the peaks and valleys in the surplus curve are dampened, the peaks may be less high and the valleys less low. In this scenario again the allocation of the costs is analysed to see the effects on the economic incentives. The runs in this scenario are done with different battery capacities. The starting point is the base case scenario no storage and the capacity is increased with 2 MW in every step. These runs are shown in Table 5.2. In the model the surplus energy is added to the battery and the shortage is taken from the battery if there is sufficient capacity in the battery. If there is still surplus or shortage left than this is traded by the service provider.

The cost of the storage are an important parameter here, because the costs of the battery need to outweigh the savings on the service costs. Although the situation for batteries is not yet very favourable as can be seen by the limited private battery storage of consumers and small businesses. The battery Capital Expenditure (CAPEX) for now are estimated by TenneT in their storage tool (Verkaik, 2018) on around 500 euro/kW and 430 euro/kWh for the power output and battery capacity of a Li-Ion battery. The CAPEX for a battery with a size of 4 MWh and 1 MW would be about 2 million euros. The Operational Expenditure (OPEX) are estimated on 7 euro/kW and are almost negligible compared to the CAPEX (TenneT, 2017). This battery can be used for 3500 full cycles (see section A.1). The costs per year for the battery are calculated in the model using the number of cycles multiplied by the cost per cycle. Since this price for the battery is still very high, the costs are not integrated in the model to calculate the total costs for the BESS scenario. Instead, the influence on the surplus is analysed and the savings on the service costs are calculated. This effect is more interesting to look at on this moment until the prices of battery storage are further dropping. Nevertheless, the costs for the battery are still presented in the results separately.

5.2.3. Solar Energy

The third scenario adds solar energy production to the model. The sun and the wind can complement each other in the production volume and availability. If these two sources can complement each other the required storage or balancing service could be reduced. The literature shows the complementary behaviour if it is viewed in month or year perspective. The seasonal behaviour is significantly reduced as can be seen in Figure 5.2, in the summer the solar energy production is high and in the winter the wind energy production is high. The effect of the combination of solar and wind on a shorter period is researched in this experiment. Several combinations are made with different wind and solar capacities as can be seen in Table 5.2. The capacity of the wind in the base case is 1.8 MW and in the scenarios a different combination is made of wind and solar capacity while keeping the production level constant. The capacities for wind are based on the assumption that 20% of the capacity of a wind park is con-

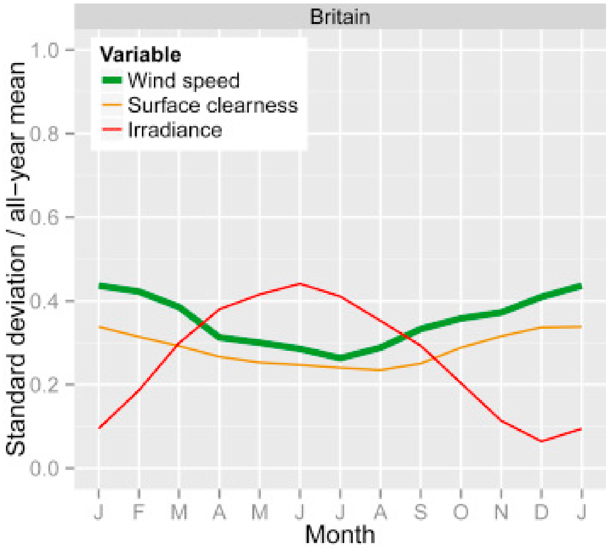


Figure 5.2: The annual cycle of monthly variability of wind and solar compared to the all-year mean value of these variables. Retrieved from (Bett and Thornton, 2016)

tracted for the demand profile of RHDHV. The total size of this wind park is 9 MW. For every experiment the KPIs are analysed to see what the effects are of the solar/wind combination.

The solar production is calculated in the same way as the wind production. The capacity factors of solar energy in the Netherlands are used from a database, this is multiplied with the capacity to calculate the production in kWh. This production is summed with the wind and plotted in a graph.

The costs for the solar capacity are calculated the same as with the wind. It is assumed that if the consumer wants to add solar capacity to their portfolio, it can contract this with a PPA in the same way as with wind. The investment itself in the solar capacity is done by an investor which gets their return on this by a direct PPA. The focus is on large solar parks of more than 1 MW which deliver its power to the grid without local self-consumption. This is an important distinction for the costs and the SDE+ subsidy category. PBL did a study to the costs of such a solar park and estimate the Capital Expenditure (CAPEX) on 740 euro/kWp and the Operational Expenditure (OPEX) on 13 euro/kWp/year (Lensink, 2018). This is based on a solar park with a capacity of 10 MWp and on average 950 full load hours. The researchers of PBL also determined a correction factor for the profile- and imbalance costs of the solar energy. This factor compensates for imbalance costs resulting from the availability of the sun and forecast errors and the profile effect of the solar energy on the market prices. This factor is used in the calculation of the PPA price.

5.3. Operationalisation

5.3.1. Data sources

The used data is summarised in the table below. In order to use the data for the model, data cleaning and analysis is done using the tool Python. This tool is also used to do the calculations of the wind factors and wind production. The wind production for the consumer is calculated using the wind capacity factors 5.1. The wind capacity factor is a factor that is based on the meteorological wind speed and the technical characteristics of a wind turbine such as heights and power curve. This factor is thoroughly validated by EMHIRES and proven to be an accurate approximation of the wind power production of turbines in European countries Gonzalez Aparicio et al. (2016). The data set specific for the Netherlands is used in this study. The prices used for this model come from the ENTSO-E Transparency Platform and the Open Power System Data platform. All the prices starting from 2015 are on hourly basis available there. Next, the demand profile RHDHV is used, this is the hourly energy demand on hourly basis of the year 2017. The difficulty is to find the electricity prices from before 2015. In this year the apx market was fully set up and the prices were published online. Formerly the electricity market was not fully unbundled and the consumers could not choose their energy provider. Therefore the prices for electricity were less transparent, the prices were determined by each energy provider. The consumers could not compare the provider, however this was not needed because they could not change their provider.

Table 5.3: Data sources for the model

Data	Type	Source	Reference
Wind capacity factor	.txt	EMHIRES	(Gonzalez Aparicio et al., 2016)
Solar capacity factor	.txt	EMHIRES	(Gonzalez Aparicio et al., 2017)
APX prices	.csv	ENTSOE Transparency Platform Open Power System Data	(ENTSO-E, 2019) (Open Power System Data, 2018)
Demand profile	.xls	RHDHV	

5.3.2. Model configuration

The model is designed using the software package Microsoft Excel. The data used in the model is of the year 2017. Within this year a selection is made of four weeks that represent the variability of the data through the year. The modelling period is one year and the four weeks are used as examples to show the periodic behaviour of the variables. The four selected weeks are selected on the amount of wind production and the height of the energy demand. One week is selected with almost no wind, one week with a lot of wind, one week with a high demand and one week with a low demand. The reason for the choice of the year 2017 is that there is enough data available for this year and the data is representative for the energy market especially for the imbalance market. This market was introduced in 2015 and in this first year the market was not very stable since the market players had to find out their strategies. In order to have a stable imbalance market the year 2017 is chosen so this teething problem do not affect the market dynamic. Moreover, 2017 is a more recent year and it includes more renewable in the market than for example 2015. The year 2018 is not selected because the energy prices did rise very high and spontaneous, in contrast to the predictions. This year will not give a representative view on the energy prices and retail prices. The choice for only year is enough to show the behaviour of KPIs, however this model period is too short to be statistical valid. The results are used to compare the different contract types and experiments, but the exact numbers can not be generalised to other years or demand profiles. It does show the structure of a direct PPA compared to a traditional contract which is the applicable to other years and other companies.

5.3.3. Match Supply & Demand

Now we zoom in further on the processes and describe the formulas used for the calculations in the model. First, the demand is used as input for the calculation of the surplus. The production is calculated using 5.1, this gives a production in kWh in time intervals of one hour. The surplus can be calculated using 5.2 by subtracting the production and demand.

$$P_{wind} = Cf_{wind} * C_{windpark} * 1000, \tag{5.1}$$

$$\begin{aligned} P_{wind} &= \text{Production in kWh,} \\ Cf_{wind} &= \text{Wind capacity factor,} \\ Cf_{windpark} &= \text{Capacity wind farm} \end{aligned}$$

$$S = P - D, \tag{5.2}$$

$$\begin{aligned} S &= \text{Surplus in kWh,} \\ P &= \text{Production in kWh} \\ D &= \text{Demand in kWh,} \end{aligned}$$

This surplus is traded by the service provider on the apx market and the imbalance market according to the trade ratio specified in the input parameters. In the base case 80% of the energy is traded on the apx market and the rest is traded on the imbalance market. The costs are determined by the market price on the moment it is traded. If there is surplus the service provider gets revenues and the costs are negative, during moments of shortage it has costs for buying extra energy. The imbalance market has variable prices that can be both negative and positive depending on the balance in the system. The trading costs are multiplied by a risk factor to compensate for the price risks and the margin of the service provider.

$$E_{trade} = E_{trade-apx} + E_{trade-imb} \tag{5.3}$$

$$E_{trade-apx} = E_{trade} * T_{apx}$$

$$E_{trade-imb} = E_{trade-imb} * T_{imb}$$

$$T_{ratio} = T_{apx} + T_{imb} = 1$$

$$C_{service} = (C_{apx} + C_{imb}) * R \tag{5.4}$$

$$C_{apx} = E_{trade-apx} * P_{apx}$$

$$C_{imb} = E_{trade-imb} * P_{imb}$$

The price for the PPA is determined by the apx price on the moment of production with an interval of one hour, a correction factor and a margin for the wind farm. All the produced energy in this hour is bought from the wind farm against the apx price of that hour plus a margin and the correction. This correction factor the same as explained for the solar production price. The factor compensates for the profile effect of the wind energy on the market prices and for the imbalance costs the wind owner makes due to the variability of the wind. This correction factor is determined by the SDE+ subsidy (Lensink, 2018). The price has an upper limit and a lower limit to decrease the price risks for both parties. The lower limit is on the minimum level of the SDE+ subsidy and the upper limit is on the maximum level of the SDE+ subsidy. The lower level guarantees a minimum income for the wind farm and the upper limit maximises the price for the consumer.

$$C_{PPA} = P_{PPA} * S\left[P_{min} \geq P_{apx} \leq P_{max}\right] \tag{5.5}$$

The total costs are then then the sum of the costs for the PPA and the balancing costs for the service provider.

$$C_{total} = C_{PPA} + C_{service} \tag{5.6}$$

5.3.4. Buffering Wind Energy

The buffering of wind is added to the matching model. The mathematical expressions will be given below.

Equations for buffering:
The buffering process consists of three elements: charging, discharging and energy losses during these two processes. The energy charge is equal to the surplus minus the losses during charge. First the delta charge is calculated, then the losses are subtracted. The battery energy level is calculated by the sum of the battery level of the previous time step and the delta charge and the energy losses. Important are the boundary conditions of the battery. The energy charge has a minimum of zero and a maximum of the capacity minus the battery level. This prevents a higher charge than the battery capacity. The discharge has a maximum of the battery level at that time step and a minimum of zero. Lastly the costs for the battery are calculated by adding up the costs for the energy capacity and the power specification (charge/discharge speed).

$$\Delta E = E_{charge} - E_{discharge} \tag{5.7}$$

$$E_{charge} = S, \qquad \text{for } [0 \geq S \leq Cf_b - E_b]$$

$$E_{discharge} = S - E_{loss}, \qquad \text{for } [-E_b \geq S \leq 0]$$

$$E_{loss} = (1 - \eta_{charge}) * \Delta E \tag{5.8}$$

$$E_b = E_{b_{t-1}} + \Delta E - E_{loss}, \qquad \text{for } [0 \geq E_b \leq Cf_b]$$

$$C_{buffer} = C_{battery} * P \tag{5.9}$$

Equations for service provider
The costs for the service provider are similar to cost calculations in the base case, except the added flow of charge and discharge. The energy trade is equal to the surplus if the battery is empty, otherwise the surplus or shortage can be reduced by charging or discharging the battery. The energy trade is split up in an apx trade and imbalance trade. The costs for the service are the costs for trading on the energy markets including a risk factor for the price risks of the service provider.

$$E_{trade} = \begin{cases} S & \text{for } [E_b = 0] \\ S - (\Delta E + E_{loss}) & \text{for } [S \geq 0] \\ S - \Delta E & \text{for } [S \leq 0] \end{cases} \tag{5.10}$$

$$E_{trade} = E_{trade-apx} + E_{trade-imb} \tag{5.11}$$

$$C_{service} = (C_{apx} + C_{imb}) * R \tag{5.12}$$

Total Costs The total costs are equal to the energy costs of the PPA, the service costs and the costs for the battery.

$$C = C_{PPA} + C_{service} + C_{buffer} \tag{5.13}$$

5.3.5. Solar Energy Production

Solar production
The solar production is calculated in the same way as the wind production. The solar capacity factor from the EMSHIRE dataset and is multiplied with the installed capacity and multiplied by 1000 to get a kWh value.

$$P_{solar} = Cf_{solar} * C_{solarpark} * 1000, \tag{5.14}$$

P_{solar} = Production in kWh,
Cf_{solar} = solar capacity factor,
$Cf_{solarpark}$ = Capacity solar farm

Total production
The total production is the sum of the wind production and the solar production. This production is subtracted by the demand to get the surplus. The energy is traded by the service provider using Equation 5.3 and Equation 5.4.

$$P = P_{wind} + P_{solar} \tag{5.15}$$

$$S = P - D, \tag{5.16}$$

S = Surplus in kWh,
P = Production in kWh
D = Demand in kWh,

6

Results

In this chapter the results of the financial model are presented. This chapter gives an answer to the financial benefit of a direct PPA compared to a traditional contract and it will show the effect of a storage unit and solar capacity on the match between supply & demand. First, the energy costs of the direct trade are presented in the base case run, this is the reference scenario to the two experiments. Second, the results of the experiment with a BESS are presented in section 6.2. This is followed by the results on experiment 2 with solar capacity (section 6.3). The model validation and verification are described in section 6.4. Finally, the three model runs come together in the conclusion in the last section. Here the last two research questions are answered and the results are compared to the costs of a traditional energy contract. The questions were: *"What is the financial benefit of a direct trade PPA compared to a traditional contract?"* & *"What is the effect of energy storage and solar production on the financial benefit of direct PPA?"*.

6.1. Financial Benefit of A Direct PPA

6.1.1. Energy Costs In A Direct PPA

In Figure 6.1(a) the production level of the wind farm is shown together with the demand profile of RHDHV. The results of this model are shown for four separate weeks of the year, as is described in subsection 5.3.2. This figure shows the profile of week 2 in January 2017. This model period shows a week in the year with very high wind production. It can be seen that the two profiles do not match, the production peaks are high when the demand is very low. Especially between the time 42 to 48 and 138 to 150 this behaviour can be seen. This mismatch needs to be managed by the service provider. The effect of the mismatch between production and demand can be seen in Figure 6.1(b). This figure shows the net surplus which is the difference between production and demand. The peaks of the surplus are almost the opposite of the demand curve, when this demand is almost zero the wind production is very high.

The energy costs of this mismatch can be calculated by multiplying this with the apx prices (Figure 6.1(c) and this results in the total costs which are shown in Figure 6.1(d). The peaks in the surplus curve correlate with the valleys in the costs curve. When there is a high surplus the costs of the service provider are negative because they get revenue for selling the surplus. Not every peak in the costs curve is due to surplus. In some case for example at t=29 the surplus is close to zero but there is still a small peak in the costs curve. This is because of the costs of the PPA, these costs and the costs for the service provider are also included in the total costs graph. The costs for the service provider are almost zero when the surplus is zero, but the power from the PPA still determines the costs for a large part.

In Table 6.1 the total cost allocation is presented. This cost allocation is a specification of the total costs that are visualised in figure 6.1(d). The total production is bought by the consumer against the

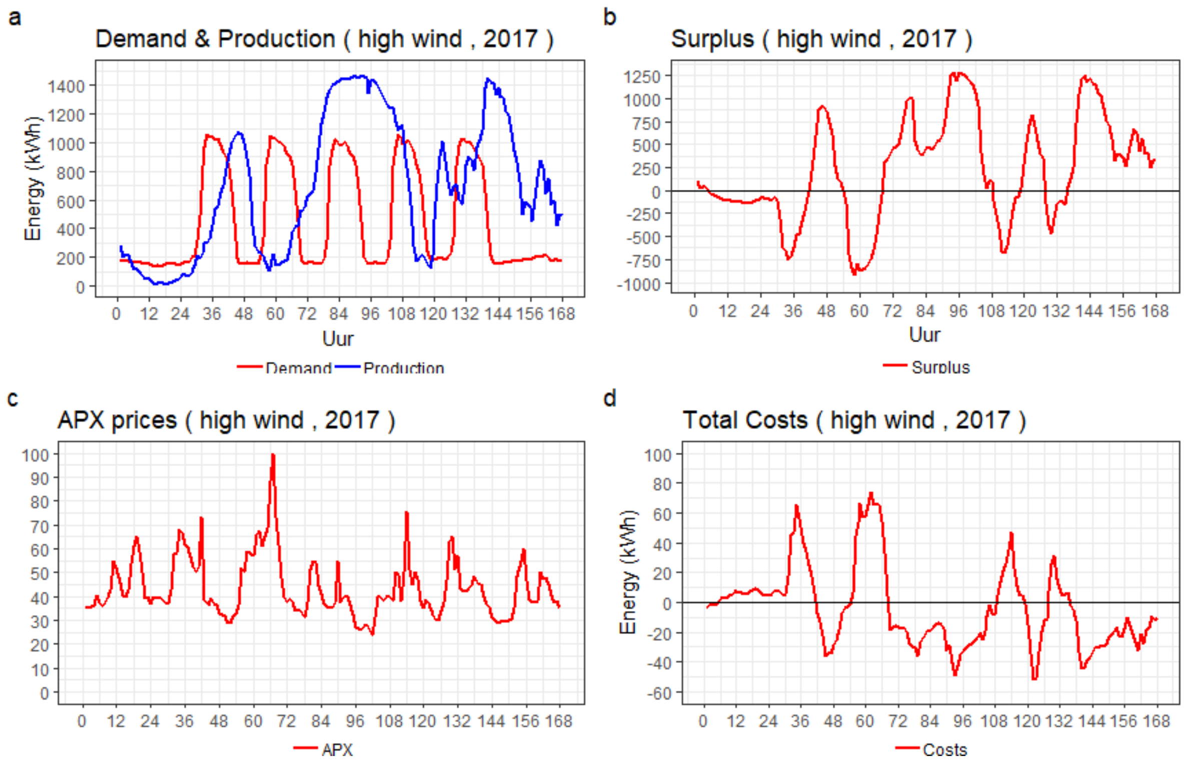


Figure 6.1: Behaviour of the KPIs in the base case: showing the output of a week with high demand in 2017

PPA price and the mismatch is managed by the service provider. These costs of the service provider consist of the costs it makes to trade the mismatch at the apx market and the imbalance market. The assumption is that the service provider can predict the wind production and the match with the demand profile one day ahead for 80 percent of the volume. The rest of the volume is to be traded on the imbalance market. The disadvantage of the imbalance market is that the costs are highly uncertain with prices that can be negative or positive depending on the direction of the balance. So ideally the amount of energy traded on the imbalance market is minimised. In order to cover for this uncertainty the service provider includes a risk factor in the tariff for balancing. This risk factor is assumed to be 30 percent in this model, but this risk factor is uncertain and its influence will be tested in a sensitivity analysis. The revenues from this risk factor are seen as benefits for the service provider, although part

Table 6.1: Cost allocation of a direct PPA contract with a fixed parameter value for the risks factor and trading ratio respectively 30% and 80% apx market / 20% imbalance market

Year: 2017	High wind	High demand	Low wind	Low demand	Average week	Total
Cost Consumer	€ 4,099	€ 4,480	€ 3,272	€ 4,168	€ 3,454	€ 179,635
Costs PPA	€ 4,690	€ 2,111	€ 1,047	€ 2,791	€ 2,826	€ 146,976
Costs Service	€ -591	€ 2,369	€ 2,225	€ 1,377	€ 628	€ 32,658
Cost Service Provider	€ -455	€ 1,822	€ 1,711	€ 1,059	€ 483	€ 25,122
Costs APX	€ -701	€ 1,018	€ 1,107	€ 764	€ 166	€ 8,630
Costs Imbalance	€ 246	€ 804	€ 604	€ 295	€ 317	€ 16,491
Benefit Service Provider	€ -136	€ 547	€ 513	€ 318	€ 145	€ 7,537
Risk factor	€ -136	€ 547	€ 513	€ 318	€ 145	€ 7,537
Benefit Wind farm	€ 4,690	€ 2,111	€ 1,047	€ 2,791	€ 2,826	€ 146,976
Trade	81,845	80,684	56,218	74,825	68,448	3,559,311
Production	114,740	59,227	33,354	73,076	316,623	3,799,481

of this is used to cover the extra costs during periods with high prices.

In Table 6.1 four model periods are shown and the allocation of the costs between the actors. The periods differ in the amount of wind production and the size of the demand. The conditions are respectively high wind, high demand, low wind, low demand. In the last column the year total is presented. The largest share of the costs is for the consumer, this is around 179k and consists of the costs for the PPA contract and the costs for the service provider. The service costs differ in the model periods, the high wind scenario has a high production and thus high PPA costs, at the same time the service costs are even negative caused by the high surplus that is sold on the market. In the low wind scenario the opposite effect can be seen with high service costs and low PPA costs. The high and low demand scenarios result in respectively high and low service costs due to the surplus and shortages that are higher with high demand and lower with low demand.

It is remarkable to see that a low wind scenario has lower costs than a high wind week. This week is however not a representative week for the whole year as can be seen by the average values for a week. The service costs are significantly higher than the 600 Euro on average. It could be that the market prices in this week were more beneficial than the price for the energy from the PPA. This does not implicate that less wind production is more beneficial over a whole year.

The service costs in this table are split up in the apx market costs and the imbalance market costs. It can be seen that trading on the imbalance market results in far higher costs than the apx market costs. That is the reason why trading on this imbalance market should be minimised. The benefit of the service provider shows the same effect as the service costs in the different periods, since these costs are a factor of the service costs. Lastly, the benefits for the wind farm are the same as the costs of the consumer for the PPA.

In section A.3 the graphs with the results of the other three model periods are shown. These will show the results of week 25, 32 and 51 respectively a week with a high demand, a week with low wind and a week with a low demand in the year 2017.

6.1.2. Comparison Direct PPA and a Traditional Contract with Variable Pricing

In Figure 6.2 a comparison is made of the price composition of a direct PPA and a traditional contract. The main difference is the service component. In the traditional contract this component consists of the profit margin of the retailer upon the energy costs. These energy costs are the same for both contract types, however the service component in the PPA is lower with 18%. This difference of two percent explains the 4k euro saving with the direct PPA. This price difference is not very large, but still is shows that the new energy contract design is competitive with the traditional contracts and in this case even beneficial. These results are based on one case and may differ due to small changes in the risk factor, the profit margin or the negotiations of the PPA price with the wind farm. The sensitivity analysis at the end of this chapter will support this. For example, the saving on the PPA can be increased or decreased with 3k as the risk factor is changed with 5%. However, in this case the PPA still remain competitive.

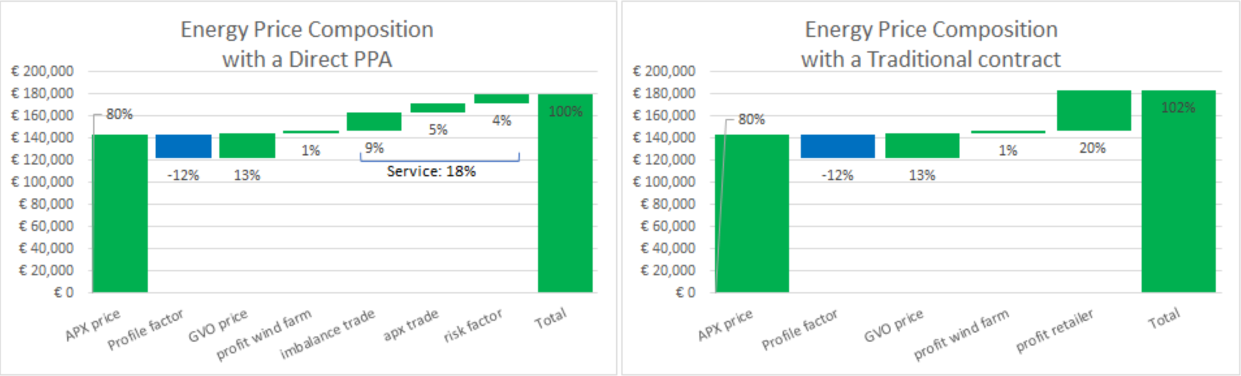


Figure 6.2: Price composition of a direct PPA and a traditional contract with variable pricing: the difference is made in the service costs

On a first sight these contracts differ not that much from each other. The energy is both produced by a wind farm and supplied to the corporate. However, in the PPA this link is direct and the consumer buys the energy from the wind farm, while in the other contract the energy is supplied by the retailer. This retailer has in turn a contract with a wind farm, but this does not mean that every time of the day the corporate is supplied by green energy. As seen earlier, the retailer buys 80% of its energy in the future energy market and the energy on this long-term market is not green. So the consumer is still supplied for a large part by grey energy that is compensated by the green certificates of the wind farm contract. This shows the biggest advantage of a direct PPA, the corporate is ensured that its investing in more renewable energy resources and that in most of the times the supplied energy is produced by a wind farm.

The incentives weigh more in this comparison than just the financial benefit. The incentive of the consumer to contribute to more investments in renewables is important in this direct PPA. Additionally, the direct PPA has a positive incentive of matching the demand and supply and gives options to be flexible with buffering options. The flexibility of demand is also possible with traditional contracts that have variable pricing based on the actual apx prices. However, most corporates prefer fixed prices for a year or longer to have a more predictable energy budget. These fixed price contracts do not have the incentives of flexible demand and saving on the costs if demand is changed in time.

6.2. Results Experiment 1: Buffering

In this experiment, a Battery Energy Storage System (BESS) is modelled with different capacities. The effect on the service costs and the match between supply and demand is analysed. This battery storage is considered to be a private battery unit on the property of an office. Another consideration is that this battery can be used as a proxy for other storage options for example the aggregated battery capacities of electric vehicles. The hypothesis is that a BESS can have a positive effect on the match and result in a saving on the service costs. The results are presented below.

In Table 6.2 the service costs are shown for different BESS sizes. The results are done for the four model periods and a year total. Compared to the base case without a battery capacity the service costs show a decline of about 2k per step. It can be seen that during high wind production the battery size does not make a real difference, since the results do not change as the battery size increases from 4 MWh on. The largest impact is seen when there is a high demand or a low wind production. This is not very surprising, hence the shortages are more frequent and larger which are situations in which the battery can be useful.

In Table 6.3 the results are presented for the KPIs of the battery. The surplus is equal for all the battery capacities that is evident, the traded energy shows a decline in the positive as well as the negative trade. The effect on the traded energy is shown for the moments of shortage (negative trade) and surplus (positive trade). In both situations the BESS has a positive impact showing a 5% reduction with a 2 MWh battery up to a reduction of 11% with the highest capacity, compared to the reference scenario without a BESS. So less energy is bought from the market and less is sold to the market. Another point that stands out, is the effect of the BESS on the costs and the match. A reduction in service costs is seen which is shown by the decrease of the cost per kWh capacity of 1.2 Euro/kWh to 0.7 Euro/kWh. This reduction is the result of a reduction of the imbalance costs with 3k Euro compared to the base case (see Table 6.4). The effect of the BESS is clearly visible, the battery reduces the imbalance costs by using the stored energy instead of buying it at a high price.

Table 6.2: The effect of different size of BESS capacity on the service costs of the consumer.

kWh battery	0	2000	4000	6000	8000
high wind	€ -591	€ -660	€ -742	€ -742	€ -742
high demand	€ 2,343	€ 2,295	€ 2,298	€ 2,270	€ 2,198
low wind	€ 2,236	€ 2,169	€ 2,077	€ 1,948	€ 1,850
low demand	€ 1,377	€ 1,292	€ 1,184	€ 1,150	€ 1,150
year 2017	€ 32,616	€ 30,150	€ 28,653	€ 27,624	€ 26,920
		-8.2 %	-13.8 %	-18.1 %	-21.2 %

Table 6.3: The effect of different sizes of BESS capacity on the surplus, the traded energy and the total costs in 2017. The percentages shown are relative to the reference scenario without a BESS.

KW battery	0	2000	4000	6000	8000
Trade neg	-1,677,857	-1,597,332	-1,561,009	-1,537,859	-1,520,876
		-5.0 %	-7.5 %	-9.1 %	-10.3 %
Trade pos	1,882,666	1,783,230	1,738,364	1,709,780	1,688,852
		-5.6 %	-8.3 %	-10.1 %	-11.5 %
Costs SP	€ 32,616	€ 30,150	€ 28,653	€ 27,624	€ 26,920
		-8.2 %	-13.8 %	-18.1 %	-21.1 %
Cost total	€ 179,597	€ 177,130	€ 175,633	€ 174,604	€ 173,901
		-1.4 %	-2.3 %	-2.9 %	-3.3 %

In this experiment a BESS capacity of 4000 kWh is chosen. This size has relatively the most effect on the service costs as can be concluded from the table 6.2 & 6.3. The 4 MWh battery shows a reduction of the service costs of 13.8%, this is per MWh more than a 6 MWh battery. A model run is done for the BESS size of 4000 kWh and the results are shown in Figure 6.3. The behaviour of the discharge is shown in Figure 6.3(b) at t=64. The discharge result in a drop of the service costs earlier in time than without the battery. The battery is charged again from t=72 when the wind production is high. The battery does not discharge at every occasion where the demand is higher than production. The battery is optimised to discharge when the prices on the imbalance market are high enough to use the relative expensive battery. That is the reason why the discharge is zero, for example in the period t=12-24 and t=54-60 when there is a high demand peak and a lower production.

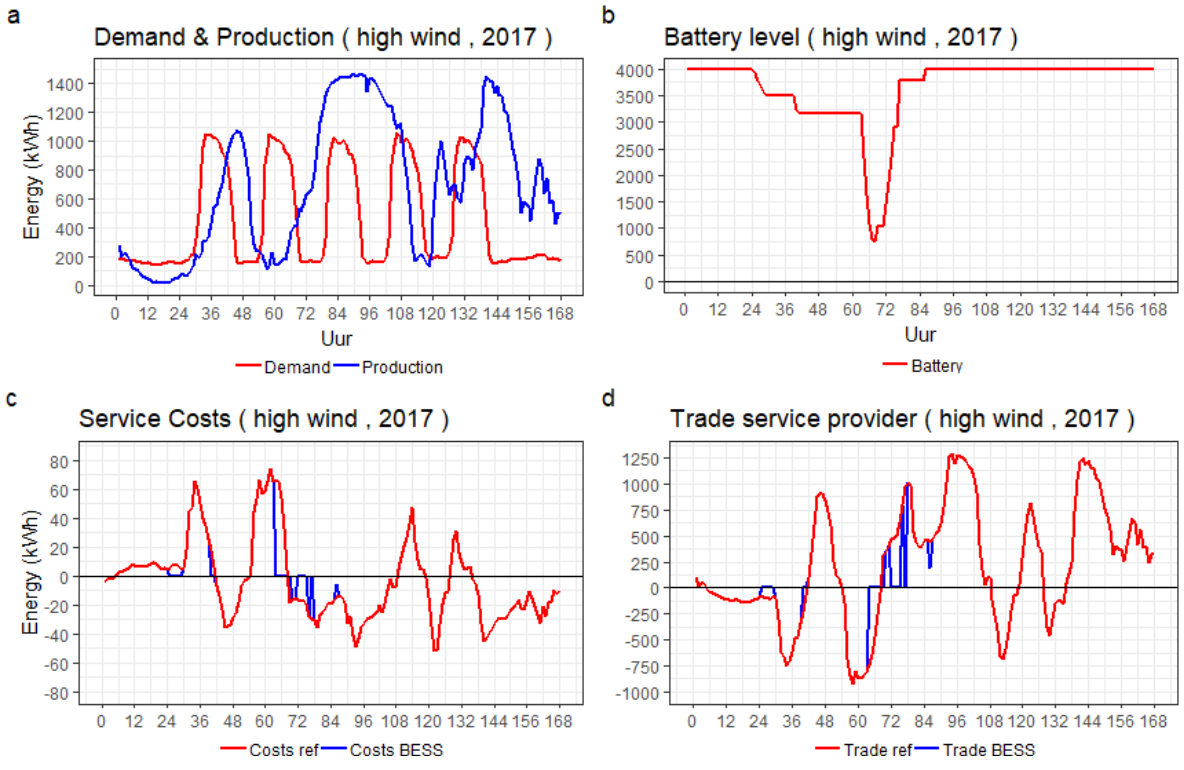


Figure 6.3: Behaviour of the KPIs in the experiment with a battery capacity of 4000 kWh

In the end the 4000 kWh battery results in a total energy cost of 175k as shown in Table 6.4, this is a saving of 4k compared to the 179k in the reference scenario. Furthermore, the costs for the battery are shown with the amount of cycles. The costs of the battery consist of yearly OPEX of 7k and one time CAPEX of 2 million Euros for this battery with a capacity of 4 MWh and 1MW. The CAPEX per year depend on the economic lifetime of the battery which depends in turn on the amount of full battery cycles per year. For the year 2017 with 41 cycles the CAPEX can be expressed in a value of 25k Euro, although this is not the general way of expressing CAPEX. In the end these costs are still very high and do not outweigh the savings on the service costs of 4k. So this result is promising as the match is increased, although this battery can be more beneficial if the prices in the electricity market are increasing. In that case the prices for trading on the markets are higher and a reduction on the amount of energy traded has a larger impact on the service costs. Moreover, the investment gets more attractive as the battery prices decline.

In this table the behaviour of different weeks is also noticeable. In the base scenario the low wind scenario draw attention since these costs were lower than a week with a lot of wind. In this experiment with a BESS the same effect is seen, although it is smaller. The overall effect on the weeks is not very significant, the cost for the consumer and the service are reduced with a few hundred Euros. On the other hand, the match of supply and demand is improved as is seen by the direct consumption and the traded energy. This shows a reduction of 5 to 10% for the different weeks. Another striking thing is that all cost components have a large gap with the average costs for a week. These selected weeks are more examples of what the boundaries or extremes are in a year, which gives also a useful insight.

Table 6.4: Allocation of the cost with a BESS of 4 MWh and 1 MW.

Year: 2017	High wind	High demand	Low wind	Low demand	Average Week	Total
Cost Consumer	€ 3,948	€ 4,435	€ 3,113	€ 3,975	€ 3,378	€ 175,671
Costs PPA	€ 4,690	€ 2,111	€ 1,047	€ 2,791	€ 2,826	€ 146,976
Costs Service	€ -742	€ 2,323	€ 2,066	€ 1,184	€ 552	€ 28,694
Cost Service Provider	€ -571	€ 1,787	€ 1,589	€ 911	€ 424	€ 22,073
Costs APX	€ -750	€ 1,075	€ 1,068	€ 722	€ 169	€ 8,766
Costs Imbalance	€ 179	€ 712	€ 521	€ 189	€ 256	€ 13,307
Benefit Service Provider	€ -171	€ 536	€ 477	€ 273	€ 127	€ 6,622
Risk factor	€ -171	€ 536	€ 477	€ 273	€ 127	€ 6,622
Benefit Wind farm	€ 4,690	€ 2,111	€ 1,047	€ 2,791	€ 2,826	€ 146,976
Trade	75,329	73,260	49,483	65,771	€ 63,426	€ 3,298,161
Production	114,740	59,227	33,354	61,056	€ 73,067	€ 3,799,481
Cycles						41
CAPEX for Cycles						€ 25,912
OPEX						€ 7,000

6.3. Results Experiment 2: Solar Production

In this last experiment an extra production capacity is added with the PV technology. These solar panels will produce energy on other times of the day due to the availability of the sun. The PV production peaks are more correlated with the demand peaks since both are high during the daytime. That is why this combination of solar and wind is analysed to see if these sources complement each other and will reduce the mismatch and service costs.

In Table 6.5 the cost allocation is given for a scenario with 1.4 MW wind (this is a 20% share of the total capacity of 7 MW) and 1.2 MW solar production capacity. The amount of energy traded and the service costs are reduced in this scenario. The costs for the PPA are kept constant with this combination of wind and solar. The allocation of cost is the same for the reference scenario. The differences in the wind production and size of the demand between the scenarios is still visible in the service costs.

Table 6.5: Allocation of the cost with a solar production of 1.2 MW and a wind production of 1.4 MW

	High wind	**High demand**	**Low wind**	**Low demand**	**Average Week**	**Total**
Cost Consumer	€ 4,150	€ 4,227	€ 3,059	€ 4,186	€ 3,394	€ 176,505
Costs PPA	€ 3,822	€ 2,660	€ 1,704	€ 2,326	€ 2,795	€ 145,360
Costs Service	€ 328	€ 1,567	€ 1,356	€ 1,860	€ 599	€ 31,144
Cost Service Provider	€ 252	€ 1,205	€ 1,043	€ 1,431	€ 461	€ 23,957
Costs APX	€ 264	€ 592	€ 414	€ 291	€ 206	€ 13,267
Costs Imbalance	€ -11	€ 613	€ 629	€ 1,140	€ 255	€ 10,690
Benefit Service Provider	€ 76	€ 362	€ 313	€ 429	€ 138	€ 7,187
Risk factor	€ 76	€ 362	€ 313	€ 429	€ 138	€ 7,187
Benefit Wind farm	€ 3,822	€ 2,660	€ 1,704	€ 2,326	€ 2,795	€ 145,360
Trade	65,855	62,816	44,254	67,726	56,088	2,916,571
Production	92,846	71,198	50,893	50,204	71,752	3,731,089
Direct consumption	1.914.455	1.996.632	2.075.222	2.149.647	42,721	2.221.507

The effect of different combinations of wind and solar capacity is analysed and presented in Table 6.6. It can be seen that the service costs are declining as the solar capacity is increased. The reduction is about 5% for the scenarios with 1.4 and 1.2 MW solar capacity. This scenario is also shown with the allocation of costs in Table 6.5. The total costs decline with about 3k, although this is partly the effect of the slight reduction in the PPA costs of 1.5k. Moreover, the apx market costs are 2k higher than the reference scenario, this is compensated by the reduction in imbalance costs. The costs shown in the this analysis are based on a second PPA with a solar farm. The option to buy solar panels for the offices themselves should give the same effect on the match, although the investment costs should be paid upfront instead of during the contract period of the PPA.

It seems that the solar experiment results in more energy trade on this market. This could be explained by less revenues on this market by trading the surplus or it can be explained by extra energy bought at this market. The production in this experiment is 60 MWh lower than the reference scenario with only wind production. This could be the reason for the higher apx costs. Although, the table also shows a lower shortage and less surplus, this does not explain the fact that more energy is bought from the market. If this result is further analysed in the model, by splitting up the apx cost in positive and negative components, the effects becomes clear. The fact is that the lower shortage and surplus result in less energy bought from the market, but also less revenue from selling energy. The costs for buying energy are decreased from 62k to 53k compared to the reference, but the revenues from selling energy are reduced from 53k to 42k. So a better match results in more costs, due to lower revenues from the surplus energy.

Furthermore, this better match is supported by the significant reduction of the direct consumption as is see in Table 6.6. This shows the positive effect of solar production on the match between production and demand, resulting in a better match and lower service costs.

Table 6.6: Results of different solar capacities on the energy costs and match of supply & demand: more solar production has a positive effect on the service costs and traded energy. The percentages shown are relative to the reference scenario without solar.

MW wind **MW solar**	**1.8** **0**	**1.6** **0.6**	**1.4** **1.2**	**1.2** **1.8**	**1** **2.4**
Total APX	€ 8,630	€ 9,660 12%	€ 10,690 24%	€ 11,720 36%	€ 12,750 48%
Total imbalance	€ 16,491	€ 14,687 -11%	€ 13,267 -20%	€ 12,061 -27%	€ 11,270 -32%
Total SP	€ 32,658	€ 31,651 -3%	€ 31,144 -5%	€ 30,916 -5%	€ 31,225 -4%
PPA	€ 146,976	€ 146,168 -1%	€ 145,360 -1%	€ 144,553 -2%	€ 143,745 -2%
Total	€ 179,635	€ 177,820 -1%	€ 176,505 -2%	€ 175,468 -2%	€ 174,970 -3%
Production [kWh]	3,799,481	3,765,285 -1%	3,731,089 -2%	3,696,893 -3%	3,662,697 -4%
Shortage [kWh]	-1,677,857	-1,517,090 8%	-1,390,683 15%	-1,289,416 20%	-1,230,963 23%
Surplus [kWh]	32,616	30,150 -10%	28,653 -17%	27,624 -23%	26,920 -27%
Total trade [kWh]	3,559,311	3,203,581 -10%	2,916,571 -18%	2,679,840 -25%	2,528,738 -29%
Direct consumption [kWh]	1,918,027	2,078,794 -8%	2,205,201 -12%	2,306,469 -15%	2,364,922 -17%

In Figure 6.4 the production of the solar capacity and wind capacity is shown together with the influence of the combination on the surplus curve. The hypothesis is whether the solar capacity has a positive influence on the match between supply and demand. In the section above this positive effect is already supported by the numbers in the tables 6.5 and 6.6. In these plots you can see that the surplus is lower for the combination of solar and wind. This is mainly seen at the curve below zero, at t=36 and t=84. On t=36 the surplus in the wind-only is about minus 1400 and in the combi it is around 1000 kWh and at t=84 the difference is about 400 kWh. In 6.4(b) the complementary behaviour can be seen as the peaks of the wind production (shown in blue) are in-between the peaks of the solar (shown in red), especially at t=72 and t=96.

In the figure with the results of a week with low wind, this effect of the reduced surplus/shortage is also visible. The wind production in this week is very low, but the PV production compensates this for a large part. The shortage is lower in the figure 6.5(d) at t=36, t=60 and t= 84 and this results in lower service costs overall. The effect is clearly visible since the shape of the curve is changed significantly.

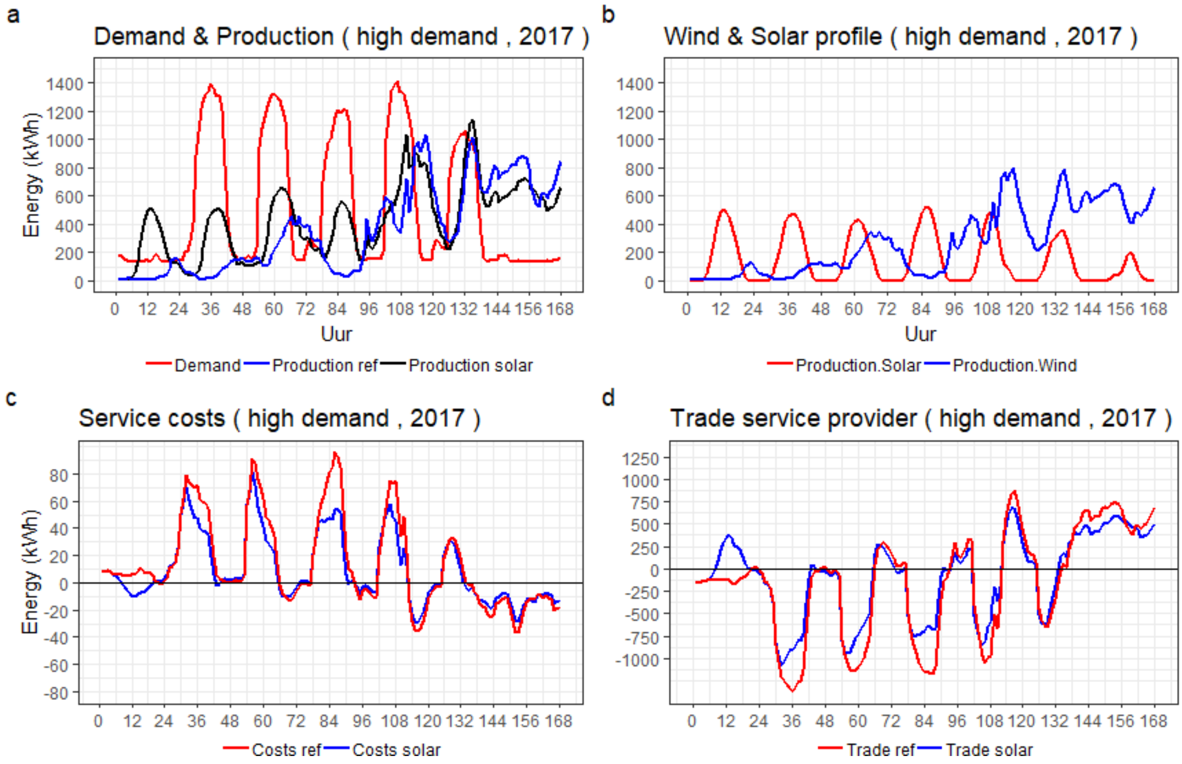


Figure 6.4: Behaviour of production and surplus curves with a combination of 1.2 MW solar and 1.4 MW wind in a week with high demand in 2017

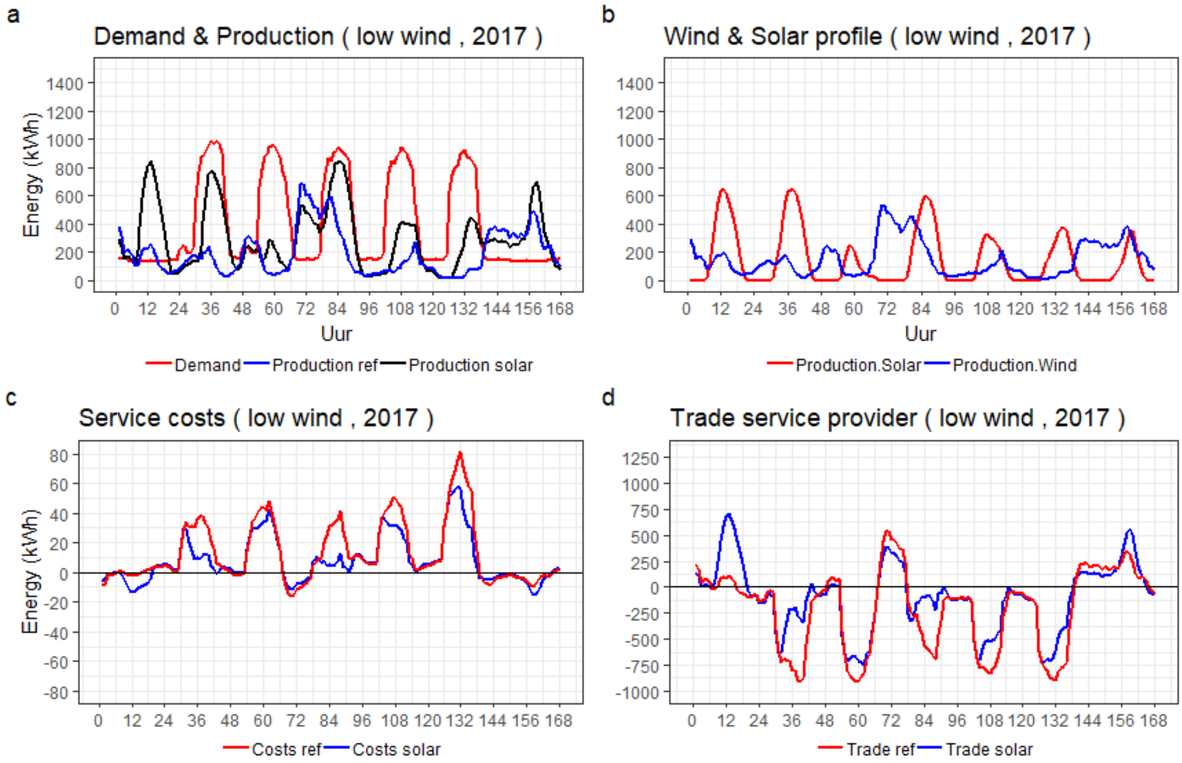


Figure 6.5: Behaviour of production and surplus curves with a combination of 1.2 MW solar and 1.4 wind in a week with low wind in 2017

6.4. Verification & Validation

The model needs to be verified and validated as with every simulation model. Verification is needed to see if the model is robust and produces output that can be expected according to the formulas. It checks whether the computerised model is line with the conceptual model (Sargent, 2013). Validation of the model is required to get an insight if the results of the model are realistic. The verification and validation is done using the software Microsoft Excel to do the calculations on sensitivity and extreme value analysis. The package 'R Studio' is used to calculate and visualise the statistical data.

6.4.1. Verification

The model is verified by using a sensitivity analysis, an extreme value analysis and by verification during the model design. By using a modular design the model is less vulnerable for errors, also these are earlier identified. The model is designed with separate tabs for input, calculations, results and experiment. Moreover the model extensions are not programmed in the same sheet as the base case which give a better overview and prevent mixing up of formulas. Lastly, the model is tested between and after every model extension or modification to see if the results are not affected. In order to test the model results after completion of the model, two methods test the impact on the output value if the input value is changed. It can identify problems in the model, for example if a small change results in a more than expected change in the output, and it can identify a limiting factor or a lack of boundaries if the input values are chosen very high or very low.

In this model the sensitivity of the input parameters is analysed and visualised in a 'tornado' diagram (Figure 6.6). In this diagram the effect of a 10 percent change of the input value on the total costs is shown. The most sensitive is the wind profile factor, this factor is calculated by ECN and used for the SDE+ subsidy scheme. The factor cannot be changed but is it useful to identify the sensitivity of this factor. The ratio for trade on the apx and imbalance market is also very sensitive. This value is analysed further in the validation (subsection 6.4.2). One factor that stands out is the capacity of the wind park, this sensitivity is asymmetrical. Apparently, an increase has more impact than a decrease. The capacity chosen as starting point may be a bit too high, which results in a relative lower surplus at a lower capacity compare to the surplus at a higher capacity. In appendix A.3.1 the sensitivity is also tested on only the service costs, since the trade ratio directly influences this. The results are comparable to the results shown here.

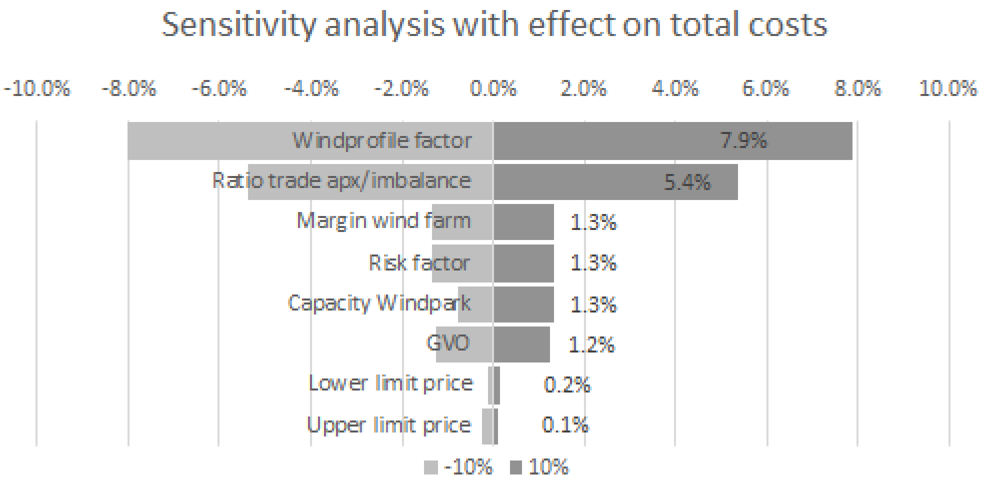


Figure 6.6: Tornado diagram: sensitivity analysis of the input parameters influencing the total energy costs of the consumer

Table 6.7: Verification of three input parameters in the base case wind model showing the impact on the KPIs by using extreme input values

	Base	Wind capacity		Risk factor		Margin wind	
		0 MW	900 MW	0	2	0	100%
Cost Consumer	€ 233,733	€ 214,128	€ 3,275,589	€ 196,377	€ 258,637	€ 231,033	€ 323,411
PPA	€ 165,247	€ -	€ 16,524,702	€ 165,247	€ 165,247	€ 162,547	€ 254,925
Service	€ 68,486	€ 214,128	€ -13,249,113	€ 31,130	€ 93,390	€ 68,486	€ 68,486
Cost SP	€ 31,130	€ 152,948	€ -9,463,652	€ 31,130	€ 31,130	€ 31,130	€ 31,130
Benefit SP	€ 37,356	€ 61,179	€ -3,785,461	€ -	€ 62,260	€ 37,356	€ 37,356
Benefit WF	€ 165,247	€ -	€ 16,524,702	€ 165,247	€ 165,247	€ 162,547	€ 254,925
Trade	3,538,889	3,595,680	376,444,230	3,538,889	3,538,889	3,538,889	3,538,889

The last verification method is the extreme value analysis. In this test the robustness of the model is tested. In Table 6.7 the wind capacity, the risk factor and the wind farm margin are selected as input. The results are shown for every KPI for every parameter change. When the wind capacity is zero, the PPA costs are also zero and the costs of the consumer are completely determined by the service costs. When the wind capacity is very high the PPA costs are very high since all production is bought by the consumer. A strange result is that the service costs are negative, this can be explained by the fact that the service provider has to sell the surplus and gets revenues from it. So the service provider makes profit in this scenario and the results are negative. The risk factor influences only the service costs, these are as expected increased by a high risk factor resulting in high cost for the consumer. A risk factor of zero leaves no benefit for the service provider from this and only the costs are calculated to the consumer. Finally, the margin of the wind farm has no unexpected results. The costs for the PPA are changed as expected with the change of the benefit of the wind farm. This benefit for the wind farm is high for a margin of 100 percent and for a margin of zero percent it does only reflect the costs for energy without a margin.

6.4.2. Validation

The validation of the model is done by an expert validation and by a statistical analysis comparing the input parameters to real data. The results of the model cannot be compared with situations in reality since these contracts are not public and the risks and margins of players in the market are not transparent. However the input parameters can be validated with real data. This is done for the trade ratio which is a measure for the amount of production that can be forecast one day ahead.

The expert validation is done by an interview with an expert and regular meetings with a RHDHV expert. These experts have evaluated the input parameters and assumptions on their validity. The expert interview is done with a partner of a service provider who offers balancing services to companies with PPA contracts. The regular meetings were with my supervisor from RHDHV who has a background in the energy sector from the perspective of a network operator. Both have validated the model structure and the model results and gave their opinion on whether the results are realistic. Especially the parameters where validated such as the risk factor, the profit margin of the retailer and the forecast error of wind energy. In these interviews they were positive about the assumptions done in the model and the values chosen for the parameters. They could agree that these are comparable to the market conditions. In the interview with the service provider I also discussed the functioning of the energy markets and the role of the large energy companies and retailers. Moreover, I have asked him his opinion on the future of the energy markets and the role that direct PPAs may play. This information was very helpful and resulted in the parameter set by which I ran the model and the experiments. The information on the future of the PPA and functioning of the markets were useful for the discussion and conclusion. A short summary of the interview can be found in section A.2.

The statistical analysis is done to validate the trade ratio which is an input parameter in the model. In the sensitivity analysis the trade ratio turned out to be a very sensitive and uncertain parameter, so that is why this value is validated by using historical data of the transmission system operators in Germany. The TSOs publish their data of the forecast and actual production of the wind turbines on-shore. The

Table 6.8: Descriptive statistics of the histogram in A.3.1: a bandwidth is shown between the 1st and 3rd quartile

	50Hertz	**Amprion**	**TenneT**	**Total**
Minimum	-0.87	-0.98	-0.81	-0.73
1st Quartile	-0.13	-0.21	-0.12	-0.11
Median	-	-0.04	0.01	-0.01
Mean	0.09	0.15	0.09	0.02
3rd Quartile	0.18	0.19	0.16	0.10
Maximum	19.72	71.80	26.29	6.44

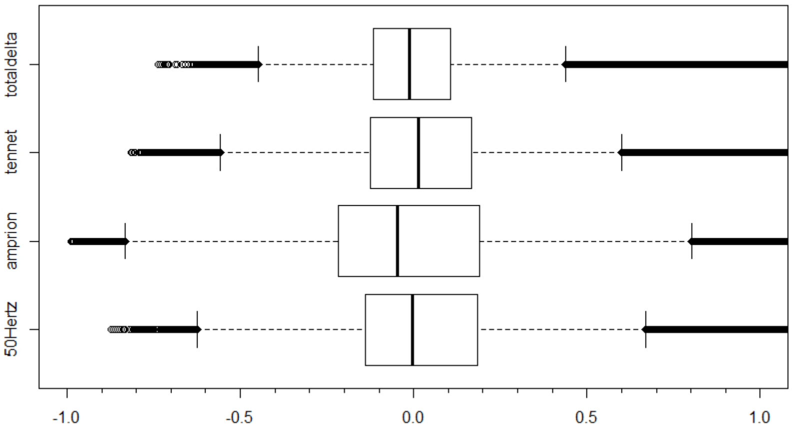


Figure 6.7: Boxplot analysis showing the bandwidth of the forecast error of wind energy in Germany by the different TSOs

data in this analysis is based on the period 2015 until 2017 and is based on the three largest TSOs in Germany. The fourth TSO ’TransnetBW’ did not have accurate and complete data so this one is left out from the dataset. This data is analysed to see what the difference is between the forecast and actual production, see Table 6.8 and Figure 6.7. In the boxplot the bandwidth is shown for the prediction error, the width is determined by the first and third quartile. This means that 75 percent of the data is higher than Q1 and 75 percent is lower than Q3. The average bandwidth of the three TSOs is between -11% and 10%, which means that 81 percent of the wind can be predicted on average. This value is in line with the parameter level of 80% trade on the apx, so this input value is valid.

6.5. Conclusion

The model results are presented separately in the previous sections. In the conclusion the results of the direct PPA are compared to the traditional PPA to answer the question whether a direct PPA is more beneficial. The experiments show the effect on match and a potential benefit. These results are all compared below in Table 6.9.

Benefit PPA
The financial benefit of the direct trade PPA is mainly depending on the match between supply and demand. From the model it is concluded that the match between supply and demand is around the 50%, this means that the wind production is sufficient to supply the demand in half of the volume in a year. The other volume is traded on the energy markets, mainly the day-ahead market and the imbalance market. During times of high wind production the wind farm produces even more than the demand, resulting in a surplus that is traded on the markets to obtain revenue from it. From the model design and the interviews with experts it becomes clear that 80% of the energy production can be forecast and traded on the day-ahead market and the rest is sold on the imbalance market. The result is that around 3.5 MWh of energy is traded on the market, this is the sum of all surplus and shortage. The balancing costs are around 32k which includes the apx cost of 8.5k, the imbalance costs of 16.5k and a risk factor of 7k. The service costs of the traditional contract are around 20% on top of the energy costs, this result in a value of 36.6k. So there is already a saving in the service costs. The assumption is that the cost component of the energy is the same since the PPA is the same for a consortium or a utility. The total energy costs for the direct PPA come down to 179.6k compared to the traditional contract of 183.6k for the year 2017. The total savings are 4k Euro per year. This saving is dependent on the assumptions in the model, especially the risk factor and the trade ratio. If the risk factor is 5% higher or lower the savings will change with 1.5k (see sensitivity analysis), so this saving could be a bit higher or lower. The saving is due to lower service cost in the direct PPA. The reason is that the profit margin on these cost is lower, a more detailed analysis is done in the discussion. The total energy costs of the direct PPA are lower than the traditional contract in the same year, so it can be concluded that the direct PPA is beneficial.

Table 6.9: Cost allocation comparison between a traditional contract, a direct trade PPA, a scenario with a BESS and a scenario with added solar capacity for the year 2017

	Total Traditional	**Total Direct PPA**	**Total S1: BESS**	**Total: S2: PV+Wind**
Cost Consumer	€ 183,598	€ 179,635	€ 175,671	€ 176,505
Costs energy/PPA	€ 146,976	€ 146,976	€ 146,976	€ 145,360
Costs Service	€ 36,622	€ 32,658	€ 28,694	€ 31,144
Cost Service Provider	€ 179,635	€ 25,122	€ 22,073	€ 23,957
Costs energy/APX	€ 32,658	€ 8,630	€ 8,766	€ 10,690
Costs service/Imbalance	€ 146,976	€ 16,491	€ 13,307	€ 13,267
Benefit Service Provider	€ 183,598	€ 7,537	€ 6,622	€ 7,187
Risk factor		€ 7,537	€ 6,622	€ 7,187
Benefit Wind farm	€ 146,976	€ 146,976	€ 146,976	€ 145,360
Trade [kWh]	0	3,559,311	3,298,161	2,916,571

Benefit Experiments
In two experiments the influence of a BESS unit and an extra production capacity of solar PV panels is researched. The experiment with the BESS unit would show if battery storage has a significant effect on the match of demand and supply and if a consumer should invest it. The hypothesis for the solar experiment is that a combination of wind and solar production shows a positive effect on the match.

The effect on the match of PV production and a battery storage is shown in Table 6.9. The BESS indeed reduces the total energy costs and the amount of traded energy which is a measure for the match between demand and supply. As this match is better the amount of energy traded is reduced.

The amount of energy and the costs for the PPA are not varied and remain the same as expected. A striking fact is that the costs for the trading energy on the imbalance market are reduced in the BESS experiment. This can be explained by the battery use during high prices on the imbalance market. The BESS has some restrictions on the battery use that trigger the charging and discharging based on the imbalance prices. The battery is quite expensive and has a limited lifetime depending on the amount of cycles the battery make. One cycle of a battery is when the battery level changes from fully charged to empty and then again to fully charged. In order to reduce the amount of cycles the battery only discharges if the imbalance prices are very high (>80 €/MWh) and charges when the imbalance price is higher than 10 €/MWh. This ensures that the battery is only used when the price in the market is higher than the price for using the battery. These restrictions have an effect on the imbalance costs and may be the explanation for the reduced imbalance costs.

The PV experiment shows the same effect as the BESS experiment. Although, the service costs show a smaller reduction in the PV experiment than the BESS experiment as is caused by the increased apx market costs. The match between supply and demand is improved as can be seen by the lower amount of traded energy, this is reduced with 12 percent. The peaks of the solar have the time timing as the demand and reduces the shortage if there is not sufficient wind available on that time. An effect of this better match is a lower revenue from selling surplus energy on the apx market, which result in an increase of this cost component. All in all, the result of the PV experiment is that the total energy costs are bit higher than the BESS case, but still show a benefit of 3k compared to the base case. So the added solar capacity has a positive effect on the match and the total energy costs.

Business Case
If we look at the costs for the BESS unit and the solar production we can consider the business cases of both in the current market conditions. Unfortunately, the business case for the BESS unit in the current market conditions is not a financial attractive option. The savings of 4k Euro per year are not enough to outweigh the battery costs of 32k per year. The battery is indeed a good technology to be used as a buffer, but it does not significantly influence the surplus. The best usage right now is to use a BESS to speculate on the market prices or to offer services to the TSO to obtain revenue from the battery. This is seen in the results as the cost for the imbalance market are decreased, the high prices on the imbalance market can be prevented by using the storage. As the battery prices decreases the business case for private BESS may be better.

Contrarily, the experiment with the added solar capacity does have a positive impact on the match and has a positive business case. The model shows that a combination of solar and wind gives a better match between supply and demand. This results also in lower service costs and total energy costs. The savings on the service costs are 1.5k. The PPA costs are 1.5k lower and this together results in a total saving on the energy costs of around 3k per year. The business case for the solar capacity is based on a second PPA contract with a solar farm. This is a positive business case with the savings on the on the service costs. The option for investments in solar panels for the offices themselves is also possible, although this gives higher upfront cost. The end results should be roughly the same since the total investment costs are the same order of magnitude in the PPA and the own solar panels. All in all the result is positive and could even be increased if the combination of solar and wind is further optimised, and the imbalance costs are reduced.

7

Discussion

The results of the property rights analysis in chapter 4 and the financial model chapter 6 are discussed in this chapter. First, the model assumptions and limitations will be addressed. Furthermore, this section will discuss the use of the property rights theory in this research and it discusses the impact of the results on the society and the energy system as a whole.

7.1. Discussion of Results and Societal Impact

7.1.1. Model Assumptions & Limitations

In every model assumptions are made in order to make a simplified version of the reality in a model. In this research the balancing costs are modelled by assuming that the cost components consist of the imbalance costs, the apx costs and the risk factor of the service provider. This assumption may be too simplified since there are 11 markets on which parties in the energy sector can trade. Moreover, the risk factor is an aggregate of multiple cost components such as the cost and revenues for trading, but also the real costs for forecasting and submitting the program. These costs could be more specified to have a better proxy to the real balancing costs. The same goes for the cost components of the retailer. In reality the retailer trades on the long-term market for most of the time instead of the apx market. Moreover, the profit margin of 20% could be decomposed in more components. A last assumption that may be discussed, is the selection of the model period. In this model the data of 2017 is used to model the energy costs. This gives a good view on the costs and the allocation of these costs between the actors. However, in further research other model periods may be included to analyse whether this effect is replicable in other years. On the other hand, PPAs are long-term contracts in which future electricity prices are very hard to predict. So a modelling approach of the costs over the whole contract term is never very accurate. The modelling of multiple historic periods could increase the knowledge on a direct PPA construction, but this proves only the construction in the past. This new PPA design is analysed with economic property rights theory that shows the allocation of benefit which is applicable to the whole period of the PPA. The financial model of the year 2017 is only an example on what the order of magnitude is for the saving on the energy costs. The structural saving is proved with the economic theory.

7.1.2. Value of Property Rights Theory for This Research

This research is unique in the field of the energy sector since it uses two approaches to answer the research question. First, the property rights theory is used to analyse transactions in the energy sector with respect to the energy contracts and second, the modelling method is used to quantify the effects of the direct trade contract compared to a traditional contract. The property rights theory does add something to this analysis since it forces the researcher to look at the sector with another perspective and try to unravel the details in the transaction. Especially, the view on the transferred properties of energy gives a clear view on how the volume risk of energy is allocated. This made clear that the benefit of a direct PPA is the effect of a higher risk that the consumer bears. Moreover, the risks & incentives that are identified are linked to the property rights framework. This is used to explain the allocation of ownership in this new contract type. The consumer has ownership of the energy and can trade this with another party to obtain revenues. The revenues can be used to bear the increased cost of the volume risk. It also shows the advantages of this PPA, for example the incentive for the service provider and for the consumer to invest more in renewables and to make the link between demand and production times more transparent by the financial benefit for a better match between supply and demand.

In the model the property rights theory is not explicitly used to operationalise the model. The insights of the property rights are merely on the transactions that take place and it gave insight in the components for the PPA contract and the service provider. For example the added risk component in the model is used to cover the costs for the service provider, in order to bare the volume risk and the risk for trading on the market. The model choices and the conceptualisation are done using the knowledge on the energy sector gained from the literature review and the insights gained from the property rights framework. So the property rights theory in the modelling phase was used as a stepping stone to analyse the sector and make a realistic model with that knowledge. It is not specifically used to quantify the cost components for example. The methods are complementary to each other, they both highlight a different aspect of the situation and are integrated in the discussion and conclusion.

7.1.3. Impact of Direct Trade PPA on Society

The transition to more renewable energy is now accelerated in the Netherlands as the deadline for the climate goals approaches. The wind farms can contribute to them in a large part and the projects are developed right now. For financing these projects the role of the PPA is already very large and widely used. The direct trade PPA is a step in the right direction to better align the wind production with the Garanties van Oorsprong (GVOs). Besides, companies are increasingly concerned about their sustainable image, and want to reduce their impact on environment. They can show with the direct PPA that they are innovative and really invest in new wind farms instead of buying the green certificates to compensate for their grey energy. As discussed in this research the direct PPA gives a direct link between time of production and time of consumption and more effective incentives for consumers to adjust their demand to match with the supply. These positive effects of the direct PPA are to be further rolled out.

This new form of a direct trade PPA does also impacts the small consumers with an energy demand below the 10 MWh. The households can join energy collectives from which they can contract indirectly a part of a wind farm or solar project. These energy collectives form a consortium by aggregating the demand of all the small consumers and can contract the wind farm in a direct trade PPA. The consumers can then join these collectives to buy the wind production and next to that contract a service provider. Another possible impact is on the development of microgrids in the Netherlands or the initiatives to become off-grid. As described in the introduction these local grids aim to be independent of the grid by investing in renewable energy resources in neighbourhoods. In this construction a direct PPA can have a central role in contracting the energy from for example a wind turbine or solar farm. The community can together contract directly the energy from the wind turbine in a collective. This collective closes the PPA with the producer and can negotiate the contract details and prices. The imbalances can be reduced by using flexibility of the people by using their EVs, local battery systems or demand response. This research has proven the direct PPA design and this research is very relevant to this situation too.

7.1.4. Impact of Direct Trade PPA on Energy Markets

The impact of more PPAs on the market structure is an important aspect to consider. The impact on the day-ahead market may be limited since this new PPA structure still uses the short-term energy markets to trade the surplus and the shortages. The biggest impact is on the future markets where less energy is traded as the amount of renewable energy is increased. The exact impact is not quantified, this requires a follow-up research. The bidding blocks that are withdrawn from the market are the base-blocks during the office hours between 8am and 5pm. The reason for this reduction is the fact that renewable energy is not controllable and is hard to forecast for more than one day ahead. The utilities bid now on base blocks which are generated mainly by coal plants. This bidding of utilities will be changed as the coal plants shut down eventually. Furthermore, when this happens the PPAs might play a larger role on the future market, as the capacity of the wind farms is traded in long-term contracts. These long-term contract reduce the risks for a fluctuating energy price for consumers. It gives a stable and predictable price. Additionally, the availability of long-term renewable energy contracts replacing the current grey blocks, is positive for the liquidity of the market as there are more different contract periods to spread the price risks. There might arise a market for PPAs that will take up the role of long-term energy trading where generation capacity is traded instead of energy blocks. This should be further investigated to really support this claim.

The effect on the day-ahead market is limited. Though, there is a small effect on the volume of energy that is traded on this market since more energy is traded in bilateral contracts. This reduction in traded energy volume can influence the price setting of the market. This is called the liquidity effect of the market. The liquidity of a market is a measure for the extent to which a commodity can be traded on a market without a significant change in its price and without incurring significant transaction costs (OFGEM, 2019). The liquidity can be influenced by total volume of the market, the number of buyers & sellers and the churn of electricity (the number of times electricity which is generated in the market is subsequently traded) (GasTerra, 2015; OFGEM, 2019). The effect on this liquidity is not easy to predict right now, this would be a subject for further research and for monitoring over time.

However, not all energy in this PPA is withdrawn from the market since the mismatched energy still has to be traded on the apx market. This mismatch is almost half of the produced energy. The effect that may arise is that the prices become more volatile and extreme because there are times of very cheap energy when the renewables can supply the full national demand and when these renewables are not available more expensive units are activated that force up the price. So there may be an effect on the energy markets with respect to the volume of energy and the volatility of the price, but this should be further looked into and monitored as the amount of PPAs increases.

7.1.5. Applicability for Other Energy Consumers

In this research the direct PPA is analysed using a demand profile of RHDHV as a case study to explore the possibilities of this new PPA design. In what degree can this PPA design be used by others in the energy market and what type of users are these? What is the potential of this design? These questions are central in this section.

Firstly, the demand profile of RHDHV is very common for corporates. The peak times are between office hours of 8 am till 5 pm and during the weekends the energy demand is very low. As this profile is very general and widespread the results of this research can be generalised to a large group of other corporates and companies. This result is, especially, interesting for companies with roughly the same size of demand. The very large corporates have a large enough demand to include one or several wind turbines in their energy supply, as is mentioned in the introduction. The potential users are the companies with a medium to low demand as they can cooperate and aggregate their demand in a PPA. These companies can form a consortium or another collaboration construction and negotiate together the contract details with a wind farm and spread the costs of these transactions. Secondly, another characteristic of potential users is the availability of Electric Vehicles. These can be used to create a more flexible demand and a better match between supply and demand. Companies with this technology are also a potential segment for this new energy contract design. Thirdly, this PPA design is not restricted to country borders, it can be used internationally by other corporates and companies. For example in nearby countries as the UK, Germany, Belgium and France who also invest highly in wind farms both onshore and off-shore in the North Sea.

The potential is very large, but there are consequences for the system on aggregated level. Most of them are identified above as the PPA contracts impact the future energy market and the day-ahead market. When a majority of the corporates will close a PPA contract the liquidity effect will be much larger and more influential on the market behaviour. It could be that the whole system of energy markets is changed. The long-term future market is in this case reduced or it will change its offers by trading PPA contracts instead of base blocks. The short-term markets will become more important. This is evident since more renewable energy means less predictable energy production, and a larger need for balancing on the day itself or even on the timescale of hours and minutes. This change in the market is, however, not only driven by the PPA constructions. This is a development that will go on as the amount of renewable energy is increasing. The PPA contracts may accelerate this market development by the effect of the bilateral contracts on the liquidity of the market, but this development will go on inevitably.

7.1.6. Application of Buffering with EVs

In this research a simplification of a buffering model was used to gain insight in the effect of buffering options on the surplus. The BESS in this model was modelled as buffering option to reduce the surplus and not primarily maximise the revenue by speculating on the market prices. This purpose of the BESS is also possible and could potentially increase the revenue and profit. This could be researched in another research. In this paragraph the focus is on the options buffering could bring to corporates who have a direct PPA and want to make their demand flexible.

A first option for buffering, is to adjust the charging times of Electric Vehicles (EVs). Charging of EVs could be made more smart by making the charge capacity dependent on the market prices of imbalance market or dependent on the availability of wind. The cars can be charged if there is a lot of wind in order to maximise the direct consumption of the wind farm. This can decrease the service costs and make the demand more flexible. This option is to be researched further to quantify the potential and analyse how many hours of the day most vehicles are connected to the charging facilities and what the minimum level of battery should be if the cars are leaving. If, for example an EV is considered with a capacity of 40 kWh, a fleet of 100 EVs could have the same effect as the BESS of 4000 kWh that is used in this study. An important aspect is that not all EVs are parked the full day, if an employee needs to take the car for an appointment the car should have enough battery to travel the required distance. So the total fleet should be larger to compensate for this.

A second option for buffering at corporates, is to use the EVs in a vehicle-to-grid setup. The batteries of the EVs in this setup can be used to store energy and also supply energy when needed. This option is comparable to one large battery that is used in this model to reduce the surplus. The EVs can be configured to supply energy during high prices on the imbalance market and sell this energy to obtain revenue, or the energy can be used for the office demand during moments of insufficient wind production. The limitation of this vehicle-to-grid setup is that the batteries of the cars will degrade faster, and the range of the vehicles is reduced(Bozyurt, 2018). Most manufacturers, for example Tesla, are not happy with this solution because they cannot guarantee the quality and the long range of the battery. The CEO of Tesla explains their choice to not implement this technology in their EVs. Although, they might reconsider it as more research is conducted into the batter degradation and smart charging (Shahan, 2016). Also the charging and discharging algorithm should be very smart to leave enough power in the batteries for employees to leave after work or earlier if needed. In the case of corporate offices, the EV fleet consist of lease cars that are renewed every four years so after this relative short period the battery would be still usable. The question is whether the board of a company can decide these things over their EV fleet or that the employees or the lease company can rule of this.

8

Conclusion & Recommendations

In this chapter the conclusion will be drawn and the research question will be answered. First, the main research question and the underlying problem will be discussed and answered. This will be supported by answering the sub questions by shortly stating the conclusions from the analyses. Second, in section 8.2 further recommendations are given.

8.1. Conclusion

The objective of this research is to propose a new design for PPAs in which there is a direct link between consumer and wind farm owner. The aim is to analyse the effects of these agreements in terms of economic efficiency and financial benefit. The main research question stated in the introduction is:

“What are the economic & financial effects of a direct PPA on the energy sector by using a property rights theory approach?”

A direct PPA agreement is an agreement between a consumer or a group of consumers directly with a wind farm owner. This construction cuts-out the role of the retailer and paves the way for the consumer to have control over their energy contract and where they get their power from. In a direct PPA the consumer buys power from the wind farm and contracts a service provider for the additional services. The property rights theory analysed this new contract form and analysed the economic effects. The direct PPA contract has a positive effect on the economic efficiency since the incentives in this contract are better allocated. The incentive is created to really invest in renewable energy in the Netherlands instead of buying green certificates compensating grey energy. Next, the consumer has a financial incentive to make their demand flexible and better match the demand with the supply. In the traditional market the supply follows the demand, but in the new energy market with more renewables, the production is less controllable and thus the demand should follow the supply.

The contract between the consumer and service providers manages the match between supply and demand, the smaller the mismatch the larger the benefit for the consumer. The consumer can decide how much risk it bears and what services it uses from the service provider. The costs for this direct PPA show a positive financial benefit. A corporate or company with a demand of around 3.5 MWh can save a few percent on the total energy costs. This is in the case for RHDHV around 4000 Euros, based on the model results in 2017. This saving assumes that all risks are covered by the service company and the demand of the consumer is not changed. Furthermore, this case is representative for a lot more corporates in the Netherlands and internationally, who can make their offices sustainable and use their EV fleet for flexibility.

All in all, this new contract design is very competitive with the traditional contracts and in some cases even more beneficial with a financial benefit of a few percent based on the assumption in the model. The main advantage is that this contract has a direct contribution to more renewable energy production in the Netherlands, compared to the grey energy from the future markets that is compensated by certificates.

The savings can even be increased if the demand gets more flexible or if more risks are taken up by the consumer. Despite the type of service contract, the direct PPA has better incentives for investments in renewable energy, a more flexible demand and a slight financial benefit.

This conclusion is further supported by answering the following sub questions below.

1. What actors are involved in a direct trading PPA contract and what transactions are present in this construction?
2. What are the risk and cost components of these transactions and how are these applied in a direct trade PPA?
3. What are the effects on economic incentives of the actors in the energy sector, using direct PPA contracts with a balancing service provider
4. What is the financial benefit of a direct trade PPA compared to a traditional contract?
5. What is the effect of energy storage and solar production on the financial benefit of direct PPA?

8.1.1. What actors are involved in a direct trading PPA contract and what transactions are present in this construction?

From the actor analysis it becomes clear that there are three main roles in a direct PPA: the developer, the consumer and the service provider. Apart from these actors, there are supporting actors like the financiers of the wind farm and the network operators on distribution and transmission level. But these are not directly involved in the PPA and do not have a direct link with the consumer. The transactions between these actors are analysed and come down to two main transactions: firstly, the agreement on the PPA price and requirements between the developer and the consumer, secondly the transaction between the service provider and consumer to divide the risks between them in the service contract.

8.1.2. What are the risk and cost components of these transactions and how are these applied in a direct trade PPA?

The property right analysis resulted in a list of risks and components of the transactions. In the first transaction of the PPA, the consumer and the wind farm transfer the energy volume, the Garanties van Oorsprong (GVOs) and the information on time of production. This transaction includes the volume risk that is transferred to the consumer. In the traditional contract this risk lies at the retailer and is included in the price. The price of this PPA consists of an energy price based on the average apx market price, a correction factor for the wind energy price, a GVO price and a margin for the wind farm.

In the second transaction between the service provider and consumer the timing of consumption and timing of production play a large role. This timing determines the match between supply and demand and needs to be in balance. The consumer has a contract with the service provider that manages the mismatch by trading on the energy markets. In this contract, the volume risk is transferred to the service provider, so that the consumer has a constant power flow despite the wind production. The cost components of this contract depend on the risks that are allocated to the service provider. The more risks they take the higher the service fee. The main components are the costs to trade the surplus/shortage on the apx market, the costs to trade on the imbalance market and the risk factor that compensates for high prices and forecast errors by the service provider.

8.1.3. What are the effects on economic incentives of the actors in the energy sector, using direct PPA contracts with a balancing service provider?

The largest difference between a direct PPA and a traditional contract is the right to benefit that is moved to the consumer. With this right the consumer can trade the energy of the wind farm with a service provider and gain benefit from that. The incentive is created at the consumer to be more aware of the timing of their demand. They can save money when they can adjust their demand in line with the wind production, for example with flexibility options like EVs or buffering. This will decrease their balancing costs and their impact on the grid. It gives opportunities to be more flexible with charging of Electric Vehicles (EVs), (electrical) heating of the house or office and use of power intensive devices in order to gain financial benefit. This is not possible with the current fixed tariffs of utilities. Additionally, the consumer contributes to more renewable energy with this direct PPA. The energy is generated by a turbine and the green certificates are used by the consumer. This increases the amount of renewable energy directly, compared to the indirect contribution of the certificates compensating grey energy.

Furthermore, the incentive of the retailer and service provider is different. The retailer in this current system has an incentive to maximise the energy delivery and to increase its portfolio to better manage the volume risk. The role of the service provider, on the contrary, is to deliver a balancing service so they do not have the incentive to maximise the supply. The service providers invest in smart algorithms to maximise the efficiency of trading the energy mismatch. Additionally, they develop techniques to predict the demand of the consumers in order to control the flexibility or the trading pattern. These tools are focused on the match between supply and demand and are not focused on the number of energy units.

The incentives for the wind farm owner are not different in a direct PPA compared to a traditional contract. Since the retailer has the same PPA with the wind farm in a traditional contract. The wind farm owner still wants a long-term contract to reduce the risk and guarantee the revenue streams.

8.1.4. What is the financial benefit of a direct trade PPA compared to a traditional contract?

The model results show that the direct PPA has a total energy cost of 179.6k which is lower than the costs for a traditional contract of 183.6k. This is a saving of 4k per year. The explanation for this is the saving on the service costs. These costs are 32.7k for the consumer in a direct PPA and 36.6k in a traditional contract. These service costs consist of the costs for trading on the apx market (8.6k euro), the imbalance costs (16.5k euro) and the risk factor of the service provider (7.5k euro). The exact numbers of this result give an example of what the savings could be. It shows that the direct PPA is at least as beneficial as a traditional contract and even a few percentages better. The model run is done for only one year, so the exact result is not directly applicable to other cases but it does show the cost structure of a direct PPA.

8.1.5. What is the effect of energy storage and solar production on the financial benefit of direct PPA?

The effect of the energy storage and solar production is analysed in two experiments. These experiments both show a financial benefit compared to the direct PPA. This benefit is shown for the year 2017 and is an example of the possible impact of the experiments. A Battery Energy Storage System (BESS) reduces the total energy cost and the amount of traded energy, which is a measure for the match between supply and demand. The total saving on the energy costs is 4k and the reduction on traded energy is 12%. However, the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for the BESS are not included in this. These are respectively 2 million in the first year and 7k per year for a BESS of 4000 kWh. The savings do not outweigh these costs and thus the benefit of a private BESS is not positive in the current market conditions. They may improve if the prices on the energy markets increase and become more extreme or if the prices for the batteries decline.

The second experiment with the solar capacity, shows a reduction on the total energy costs of 3k. This saving is the result of lower service costs (1.5k saving) and a lower production and thus lower PPA costs of about 1.6k. However, the saving on the service cost are limited by an increase in the apx market costs of 2k, but this is compensated by the saving on the imbalance costs of 3k and risk factor of 0.5k. The bottom line is that the solar capacity results in a better match between supply and demand. This can be seen by the amount of traded energy which reduced with 25 percent. The solar production compensates for the times of insufficient wind production and the timing of solar production is during office opening hours which has a positive effect on the energy that is directly consumed.

8.2. Recommendation

As a result of the discussion in the previous chapter and the conclusion in this chapter a few opportunities can be identified for further research. The result of this research gives a promising answer to the benefit of a direct trade PPA, subsequently a follow-up research can be done focusing on more modelling periods and other demand profiles. This could also include a better optimisation of the BESS to speculate on prices and the optimisation of the wind capacity vs demand size. The proposed options for the use of EVs could be further looked into, in order to quantify the effect of smart charging and vehicle to grid. These studies are abundant in literature, but can be linked to this PPA structure. Furthermore, the effects of this PPA type on the energy sector and the society could be studied more to gain insight in the consequences when this PPA type is largely rolled out. This research could be focused on the potential users for this PPA and identify the type of users. Another research could look into the future of the energy markets with a high share of renewables and the effect of more bilateral contracts on the market behaviour. Lastly, as mentioned in the limitations, the cost components of the retailer could be decomposed further in another research.

As a final point this new direct trade PPA is already shown to be a beneficial option so it could be promoted to more corporates that want to invest in renewables. Additionally, as this PPA is further implemented and shown its success others can look into the opportunities of bringing this contract type to smaller consumers.

9

Reflection

In this chapter the academic reflection is elaborated on. It will discuss the insights gained in this research and it will address the gaps that are filled in the academic literature.

9.1. Academic Reflection

9.1.1. New Insights

Firstly, a new insight gained from this research is that splitting up the energy contract and the imbalance contract can be beneficial to the consumer. The service provider is at least as effective in trading the imbalances as the large retailers is with their large portfolio of generators and consumers. The model results show that a large portfolio has not a large advantage against a small company that trades solely on the energy markets, in terms of cost for the consumer. The results show that the costs for balancing do not differ a lot between a large retailer and a small service provider. One thing to notice is that the costs for a smaller player on the imbalance market are more volatile. The volatile prices on the imbalance market have more impact on the costs for an individual party than a large portfolio. The high prices are both low and high and they balance each other out. So on average the costs are the same for a portfolio and an individual party. Although, incidentally the costs in a specific year could be high or low for an individual party, for a portfolio these are more stable. Moreover, another small difference is the administrative fee and the ’prikkelcomponent’ in the imbalance market. These extra costs are a relative larger part of the costs for a smaller party than for a portfolio of multiple parties. However, these costs are not a significant part of the costs. So in the end, trading imbalances on the imbalance market is roughly the same in terms of costs for an individual party and a portfolio of a retailer.

Secondly, new insights are gained on the transactions in the energy sector and the allocation of economic incentives and risks to all the parties in this sector. The property rights theory has not been applied to a technical complex system as the electricity sector. Although, the theory is used to analyse the gas sector, but the technical characteristics of gas and electricity differ very much. In the gas sector the timing of supply and demand is less critical than in the electricity sector. Gas can be stored in the network, but electricity should always be in balance and cannot be stored in the network without causing congestion on the transmission lines. This gives differences in the allocation of property rights. This developed framework for the energy sector gives insights that can be used to develop new policies which give incentives to energy consumers to invest in more renewables and more flexibility.

Thirdly, this research shows the energy contracts that may be part of a new energy market and way in which energy is priced. The energy sector is becoming more and more renewable and more consumers generate their own energy. So the market moves to a more service-based model where consumers can contract a separate service for balancing and a separate contract for their energy.

To conclude, in the introduction the problem statements addressed a few problems and gaps in the literature. The prices of the energy providers were not completely transparent, especially the price or costs for balancing supply and demand, next, a framework of the relations and actors in a direct PPA lacked, moreover, the benefits of a direct PPA were not described in the literature. This research has aimed to fill all these three gaps. The property rights framework is an addition to the literature with the purpose to analyse a direct PPA construction and to give insight in the transactions and incentives in the energy sector in general. The price for balancing is now more split out based on the costs for trading on the apx market and imbalance market. Furthermore, the benefits of a direct PPA are quantified in a model and supported by the economic theory. All in all, this research is a step in the right direction to more academic research in the field of direct Power Purchase Agreements.

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A

Appendix

A.1. Model parameters

In Table A.1 the model parameters and constants are shown. These parameters are used as input for the model and are divided in production, price and battery parameters. The abbreviation is shown that is used in the mathematical formulas in section 5.3. The sources of these parameters are given here:
[1] Infinergy (2019)
[2] Gonzalez Aparicio et al. (2016)
[3] Royal HaskoningDHV
[4] Lensink and Van Zuijlen (2015)
[5] Verkaik (2018)
[6] Validation by using data from Open Power System Data (2018)
[7] Lensink (2018)[p.77]
[8] Gonzalez Aparicio et al. (2017)
[9] CE Delft (2016); Wise (2019)

Table A.1: Overview of the input parameters of the financial model with abbreviation, value, unit and reference

Variable	Parameter	Value	Unit	Source
Production				
Capacity Ferrum Wind	Cf_turbine	3	MW	[1]
Capacity factor wind	Cf_wind	-	%	[2]
Windprofile factor	PIF_wind	0.85		[7]
Capacity Solar	Cf_pv	4	MW	
Capacity factor solar	Cf_solar	-		[8]
Solarprofile factor	PIF_pv	0.89		[7]
Percentage Haskoning DHV		20	%	[3]
Number of turbines	Cf_turbine	3	#	[1]
Energy in kW		1000	kW	-
Price				
Margin wind farm		2	%	[3]
GVO price		0.005	€/kWh	[9]
Upper limit price	P_max	0.058	€/kWh	[4]
Lower limit price	P_min	0.025	€/kWh	[4]
Ratio trade on apx		80	%	[6]
Ratio trade on imbalance		20	%	-
Risk factor		30	%	-
Margin retailer		20	%	[3]
Battery				
Battery Power	Cf_b	1000	kW	[5]
Battery Capacity	Cf_b	4000	kWh	[5]
Discharge capacity		90	%	[5]
Ramp rate		1	C	[5]
Efficiency charge/discharge	\texteta charge	90	%	[5]
Minimum energy level		10	%	[5]
Battery Power price	P_batteryP	492	€/kW	[5]
Battery capacity price	P_batteryC	430	€/kWh	[5]
Battery lifetime		3500	cycles	[5]

A.2. Validation Expert Interview

Expert Interview with Rob van Leeuwen from the service company 'GigaWatts'

How predictable is the wind on the day-ahead market?
Rob said that most energy companies currently use a prediction factor of 70 – 80% for the wind energy. This means that if a wind park has a forecast for the wind production that I sell 80% of this energy on the day-ahead market and the rest will be sold on the intraday and imbalance markets.

Is the bandwidth of this prediction error dependent on the size of a wind park?
Yes it is, a single wind turbine has a larger uncertainty than a large wind park. The turbines in a park can level out the variability of the wind out for a bit. However, sometimes this prediction can go sideways. For example in Germany there was a wind park of 300 MW at which the eye of a storm passed exactly by this wind park. This resulted in a wind still period of half an hour what caused a large imbalance.

Are these risks, as the example of this storm, included in the energy price?
Yes, according to Rob they calculate a fixed price for the consumer and in this price, there is a risk factor. The company does a risk analysis and estimate the chance of the case when there is a period without power. In the current market, the effect of renewables is not seen in the risk analysis since the coal plants are still running and can manage these imbalances. At the time when these plants are shut off the prices for imbalances will rise as the renewables have a larger impact.

*What is the risk for you to manage these imbalances on the imbalance market?*Yes, some hours are very expensive on this market but there are also hours when this is the opposite. You have to calculate the demand profile and production profile and compare this to the historic prices of the last five year. Then you can calculate an average imbalance cost and include this in the risk factor.

Is it possible to trade a large part of the wind energy in advance?
Well that is very difficult since you do not know exactly what the wind will do. There is a long-term market on which capacity is traded, but this is not possible for the renewables. This market needs controllable units or something that is 100% predictable like a hydropower plant, nuclear plants or wave power.

Is there a difference between a small service party and a large utility?
Rob agrees and says that when they also include a green certificate to sell the energy as 'green energy'.

Is there any predictable behaviour in the imbalance market or trends you can act on?
Rob: I wish I could forecast the imbalance market, that would give me large revenues if I sell all my power on the imbalance market. The market prices are very unpredictable. You can look at the power that is bid to see if there is a high chance on a shortage in a specific time block. The thing is that the imbalance is caused by a forecast error, not by the mismatch in the program of the TSO. I can predict the price for a block 5 minutes ahead with an accuracy of 70%.

In what times do you use a battery as a tool to manage the imbalance?
The battery I have is focused on the imbalance market. If the prices are high I will sell the energy from the battery and during low prices I charge the battery. At this moment it is not financially attractive to immediately use the energy from the battery to manage the surplus of a customer. The battery is mainly used for short periods like a few days. If you have a week without wind, there must be other buffering sources like hydrogen. The battery can be bid on three markets: the aFRR, the imbalance market and the FCR. You can get contracted by the TSO to be standby until you get a signal from them to supply energy. What are realistic numbers for the costs of a storage unit? I have assumed a price of 500 euro/kWh and 430 euro/KW These numbers are quite accurate, however there are additional costs such as the transformer costs and the network costs. A battery is quite expensive still, they will only get attractive when the coal plants are shut off.

I have assumed a risk factor of 30%, but this is very uncertain. Can you say something about the order of magnitude of this risk factor?
The market price right now is about 5 cent per kWh and the difference between a PPA contract and the consumer price is about 1,5 cents. This margin includes the risk factor, the portfolio risks and the mismatch. These 1,5 cents can be split up to get the risk factor. If you take around 20% than I think you will have a good proxy for the risk factor. So the number you have used is in the range of these 1,5 cents.

How do you look at the pilot projects in the Netherlands about using EVs as vehicle to grid?
That is a very political story. On the market only Nissan pursues this project of vehicle to grid technology. Car manufacturers like Tesla are not very enthusiastic since they cannot guarantee their claim on the range of the EV if the battery is degraded by this vehicle to grid technology. Moreover, the battery is very small for a household to fully make use of for their demand and they have the risk of not having enough battery power left when they leave in the morning to work.

The tax office in the Netherlands is also not very fond of this initiative. This is because the tax on the power supply to the EV is very low, since a large part of the demand is charged against the lowest tax scale. This cheap energy is then used to power the households, instead of the 14 cent that is charged on the energy that is used in-house.

What is your vision on the future energy sector related to this direct PPA contract?
I think the long-term market gets less important as the number of renewables is increasing. The day markets will play a much larger role. In the current structure the generated power is not linked to the demand, the majority of energy is traded in the long-term market. On the contrary, the direct PPAs have a direct link with the demand of consumers and can show directly the origin of the power and ensure that the power is generated by renewables.

Many corporations have the will to use their own power and these contracts play a large role in that. Despite I am not in favour of users that go off-grid, because the surplus power can be easier transported and allocated to everyone if there is a high inter-connectivity.

In the future I think companies will be more in the market of direct PPAs with renewable sources. The consumers will also have a similar construction, but they will take only a small piece of a wind park by joining a corporation that has a contract with the wind park.

How will the market be functioning if more users have direct contract instead of a contract with a large utility?
In my opinion the market does not change much. The imbalance of every user is still traded on the market, but instead of 35 large utilities you have a factor 100 more that trade energy on the markets. I think you will get a new market between the intraday and the imbalance market where users can trade their shortages and surplus, like a small apx market. There are already initiatives of this in Amsterdam, called ETPA. In the new situation the traditional utilities and the service providers become administration offices that do the forecasts and submit the programs to the TSO instead of a focus on trading on the long-term market.

A.3. Results Base Case

In Figure A.1 a week with a relative high demand is simulated in the model to see the effects on the surplus and the cost curve. The demand peaks at 1700 kWh during the day while the production in this week is on the highest point only 1000 kWh. This results in long periods of shortage as can be seen at the negative surplus curve. The prices in the apx market show normal behaviour and do not have a big impact on the total costs. These costs are more directly related to the peaks in the surplus curve as can be seen in the figure. These costs vary around the 75k and 100k.

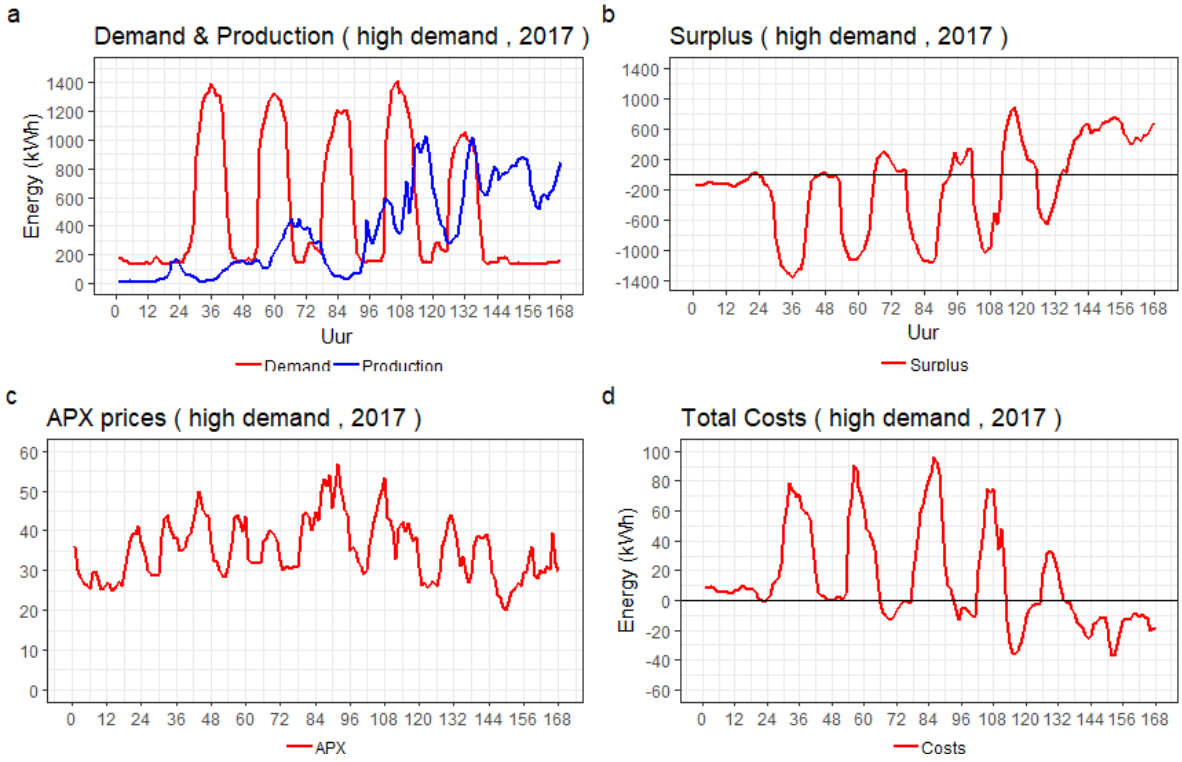

Figure A.1: Effect of a high demand on the surplus and total energy costs in 2017

Next the scenario of a windless week is shown. This is an important scenario to analyse since it is realistic that during the year a few weeks have almost no or very low wind production. During these times a large part of the energy needs to be managed by the service provider. These periods cannot be covered by buffering since this is limited to a period of one day. A possibility is to cover these periods with solar production which may be available during these periods. This is analysed in the second experiment in section 6.3 and in Appendix A.5. In Figure A.2 it can be seen that the surplus is negative almost all the time except for one wind peak during the night when demand was low. The total cost curve shows peaks at 50k for every day of the week since all energy needs to be bought from the apx. The costs are also not lowered by revenues from selling surplus as is the case in a normal wind day.

Lastly, the scenario of a week with a relative low demand is shown in Figure A.3. This is a week in the end of the year during the holidays when the offices are quiet. The demand drops to 750 kWh at the end of the week in the top left figure. The production profile shows high peaks during the weekend, surprisingly not during the weekdays. So this profile does not exactly show high surpluses caused by low demand. The surplus graph is mainly influence by the wind profile which shows high positive peaks in the beginning and end of the week during non-working days. The total costs are lower compared to a week with a normal demand profile, the shortages are lower which reduce the total costs. In conclusion, this week is not very representative for a low demand week, because the wind profile does not as expected cause high production peaks caused by the lower demand.

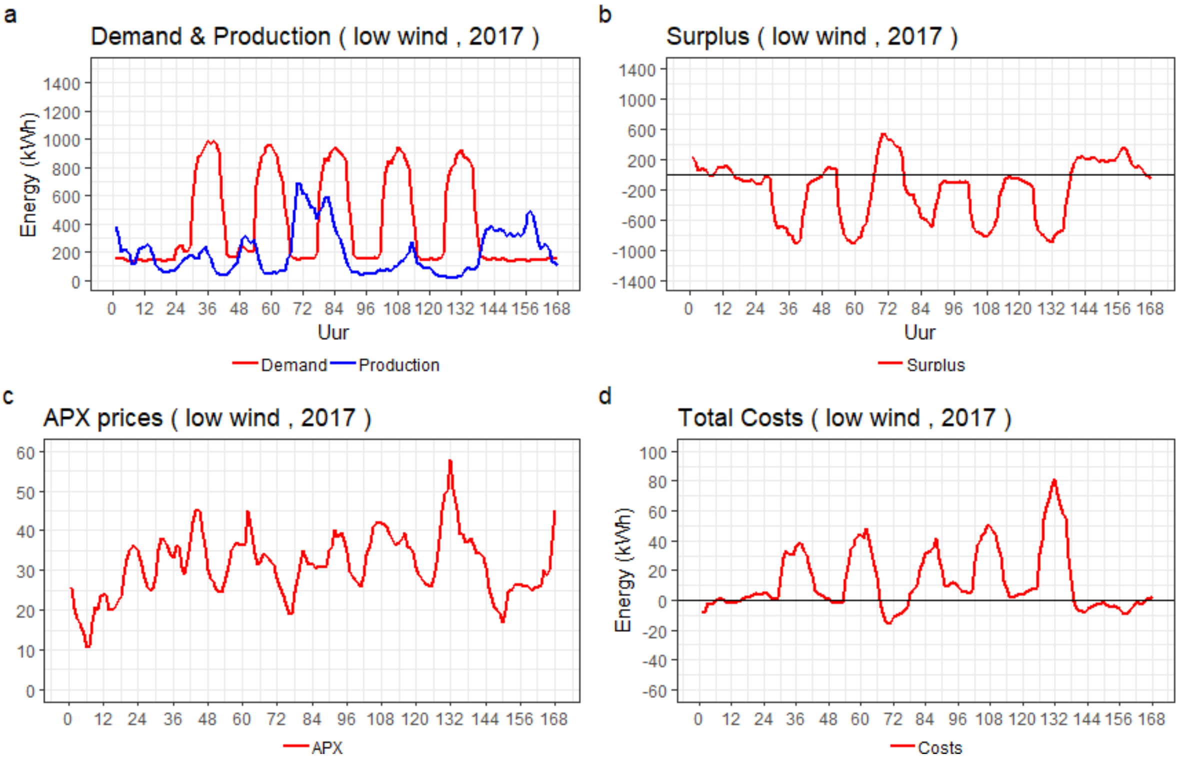

Figure A.2: Effect of a windless week on the surplus and the total energy costs in 2017

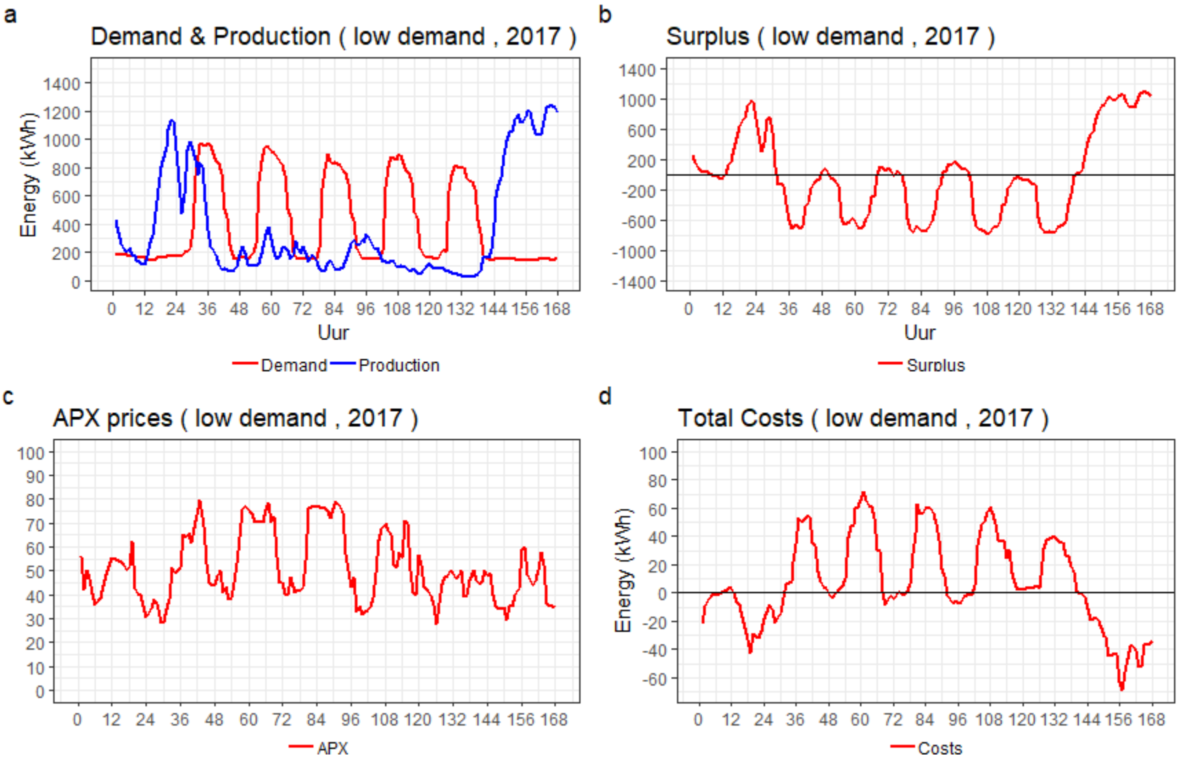

Figure A.3: Effect of a low demand on the surplus and total energy costs in 2017

A.3.1. Sensitivity Analysis

In this section two parameters are more in depth analysed. The trade factor has a high sensitivity and the risk factor is highly uncertain. Both factors determine mainly the service costs of the consumer. The risk factor is a supplement on the balancing price and the trade ratio determines the share of the mismatch that is traded at the apx and the imbalance market. These two factors are analysed using a sensitivity analysis method to see their effect on the results. This is shown in Table A.2 and Table A.3.

The risk factor is varied between 10 percent and 120 percent with a gradually increasing step size. The effect of this changing parameter values is not significantly since the increase from 10 to 20 results in a 9 percent increase of the service costs. The effect of the step from 20 to 40 and 40 to 80 are respectively 17 and 29 percent. So as the input parameter increase with 10 percent, the output is changed by less than 10 percent which is to be expected. This risk factor is not a very sensitive parameter. As the risk factor increases the benefit will decrease. In the model a risk factor of 30% is assumed. For a risk factor of 20% the benefit of a direct PPA will increase to 10k, compared to 4k in the current parameter configuration. On the other side, if the risk is increased to 40% the benefit is evaporated resulting in an extra cost of 2k instead of a saving of 4k.

Table A.2: Sensitivity analysis: The effect of the service provider's risk factor on the service costs of the consumer

Year: 2017	High wind	High demand	Low wind	Low demand	Total Service Costs
Risk factor 10%	€ -410	€ 2.114	€ 2.150	€ 1.153	€ 34.243
Risk factor 20%	€ -447	€ 2.306	€ 2.345	€ 1.258	€ 37.356
Risk factor 40%	€ -520	€ 2.691	€ 2.736	€ 1.468	€ 43.603
Risk factor 80%	€ -670	€ 3.459	€ 3.518	€ 1.887	€ 56.034
Risk factor 120%	€ -819	€ 4.228	€ 4.299	€ 2.307	€ 68.486

Next, the trade ratio is varied starting with a ratio of 80/20 (apx market against imbalance market). As can be seen in the results in the table the impact is quite high. The first step from 80/20 to 60/40 results in a change of the output of 62 percent, while a change of around 20 percent was expected. The other steps result in a 38 percent, 28 percent and 22 percent change in the output value. These last steps from 40/60 to 20/80 and from 20/80 to 0/100 are more in line of the expected 20 percent change. It may be that the imbalance market has a high impact on the service costs, as the service costs are highly increased as the share of the mismatch traded on the imbalance market is enlarged. However, if we look at the absolute difference between the five parameter configurations than we see a constant change. The service costs are increased by 20k as the trade ratio of the imbalance market is increased. This explains why the relative change is high, since the absolute change of 20k has a larger impact on the lower service costs. It can be concluded that the trade ratio is very sensitive and that trading on the imbalance market results in high service costs. The trade ratio in the model is 80/20 and shows a saving of 4k Euros. However, if the trade ratio is changed to 70/30 due to incorrect predictions the savings will drop with 10k. However, the value for the prediction error is carefully selected in this model and the chosen ratio is also validated by the histograms shown below.

In Figure A.4 the histogram plots are shown of the wind prediction errors of the TSOs in Germany. These plots show the range of the error and the frequency. It can be seen that most errors lie around 0 and approximately 0.2. This means that 80% of the wind production can be accurately forecast and on average 20% is variable during the day and need to be balanced by trading on the imbalance market.

Table A.3: Sensitivity analysis: The effect of the service provider's trade ratio on the service costs of the consumer

Year: 2017	High wind	High demand	Low wind	Low demand	Total Service Costs
Trade ratio 80/20	€ -835	€ 2.334	€ 2.471	€ 1.368	€ 33.225
Trade ratio 60/40	€ -208	€ 3.048	€ 3.001	€ 1.568	€ 53.939
Trade ratio 40/60	€ 419	€ 3.762	€ 3.531	€ 1.767	€ 74.653
Trade ratio 20/80	€ 1.046	€ 4.476	€ 4.061	€ 1.967	€ 95.366
Trade ratio 0/100	€ 1.673	€ 5.191	€ 4.591	€ 2.166	€ 116.080

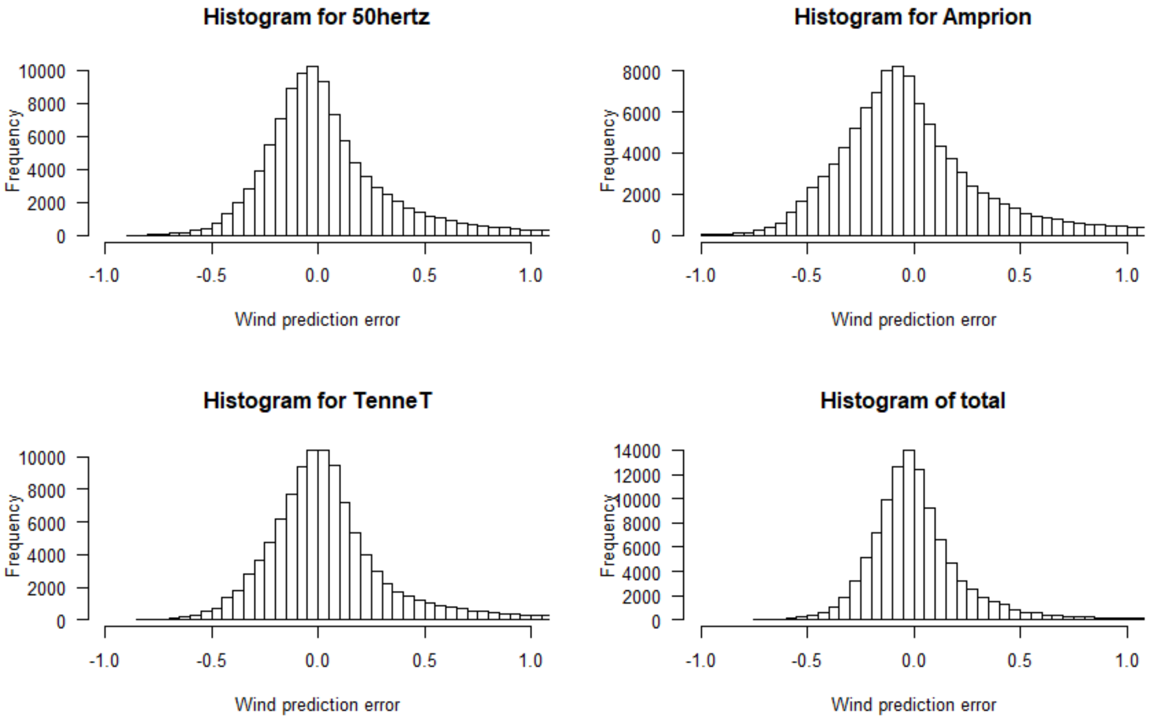

Figure A.4: Histograms of the wind predication error of the TSOs in Germany: showing the distribution of the errors in the period of 2015 until 2017

A.4. Results experiment 1: Buffering

The results of the other model periods are shown in this appendix. The behaviour of the surplus, service costs and battery level are shown for a week with high demand, a week with low demand and a week with low wind production. The figures are briefly described below.

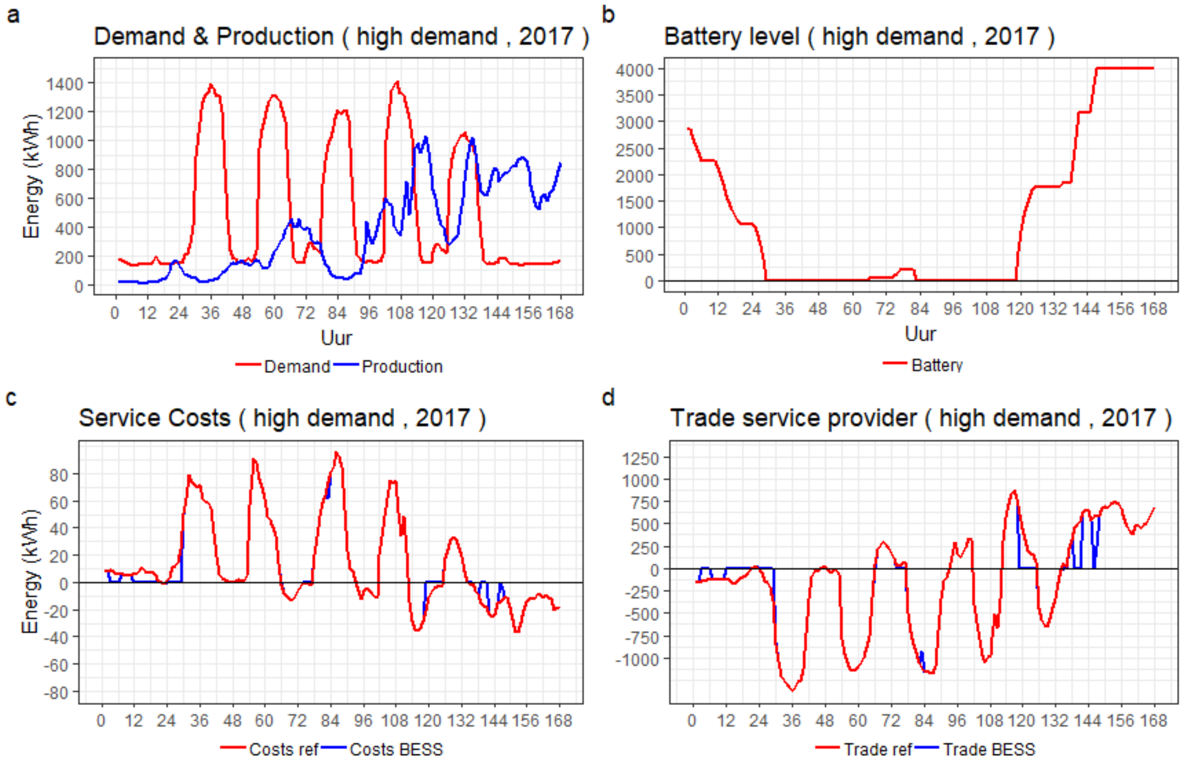

Figure A.5: Behaviour of KPIs with a battery capacity of 4 MWh: week 25 in 2017

In this model period it can be seen that the demand curve is often far higher than the production. This results in a very negative surplus as can be seen in Figure A.5(d). The battery capacity is not sufficient to supply energy during this frequent and high shortages, the battery level is emptied after the first demand peak and only recharged at the end of the week. Evidently the effect on the service costs is minimal.

In Figure A.5 a same result is visible as a week with a high demand. The low production in this week results in a high shortage even when the demand is normal. One thing that stands out is the battery which is discharged at t=84. Even though there are shortages earlier in the week the battery is not used. This could be explained by the restrictions on the battery use that specify the range of imbalance prices within the battery can be used. It could be that the prices on the imbalance market are very low or negative in which the trade of the surplus on the market is more beneficial than using the battery.

In the last figure the results of a week with a low demand is presented. The demand is reduced to a peak of only 800 kWh compared to the normal demand of 1000 kWh. However, while the demand is low the production is still not dominant in the profile and does not result in a very high surplus. The surplus is mainly present during the weekend and night periods when the demand is always low. In this view it is again visible that the battery is only used at t=64 and not in the shortage at t=36. The battery is able to reduce the surplus for a very short period until maximal one day, but after that the battery loses its buffering function since it is not recharged due to low surplus.

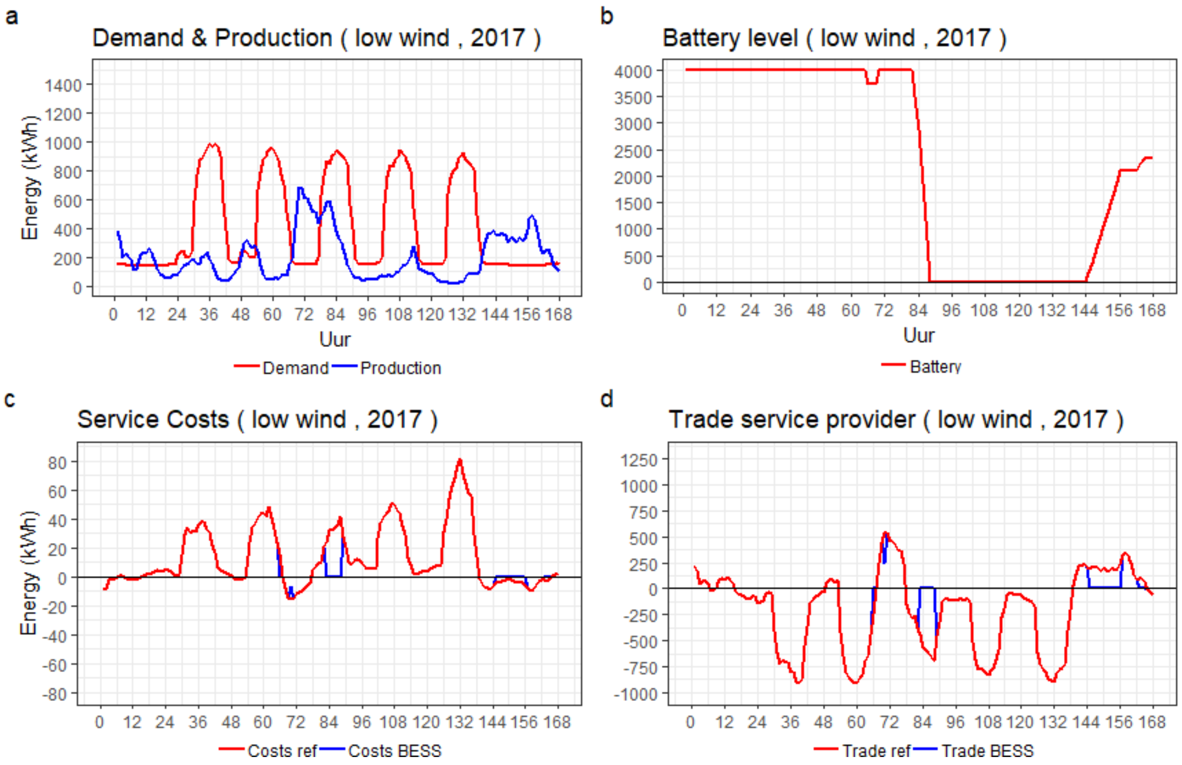

Figure A.6: Behaviour of KPIs with a battery capacity of 4 MWh: week 32 in 2017

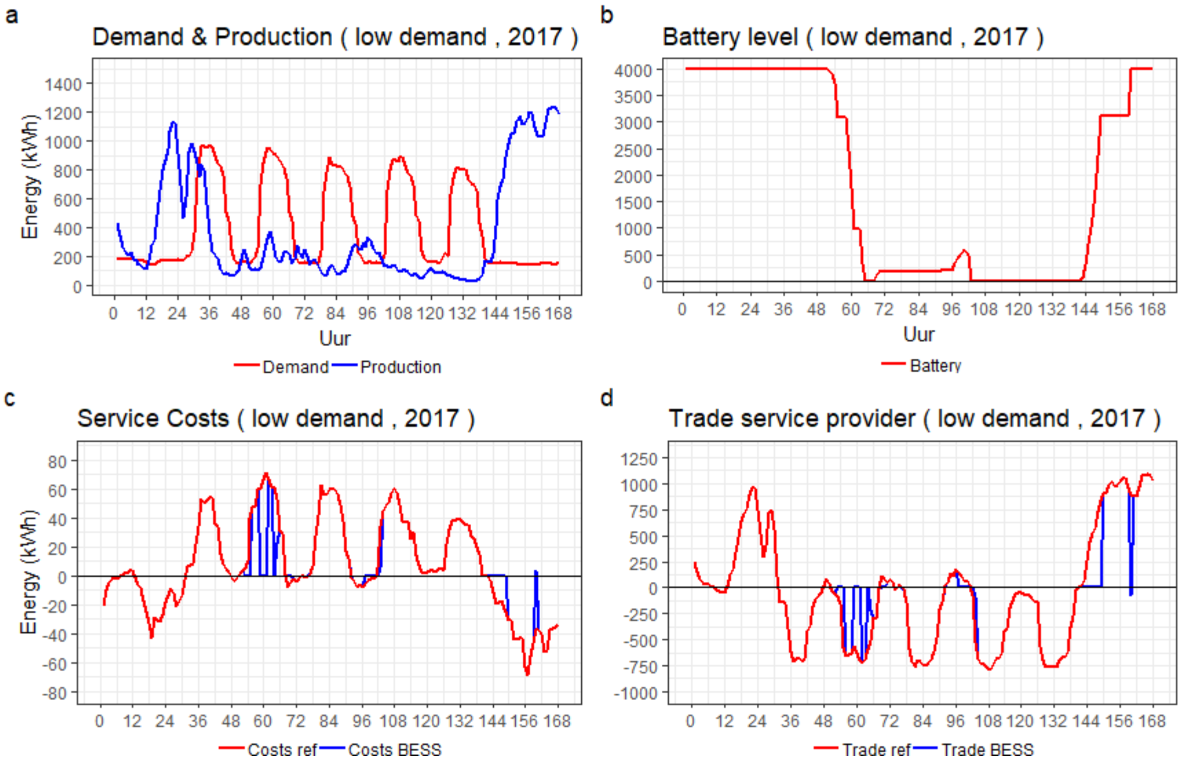

Figure A.7: Behaviour of KPIs with a battery capacity of 4 MWh: week 51 in 2017

A.5. Results experiment 2: Solar production

In this chapter the results of the solar experiment are shown. In chapter 6 the results of a high demand week and a windless week are shown. Here the plots of the other two model periods are shown for the scenario of a week with high wind production and a week with a low demand. These are briefly described below.

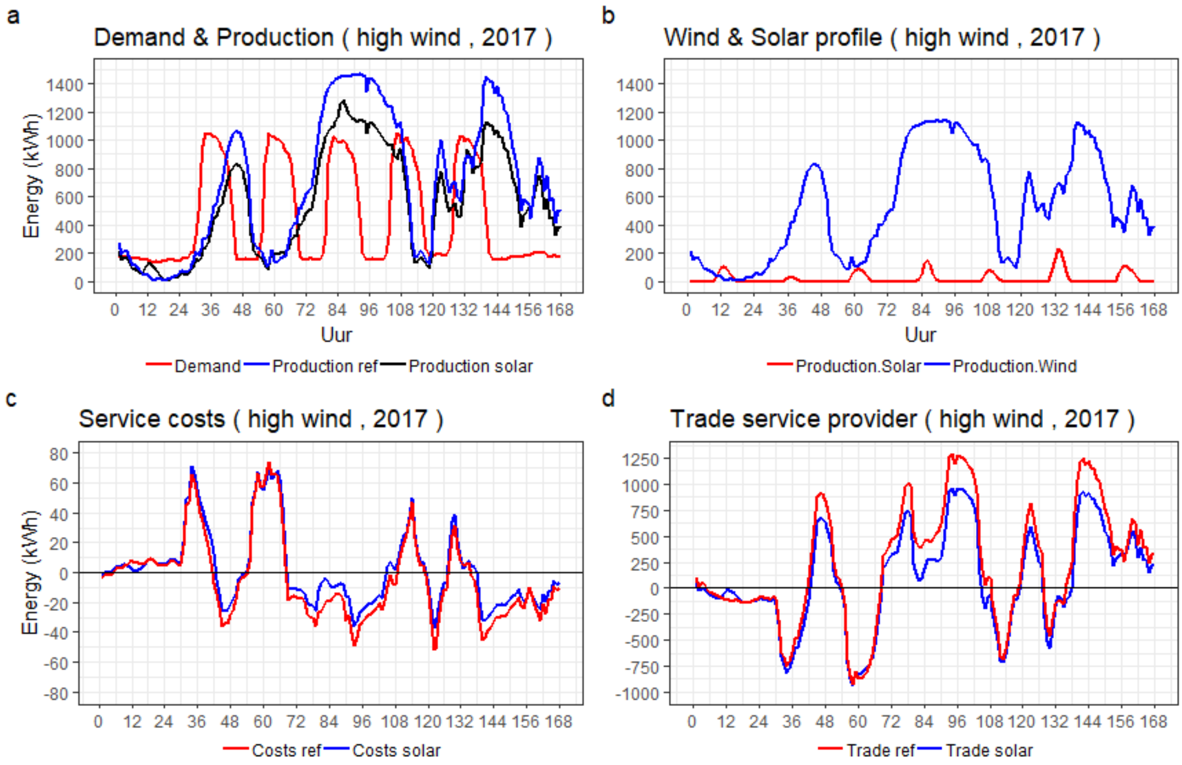

Figure A.8: Behaviour of the production and surplus curves of solar (1.2 MW) and wind (1.4 MW) combi in week 2 of 2017

In Figure A.8 the results are shown for week with a high wind production. In the top left plot the demand is shown together with the production profile of the reference scenario and the solar-wind combination. In both production profiles the production is higher than the demand profile caused by the high wind in this week. The addition of the solar production is almost zero and has not a significant impact on the results. However, the experiment has still a positive influence on the traded energy as is seen in A.8(d). As the production in the solar experiment is lower than the reference scenario the surplus is less high. This has a positive impact on the service costs as these are lower in figure A.8(c). An explanation could be that the prices on the imbalance market are negative at t=72 and t=84 which cause the negative costs during the time of surplus.

In this last plot of a week with low demand the influence of the solar experiment is minimal as can be seen in Figure A.9(b & c). Both the solar production and the wind production are very low and do not match with the demand curve. The production results in high surplus and during the periods of high demand there is a lack of production resulting in shortages. This week is an example of an unfavourable week in the year, but it is good to show this result to show that not every week is favourable for a PPA contract with a wind and solar farm.

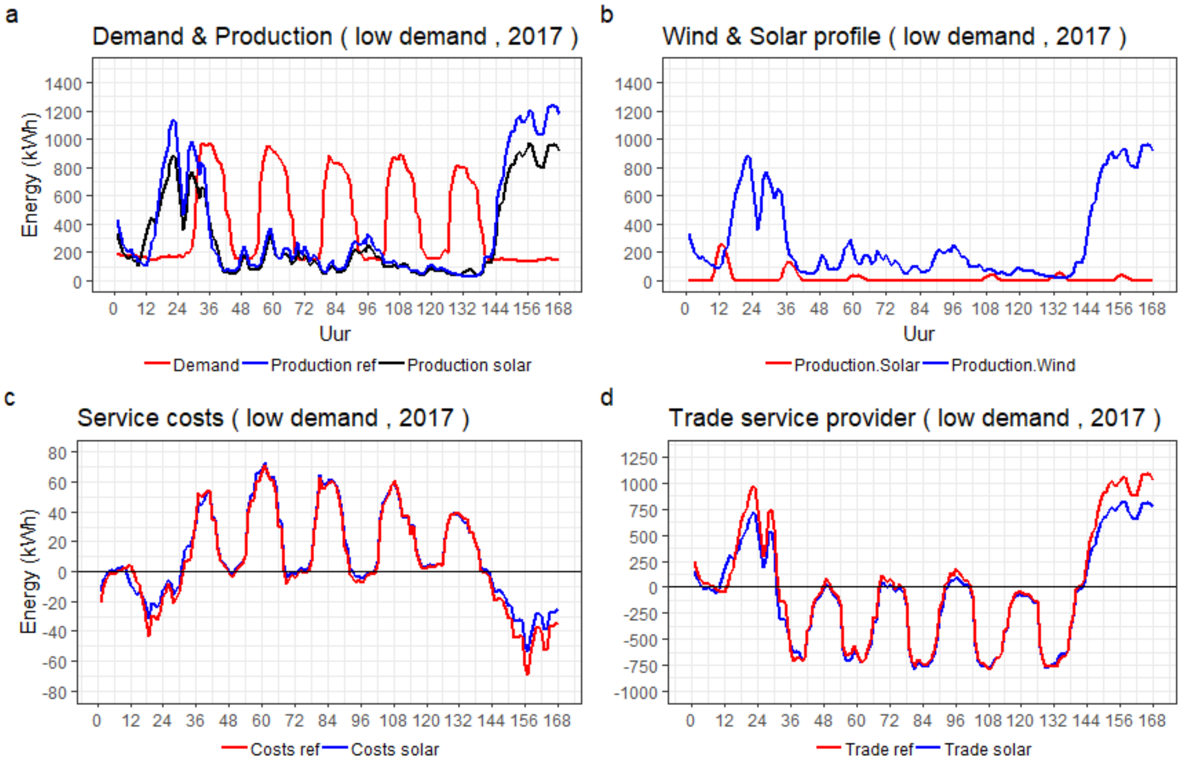

Figure A.9: Behaviour of the production and surplus curves of solar (1.2 MW) and wind (1.4 MW) combi in week 51 of 2017