DERCK KOOLEN

Market Risks and Strategies in Power Systems Integrating Renewable Energy

Market risks and strategies in power systems integrating renewable energy

Market Risks and Strategies in Power Systems Integrating Renewable Energy

Marktrisico's en -strategieën bij het Integreren van Hernieuwbare Energie in Elektriciteitssystemen

Thesis

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Foreword

"Learning is a lifelong process of keeping abreast to change." - P. F. Drucker

This quote, by one of the most influential management scholars in the modern era, nicely relates to my PhD dissertation in front of you. After obtaining my Master's degree in energy engineering about four years ago, I decided to continue learning and move to the fields of economics and management, with a focus on the vibrant and fast changing power sector. Understanding and analyzing the economics, market design challenges and policy implications of the ongoing decarbonization in this sector provided the perfect combination for an exciting, challenging and timely PhD research topic. Now that I have completed this trajectory, there are a number of people I would like to thank for their continuous support along the way.

First of all, I would like to thank my supervisors Prof. Wolfgang Ketter and Dr. Ronald Huisman. Wolf, thank you for getting me on board four years ago and being one of the most positive and energizing scholars during that time, both in Rotterdam and Berkeley. You are a great adviser who always motivates people to raise the best in themselves. Ronald, your enormous enthusiasm and expertise in energy economics definitely inspired and helped me to successfully finish this project. Thank you for all your guidance and support, as well as being a great mentor in general.

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I further would like to express my appreciation to all the amazing colleagues at Rotterdam School of Management. In particular to one of my ’paranimfen’ Micha, not only as an academic brother but also as a great friend. Besides learning the tricks of the PhD trade, I definitely also enjoyed kitesurfing, snowboarding and all the adventures on our conference trips. Davide, Marcel, Christina, Konstantina, Thomas, Amanda, Henk, Mo, May, Laura, Jelle, Timo, Rodrigo, Otto, Cheryl and Ingrid, thank you for making the whole PhD trajectory a whole lot more fun! Special thanks as well go to the scientific developers Erik and Govert, as well as their colleagues next door at the Erasmus Research Institute of Management Natalija, Miho, Kim, Tineke and Balint for all their assistance along the way.

A very warm and loving word of gratitude goes to my family, especially to my parents and both my sisters Ninah and Inez. Thank you for always supporting and believing in me. And of course to my other ’paranimf’, but foremost a very special girl, Stephanie. I am grateful this PhD journey brought you into my life and look forward to all the wonderful moments ahead of us.

And lastly, I would like to thank you, for taking the time to read this manuscript. I hope you enjoy your reading.

Rotterdam, December 2018
Derck Koolen

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Chapter 1

Introduction

Energy markets are going through a series of radical transformations, with the demand for affordable, reliable and sustainable electricity on the rise. Public concerns about the adverse effects on the environment of using fossil fuels to generate electricity have led to a, often politically motivated, increase of renewable energy sources in global power systems. With climate policies at odds with the basic principles of the free market (Mulder, 2017), it is key for a successful energy transition to ensure that markets provide adequate price signals for assets and investments, ensuring security of supply in an efficient and sustainable manner.

The liberalization of electricity markets and the integration of renewable energy have a dramatic impact on power prices. The integration of wind and solar energy sources introduced more low marginal costs suppliers to the market, as no fuels are needed to produce electricity. Most electricity produced by renewable energy sources is however variable and difficult to predict by nature, which in combination with factors such as limited storability and variable consumption, puts current power system operations under pressure and causes prices to fluctuate heavily. Increased competition, new production technologies, lower prices and increasing price volatility completely changed operations in power markets.

There exists extensive research on how producers, retailers and consumers make decisions in power markets (see for instance Conejo et al., 2010). Decisions in electricity markets are affected by uncertainty, as volatile supply and demand profiles may result in price fluctuations or spikes, motivating power agents to engage in forward trading in order to mitigate risks. In this dissertation, we address the effects of an increasing share of intermittent renewable energy sources on price formation in short-term sequential power markets via a multi-method approach. Combining analytic modeling, experimental simulation and empirical validation, the impact of the decarbonization of the power sector is assessed in terms of strategic and risk related behavior, the value of flexibility and market efficiency in relation to the design of electricity markets.

1.0.1 Decarbonizing Power Markets with Intermittent Renewable Energy Sources

At the 21st Conference of the Parties (COP21) in Paris in December 2015, 195 countries adopted the first-ever universal and legally binding global climate agreement. Governments agreed to ensure that temperature increases remain well below 2 degrees Celsius above pre-industrial levels. Likewise, the 2030 climate & energy framework of the European Union contains a binding target for EU member states to reach 40% cuts in greenhouse emission levels compared to 1990 and a 27% increase of the share of renewable energy in total energy consumption by 2030 (European Commission, 2018). As these agreements on the reduction of carbon emissions as well as advances in energy technologies pave the way for reaching a high integration of renewable energy sources in power markets, global investments in renewable energy are on the rise. A record 157GW of renewable power has been installed in 2017 (International Energy Agency, 2018), compared to 70GW in net fossil fuel generation. Recent market developments push this transformation even further with a shift from feed in tariff subsidies to auctions. This resulted in 2017 in a tender for zero-subsidy offshore wind in the Netherlands, zero-subsidy bids in German Contract for Difference auctions and subsidy-free solar wind farms opening in the United Kingdom. With wind generation currently having the largest share of new installed capacity and solar generation the highest rate of growth (International Energy Agency, 2016), this trend is expected to contribute to an increasing amount of variability and uncertainty flowing into power systems and markets.

Power markets are auctions where buyers (retailers) and sellers (producers) can match demand and supply for a given moment. The supply stack is formed by a so-called step curve, ordering short-run marginal costs of different production technologies, as visualized in Figure 1.1. Producers on the one hand may depend on different technologies, which vary on underlying fuel costs and other factors like maintenance, load factors and policy support mechanisms (e.g. subsidies or contracts for difference). The demand curve on the other hand represents the relatively inelastic load of customers (Knaut and Paulus, 2017). Supply and demand are subject to uncertainties and prices may as a result experience volatile and erratic behavior,

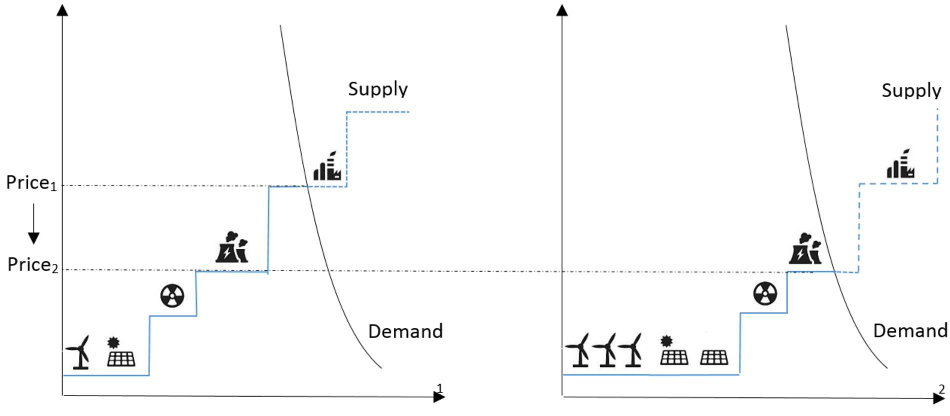

Figure 1.1: Impact of technology on the merit order, visualizing the direct downward effect of an increasing share of renewable energy on power prices in two time periods.

characterized by temporal patterns. Since the renewable energy trend and related technological advances may amplify uncertainties further, adequate pricing in short-term power markets becomes increasingly important for both producers and retailers.

Figure 1.1 visualizes price formation in competitive electricity markets and the effect of technology with an increasing share of renewable power sources. Renewables run at low marginal cost and may even bid at negative prices, when subsidies are sufficiently large. They are followed by nuclear power plants, coal fired power plants and several types of gas power plants, which run at higher marginal costs to compensate for higher fuel costs. Power markets function according to the double auction principle, meaning that the market price, set by the producer running on the margin, is paid to all operating producers. As such, producer surplus is generated to cover fixed costs for all producers with lower marginal costs than the market price. The direct effect of pushing more low marginal cost renewable power on the grid, is however that the expected power price drops. Multiple studies give evidence for decreasing power prices with the integration of renewable energy. Sensfuß et al. (2008) indicate for example that price reduction levels are significant in the German market and may generate profits for consumers, simulating power agent behavior based upon the merit order curve. Empirical studies confirm these results in for example the Dutch (Mulder and Scholtens, 2013) and German day-ahead markets (Benhmad and Percebois, 2018). In this dissertation, we study the direct negative effect on power prices in relation to the intermittent character of renewable energy sources and relate to notions of risk mitigation and strategic behavior in short-term sequential markets.

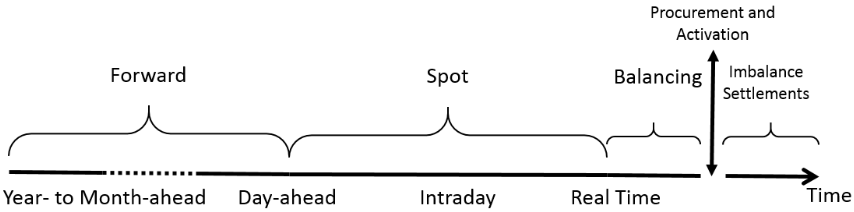

Figure 1.2: Financial electricity wholesale markets with respect to time-to-delivery.

1.0.2 Electricity Auctions: Bidding in Sequential Markets

Electricity is traded in multiple sequential financial markets, which we refer to as a set of forward and spot markets. Sequential markets may help with the efficient allocation of resources for commodities that face uncertainty in price or quantity for a future time of delivery (Ito and Reguant, 2016). Forward markets provide information about future prices and allow market participants to adjust portfolio decisions for future production and consumption. Given that power companies can often only make relative accurate predictions for a limited time horizon (Borenstein et al., 2002), forward markets allow for contract adjustment and risk sharing over spot uncertainty close to real-time. An overview of the different sequential electricity markets with respect to time-to-maturity is given in Figure 1.2. In this dissertation we focus on the relation between short-term forward and spot contracts.

Classic financial literature defines a spot market as the market where the transaction is carried out in the same period as when the decision is made (Mulvey and Vladimirou, 1992). In this dissertation, we consider the spot market to be such a short-term financial market. We define the forward[1] market as the place where agents trade contracts for delivery of power during future periods of time ranging from one day to several years ahead.

Most electricity is traded on forward markets, where market participants aim to balance their physical portfolio through multi-year and month-ahead contracts. Where forward contracts are typically traded over-the-counter via bilateral agreements, day-ahead auctions allow market participants to trade power and adjust nominations according to the double auction principle for every hour of the next day. When during

[1] In this dissertation, we do not distinguish between futures and forward contracts. Both contracts allow traders to buy or sell electricity for a future time-of-delivery. Where forward contracts are typically traded as bilateral contracts, futures are traded on organized exchanges. This means that the value may change as time-to-maturity decreases, converging to the spot price close to real-time. Given we focus on short-term contracts in this dissertation, we refer to both forward and futures contracts when mentioning forward trading.

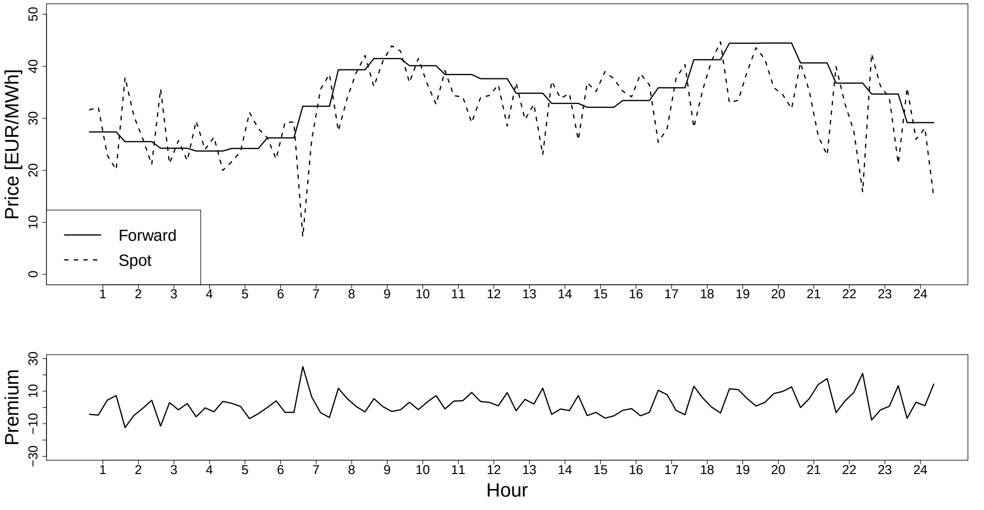

Figure 1.3: Average daily profile of forward (day-ahead) and spot (imbalance) prices in Germany in 2017, and according ex-post premium. Data from ENTSO-E (2018).

the day itself traders still anticipate any imbalances, short-term trading opportunities on intraday auctions allow for trading contracts with a shorter duration on a continuous basis, up to 5 minutes before delivery. Spot markets generally aim to adjust any remaining imbalance in real-time, as the system operator settles bids and asks in order to secure grid stability and reliability. Figure 1.3 gives an illustration of German forward (day-ahead) and spot (imbalance) prices for the average of all days in 2017[2]. The illustration shows a typical daily day-ahead power price profile, with a peak just before midday and another peak in the evening. Following Figure 1.1, these peaks occur on moments when there is a high demand for power. We further observe quarter-hourly spot prices to present more volatile profiles, fluctuating around hourly forward prices.

We focus on rationales for price formation and variations in forward and spot markets in relation to the decarbonization of power markets. With electricity not yet economically viable to store[3], the expectation theory explains the price of a forward contracts to reflect the expected spot price for delivery plus a premium (Fama and

[2]For the purpose of this illustration, we used the German reBAP price, which reflects secondary and tertiary imbalance prices in the German control area. For more information, see Regelleistung (2018).

[3]The economic viability to store electricity varies per country and region. For example hydro power facilities allow a certain degree of flexibility in power systems but are limited by geographic constraints. Furthermore, the implementation of large-scale batteries remains low as arbitrage strategies indicate only limited profitability (Bradbury et al., 2014).

French, 1987). Let us define $p_f^{t,T}$ as the forward price per MWh of a contract that is quoted at time t, for delivery in a future period T. Let $E^t(p_s^T)$ be the expected spot price at time t for delivery of the 1 MWh of electricity in time period T, with the expectation subject to all information available in the market to all participants at time t. The expectations theory states that the forward price equals the expected spot price plus a varying risk premium, with $\Delta p^{t,T}$ the expected forward risk premium at time t to be realized at time T:

$$p_f^{t,T} = E_t(p_s^T) + \Delta p^{t,T} \tag{1.1}$$

The expectations theory deals with deriving the forward price by modeling expectations of spot prices[4] or forward risk premiums. Focusing on the latter, it is usual to translate risk premium behavior to risk-related factors of market agents (Borenstein et al., 2002). Bessembinder and Lemmon (2002) indicate via a general equilibrium model that forward prices are biased predictors of spot prices, and account the emergence of risk premiums to the heterogeneous hedging pressure of producers and retailers. Thereby, the forward premium in essence reflects the net hedging cost of all market participants against spot price uncertainty in competitive markets. Other factors such as limited arbitrage (Jha and Wolak, 2015), trading inefficiencies (Borenstein et al., 2008) and strategic behavior (Murphy and Smeers, 2010; Peura and Bunn, 2016) further also play a role in the emergence of the forward premium.

Several empirical studies have suggested the emergence of positive ex-post risk premia[5], with forward prices higher than realized spot prices for example, for different times to maturity for the American PJM market (Jha and Wolak, 2015) and the NordPool market (Botterud et al., 2010). Others find evidence for negative forward premia, for example Cartea and Villaplana (2008) indicate backwardation in the Nordic, British and PJM market and Redl et al. (2009) in the German EEX market for various time-to-maturity contracts. Moreover, empirical studies that address the behavior of forward premiums in relation to the impact of technology present mixed findings. For example, Huisman and Kilic (2012) discuss significant differences may

[4] Lucia and Schwartz (2002) apply stochastic modeling to observe the seasonal behavior of spot prices. They find expectations over spot prices to consist out of two components; an equilibrium long-term spot price and a mean-reverting short-term price, and hence vary over time in size and sign. They successfully find empirical evidence for the model using data from the Scandinavian NordPool market. Other stochastic models indicate seasonality in both the size and the sign of the risk premium (Pirrong and Jermakyan, 2008). As there is no clear relation between the electricity price and underlying fundamental price drivers like production technologies in these models, we focus on other methodologies in this dissertation.

[5] Note that empirical testing of the expectations theory is challenging as (1.1) presents two ex-ante terms of prices that are observed ex-post.

occur depending on the specific market set-up. Hence, they state that one cannot apply the same model to all markets. As there is hitherto no conclusive view on the role of such heterogeneous production technologies in forward power pricing, we apply a multi-method approach in this dissertation to study the role of technology and renewables in relation to risk preferences and strategic decision making in the context of sequential power markets.

1.1 Main Contributions

Understanding relationships between market participants, renewable technologies and decision behavior are of key importance for devising a robust well-functioning electricity market, its design and its governing policies. Concerned with the effects of increasing market share of intermittent renewable energy sources on price formation processes in sequential electricity markets, the different chapters contribute to two major emerging streams in the management science literature; sustainable operations management (Kleindorfer et al., 2005; Drake and Spinler, 2013) and green information systems (Melville, 2010; Loock et al., 2013; Ketter et al., 2018), and do so via a multi-method approach.

First, we analyze the main functions of forward markets, future price information aggregation and mitigating price risk, in a heterogeneous technological agent setting. The work builds on equilibrium pricing models with risk-averse traders and provides a comprehensive approach by including both high-cost (conventional) and low-cost (renewable) producers. With uncertainty in both demand and supply, non-monotonic risk preferences of producers and retailers result in a tipping point of the forward risk premium with increasing intermittent market capacity. Next to showing the relevance of introducing heterogeneous agents in power market modeling[6], a numerical analysis on the relation to other exogenous market parameters provides further insights.

Second, we explore market information asymmetries and technology non-neutrality by studying different renewable technologies, namely large-scale utility versus distributed 'rooftop' integration. Where the effect of information asymmetries between producers and retailers on market efficiency is relatively well investigated (Bapna et al., 2009; Gregg and Walczak, 2008), environmental transparencies of technologies are still underexposed. Moreover, relatively little work has been done so far to understand the effect of heterogeneous renewable technologies on pricing and risk

[6]This in comparison to the seminal work of Bessembinder and Lemmon (2002), who model a set of homogeneous suppliers in a closed system with unlimited capacity.

behavior. We relate the differences in terms of producer and retailer risk related hedging pressure and validate empirically by comparing short-term prices in two sequential power markets: California and the United Kingdom. Where both countries have experienced a pronounced increase of renewable energy sources in recent years, they differ significantly in the degree of centralization. We contribute by investigating implications for existing market structures, showing evidence for an opposing effect on the forward premium, and their participants' strategic space.

Third, an experimental market setting allows us to evaluate trading behavior of intermittent and non-intermittent producers under truly ceteris paribus conditions. Next to the established function of forward markets to facilitate hedging needs of market agents, the literature also suggests that forward markets enhance efficiency via strategic behavior in oligopolistic market structures (Bushnell et al., 2008; Peura and Bunn, 2016). This second rationale is however still under debate, as different authors discuss the instability of the result (Murphy and Smeers, 2010; Le Coq and Orzen, 2006). We contribute to the discussion by developing an online experimental market environment, simulating trading behavior under different market shares of intermittent capacity. This allows us to spur innovation as it enables us to evaluate market structures under various real-world conditions and alter market design both from market and individual perspective.

Besides these main differences in primary focus, Table 1.1 highlights further differences between the three main chapters in this dissertation. Combining analytic modeling, experimental analysis and empirical validation, the research' multi-method approach allows for a more comprehensive understanding and strengthens claims to validity (Brewer et al., 2006). Furthermore, the chapters incorporate data from distinct geographical locations, based upon the applicability for each specific research question. In terms of renewable energy sources, the Texan (on-shore wind) and Californian (solar and on-shore wind) markets are predominantly characterized by utility-level installations. The British and German markets on the other hand present a more balanced mix of utility-scale and distributed solar as well as on- and off-shore wind installations. Note that spot market design and auction mechanism differ slightly per country and region. As such, the work in this dissertation attempts to give a comprehensive overview of the effects of the integration of renewable energy sources on market market efficiency and pricing in short-term sequential power markets.

Table 1.1: Overview of the differences between the three main Chapters in this dissertation.

	Chapter 2	**Chapter 3**	**Chapter 4**
Primary focus	Risk preferences of heterogeneous producers and retailers	Information asymmetries between renewable technologies	Decision strategies of (non-)intermittent producers
Method	Analytic modeling (competitive equilibrium model)	Empirical study (multi-factor analysis)	Experimental analysis (Online trading environment)
Type of renewable energy sources	Homogeneous (intermittent producers)	Heterogeneous (large-scale and distributed)	Homogeneous (intermittent producers)
Country or region of empirical validation	Texas	California and the United Kingdom	Germany
Time granularity of forward and spot prices	Hourly day-ahead and quarter-hourly real-time (ERCOT)	Hourly day-ahead and 5-minute real-time (CAISO); Hourly day-ahead and half-hourly imbalance (ENTSO-E)	Hourly day-ahead and quarter-hourly imbalance (ENTSO-E)
Programming language	R (simulation analysis)	R (statistical analysis)	Java (Online simulation environment)

1.2 Practical Relevance

The findings in this dissertation are directly relevant for practice and policy[7]. Due to environmental policies, electricity generated by renewable energy sources is recently experiencing a sharp increase with specific annual growth rates as high as 35% (International Energy Agency, 2016). With the ongoing decarbonization, policy makers need to devise measures carefully and ensure that markets provide adequate price signals for assets and investments, as climate policy measures are often in direct conflict with the principles of the free market (Mulder, 2017). Market rules should allow to facilitate the renewable energy transition as well as enhancing the flexibility of power systems, while ensuring security of supply. In this dissertation, we aim to engage policy makers in efficiently evaluating sustainable measures in order to not only facilitate a high integration of renewable energy sources, but also achieve it in a flexible and sustainable manner.

The increase of renewable energy sources and their intermittent character moreover play a crucial role in the investment decision making of power companies, both incumbent utilities and new distributed systems, bound by stringent emission regulations. For example, in 2013 Germany's second largest utility, RWE, posted its first loss since 1949. It attributed the 2.76-billion-euro shortfall to a write-down of its European power plants and since losses continue to increase (Chazan, 2017). In the same year, the country's largest utility, E.ON, said that highly subsidized solar power was a factor in their 14% decline in profits. As short-term financial instruments close to real-time gain liquidity (Knaut and Paschmann, 2017), with increasing uncertainties on both the demand and supply side, understanding risk-sharing and strategic behavior on such markets becomes an increasingly important aspect of utilities' asset management activities in dealing with the ongoing renewable energy transition.

1.3 Outline

The dissertation is structured as follows. In chapter 2, we present a competitive equilibrium model with two heterogeneous types of producer agents and model the role of increasing intermittent production capacity and flexibility. We extent this model in chapter 3, including distributed production at the retail side, and empirically investigate the effect on sequential price formation in California and the United

[7]The main chapters in this dissertation have been presented for a set of different practical stakeholders, policy advisers and governmental institutions. An overview may be found in the back matter of this dissertation.

Kingdom. Next, chapter 4 uses an experimental approach to investigate the effect of intermittent production under truly ceteris paribus conditions, related to notions of both hedging and strategic behavior in sequential markets. We conclude our work in Chapter 5 by revisiting the main conclusions and providing directions for future research.

In the following, we present a brief abstract of each chapter in the dissertation.

Chapter 2 - Abstract Motivated by the ongoing integration of intermittent renewable production sources in wholesale electricity markets, this study focuses on operations in sequential markets with producers operating under heterogeneous constraints. We propose a multi-stage competitive equilibrium model to evaluate the effect of a technology shift from conventional (e.g. natural gas) to intermittent renewable (e.g. wind) producers on sequential price formation. We find a tipping point in the forward premium, driven the non-monotonic behavior of risk related hedging pressure from producers and retailers in relation to increasing intermittent capacity. We explore the technology-varying risk premium in relation to demand, as main drivers of uncertainty on both sides of the market. Our empirical findings suggest evidence for hourly varying fluctuations of the forward premium, oppositely affected by the level of wind penetration and demand. We furthermore quantify the value of flexible trading strategies and find a first mover advantage for integrating flexible assets. The work ultimately engages policy makers to adequately evaluate heterogeneous technological operations and achieve a market efficient integration of renewable energy sources.

Chapter 3 - Abstract While the influence of information transparency on market efficiency is relatively well investigated from a market point of view, environmental transparency affecting the capability of traders to accurately predict and gather information is still underexposed. Power markets provide us a setting to do so, with traditional flexible being replaced by intermittent renewable energy sources. This takes place at both the supply side, from traditional to renewable power sources, and the demand side, with the emergence of distributed renewable power sources. We propose a multi-stage competitive equilibrium model, including intermittent production on both sides of the market, to analyze price formation and the effect of information asymmetry in sequential decarbonizing power markets. We validate the model by analyzing data of sequential short-term markets in California and the United Kingdom; two markets recently experiencing a significant increase of renewable power, respectively predominantly in terms of utility scale and distributed sources. We discuss results and policy measures for creating sustainable smart electricity markets in terms of analytics and IoT devices.

Chapter 4 - Abstract The ongoing energy transition has dramatic impact on pricing and decision making in short-term power markets. This motivates power agents to use forward contracts in order to mitigate risk. Pricing forward contracts however is tedious and empirical literature has presented mixed results applied to markets with different technological constraints. We study strategic decision making and price formation in short-term sequential power markets with increasing intermittent supply by developing a power trading environment. This allows us to implement variations with a high degree of control. Intermittent renewable suppliers drive conventional non-intermittent suppliers out of the forward market, making use of their relative advantage of low marginal costs. In spot markets, however, non-intermittent producers have an advantage as they can adjust their volumes flexible in respond to variation in renewable supply and volatile demand. We find non-intermittent suppliers to change their selling strategy such that they may retain profits when the share of renewable supply in the market increases. We validate our findings empirically for the German short-term power markets and provide insights on the convenience yield for flexibility in future sustainable power markets.

Chapter 5 We revisit the main conclusions and findings in Chapter 5, discuss limitations and give directions for future work.

1.4 Declaration of Contribution

Chapter 1: This chapter is written by the author of this dissertation.

Chapter 2: This chapter is joint work from the author of the thesis, Prof. Dr. W. Ketter, Dr. L. Qiu, and Prof. Dr. A. Gupta. The author of this dissertation is the first author of this chapter and has done the majority of the work. The theoretical framing, analytic modeling, programming of the simulation, and writing of the paper was done by the author of this dissertation. The co-authors contributed by providing significant guidance and feedback in terms of structuring, improving modeling aspects and writing of the paper. A part of the data collection was done by F. van Wegen, for his Master thesis project supervised by the author of this dissertation. The paper is currently under review at a top-ranked journal.

Chapter 3: This chapter is joint work from the author of the thesis, Prof. Dr. D.W. Bunn, Prof. Dr. W. Ketter, and Prof. Dr. A. Gupta. The author of this dissertation is the first author of this chapter and has done the majority of the work. The theoretical framing, analytic modeling, empirical data collection, data analysis and writing of the paper was done by the author of this thesis. The second co-author of this chapter contributed by giving significant feedback in terms of structuring, improving modeling aspects and writing of the paper. The third and fourth co-author of this chapter provided significant feedback in terms of structuring and embedding the work.

Chapter 4: This chapter is joint work from the author of the thesis, Dr. R. Huisman and Prof. Dr. W. Ketter. The author of this dissertation is the first author of this chapter and has done the majority of the work. The theoretical framing, experimental design, testing and conducting of the experiments, data analysis and writing of the paper was done by the author of this thesis. The second co-author of this chapter provided significant feedback in terms of theoretical framing and experimental set-up, and giving it more focus by rewriting parts of the chapter. The third co-author of this chapter contributed by giving significant feedback in terms of structuring and writing. This chapter is currently under review at a top-ranked journal.

Chapter 5: The author of this dissertation wrote this chapter.

Chapter 2

The Sustainable Electricity Tipping Point: The Value of Flexibility in Sequential Markets [1]

2.1 Introduction

The future of the energy sector will, to a large extent, be formed by a transformation of electricity markets, raising economic and societal challenges for traditional electrical power systems. Where the vertical disintegration of utilities and the liberalization of wholesale electricity markets have enabled greater market competition and reduction of prices, electricity markets currently face a transition to meet the growing demands

[1] This paper won the Best Student Paper Award at the 2018 international conference of the International Association for Energy Economics (IAEE) in Groningen, the Netherlands. The paper is currently under review at a top-ranked management journal and parts of the chapter appear in the following peer reviewed conference proceedings:
Koolen, D. (2018). Forward Trading and the Value of Flexibility in Sequential Electricity Markets with Increasing Intermittent Supply. *Proceedings of the 41st International Association for Energy Economics (IAEE) International Conference.* Groningen, Netherlands (10-13 June 2018).
Koolen, D., Ketter, W., Qiu, L. and Gupta, A. (2017). The Sustainability Tipping Point in Electricity Markets. *38th International Conference on Information Systems (ICIS).* Seoul, South Korea (10-13 December 2017).
Koolen, D., Ketter, W., Qiu, L. and Gupta, A. (2017). Market Efficiency and Design in Electricity Markets Integrating Renewable Energy: Theory and Simulation. *2017 Winter Conference on Business Analytics (WCBA).* Snowbird (UT), United States (2-4 March 2017).

for sustainable energy. The shift is complex of nature (Ketter et al., 2016a), involving issues in multiple dimensions including eco-social development and environmental awareness, next to issues related to the security and reliability of supply and critical infrastructure. At odds with the traditional top-down approach in electricity supply chains, these new developments are drastically changing operations in wholesale electricity markets.

The integration of wind and solar power introduces more low marginal cost suppliers to the market, as no fuels are needed to produce electricity, and power prices drop as a result. However, the integration of renewable energy sources, which operate at a variable intermittent production rate, increases the need for flexibility in order to maintain the necessary pre-requisite of balancing load and generation. Intermittent supply from wind turbines and solar panels in combination with limited storability of electricity and relatively price inelastic demand, have caused prices to fluctuate heavily. Key in the transition process is to understand relationships of market behavior by producers operating under heterogeneous constraints (Al-Gwaiz et al., 2016), in order to ensure that markets provide adequate price signals for all assets and investments next to ensuring long-term security of supply in a market efficient manner.

With adequate pricing essential for efficiently integrating sustainable sources in electricity supply chains, we focus on the price dynamics of electricity forward and spot contracts. Sequential commodity markets allow for risk sharing with uncertainty over the good's delivery price or quantity and allow participants to engage in hedging activities to avoid spot market risks from volatile demand and supply conditions. Hedging is however observed to be not fully efficient as persistent price differences are observed based upon the notions of market power (Borenstein et al., 2008), trading period (Longstaff and Wang, 2004) or operational market characteristics (Chod et al., 2010). In the above setting, our study investigates how technological production characteristics, i.e. a heterogeneous set of conventional and renewable producers, affect price formation and producers' ability to trade in sequential electricity markets. As electricity is not yet economically viable to store, agents have to rely on expectations or variation of the forward premium to link spot and forward prices in competitive risk-averse markets. Modeling competitive forward and spot wholesale electricity markets via a two-stage equilibrium approach, we find evidence for a tipping point in the forward premium and quantify the value of flexibility with increasing intermittent supply.

Our paper makes several contributions to both theory and practice of sustainable operations management in the context of sequential electricity markets. First, we contribute to the growing literature on sustainable operations management, adding to one of the key promises of this emerging stream of literature (Drake and Spinler, 2013); to enable production systems to operate more efficiently with respect to their environmental and social impact. We analyze operations in electricity markets transitioning to high market shares of renewable production sources, by developing a theoretical equilibrium model and study optimal forward and spot market positions in order to validate market behavior under varying operational constraints. This allows us to understand how market efficiency and trading by heterogeneous participants may change in future market set-ups. We further study conduct a simulation analysis to mitigate analytically intractable issues and find that operational characteristics of producer technologies affect risk related hedging pressure of both producers and retailers, resulting in a tipping point in the forward premium with increasing intermittent capacity. With prior work indicating non-monotonic behavior of the forward premium, albeit as a function of different quantities like demand variation (Bessembinder and Lemmon, 2002), we explore the relation of the technology-varying forward premium in relation to demand. We next include the notion of flexible trading, and find evidence for a first-mover advantage in quantifying the value of flexibility. As such, the work ultimately contributes to one of the key goals of sustainable operations management; to engage policy makers in facilitating a high integration of renewable energy sources in an efficient manner.

The rest of the paper is organized as follows. We first review the related literature on sequential market trading and relate it to the work on sustainable operations management in the power sector. Next, we develop a two-stage competitive equilibrium model in which different types of power producers are active and conduct a numerical analysis to investigate the implications of the model and relate to the Texan power market. Finally, we include flexible trading to assess optimal market operations in future power systems for both risk-averse and risk-neutral traders. We conclude with a discussion on the contributions and implications, both from a market-economic and policy point of view.

2.2 Background and Related Work

There exists extensive operations management literature analyzing sequential market trading for different commodities (Hankins, 2011; Secomandi and Kekre, 2014), with operational and financial interactions clearly linked in the decision making of the firm (Birge, 2014). Sequential markets help with efficient allocation of resources for commodity goods like electricity, coal, oil and agricultural products, that face uncertainty in price or quantity at delivery (Ito and Reguant, 2016). Our paper considers a model with two sequential power markets, the forward and the spot market. Both markets trade the same commodity, electricity, physically delivered at a specific time slot in the future.

As electricity is not (yet) economically storable on a mass scale, it cannot be carried from one period to another. As a consequence, the cost-of-carry relationship that links spot prices to forward prices, by purchasing an asset in the spot market and storing it for selling it later, cannot be used directly for electricity forward prices. Due to the non-storability of electricity, studies typically model expected forward or risk premium, taking into account notions of risk-aversion and hedging. The seminal work of Bessembinder and Lemmon (2002) discusses the behavior of the forward premium in wholesale electricity markets via an equilibrium approach. The model considers a homogeneous closed system and shows that the price of an electricity forward contract is a biased predictor of the expected spot price during the delivery period, depending on the risk related hedging pressure of producers and retailers. Aïd et al. (2011) have a similar approach, studying the relation between hedging and vertical integration of firms in competitive electricity markets. Motivated by the decarbonization of the power industry, we build upon this work in a heterogeneous producer setting with suppliers operating under different technological constraints.

In recent years, a significant number of countries have experienced, mainly motivated by environmental policies, a sharp increase of renewable energy. With renewables currently accounting for more than 20 percent in global power production and expected to cover more than 60 percent of global power capacity growth until 2020 (International Energy Agency, 2016), the renewable energy turnaround impacts market operations, trading and price formation, as new low-cost technologies are pushed in the supply stack. As a consequence, sustainable operations are recently attracting more attention within operations management (Drake and Spinler, 2013), for example with respect to investment strategies (Aflaki and Netessine, 2017; Hu et al., 2015), market power (Al-Gwaiz et al., 2016) and price formation processes (Gianfreda and Bunn, 2018). With respect to the latter, previous research has however mainly focused on single-period decision problems and relatively little work is available analyzing the effect in sequential markets. Peura and Bunn (2016) model forward and spot trading in oligopolistic power markets with conventional, inflexible and intermittent producers. They find that with increasing supply uncertainty, spot risk may induce an increase of prices when trading incentives favor suppliers. Ito and Reguant (2016) also focus on the strategic behavior in sequential short-term power markets, indicating that incentives for flexible producers with market power to engage in limited arbitrage and prevent full price convergence are larger in the presences of intermittent producers. In turn, we quantify the value of flexible trading and focus on evaluating the technology-varying market price of risk as we consider future power markets with high penetration levels of intermittent sources, where it is reasonable to assume high degrees of competition (Li et al., 2015).

Integrating flexible assets is one of the key solutions to deal with the intermittency of renewable energy producers and can be approached from various perspectives. Next to the relatively well-known approach to consider the value of storage at different delivery times (Zhou et al., 2015), price differences in sequential markets also provide trading opportunities for flexible assets. For example, Wu and Kapuscinski (2013) discuss how renewable operations can be optimized with respect to curtailment. Al-Gwaiz et al. (2016) show that power market competitiveness is affected by generators' technology and degree of flexibility. With only limited financial (virtual) arbitrage available in wholesale electricity markets, we approach the availability of operational flexibility as a prerequisite to exploit arbitrage opportunities from a technology-varying forward premium. This allows us to quantify the value of flexible arbitrage trading in sequential electricity markets with increasing intermittent capacity.

2.3 Approach

We consider two types of power producers, intermittent and conventional, supplying one homogeneous product, electricity. We refer to them as zero-cost producers and high-cost producers respectively and denote the set of the former as Z and the latter as H. Zero-cost producers only have fixed costs and do not bear any marginal costs for producing electricity. Most renewable power plants function in this way and are dependent on weather conditions like solar radiation or wind speed. High-cost producers bear a marginal producing cost increasing with output. This type of producers reflects the more traditional set of power producers, a various set of fuel

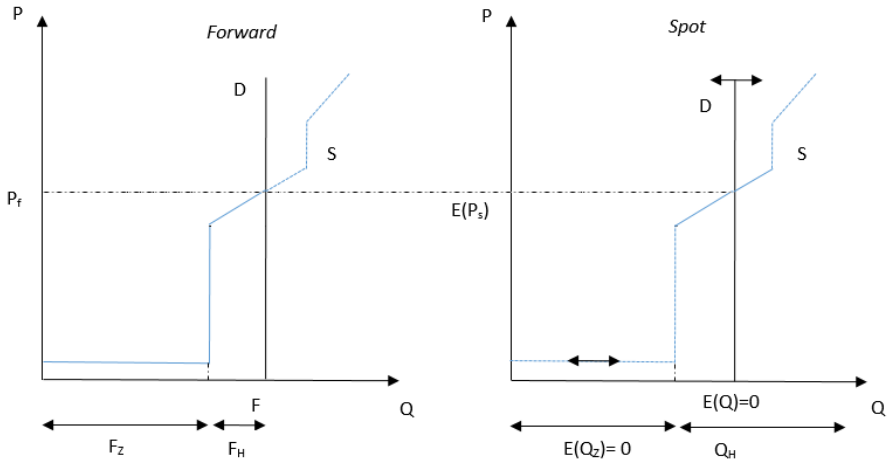

Figure 2.1: Equilibrium forward and spot pricing in a risk-neutral environment.

producers in industry who use different types of technologies, like natural gas, coal or nuclear.

Figure 2.1 provides a graphical interpretation of the price convergence in electricity forward and spot markets. Demand is represented by the inelastic demand curve D and supply by a step curve S, due to heterogeneous supply. For simplicity, we depict only three different types of production sources in the merit order, but this can be extended for markets with an array of different production technologies such as solar, wind, hydro, nuclear oil and gas. F_Z and F_H represent the forward bids, while Q_Z and Q_H represent the spot bids, respectively from zero-cost and high-cost producers. In a fully efficient market, the forward price P_f equals the expected spot price P_s, since market participants will agree on a price on the intersection of the inelastic demand curve with the supply curve following a step function. The expected spot price is in equilibrium equal to the highest marginal cost born by any of the producing facilities. Deviations occur when the demand differs from forecasts or when random shocks occur in the supply curve (Borenstein et al., 2008). The deviations have an expected value of zero and the spot market resolves any mismatches between demand and supply in real time. Therefore, when real-time demand is lower than the forecast or when net supply is lower than expected, net transaction will be negative and the spot price moves down. The opposite occurs when there is a positive demand or excess supply.

As empirical research has shown the emergence of systematic forward premiums (Longstaff and Wang, 2004; Bunn and Chen, 2013), most literature considers the forward premium to reflect risk preferences of various market agents. Interpreting the interplay of risk related hedging pressure of producers and retailers (Bessembinder and Lemmon, 2002), the forward premium is also referred to as risk premium. We follow this approach in this paper, modeling the effect of heterogeneous technological producers on the forward premium in a risk-averse market setting. In the second part of the paper, we investigate how the resulting technology-dependent forward premium induces risk-neutral flexible arbitrage, and model to which extent this in turn results in market efficient behavior similar to Figure 2.1.

2.3.1 Equilibrium model

In order to assess optimal forward and spot positions of power producers, we model the electricity market in a two-stage equilibrium approach. We consider N power producers i that use different technologies to produce homogeneous, non-storable electricity in a competitive electricity wholesale market. There are N_z zero-cost producers and N_h high-cost producers in the supply side of the market.

$$N = N_z + N_h \tag{2.1}$$

Zero-cost producers depend on intermittent weather conditions like the influx of solar radiation, wind speed or rainfall for generating power. The production capacity of each zero-cost producer is therefore represented by a random variable K_i, and can be interpreted as a production constraint by nature, enforcing prediction and forecast accuracy in the forward market. Although not all renewable production sources operate in such way, solar output can for example naturally be ignored during night hours, we focus similar to Ito and Reguant (2016) on the volatile and intermittent production character of zero-cost producers when running at nominal production levels. Total capacity is denoted by $K = \sum_{i \in Z} K_i$. With q_i the quantity of electricity produced by producer i and G_i the fixed operational costs, the production cost is given by:

$$\forall i \in Z; c(q_i) = G_i \tag{2.2}$$

On the other hand, we assume a convex production cost function for high-cost producers. In reality, the cost function normally follows a stepwise convex-similar shape (Bessembinder and Lemmon, 2002), which is usually simplified to a quadratic form to guarantee an interior solution:

$$\forall i \in H; c(q_i) = G_i + e_i {q_i}^2 \tag{2.3}$$

where e_i is a parameter capturing variable cost efficiency. Note that producers employing different production technologies have different fixed cost G_i and variable cost efficiency e_i. We assume G_i to be equal to zero in this work representing a sunk cost thus not affecting the decision-making process.

There are M power retailers j that purchase power in both the forward and spot market and sell it to end consumers at a fixed unit price p_c. Since retailers interact in most countries in the world with their customers via fixed-price contracts on a long-term basis, we consider the retail demand side of the market as inelastic. The end consumers' total demand for electricity is $D = \sum_{j=1}^{M} D_j$, where D_j is a random variable representing the demand for retailer j. We assume the existence of D_j its first moment and second moment. The price inelastic demand assumption is widely used for stylized modeling of short-term electricity markets (Knaut and Paulus, 2017). Retailers are required to meet the demand from end consumers, with the sum of all quantities sold by retailers equal to total demand:

$$D_j = -F_j - Q_j \tag{2.4}$$

Retailers are price-taking in both the forward and spot market. They base their optimal forward position on the expected spot position. For grid stability and security reasons, electricity market operators do not allow speculators to operate in spot markets, nor have contracts with customers directly. They are thus required to offset any remaining position before real-time and translates a cost for market entry. We assume a market where only producers and retailers are active.

At time 1, representing the forward market, each producer i and each retailer j take their forward positions, F_i and F_j, respectively, where $F_j < 0$ represents a purchase from producers, and $F_i > 0$ represents a sell to retailers. At time 2, representing the spot market, the end consumer demand uncertainty is realized. Each producer i and each retailer j chooses their spot positions, Q_i and Q_j, respectively, where $Q_j < 0$ represents a purchase from producers, and $Q_i > 0$ represents a sell to retailers. The market clearing conditions on the forward and spot markets are given by the following two equations, respectively:

$$\sum_{i=1}^{N} F_i + \sum_{j=1}^{M} F_j = 0 \tag{2.5}$$

$$\sum_{i=1}^{N} Q_i + \sum_{j=1}^{M} Q_j = 0 \tag{2.6}$$

Using (2.4), we obtain:

$$-\sum_{j=1}^{M} F_j - \sum_{j=1}^{M} Q_j = D = \sum_{i=1}^{N} F_i + \sum_{i=1}^{N} Q_i \tag{2.7}$$

2.3.2 Spot Market Stage

We solve the equilibrium model of wholesale spot and forward electricity markets by using backward induction. Assuming that the forward market position is given, we begin by analyzing the wholesale spot market equilibrium. Once the optimal positions in the spot market are known, we work back to find optimal positions in the future market. At time 2, the consumer demand uncertainty is realized, and the forward market positions have already been made. The profit maximization problem of producer i is given by:

$$\max_{Q_i} \Big[p_f F_i + p_s Q_i - c(F_i + Q_i) \Big] \tag{2.8}$$

where the spot market price is p_s and the forward price is p_f. The first-order-condition gives us the profit-maximizing quantity sold in the spot market for the high-cost producer;

$$\forall i \in H; Q_i^* = \frac{p_s}{2e_i} - F_i \tag{2.9}$$

The zero-cost producer operates under the constraint that he has to sell K_i at time 2. The spot market position is given once the optimal forward position F_i is known:

$$\forall i \in Z; Q_i^* = K_i - F_i \tag{2.10}$$

Finally at time 2, the consumer demand uncertainty D and low-cost production uncertainty K_i are realized, and the demand from end consumers are required to meet. The equilibrium spot market price is derived using equation (2.7), (2.9) and (2.10):

$$p_s^* = \frac{D - \sum_{i \in Z} K_i}{\sum_{i \in H} \frac{1}{2e_i}} \tag{2.11}$$

The equilibrium spot price depends on all producers their respective e_i and K_i, but when a producer makes a decision, he just treats the price as given. In the spot market maximization problem, a producer does not need to know other competitors' cost parameters or total capacity when deciding its spot market position, since in a competitive market each producer is just a price taker and treats the price as given. Retailers finally are price-taking and required to meet the demand from end consumers following following (2.7).

2.3.3 Forward Market Stage

At time 1, the forward market profit functions of high-cost producer i and zero-cost producer i by considering respectively the optimal quantity Q_i^* given by (2.9) and Q_i^* given by (2.10), and the equilibrium spot market price p_s^* at time 1 are:

$$\forall i \in H; \Pi_i = p_f F_i + p_s^* Q_i^* - G_i - e_i \left(F_i + Q_i^*\right)^2 = \left(p_f - p_s^*\right) F_i - G_i + \frac{1}{4e_i} \left(p_s^*\right)^2 \tag{2.12}$$

$$\forall i \in Z; \Pi_i = p_f F_i + p_s^* Q_i^* - G_i = \left(p_f - p_s^*\right) F_i + p_s^* K_i - G_i \tag{2.13}$$

Note that at time 1, both the consumer demand uncertainty D and zero-cost production capacity K_i are random variables. Retailers sell power to end consumers at a fixed unit price p_c, so the profit function of retailer j is given by:

$$\Pi_j = p_c D_j + p_f F_j + p_s^* Q_j^* = \left(p_c - p_s^*\right) D_j + \left(p_f - p_s^*\right) F_j \tag{2.14}$$

We assume that producers and retailers are risk-averse and use a mean-variance utility function (Levy and Markowitz, 1979). With μ_i the risk-averse coefficient, representing a trade-off between mean and variance, the utility optimization problem for producer i is:

$$\max_{F_i} \Pi_i = \max_{F_i} \left[E(\Pi_i) - \mu_i \mathrm{Var}(\Pi_i) \right] \tag{2.15}$$

We consider a similar utilization optimization problem for retailer j. By solving the first order conditions of optimization problems (2.12) and (2.13), we obtain the optimal forward positions $F_i^*(p_f)$ and $F_j^*(p_f)$, which are function of the forward price p_f.

Using properties of variance and covariance and solving the first order condition gives the profit maximizing quantity sold on the forward market for every market participant:

$$\forall i \in H; F_i = \frac{p_f - E(p_s^*)}{2\mu_i \text{Var}(p_s^*)} + \frac{1}{4e_i} \frac{\text{Cov}(p_s^{*2}, p_s^*)}{\text{Var}(p_s^*)} \tag{2.16}$$

$$\forall i \in Z; F_i = \frac{p_f - E(p_s^*)}{2\mu_i \text{Var}(p_s^*)} + \frac{\text{Cov}(p_s^* K_i, p_s^*)}{\text{Var}(p_s^*)} \tag{2.17}$$

We find that optimal forward positions contain two components. The first term on the right side of (2.16) and (2.17) reflects the response in the forward position to the bias between forward and expected spot price. For example, when the market is in contango, with forward prices higher than expected spot prices, market agents will engage in higher forward position. The second term reflects the forward market position to minimize the variance of profits to the bias in forward price. We indicate that, using (2.11), the covariance in the second term on the right hand side in (2.16) and (2.17), is higher for high-cost producers than for zero-cost producers. Consequently, risk-averse high-cost producers engage initially in higher forward positions with increasing demand and supply uncertainty.

Similarly the profit maximizing quantity for the retailer can be found.

$$F_j = \frac{p_f - E(p_s^*)}{2\mu_j \text{Var}(p_s^*)} + p_c \frac{\text{Cov}(D_j, p_s^*)}{\text{Var}(p_s^*)} - \frac{\text{Cov}(D_j p_s^*, p_s^*)}{\text{Var}(p_s^*)} \tag{2.18}$$

We find that the optimal forward position of retailers depend on three components. The first term on the right hand side represents the response to the bias between the forward and expected spot price. Note from (2.5) that retailers will take opposite optimal forward positions to producers. The second term represents that with fixed retail prices, revenues covary positively with wholesale prices. Opposite to this, the third term represents that for acquiring power, retailers bear risk in wholesale markets. With increasing intermittent zero-cost production, and using (2.11) more volatile spot prices, the third term becomes dominant over the second term and retailer optimal forward positions increase.

For simplification we consider all producers and retailers to have the same risk-aversity coefficient: $\mu_i = \mu_j = \mu$. The optimal forward price can be found inserting (2.16), (2.17) and (2.18) in (2.5):

$$p_f = E(p_s^*) + \frac{2\mu}{N+M}\left[\frac{-N_h}{4e_i}\text{Cov}(p_s^{*2}, p_s^*) - \text{Cov}(p_s^* K, p_s^*) - p_c \text{Cov}(D, p_s^*) + \text{Cov}(p_s^* D, p_s^*)\right] \tag{2.19}$$

The forward price converges to the expected spot price, with infinite number of firms in the industry or if risk is irrelevant to all market participants. The forward price differs from the expected spot price by the sum of four risk related terms between brackets in (2.19). The first two terms represent high-cost and low-cost producer sales revenue risk respectively. The second two terms reflect retailer revenue risk and retailer procurement risk as indicated by (2.18), with the last term opposite to the first three terms. With increasing shares of intermittent capacity, the first and third term experience a linear increase of hedging pressure, whereas the second and fourth term experience an quadratic effect, due to the dependence on both supply and demand uncertainty. Inserting (2.11), we can simplify (2.19) further:

$$p_f = E(p_s^*) + \frac{\mu N_h}{(N+M)2e_i}\left[\text{Cov}(p_s^{*2}, p_s^*) - 2p_c \text{Var}(p_s^*) - \frac{p_c 4e_i}{N_h}\text{Cov}(K, p_s^*)\right] \tag{2.20}$$

2.4 Numerical Analysis

We illustrate the implications of the model with a set of numerical simulations. Empirical testing of the postulate is constrained since the integration of intermittent renewable power sources is a very recent phenomenon and data is scarce. The results of the simulation are illustrative for the relative performance of the forward premium in relation to a changing production technology mix. The absolute numbers are as such not of importance, we follow Bessembinder and Lemmon (2002) for comparison, but shed light on the relative performance via a sensitivity analysis. The aim is to derive qualitative insights and policy recommendations on efficient market integration of renewables.

2.4.1 Tipping Point

In an efficient commodity market, the forward price is an optimal forecast of the spot price at contract termination in the sense that it will only deviate to the extent of a random unpredictable zero-mean error. Following Kellard et al. (1999), we denote the ability of forward markets to predict subsequent spot prices by taking the distance between the forward price (2.20) and expected spot price (2.11). In efficient commodity markets systematic price differences would cause arbitrage, leading to price convergence. Although the specific nature of electricity leads to the existence of no-arbitrage forward premiums, we first focus on the relative behavior of the forward premium with increasing intermittent capacity from (financial) efficient market perspective. The ex ante forward premium is defined as:

$$\Delta p = |p_f - E(p_s^*)| \tag{2.21}$$

In equilibrium, total supply of energy is equal to total demand. Substituting (2.19) in (2.21) suggests that the premium depends on the realized share of intermittent capacity $K/D \in [0,1]$ in the market. Let $T_0 = \left|\Delta p_{(K/D=0)}\right|$ be the equilibrium forward in an initial market without intermittent capacity. We define the tipping point T^* as the optimal share of intermittent capacity in terms of this original market efficiency.

$$T^* \equiv T_0 + \text{argmin}_{K/D} |\Delta p| = T_0 + \text{argmin}_{K/D} |p_f - E(p_s^*)| \tag{2.22}$$

We run a set of simulations to illustrate the dominant risk related hedging pressure effects in (2.21) with increasing intermittent market capacity. Simulating 100,000 demand realizations, the spot price is computed according to (2.11). Next, optimal forward positions are calculated via (2.16), (2.17) and (2.18), rendering the forward price via (2.19). Demand D is normalized with an expected value of 100 MWh. The demand's standard deviation is set to 10 (i.e. up to 10% of mean demand). The number of producers and retailers are set to 100, with a risk-averse coefficient for both producers and retailers μ= 1. The fixed retail price p_c is set as 2 times the wholesale spot price. For simplicity, we assume e_i and K_i to be equal for all high-cost producers and zero-cost producers respectively and we fix $\text{Var}(K_i) = \sigma_K^2$, in accordance with distributions of production prediction errors (Boyle, 2012). Lastly, the cost variable parameter of producers is set to e_i=10, resulting via the derivative of (2.3) in an expected spot price of 20. As such, the spot price is independent of the intermittent market capacity share, allowing to evaluate forward premium behavior across different levels of wind penetration K/D.

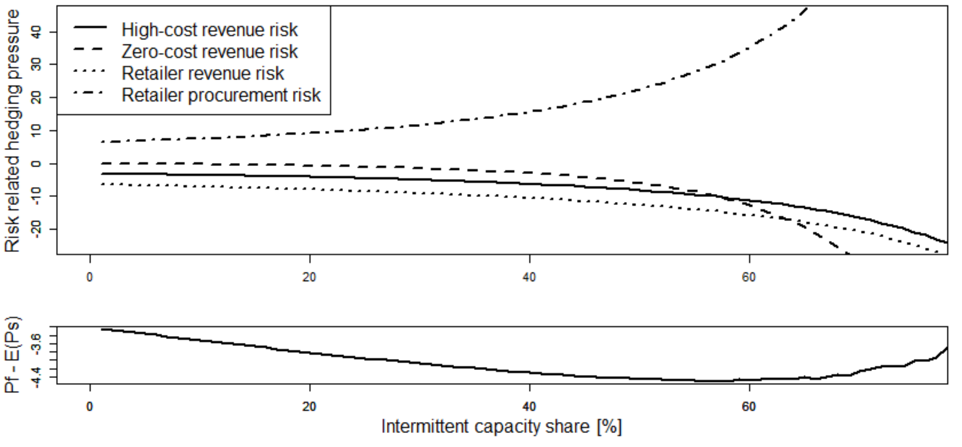

Figure 2.2: Market participants risk related hedging pressure and absolute forward premium with an increasing market share of intermittent capacity.

Figure 2.2 displays the influence on the risk related hedging pressure from high-cost, zero-cost and retailers in (2.19) in price units and the resulting expected forward premium. With more intermittent capacity in the market, producer revenue risk increases, as volatility of the expected spot price increases. Initially, both producer types have similar hedging pressure with increasing intermittent capacity. With wind penetration K/D sufficiently high, zero-cost producers' hedging pressure becomes dominant, facing risks from both spot price uncertainty and supply uncertainty. Retailer revenue risk follows a similar profile to that of high-cost producers, as revenues covary positively with wholesale prices. Retailer procurement risk however becomes dominant with high K/D, as spot demand becomes increasingly volatile. Figure 2.2 shows that through the interplay of market participants' risk related hedging pressure, in sum the forward premium is decreasing for low levels of intermittent capacity, reaches a minimum and increases for higher levels of intermittent capacity. The function of the forward premium thus reaches convexity in K/D, resulting in the existence of T^* in markets with high integration of intermittent capacity.

Figure 2.3 depicts relative forward positions for both types of producers with increasing market share of intermittent capacity with respect to the bias in forward price. At T_0, relative forward and spot positions are equal for both producers. Forward

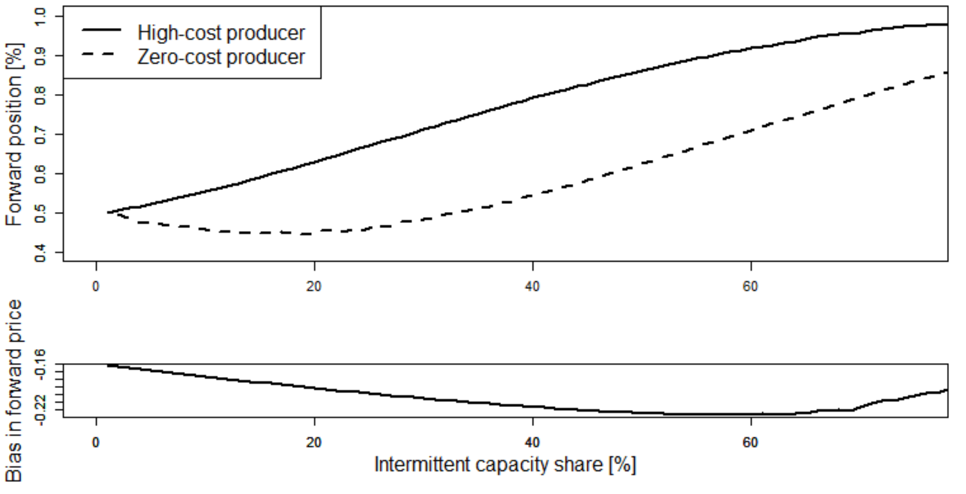

Figure 2.3: Relative forward position of high-cost producers and zero-cost producers with increasing intermittent capacity market share K/D, and bias in forward price with respect to the expected spot price.

positions increase as producers face higher risk related hedging pressure with increasing intermittent production. For relatively low levels of wind penetration K/D, and hence little correlation between K and p_s^*, zero-cost producers face lower hedging pressure than high-cost producers. Figure 2.3 indicates that this results in higher revenues per unit for zero-cost producers, as they do not face producer cost risk.

2.4.2 Sensitivity Analysis

The above analysis shows that with an increasing market share of intermittent production, the bias in forward price with respect to the expected spot price decreases, reaches an optimum and starts increasing again as the results of the interplay between different risk related hedging pressures of the different market participants. We conduct a sensitivity analysis in order to visualize the relative behavior of the tipping point.

Supply and demand uncertainty. The tipping point in the forward premium with increasing intermittent capacity primarily depends on the extent of uncertainty in the market related to risk preferences of market participants, both supply uncertainty of intermittent producers as demand variation of end-consumers. Figure 2.4 illustrates

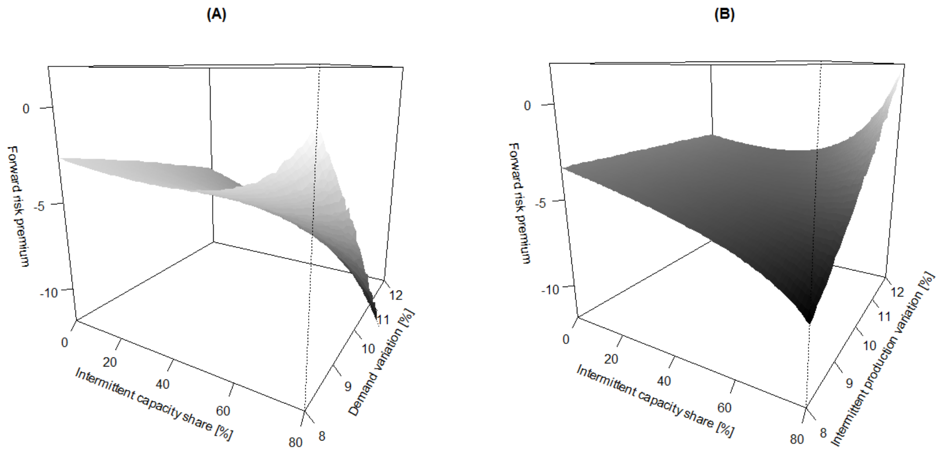

Figure 2.4: Forward premium Δp as a function of intermittent capacity market share K/D and (A) percentage of intermittent production variation and (B) percentage of demand variation. Design for comparison based upon Bessembinder and Lemmon (2002).

the forward premium in terms of these two components. In Figure 2.4(A), the bias decreases with increasing demand variation. This is similar to Bessembinder and Lemmon (2002), who indicate that risk related hedging pressure of producers is dominant over that of retailers with quadratic supply cost functions. Interestingly however, we observe that with low demand uncertainty and high intermittent capacity, the bias may reach a tipping point. The intuition is that, following from (2.11), demand uncertainty and intermittent production uncertainty relate oppositely to the forward premium. Hence, retailer related hedging pressure will be dominant at low demand uncertainty levels. Figure 2.4(B), showing the forward premium with increasing intermittent production variation, indicates a similar result. The bias decreases for low intermittent capacity variation and increases for higher relative variation. The intuition is that in markets with low supply uncertainty τ_K, producer revenue risk is dominant over retailer revenue risk. With higher supply uncertainty, wholesale procurement risk of retailers increases and becomes the dominant factor.

Empirical exploration of relation to demand. Market characteristics, fixed in the simulation by exogenous parameters, define the degree of convexity and relative dominance of the risk related hedging terms in (2.19). The role of demand is thereby particularly crucial, as the variation is one of the main drivers for uncertainty. For example, Bessembinder and Lemmon (2002) also indicate non-monotonic behavior of the forward premium with increasing demand, but find this result for closed systems with homogeneous set of producers. In Figure 2.5, we explore this relation further in our set-up with heterogeneous producers and uncertainty on both sides of the market. The figure shows a sensitivity analysis of the k-contour curve representing $|\Delta p| = k$ with given share of intermittent capacity for demand D. We observe that the optima of the k-contour curves in Figure 2.5 divide the behavior of the forward premium in the K/D space. First, with high demand and low intermittent capacity, increasing market share of intermittent producers results in decreasing forward premiums. Second, with low demand and high intermittent capacity, forward premiums increase with higher market share of intermittent producers. This suggests that producer risk related hedging pressure is dominant in the upper-left part of the figure, whereas retailer risk related hedging pressure is dominant in the lower-right part. With power demand levels experiencing significant variations throughout the day (Knaut and Paulus, 2017), an increase in intermittent capacity may therefore drastically impact the forward premium.

We compare the qualitative result with power prices from Texan short-term power markets. Summary statistics for our data set are given in Table 2.1. Two interesting developments in this market drive the motivation to select the Texan market. First, Texas is defined by a vast share of wind production resources, with in 2016 generation accounting for 15% of total generation and a outspoken political target to rely fully on wind by 2025 (Potomac Economics, 2018). Second, Texan wind farms are characterized by specific daily generation profiles, with high production during night hours and low production in the morning hours as a result of a specific wind stream in the West (Potomac Economics, 2018). Figure 2.6 visualizes load and wind output levels for the average day over the period of 2016. We observe that there is pronounced mismatch between wind output and load levels in Texas. This allows us to obtain a high-quality data set over a relatively short period of time, which is necessary to assume that all other driving price factors, for example gas prices or number of market agents, remain similar. Following the result of the simulation in Figure 2.5, we thus expect negative forward premium correlations with wind during peak hours and positive correlations during off-peak hours.

Similar to Longstaff and Wang (2004), realized ex post forward premiums can be expressed as:

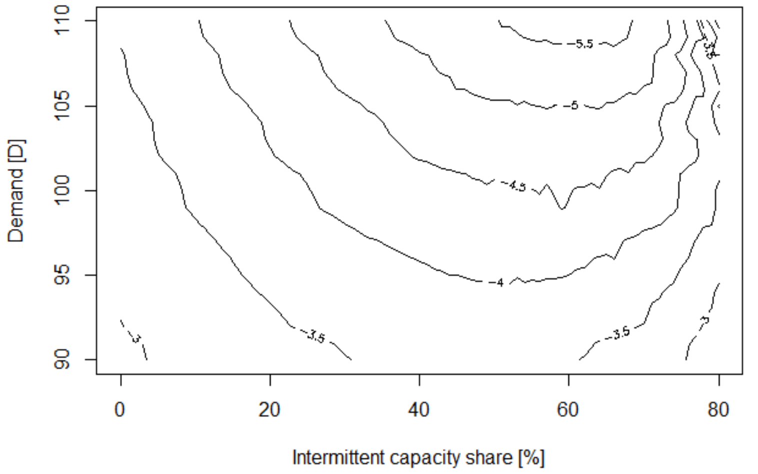

Figure 2.5: Forward premium Δp contour plot as a function of intermittent capacity market share K/D and demand.

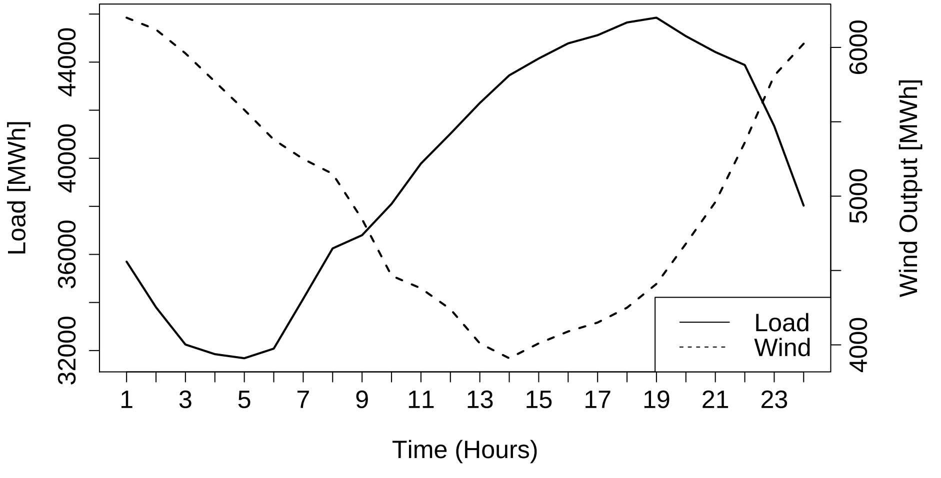

Figure 2.6: Average hourly load (left) and wind output (right) for 2016 in the Texan power market. Data from ERCOT (2018).

Table 2.1: Price and market summary statistics, Texas (ERCOT) 2014-2016.

	mean	sd	median	min	max
Forward price	28.65	31.80	24.23	1.18	2236.63
Spot price	27.32	51.81	22.35	−108.81	2038.82
Load	39481	9169	37305	24018	71243
Wind Output	4940	3074	4498	14	15722

$$p_f^{t,T} - p_s^T = E_t(p_f^{t,T} - p_s^T) + \epsilon^T \tag{2.23}$$

Where the unexpected component of the forward premium ϵ^T is orthogonal to all information available at t. We estimate the effect of hourly wind penetration predictions set at time t on the ex post forward premium via univariate OLS, parallel to the approach of Longstaff and Wang (2004). As before, we refer to wind penetration as the share of wind output over the load for every specific hour in time K/D. In order to ensure the maximum likelihood estimator, we square root transform the data to a near normal distribution. Hypothesis tests use the Newey-West covariance matrix, robust to heteroskedasticity and serial correlation. Results are given in Table 2.2.

Regression results generally support our model's predictions in Figure 2.5, with respect to coefficient sign, hourly pattern and statistical significance. We observe mainly positive significant correlations for the morning hours, with as indicated by Figure 2.6 wind penetration levels relatively high compared to load. In contrast, negative significant correlations are found for the afternoon and evening hours, where load is much higher compared to wind penetration. Note that actual load may increase significantly during peak hours in the afternoon and evening. Although the assumption of quadratic costs in (2.3) may not hold any longer in that case, generalizing (2.11) by following Bessembinder and Lemmon (2002), suggests that our qualitative result remains the same, indicating an opposite effect between demand and wind penetration levels.

To conclude, our simulation results show that including heterogeneous agents is key in competitive power market modeling, as the sign of the forward premium may change dependent on the share of intermittent producer capacity. With uncertainty on both the demand ans supply side, the technology-varying forward premium can be related back to risk related hedging pressures of producers and retailers. The following

Table 2.2: Hourly estimates of wind penetration K/D correlation with the forward premium, 2014-2016. T-statistics in parentheses.

Dependent variable: $p_f^{t,T} - p_s^T$			
Hour	Wind Penetration K/D	Hour	Wind Penetration K/D
1	1.06 (0.52)	13	-2.40*** (-7.45)
2	1.84*** (3.5)	14	-2.54*** (-3.95)
3	5.45* (1.88)	15	-0.17 (-0.47)
4	5.03** (2.2)	16	-2.52*** (-5.83)
5	1.54* (1.70)	17	-0.77* (-1.74)
6	1.74 (0.97)	18	-1.58 (-0.87)
7	3.17 (1.56)	19	-1.79 (-1.15)
8	1.50* (1.93)	20	-1.41** (-2.04)
9	-0.62 (-0.61)	21	0.57 (0.54)
10	-0.17 (0.47)	22	-1.15** (2.1)
11	-1.57* (-1.86)	23	1.06 (0.53)
12	-1.54 (-1.5)	24	1.93 (1.33)
Observations per hour			1096

Note: *p<0.1; **p<0.05; ***p<0.01

section discusses the rationale of deployment of flexibility, next to the rationale of hedging, in sequential electricity markets.

2.5 The Value of Flexibility

In the present-day market context, the above model indicates a value for arbitrage trading strategies in electricity markets transitioning towards a high market penetration of intermittent renewable power sources. Although participation by purely financial companies is still limited in many wholesale electricity markets, virtual bidding has recently been introduced in several markets in order to enhance efficiency in wholesale electricity markets by converging market prices (Li et al., 2015). Virtual bidding allows market participants to arbitrage price differences, most commonly between day-ahead and real-time markets, without physically trading energy. Pure financial traders or virtual bidders are active in most major liberalized American wholesale markets (Birge et al., 2017), whereas profitable financial trading strategies have also been identified in for example Germany (Just and Weber, 2015) and Spain (Ito and Reguant, 2016). Virtual financial bidding and arbitrage however only play a limited role in current power markets, as price differences continue to persist in many markets. This has mainly been attributed to market design issues and market manipulation (Borenstein et al., 2008; Birge et al., 2017), high transaction costs(Jha and Wolak, 2015), low risk-adjusted return (Li et al., 2015) and limited access to capital (Birge et al., 2017). Furthermore, Ito and Reguant (2016) indicate that exogenous arbitrage is often limited in power markets as participation is restricted to traders with production assets. We therefore consider physical flexible assets to be a necessary requirement for traders to engage in profitable trading strategies from the above indicated fluctuating forward premium.

We include the notion of operational flexibility in sequential power markets by first considering a cooperation of intermittent and flexible assets. Combining the ownership of these two assets in the same portfolio allows to mitigate the risks from uncertainty from either side of the market in agents' production portfolios. Second, we consider pure arbitrage with flexible assets, in order to avoid distortions of market competition.

2.5.1 Flexible Cooperatives

We consider the presence of energy cooperatives in the market, combining intermittent production and flexible storage assets in the same portfolio. With intermittent capacity fixed, introducing energy storage in the portfolio of intermittent renewable energy producers makes sense as it creates an incentive to store(discharge) energy for the future, when the spot price is low(high). To derive equilibrium prices in sequential markets with the existence of cooperatives, we need to find optimal spot and forward positions of the cooperation in the market. We assume all zero-cost producers to have the same maximum amount of flexible storage available C, with C_i the maximal individual flexible capacity. We therefore keep the set of market participants the same as in (2.1).

At the *spot market stage*, the positions of the zero-cost producer with flexibility is updated to:

$$\forall i \in Z; Q_i^* = K_i - F_i + B_i \tag{2.24}$$

Where B_i represents the amount that is stored in the individual flexible storage capacity, for example a battery, at spot stage with $B = \sum_{i=1}^{N_f} B_i$. As indicated, high spot supply uncertainty renders high risks for all market participants. In equilibrium, a zero-cost producer with flexible capacity will optimally utilize B_i by reducing his own spot uncertainty:

$$\forall i \in Z; B_i = \begin{cases} \max\Big(-C_i, -\eta(K_i - E(K_i))\Big) & \text{if } K_i > E(K_i) \\ \min\Big(C_i, -\eta(K_i - E(K_i))\Big) & \text{if } K_i < E(K_i) \end{cases} \tag{2.25}$$

The flexible storage position is a random variable with expected mean of zero and opposite from the cooperation's production deviation. To be stored, electricity must be converted into other forms of energy and converted back to electricity when called upon. The efficiency of the process depends highly on the technology used. For example, see Dunn et al. (2011) for an overview of battery technologies, identifying charge and discharge rate, lifetime and system costs as key performance measures for the efficiency of the storage system. The storage efficiency, denoted by η, measures the proportion of energy recovered after the storing and releasing operations. In equilibrium, this represents an opportunity cost for the cooperation, as part of the stored energy is not resold in the spot market. The updated optimal spot price becomes:

$$p_s^* = \frac{D - \sum_{i \in Z} \big(K_i + B_i\big)}{\sum_{i \in H} \frac{1}{2e_i}} \tag{2.26}$$

At the *forward market stage*, we assume that cooperations are risk-averse and use the mean-variance utility function to optimize their respective profit function. Following similar steps as before, we obtain the optimal forward price.

$$p_f = E(p_s^*) + \frac{\mu N_h}{(N+M)2e_i}\left[\mathrm{Cov}(p_s^{*2}, p_s^*) - 2p_c\mathrm{Var}(p_s^*) - \frac{(p_c 4e_i)}{N_h}\mathrm{Cov}(K+B, p_s^*)\right] \quad (2.27)$$

When we compare (2.27), where intermittent production forms a cooperative with flexible assets, with the result without cooperatives in (2.20), we find a reduction of hedging pressure related to supply uncertainty. In this set-up, high-cost producer revenue risk becomes dominant over risk related hedging terms in (2.19) and the forward premium would decrease monotonically with increasing intermittent supply. The result shows the beneficial impact for traders with flexible assets over those without, by mitigating uncertainty in the production portfolio. Intuitively, other market agents would follow, minimizing the risks from supply uncertainty across the whole market in equilibrium. In the following we therefore model flexibility as separate trading entity, to isolate the impact of technology and flexibility.

2.5.2 Flexibility Trading

We next focus on flexible traders that speculate on the forward premium in competitive sequential electricity markets. Each flexible trader is denoted by i belonging to the set of flexible traders F. We update our model, given the presence of N_f flexible traders:

$$N = N_z + N_h + N_f \quad (2.28)$$

A flexible trader, unlike a pure financial speculator, can assure trading capacity up to his maximum production or storage capacity. Therefore, we limit the total maximum trading position of flexible traders to W, representing maximum capacity of the physical flexible assets in the trader's portfolio. Flexible traders maximize utility by acting as speculators in sequential markets, with in equilibrium, benefiting from uncertainty in both markets.

In the *spot market stage*, each position of flexible traders is given once the optimal forward position F_i is known:

$$\forall i \in F; Q_i^* = -F_i \quad (2.29)$$

With W_i is the maximum individual capacity, which we consider equally divided over all N_f flexible traders, the profit of speculator $\forall i \in F$ is given by:

$$\max_{F_i}\left[(p_f - p_s^*)\,F_i\right], |F_i| \leq W_i \tag{2.30}$$

At time 2, consumer demand uncertainty and low-cost production uncertainty are realized. Flexible traders act as price takers and hence the equilibrium spot market price remains equal to (2.11).

At the *forward market stage* or time 1, flexible traders optimize their expected profit, taking into account the optimal spot quantity in (2.29).

$$\forall i \in F; \Pi_i = p_f F_i + p_s^* Q_i^* = (p_f - p_s^*)\,F_i \tag{2.31}$$

Incorporating the positions of flexible traders, the forward price p_f in (2.19) is updated. Given that in the forward market stag, p_s^* is unknown, as demand uncertainty D and zero-cost production capacity K_i are random variables, flexible traders maximize expected utility. First, we assume flexible traders' risk-averse coefficient $\mu_i =]0, \mu]$, with μ representing the risk-averse coefficient by all other market participants similar to before. By solving the first order condition of optimization problem (2.31), we obtain the optimal forward position for a flexible trader.

$$\forall i \in F; F_i = \begin{cases} \min\left(W_i, \frac{p_f - E(p_s^*)}{2\mu_i \mathrm{Var}(p_s^*)}\right) & \text{if } p_f > E(p_s^*) \\ \max\left(-W_i, \frac{p_f - E(p_s^*)}{2\mu_i \mathrm{Var}(p_s^*)}\right) & \text{if } p_f < E(p_s^*) \end{cases} \tag{2.32}$$

Note that separating flexible assets from other agents implies that optimal forward positions in equations (2.16), (2.17) and (2.18) remain the same. Filling in respective forward positions and (2.32) in (2.5) renders the forward price with flexible trading. When the maximum trading capacity W is not reached in (2.32) and $\forall i; \mu_i = \mu$, the optimal forward equation remains similar to (2.19), only with updated number of market participants according to (2.28). When flexible traders become more risk-neutral, adding flexibility does not change the interplay between risk related hedging terms of other market participants, but does decrease the absolute effect.

With risk-neutral flexible traders and enough available speculative capacity, the forward price is equal to the expected spot price. However, in case maximum trading capacity $W_i^* \in (-W_i, W_i)$ is reached, the forward premium becomes:

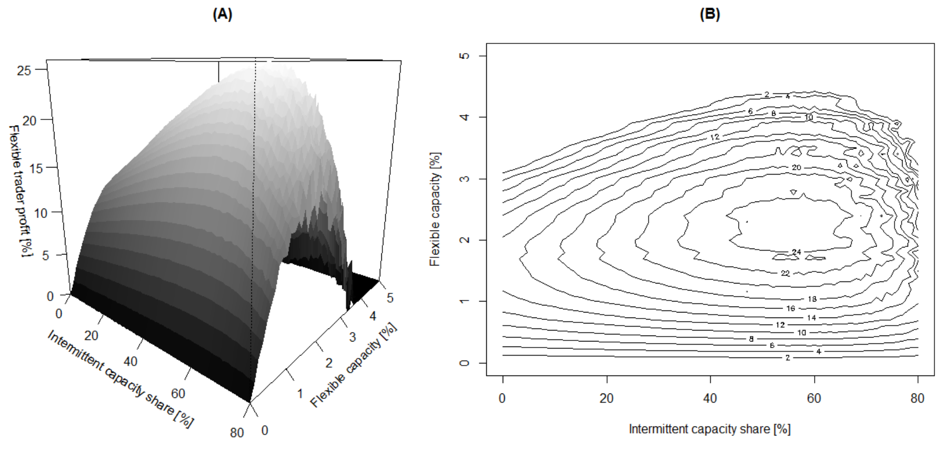

Figure 2.7: Total flexible trader profits as a percentage of the expected spot price and intermittent capacity market share K/D (A) and contour plot (B).

$$p_f - E(p_s^*) = \frac{\mu N_h}{(N+M)2e_i}\left[\mathrm{Cov}(p_s^{*2}, p_s^*) - 2p_c \mathrm{Var}(p_s^*) - \frac{(p_c 4e_i)}{N_h}\mathrm{Cov}(K, p_s^*)\right] - W_i^* N_f \tag{2.33}$$

The negative sign of the second term on the right-hand side in (2.33) indicates that adding speculative flexibility, will always decrease the difference between forward price and expected spot price. Market efficiency by (2.21) hence increases with more flexibility added to the market. Moreover, (2.33) indicates that there is not only a value for adding flexibility in the market with an increasing share of intermittent production, it also makes the labile optimal tipping point of highest market efficiency stable, indicating the well-known short-term value of flexibility.

We visualize and discuss the implications of (2.33) in Figure 2.7 via a simulation with the same set of parameters as before, in order to compare to the market without flexibility. The Figure displays the total profits for flexible traders as a percentage of the expected spot price with increasing intermittent capacity. With N in (2.28) constant and N_h fixed, (2.33) indicates the absolute effect in terms of equilibrium prices and profits for flexible traders. As we consider only speculative trading behavior, enabled by reaching a threshold of flexible capacity, efficiency losses from energy conversion processes are ignored. We assume flexible traders to be risk-neutral and all other market participants risk-averse with $\mu = 1$ to clearly distinct hedging and flexible trading opportunities. The share of flexible capacity varies from 0 to 5 percent in terms of total market capacity.

We observe with increasing flexible capacity, first a monotonically increasing investment incentive for flexible assets constraint by the flexible capacity. Once the flexible capacity becomes sufficiently large, the arbitrage condition in (2.32) becomes the dominant constraint. The value of flexibility reaches a tipping point and decreases again. Moreover, the total value of flexibility also increases with intermittent capacity, however decreases for very high market shares of volatile production, indicating the tipping point discussed before.

The analysis indicates a first mover advantage for integrating flexible assets in the trading portfolio. With storage technologies still economically unviable in many markets, conventional technologies that are capable of adjusting positions in short-time notice would typically benefit the most. Policy makers should therefore value the product flexibility accordingly, and preferably give economic incentives to sustainable solutions like batteries, in order to not facilitate unintended indirect consequences from polluting resources.

2.6 Conclusions and Future Work

In this paper we study how the integration of intermittent production technology affects equilibrium forward and spot pricing in sequential electricity wholesale markets. Where integrating intermittent renewable production sources indeed provides sustainable benefits, and helps to achieve political targets, their recent sharp increase has pronounced challenges for integration in the electricity system. It is key that markets give adequate price signals to producers and retailers, are transparent in communicating the correct production cost of electricity, and appreciate the value of flexibility in integrating intermittent sustainable energy sources. Taking into account the operational constraints of production technologies, we combine analytic modeling and numerical simulations to demonstrate how a large-scale integration of intermittent production sources affects forward price behavior respective to risk related hedging and flexible trading of producers.

We simulate the relative performance of forward and spot markets with the increase of renewable intermittent power supply. Such sequential markets help with efficient allocation of resources for commodities facing uncertainty from demand and increasing intermittent supply. As operational constraints affect producers' trading behavior, we analyze how market conditions define risk behavior of heterogeneous market participants and influence the ability of forward prices to predict spot prices. We find non-monotonic behavior of the forward risk premium in relation to an increase of intermittent supply. The relative behavior of the resulting tipping point is related back to the interplay of risk related hedging pressures between heterogeneous producers and retailers and depends on producer technology mix, risk-aversity and variation of demand and supply. We explore the technology-varying risk premium in relation to demand, as main drivers of uncertainty on both sides of the market. Our empirical findings suggest evidence for hourly varying fluctuations of the forward premium, oppositely affected by the level of wind penetration and demand.

The model further indicates a convenience yield for flexibility in markets transitioning towards a high integration of intermittent supply. We extend the model by including flexible risk-neutral trading, next to risk-averse traders, and indicate a first mover advantage for producers integrating flexible assets in their portfolio. As the value of flexibility is derived from systematic differences between forward and spot markets, it only forms a lower bound and future work may evaluate hybrid trading opportunities arising from price differences with respect to sequential markets as well as storage for different delivery times. Although, our model is simplified with no curtailment of intermittent supply or market power, we believe that the main insights on forward price behavior are robust to such extensions. Another avenue for future research may be to explore the notion of flexibility or flexible cooperatives with respect to issues related to transactions costs, financial constraints and market power.

With relative performance of spot and forward markets bound by the producers' operational constraints, it is key for policy makers to adequately validate the effects of sustainable policies on operations in wholesale electricity markets. In doing so, this study calls for sustainable policies to adequately evaluate the role of flexibility, in order for electricity supply chains to not only achieve a high penetration of sustainable energy sources, but also achieve it in a sustainable manner.

Chapter 3

Technology Non-Neutrality in Short-term Renewable Power Markets [1]

3.1 Introduction

Energy market participants face new challenges with the integration of sustainable and distributed production sources, electric mobility, and related advances. These are at odds with traditional power systems, where central, large-scale generation of electricity largely follows inelastic consumer demand. One of the main factors in the energy transition is the decarbonization of the generation portfolio, moving generation away from conventional and polluting technologies toward production from renewable energy resources, which are inherently variable and uncertain. Moreover, distributed energy sources and digital advances have created opportunities for tech-savvy end-consumers and prosumers to become increasingly, but not entirely, independent from the grid.

Environmental sustainability, defined as "development that meets the needs and aspirations of the present without compromising the ability of future generations to meet their own needs" (Jenkin et al., 2011), is linked to ongoing sustainable economic

[1] Parts of this chapter appear in the following peer reviewed conference proceedings:
Koolen, D., Bunn, D.W., Ketter, W. and Gupta, A. (2018). Effect of Technology Non-Neutrality and Information Transparency on Sequential Pricing in Decarbonizing Power Markets. *29th Workshop on Information Systems and Economics (WISE).* San Francisco (CA), United States (17-18 December 2018).

growth and development. Even though sustainability does not have a cost and actually pays in terms of innovation, productivity and environmental benefits (Elliot, 2011), the engagement does go together with business uncertainties. Reducing uncertainties is possibly done via developing smart markets (Bichler et al., 2010), using analytics to increase market efficiency and individual trading. Innovations in Information Systems (IS) can enhance this transition (Melville, 2010; Ketter et al., 2016b), using real-time information streams and price signal to predict, analyze and steer bidding behavior on financial markets. A prime example is the roll-out of advanced metering infrastructure in power networks, increasing information transparency among market participants and allowing for more efficient coordination between power generation and consumption (Römer et al., 2012). As a result, such smart meters allow for significant reductions of end-customers' electricity use and costs (Dedrick, 2010), as well as providing utilities with large amounts of data and information (Corbett, 2013). Despite these benefits, the adoption of Green IT and smart IoT devices remains relatively low (Chen et al., 2011). This has been linked to a number of issues and concerns on the consumer level, like privacy and control, attitude and perceived usefulness (Römer et al., 2012; Wunderlich et al., 2012), however the role of utilities and retailers remains rather unclear. As the latter face the challenging task to maintain the reliability of delivered energy with fewer firm resources and more uncertainty through intermittent production and decentralized demand at the interfaces between the wholesale and retail segments, green IS may play a vital role in collecting, transmitting and supplying data from sensor networks to automated controllers, network and utility managers and consumers (Watson et al., 2010).

In this paper, we investigate the role of environmental information transparency, defined by the capability of traders to accurately predict and gather information, by evaluating risk attitudes of traders with asymmetric information aggregation in short-term power markets. We thereby focus on the short-term forward risk premium, rather than spot market processes itself, as it nicely reveals the balance of behavior and risk preferences among producers and retailers (Bunn and Chen, 2013). In order to do so, we study the integration of both large-scale and distributed (or 'rooftop') renewable energy sources, affecting both the producer and retailer side of the market. The former are typically controlled by large utilities, often able to make relatively good short-term predictions on the renewable production levels in their own portfolio. Contrarily, the latter are owned by residential customers with little to no benefits from the retailer perspective, facing high uncertainties as it is unclear what is exactly taking place behind the meter. This study aims to investigate this information asymmetry, focusing on the effect of different renewable energy technologies on sequential short-term power pricing.

Our paper makes several contributions to both theory and practice of operations and information management in the context of sustainable power markets. First, we contribute to the literature on buyer-seller equilibria in supply chains with an asymmetric information structure (Esmaeili and Zeephongsekul, 2010). Pricing and decision behavior in sequential markets of buyers and sellers depends on auction design (Bapna et al., 2009) and incomplete information structures (Gregg and Walczak, 2008). This study aims to investigate the effect of information transparency on the buyer-seller relation in sustainable power markets, where the individual agents and their operational structure drive the degree of information at both sides of the market. Second, we derive a theoretical and analytic motivation for our model, studying optimal forward and spot market positions via an equilibrium market approach, integrating both large-scale and distributed renewable energy sources. As such, we approach one of the core questions of Green IS, finding the association between information systems and supply chain performance from an efficiency and environmental perspective (Melville, 2010; Loock et al., 2013). Lastly, we contribute to the emerging discussion on an efficient market integration of renewable energy resources (Ketter et al., 2018). We validate our model empirically for short-term power market in the United Kingdom and California, two markets that recently have experienced a significant increase of renewable power, respectively predominantly in terms of utility scale and distributed sources. With increasing renewable energy capacity on both sides of the market, the empirical results show evidence for differing information aggregation between producers and retailers, influencing market behavior and price formation. Key in the transition process is therefore to ensure that markets have tailored policies in order to provide adequate price signals for assets and investments, ensuring an increase of both large-scale and distributed renewable energy sources in an efficient and sustainable manner.

The rest of the paper is organized as follows. We first discuss the related work on forward trading in sequential power markets and propose a multi-stage competitive equilibrium model with both large-scale and distributed renewable energy technologies. We next elaborate with a set of simulations, which lay the foundation for our multi-factor propositional framework on the effects of technological, fundamental and dynamic factors on sequential price formation. We validate the model by conducting an empirical analysis with data from short-term power markets of the United Kingdom and California from 1 January 2015 to 31 December 2017. Finally, we discuss results and implications and reflect by pointing out directions for future work.

3.2 Approach

The intermittent character of renewable power supply makes prediction accuracy decrease drastically for longer time horizons. As a consequence, trading on most competitive power markets is moving closer real-time, with new short-term financial products becoming increasingly liquid (Knaut and Paschmann, 2017), and wholesale power market participants may engage in forward and spot trading in order to mitigate risks and uncertainty (Bunn and Chen, 2013). With electricity not yet economically viable to store, traditional cost-of-storage models for forward pricing cannot be used. This motivated Bessembinder and Lemmon (2002) to model the electricity forward price p_f as a result of an expectation over the spot price p_s plus a premium, modeling the supply and demand side of electricity markets in a closed system. They provide empirical evidence for their results from the American PJM market, but empirical support is mixed when applied to other markets (during different time periods). Other studies have assessed modeling forward pricing in electricity markets, but also find mixed empirical support. For example, Longstaff and Wang (2004) conduct an empirical analysis of the above model by using hourly prices and find that the risk premiums are time-varying and directly related to economic risk factors, such as the volatility of unexpected changes in demand, spot prices, total revenues and the risk that the electricity transmission system reaches its capacity limit. Douglas and Popova (2008) empirically relate forward risk premiums to indirect storability, associating the forward risk premium back to gas inventory levels. Redl and Bunn (2013) conduct a multi-factor analysis to study that the forward premium in electricity is dependent on fundamental, behavioral, dynamic and shock components. Huisman and Kilic (2012) also find evidence for the dependence of the risk premium on the level of (in)direct storability in the market, comparing the Dutch (mainly gas) and Scandinavian (mainly hydro) markets. They state that one cannot apply the same model to all electricity markets, as forward risk premium behavior heavily depends on the technology mix of the underlying production sources.

Analytic studies modeling the effect of (renewable) technology on sequential power trading are recently attracting more attention. Influenced by market conditions as flexibility, producer set up and risk aversion, relative performance of the forward price p_f and spot price p_s is bound by the markets' technological constraints (Peura and Bunn, 2016; Al-Gwaiz et al., 2016). We relate these notions to the effect of environmental information transparency; with asymmetries between market agents' ability to gather and predict information as a consequence of increasing heterogeneous intermittent renewable technologies on both sides of the market. With the increase of (intermittent) renewable energy sources in worldwide power markets only a very recent phenomenon, to the best of our knowledge this paper is one of the first to combine analytic modeling and empirical validation in order to analyze the effects of both large-scale and distributed renewable technologies on sequential pricing in wholesale power markets.

3.2.1 Equilibrium Model

In order to assess sequential power trading with increasing intermittent supply, we model optimal forward and spot positions in a two-stage equilibrium approach, based upon the work in the previous chapter and work by Koolen et al. (2017). The study focuses on heterogeneous production technologies and models the supply and demand side of power markets in a closed system. This allows to relate forward and spot price formation processes back to dynamic risk preferences of producers and retailers. In the following, we briefly revisit the model and extend it by incorporating renewable technologies on both the producer and retailer side of the market. The complete derivation of the whole model in this paper can be found in the appendix.

There are N power producers i and M power retailers j that trade the homogeneous, non-storable commodity electricity in a competitive electricity wholesale market. Retailers are required to meet the demand of end-consumers and sell it against a fixed price p_c. The demand of end-consumers is represented by a random variable $D = \sum_{j=1}^{M} D_j$. With each producer and retailer taking respectively forward positions, F_i and F_j, and spot positions, Q_i and Q_j, the market clearing condition indicates that total physical production of producers is equal to total retailer demand:

$$-\sum_{j=1}^{M} F_j - \sum_{j=1}^{M} Q_j = D = \sum_{i=1}^{N} F_i + \sum_{i=1}^{N} Q_i \tag{3.1}$$

We distinguish between two types of renewable energy agents, characterized by intermittent production profiles dependent on variable weather conditions. First, there are large-scale utility producers, to which we refer as a set Z consisting out of N_z zero-cost producers. They only have fixed costs and do not bear any marginal costs for producing electricity. The production capacity of each zero-cost producer is represented by a random variable K_i and total capacity by $K = \sum_{i \in Z} K_i$. Second, end-consumers have own production capacity in the form of distributed 'rooftop' capacity. We refer to this set of end-consumer as so-called prosumers. Total capacity is represented by a random variable C, and can similarly to K be considered as a production constraint by nature. We assume the existence of K and C its first and second central moment. Note that the ability to predict and gather information on production profiles affects the second central moment and hence may cause information asymmetries between market agents.

Next to renewable energy agents, conventional plants that burn fossil fuels to produce power are represented by a set H consisting out of N_h high-cost producers. They bear a marginal production cost increasing with output, reflecting that there are a number of production technologies with differing out-of-pocket costs (Bessembinder and Lemmon, 2002). Increasing marginal costs are in correspondence with empirical evidence that power prices are higher during peak hours than off-peak hours (Zhou et al., 2015). With e_i the variable cost efficiency parameter, G_i the fixed costs and a the cost parameter, the production cost function is given by:

$$\forall i \in H; c(q_i) = G_i + e_i {q_i}^a \tag{3.2}$$

We solve the equilibrium model to derive equations for the spot price p_s and forward price p_f using backward induction. In the spot market, consumer demand uncertainty D, large-scale intermittent capacity K and prosumer intermittent capacity C are realized. Producers i optimize the profit function representing a trade-off between revenue and costs. Assuming that forward positions are known, profit-maximizing spot quantities are derived by taking the first-order-condition of the profit maximization problem of producer i. Using (3.1), the optimal equilibrium spot market price p_s^* is derived:

$$p_s^* = \frac{(D - C - \sum_{i \in Z} K_i)^{a-1}}{\left[\sum_{i \in H} \left(\frac{1}{a.e_i}\right)^{\frac{1}{a-1}}\right]^{a-1}} \tag{3.3}$$

In the forward market, demand D and renewable technology quantities K and C are random variables. We assume that producers and retailers are risk averse and optimize their forward positions according to the mean-variance utility function, representing a trade-off between mean profit and the variance of the profit. By solving the first-order-conditions, we obtain the optimal forward positions $F_i^*(p_f)$ and $F_j^*(p_f)$. The forward price may finally be derived using the forward market clearing condition:

$$\sum_{i=1}^{N} F_i^*(p_f) + \sum_{j=1}^{M} F_j^*(p_f) = 0 \tag{3.4}$$

3.3 Multi-Factor Propositional Framework

We illustrate the implications of the model with a set of numerical simulations. The aim is to render qualitative insights that allow us to form a multi-factor propositional framework for our empirical analysis. From the model, we seek to embed and extend various factors introduced in previous work into a technology specific framework. The results of the simulation may vary arbitrarily depending on a set of exogenous parameters and are thus only illustrative for the relative performance of the forward premium. The number of producers and retailers are set to 100, with a risk-averse coefficient for both producers and retailers $\mu= 1$. We assume normal distributions for demand ($\mu_D = 100$, $\sigma_D = 10$), zero-cost producer capacity K and distributed renewable capacity C are normally distributed. The fixed retail price p_c is set as 2 times the wholesale spot price. For simplicity, we assume K_i to be equal for all zero-cost producers and we fix $\text{Var}(K_i) = \sigma_K^2$ and $\text{Var}(C) = \sigma_C^2$ to 10% of total capacity. We further assume e_i to be equal for all high-cost producers and is set to 10, in order to maintain comparability across cost structures, and the respective shares of intermittent production K/D and C/D.

For brevity and in light of the empirical evidence presented later, we only focus on variations in the parameters of uncertainty. First, we explore the effect of hourly demand regimes as peak and off-peak hours experience significant different price formation behavior. Next, we focus on the effect of the non-neutrality of renewable technologies on sequential pricing, relating the resulting information asymmetries back to risk preferences of producers and retailers.

3.3.1 Time-varying Demand Effects

The non-storable character of electricity in combination with varying load profiles makes that power prices experience significant differences throughout the day. This in turn affects forward and spot trading, as literature has found evidence for the hourly variation in sign and magnitude of the forward premium (Longstaff and Wang, 2004; Hadsell and Shawky, 2006). For example, Bunn and Chen (2013) show that it is important to control for hourly shocks of fundamental price drivers in estimating the forward premium. They indicate that mainly behavioral drivers affect peak (day)

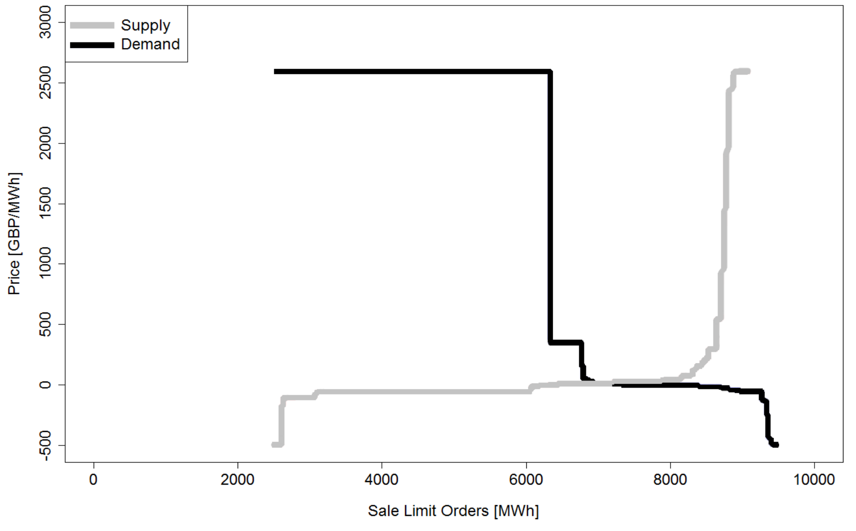

Figure 3.1: Aggregated bidding curves for the UK power day-ahead market, 26 October 2018, 12:00PM. Data from EPEX (2018).

premia, whereas more fundamental drivers affect off-peak (night) premia, reflecting different strategic and risk preferences of market participants throughout the day.

Figure 3.1 illustrates aggregated supply and demand bidding curves at noon for a specific day in the British day-ahead market. Note that the demand curve only portrays the trading positions of market participants, and thus not reflect the relatively inelastic demand of end-customers. It is clear that for the supply curve on the other hand, different cost functions with cost parameter a in (3.2) need to be considered. Where small demand deviations may only cause small price variation during off-peak hours, it may cause much larger price volatility during peak hours. We therefore discuss a quadratic and a cubic model in the following to explore the hourly dynamics on the forward premium. Other geographic markets present similar shapes for the supply curve, see for example Kohansal et al. (2017) for an overview of aggregated supply bids in the Californian market.

Quadratic model Quadratic costs ($a = 2$) in (3.2) imply a linear supply curve and thus link well to off-peak hours. Optimizing for the first-order-condition of the profit-maximizing function in gives the optimal spot quantity of the high-cost producer in the spot market, rendering the optimal spot price using the market clearing condition (3.1):

$$p_s^* = \frac{D - C - \sum_{i \in Z} K_i}{\sum_{i \in H} \frac{1}{2e_i}} \tag{3.5}$$

Using properties of variance and covariance and solving the first-order-condition of the mean-variance utility function renders the profit maximizing quantities sold on the forward market. The forward price is subsequently derived from the market clearing condition:

$$\begin{aligned} p_f = E(p_s^*) + \frac{2\mu}{N+M} \Bigg[& \frac{-N_h}{4e_i} \text{Cov}(p_s^{*2}, p_s^*) - \text{Cov}(p_s^* K, p_s^*) \\ & - p_c \text{Cov}((D-C), p_s^*) + \text{Cov}(p_s^*(D-C), p_s^*) \Bigg] \end{aligned} \tag{3.6}$$

Cubic model Strictly convex marginal costs ($a > 2$) render a better representation of the supply stack curve in power markets during peak times. We update the model with $a = 3$ in (3.2), implying quadratic growth of marginal costs. Following a similar derivation to the quadratic model, we find the optimal spot and forward price to become:

$$p_s^* = \frac{(D - C - \sum_{i \in Z} K_i)^2}{\sum_{i \in H} \frac{N_h}{3e_i}} \tag{3.7}$$

$$\begin{aligned} p_f = E(p_s^*) + \frac{2\mu}{N+M} \Bigg[& \frac{-2N_h}{3\sqrt{(3e_i)}} \text{Cov}(p_s^{*1.5}, p_s^*) - \text{Cov}(p_s^* K, p_s^*) \\ & - p_c \text{Cov}((D-C), p_s^*) + \text{Cov}(p_s^*(D-C), p_s^*) \Bigg] \end{aligned} \tag{3.8}$$

In both (3.6) and (3.8), the forward price converges to the expected spot price, with infinite number of producers and retailers or if with risk-neutral traders. Similar to Koolen et al. (2017), we find the forward risk premium to consist out of individual risk preferences from producers and retailers, making the forward price differ from the expected spot price. Where the first two terms represent high-cost and low-cost producer sales revenue risk respectively, the third reflects that retailer profits covary positively with expected spot prices while the fourth term represents retailer procurement risk, with the last term opposite to the first three terms. Note that we have three parameters with uncertainty in our model, demand D, large-scale

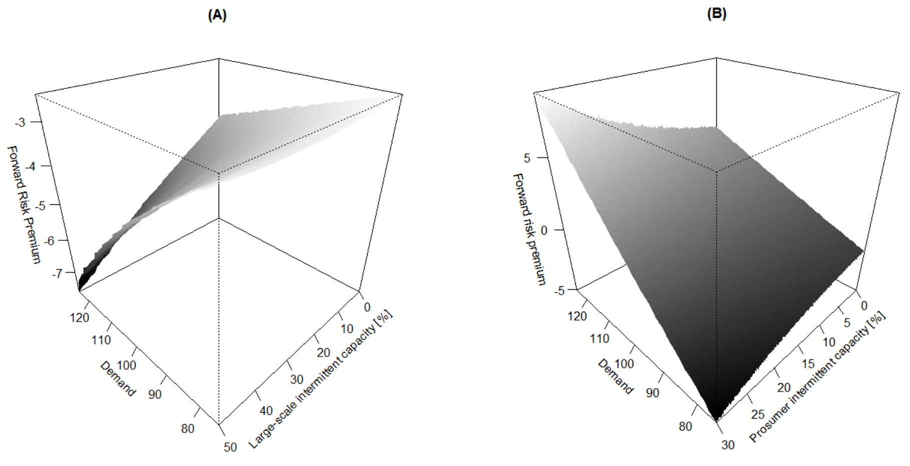

Figure 3.2: Forward premium Δp as a function of demand. Panel A shows the relation to large-scale intermittent capacity for off-peak periods ($a = 2$). Panel B shows the effect to distributed prosumer capacity for peak periods ($a = 3$). Design for comparison based upon Bessembinder and Lemmon (2002).

intermittent production K and distributed prosumer production C. Where large-scale intermittent capacity only directly influences zero-cost producers' risk related hedging pressure and distributed prosumer only directly influences retailers' risk related hedging pressure, they indirectly influence each other through volatile spot prices. We run a set of simulations in order to illustrate the interplay of producers and retailers their risk preferences with increasing volume uncertainty on both sides of the market. This allows us to evaluate how asymmetries between these two types of market agents in the ability to gather and predict information affects the pricing of forward and spot contracts.

Figure 3.2 displays simulation results for the effect of demand and cost function on the forward risk premium. Panel A shows that for quadratic costs ($a = 2$), increasing demand correlates negatively with the forward premium. With increasing demand correlating to increasing spot prices via (3.5), risk related hedging pressure of high-cost producers is becomes more dominant over other risk factors in (3.6). As a result, the forward premium will become increasingly negative with increasing demand. This is similar to Bessembinder and Lemmon (2002), who find that the forward risk premium correlates negatively to the variance of spot prices and positively to the skewness of spot prices. As quadratic costs functions imply a linear marginal supply

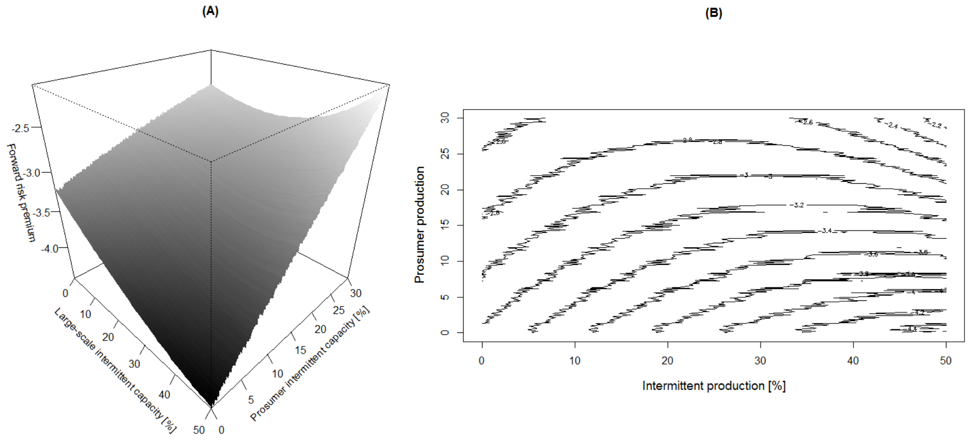

Figure 3.3: Panel A depicts Forward premium Δp as a function of large-scale intermittent capacity K and distributed prosumer capacity C in percentage of total demand. Panel B shows the forward premium contour plot.

curve, only the variance of spot prices is relevant and influences the forward premium negatively with increasing uncertainty. Panel B indicates that the opposite takes places for cubic cost functions ($a = 3$), as increasing demand correlates positively to the forward premium. As risk related hedging pressure of high-cost producers becomes less important in (3.8) compared to (3.6), the last risk related hedging factor representing retailer procurement risk becomes the dominant risk factor. The simulation therefore indicates that the effect of increasing demand levels varies between off-peak and peak hours throughout the day.

3.3.2 Renewable Technology and Information Asymmetries

The main focus of this paper is the relation of large-scale and distributed intermittent capacity on forward and spot pricing. Figure 3.2 shows the effect of demand on the forward premium in relation to these two sources of uncertainty. An interesting observation is that in both panel A and panel B the effect of demand, as discussed in the previous paragraph, is amplified with increasing large-scale intermittent capacity K and distributed prosumer intermittent capacity C. The intuition is that both factors amplify spot price uncertainty and thus increase the dominance of the respective risk related hedging pressures of producers and retailers.

To investigate the implications of the model with respect to variations in both sources of intermittent production, we conduct simulations for the quadratic cost model with only variations in large-scale intermittent production K and distributed prosumer intermittent production C. The simulation results displayed in Figure 3.3 show that the model implies that the forward premium increases with increasing prosumer intermittent capacity C, indicating dominant retailer risk related hedging pressure. Contrarily, the forward premium decreases with increasing large-scale intermittent capacity K, indicating dominant producer risk related hedging pressure. The sensitivity of the premium to large-scale intermittent capacity is largest when prosumer capacity is little, reaches a tipping point and may even increase with high share of prosumer capacity.

The intuition behind the simulation result is that large-scale intermittent capacity mainly relates to producer risk related hedging pressure, thus negatively influencing the forward risk premium. This in contrast to distributed prosumer intermittent capacity, mainly relating to retailer risk related hedging pressure and thus positively influencing the forward risk premium. We therefore find a non-neutrality of renewable technologies in their effect on forward and spot pricing. Note that in the simulations $\sigma_K^2 = \sigma_C^2$ for equal shares of intermittent production sources K and C. Information asymmetries caused by the ability to gather and predict information of producers and retailers would therefore amplify the indicated effects further.

3.3.3 Propositions

We form a set of propositions based upon our model and insights from the simulations on the role of renewable technology and information asymmetries. We further relate technological factors to fundamental and dynamic price drivers. Specifically the following propositions are addressed.

The non-neutrality of renewable intermittent production technologies. Intermittent production sources are non-dispatchable or non-flexible sources with variable and uncertain production profiles. Although not all renewable power sources are non-dispatchable, hydropower for example can adjust its production based upon reservoir levels, most renewable energy sources are intermittent and dependent on factors that cannot be controlled, for example the weather. We focus on the main intermittent renewable energy sources that contribute to decarbonizing global power grids: wind and solar.

- *Solar.* The global solar power market has steadily grown as costs for photovoltaic panels have dropped over the past decade, with currently over 300GW solar capacity installed world wide. Growth rates are still increasing, driven by improvements in production processes and efficiency gains through new cell designs. Solar power projects can largely be categorized into two main groups; utility-scale and distributed production. The underlying technology for both is different. Large-scale solar power makes use of solar collectors to heat a power steam turbine and generate a large capacity output. Alongside smaller issues like water management and land use, such projects are capital intensive, and involve large risks for financial institutions. An increase in large-scale solar power installations is expected to negatively influence the forward risk premium. In most developed countries distributed solar power is therefore the dominant technology. Policy schemes have caused residential rooftop PV power to surge, spreading capacity over the country and reducing end-consumer demand. As consumers only need a smart meter to plug feed their individual solar cells in to the grid, information on production profiles is not transparent for retailers. Thus an increase in distributed solar power is expected to positively influence the forward risk premium.

- *Onshore wind.* Wind turbine technology has evolved substantially during the past decade and onshore wind energy is regarded one of the most mature renewable energy technologies with relatively low costs, with global capacity reaching 500GW globally. With turbine manufacturers offering a range of turbines, with increasing competitiveness driven with corresponding increasing hub-heights, blade lengths and output capacity, onshore wind capacity has drastically increased in various parts of the world. With national political-motivated subsidies decreasing and constraints in terms of large geological interesting space, the highest growth rates are achieved for smaller scale distributed wind farms. These production facilities are typically connected to the distribution grid, changing visualization and asset management as flows are registered by network operators as negative demand. Moreover, output prediction is outlined by extrapolation, rather than exact metering, as operators are not able to exactly monitor what is going on behind the meter. This lack of information transparency means that an increase of onshore wind production is expected to positively or negatively impact the forward risk premium, depending respectively on the share of distributed versus large-scale production units.

- *Offshore wind.* Although still a less mature technology, offshore wind energy is advancing at a rapid pace. Increased investments, falling costs and new technologies, with turbines and blades growing ever larger make it possible to achieve high generation capacity per unit. Cumulative offshore capacity has risen to over 15GW, primarily installed in Northwestern Europe. Due to the availability of good wind resources offshore, steady wind and less turbulence, these wind farms reach the highest nominal capacity for renewable power farms. Offshore wind farms are however characterized by long lead times, as construction is more complex and high grid connection costs. This makes that offshore farms are typically owned by large incumbent utility companies, often back by state-funded subsidies. The first subsidy-free offshore wind farm was however recently contracted in the Netherlands and many other countries are expected to follow (Crooks, 2018). This ownership structure makes that asset information is largely transparent and the intermittent character is expected to mainly influence hedging and strategic decisions on the producer side of the wholesale market. Thus an increase of offshore wind production is expected to negatively influence the forward risk premium.

Fundamentals. Fundamental drivers of power prices are demand, marginal costs of high-cost producers and scarcity (Bunn, 2004). As controlling for scarcity would require privacy sensitive data from power plants revealing scheduled capacity levels, we focus on the former two; demand and marginal costs.

- *Demand.* Varying demand for power between peak and off-peak hours leads to price variations throughout the day. Related to risk preferences of producers and retailers in our model, the effect of demand is negative with linear increasing marginal costs but becomes positive for convex cost functions. As demand forecasts of end-consumers are published with an hourly frequency and the level of convexity of the supply curve varies through the day, i.e. peak versus off-peak hours, it is expected that the time of the day influences the sign of the premium.

- *Marginal costs.* The underlying fuel costs of the technology running on the margin is a fundamental power price driver. Gas-fired power stations often form the marginal technology, as albeit flexible, these power stations are typically more costly in terms of maintenance and fuel costs. As gas-fired power plants typically determine the merit order, even when other technologies like renewable energy sources form a substantial part of the supply curve, we use (daily) day-ahead gas spot prices as a proxy for the marginal cost of production. An increase of the gas price means that the supply curve moves up and hence we expect a positive effect on the premium.

Behavioral and Dynamic effects. Risk assessment of market participants is subject to adaptive behavior to market price dynamics (Redl and Bunn, 2013). We therefore consider market agents to derive information about future price distributions by observing recent price developments. Specifically we consider the variance of spot prices and the basis to be two main behavioral price drivers.

- *Variance.* Variance is a measure for spot price risk, and clearly affects risk preferences of producers and retailers in our model. Previous literature has presented mixed findings with respect to the influence of variance on the premium, as both positive (Redl and Bunn, 2013) and negative (Longstaff and Wang, 2004) relations have been reported. We include the variance as backward-looking measure, i.e. a proxy for expectations on spot price distributions by computing a weighted average over the 7 previous days for the same respective hour.

- *Basis.* The basis is defined as the forward price minus the weekly average of spot realizations for the same respective hour. We assume that recent spot realizations serve as proxies for agents' anticipations on actual spot realizations and thus contains reliable information on future change of the spot price. Indeed, market participants' risk assessment techniques consider ongoing market dynamics and expectations adapt to recent price developments. Although not specifically addressed in our analytic model, the basis therefore forms an important parameter in the formation of expectations on forward and spot prices in power markets (Bunn and Chen, 2013). We hypothesize that the basis positively influences the forward premium.

3.4 Empirical Analysis

Based upon the analytic model and the derived propositions, we analyze the effects of production technologies on the forward premium via a comprehensive approach. We propose the following model:

$$p_f^{t,T} - p_s^T = \alpha + \beta_i X_i^t + \epsilon^{t,T} \tag{3.9}$$

Where the dependent variable represents the ex-post forward premium, with $p_f^{t,T}$ the forward price per MWh of a contract that is quoted at time t, for the delivery in period T, and p_s^T the price on the spot market for real time delivery in period T. Note that we consider the ex-post premium to be a valid estimator of the ex-ante premium in our model, assuming a relatively small normally distributed random error on the difference between both. X_i^t include all the exogenous variables discussed in our propositional framework. Although extensive multi-factor models with several exogenous variables raise concerns of overfitting, each non-technical variable has been motivated by previous analytic and empirical specifications. Note that all exogenous variables are quoted at time t, meaning we use day-ahead prediction forecasts on generation levels for wind and solar, day-ahead gas spot prices and day-ahead forecasts on demand variations. Behavioral price drivers like the variance of spot prices and the basis were estimated observing the moments of past distributions. Thus, with all information available to producers and retailers prior to market bidding and price setting, the variables can be considered non-endogenous.

3.4.1 Californian and British Power Market Data

We estimate the empirical model in equation (3.9) using market data from the Californian and the British power market for a time span of 3 years, from 2015 to 2018. Liberalized power markets have globally experienced a sharp increase of an array of intermittent renewable production sources in recent years, mainly politically motivated to achieve sustainability targets. With variations in national and regional policies, the implementation of various renewable technologies is however taking place in different forms and paces. As a result, we collected market data from two competitive liberalized power markets that have not only experienced a sharp increase of renewable energy generation, but also show variation in type of renewable technologies. Figure 3.4 visualizes the yearly net generation in GWh per renewable technology type, respectively for California and the United Kingdom. To put these numbers in perspective, power generation of wind and solar sources summed up to 19.6 % and 29.4 % of total power demand for respectively California (292 TWh) and the United Kingdom (336 TWh).

Small-scale solar plants are generally considered plants with up to 5MW in generation capacity, although this remains rather generic. Where in California the majority of small-scale solar generation is installed in the form of smaller solar farms between 1 and 5 MW, as installations below 5MW are offered more favorable feed-in tariffs, about 60% of small-scale solar in the United Kingdom comes from residential rooftop installations, as end-consumers enjoyed relatively high subsidies for generating their own distributed capacity. Note that this difference has a major impact on the

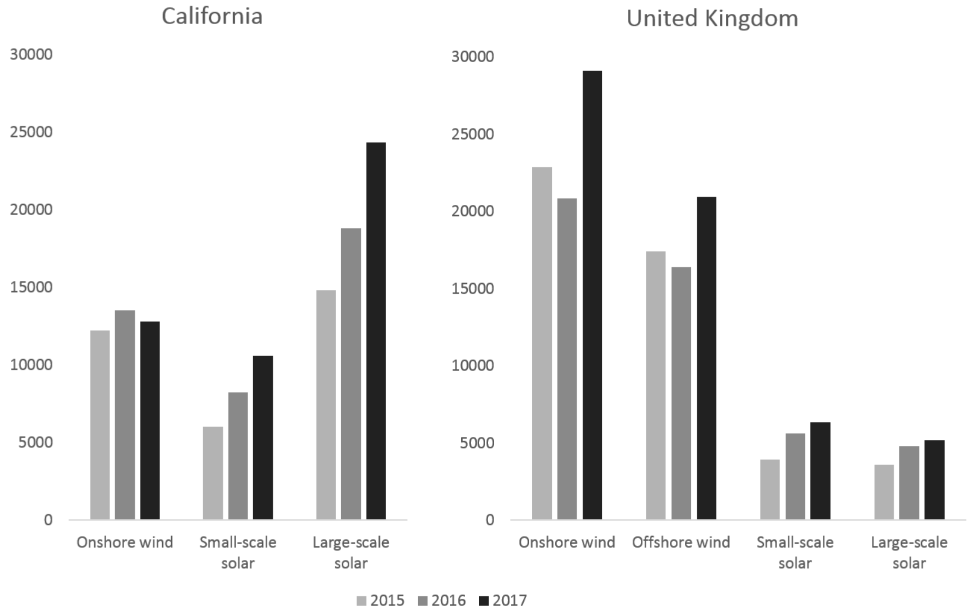

Figure 3.4: Net generation in GWh of intermittent renewable energy sources, by type, 2015-2017. Data from EIA (2018) for California and Department for Business, Energy & Industrial Strategy (2018) for UK.

ability of market agents to predict and gather information, as retailers have much less transparency on what is going on behind the meter. We therefore consider solar power to mainly affect producer risk preferences in California, related to an increase of large-scale intermittent production sources in our model. Contrarily, solar power is expected to predominantly affect retailer risk in the United Kingdom, related to distributed prosumer capacity. In terms of wind specifications, onshore and offshore wind net wind generations are in the same order of magnitude for the United Kingdom, although average onshore wind turbine capacities are well below those of offshore wind. We only consider onshore wind levels in California, as currently hardly any offshore wind turbines are installed.

For California, data is obtained from the Californian Independent System Operator (ISO) open access same-time information system (CAISO, 2018). Day-ahead predictions on wind and solar generation, as well as load are available for all trading hubs within the California power market area. As the majority of renewable energy sources are placed in the Southern trading hub, we focus on this area. Hourly forward (day-ahead) and 5-minute spot (real-time) prices are available via Locational Marginal

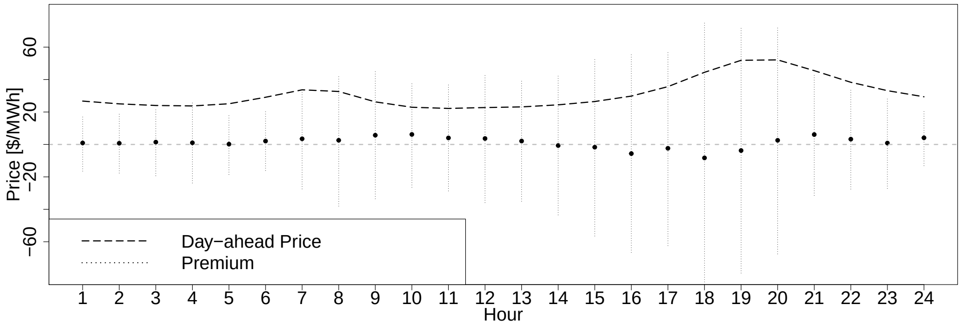

Figure 3.5: Average hourly forward price and premium [USD/MWh] between day-ahead and real-time price in California, 2015-2017. Data from CAISO (2018).

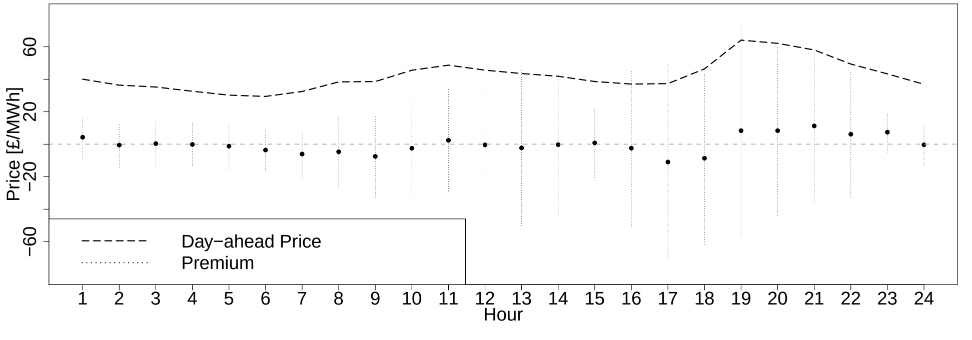

Figure 3.6: Average hourly forward price and premium [GBP/MWh] between day-ahead and imbalance price in the United Kingdom, 2015-2017. Data from ENTSO-E (2018).

Price (LMP) levels and are aggregated across the respective trading hub on an hourly basis. Finally, hourly Henry Hub gas spot prices are used, as only limited financial arbitrage between the hub and California is taking place and gas power plants are the marginal production type in California (Brown and Yücel, 2008).

We collect data on the British power market from the ENTSO-E Transparency platform (ENTSO-E (2018)). Wind and solar day-ahead predictions are provided by the Transmission System Operator (TSO) with an hourly frequency. Note that the reported data by the TSO is not based on exact metering for each utility but rather via extrapolations from specific metered utilities in combination with weather data. Hourly forward (day-ahead) and half-hourly spot (imbalance) price data, as well as corresponding day-ahead predictions of the load are reported by the TSO and aggregated on an hourly basis. Finally, with gas power plants operating most of the time on the margin in the UK, hourly NBP gas spot prices serve as a proxy for marginal costs.

Figure 3.5 and 3.6 depict the average hourly forward price and variance of hourly realized ex-post premia for respectively California and the United Kingdom over the entire data set. The illustrations nicely visualize typical daily power price profiles, with the highest prices when demand is peaking just before midday and another peak in the evening. The effect is more pronounced for California, creating the so-called duck curve as relatively high shares of solar generation cause prices to drop in the afternoon hours. We observe the premium $p_f^{t,T} - p_s^T$ to fluctuate around zero, with larger variations in the evening hours and more spread out for California. Note that average power prices are considerably higher in the United Kingdom than in California.

3.4.2 Results

We use OLS regression to estimate equation (3.9) and test coefficients with the Newey-West covariance matrix to control for heteroscedasticity and autocorrelation. In general, regression results support our multi-factor propositional framework in terms of coefficient sign and statistical significance. In the following, we first discuss the results for each market separately before comparing the effect of renewable technologies and information asymmetries between both markets.

Results for California are given in Tables 3.1, 3.2 and 3.3. Adjusted R^2 statistics suggest a good fit particularly just before noon. The sign of the solar coefficient is significantly negative throughout the day. We thus find evidence that day-ahead predictions on solar generation levels predominantly affect producer risk, with installed large-scale solar capacity is an order of magnitude larger than small-scale solar. The effect is less obvious for onshore wind, as the installed wind capacity is relatively low and turbines vary in size.

Results for the United Kingdom are given in Tables 3.4, 3.5 and 3.6. The adjusted R^2 statistics generally suggest a good fit for the whole day, but particularly in the afternoon. Although we find offshore wind to correlate with onshore wind prediction levels ($\eta = 0.7$), the relation of offshore wind is found to be significantly negative for more hours when both are presented separately and thus does not raise concerns of multicollinearity. We observe offshore wind to influence risk related hedging pressure of producers, with a significant negative sign throughout the day. Solar generally

Table 3.1: California 00:00-08:00

	Dependent variable: $p_f^{t,T} - p_s^T$							
	Hours							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Solar $.10^{-3}$						-165.23^{**}	-7.88^{**}	-1.80^{*}
						(74.25)	(3.47)	(1.43)
Onshore Wind $.10^{-3}$	−0.75	−0.43	−0.01	0.46	−0.90	−0.62	0.18	1.12
	(0.71)	(0.74)	(0.84)	(0.72)	(0.83)	(0.82)	(1.43)	(1.83)
Gas Price	3.66^{***}	2.42^{*}	2.06	5.23^{***}	3.36^{**}	4.34^{***}	6.21^{***}	4.76^{*}
	(1.17)	(1.27)	(1.40)	(1.15)	(1.34)	(1.33)	(2.08)	(2.59)
Load	0.001	0.001	0.001^{*}	0.001	0.001	−0.0005	0.001	−0.001
	(0.0004)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Basis	0.70^{***}	0.46^{***}	0.56^{***}	0.86^{***}	0.65^{***}	0.60^{***}	0.76^{***}	0.47^{***}
	(0.08)	(0.11)	(0.10)	(0.07)	(0.10)	(0.10)	(0.12)	(0.11)
Var	0.003^{*}	0.002^{*}	−0.002	0.002	−0.001	-0.005^{***}	-0.002^{***}	-0.002^{***}
	(0.001)	(0.001)	(0.0003)	(0.0002)	(0.001)	(0.001)	(0.0004)	(0.001)
Cst.	−4.28	−1.58	−3.11	1.47	1.97	13.30^{**}	2.06	22.02^{**}
	(4.83)	(5.22)	(6.36)	(5.66)	(6.54)	(6.31)	(9.96)	(10.95)
Obs.	1,090	1,090	1,090	1,090	1,090	1,090	1,090	1,090
Adj. R^2	0.16	0.17	0.15	0.58	0.18	0.15	0.15	0.19
Note:						$^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$		

Table 3.2: California 00:09-16:00

	Dependent variable: $p_f^{t,T} - p_s^T$							
	Hours							
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Solar $.10^{-3}$	-1.10^{*}	-0.68	-2.88^{***}	-1.37^{*}	-2.05^{**}	-1.44^{*}	-1.19^{*}	-0.49
	(1.11)	(0.89)	(0.80)	(0.94)	(0.88)	(1.05)	(1.26)	(1.32)
Onshore Wind $.10^{-3}$	1.40	0.15	2.74^{*}	1.57	2.10	1.78	1.08	-2.26
	(1.93)	(1.55)	(1.53)	(1.77)	(1.57)	(1.86)	(2.27)	(2.47)
Gas Price	6.33^{**}	4.43^{**}	6.65^{***}	6.10^{**}	2.28	4.22	3.49	6.17
	(2.67)	(2.24)	(2.12)	(2.63)	(2.42)	(2.94)	(3.68)	(3.94)
Load	0.001^{**}	0.0004	0.001^{**}	0.001^{*}	0.002^{***}	0.001^{**}	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.0005)	(0.001)	(0.001)	(0.001)
Basis	0.69^{***}	0.66^{***}	0.78^{***}	0.53^{***}	0.70^{***}	0.61^{***}	0.59^{***}	0.44^{***}
	(0.08)	(0.07)	(0.07)	(0.09)	(0.09)	(0.10)	(0.10)	(0.10)
Var	-0.002^{**}	-0.001	-0.01^{***}	-0.004^{***}	-0.003^{***}	-0.004^{***}	-0.004^{***}	-0.003^{***}
	(0.001)	(0.002)	(0.002)	(0.0005)	(0.001)	(0.001)	(0.001)	(0.001)
Cst.	14.09	3.99	-3.54	-10.05	-6.11	-4.55	1.65	-13.53
	(10.97)	(8.62)	(7.67)	(9.04)	(8.01)	(9.12)	(11.60)	(12.31)
Obs.	1,090	1,090	1,090	1,090	1,090	1,090	1,090	1,090
Adj. R^2	0.17	0.17	0.20	0.17	0.19	0.18	0.14	0.17

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 3.3: California 17:00-24:00

	Dependent variable: $p_f^{t,T} - p_s^T$							
	Hours							
	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
Solar $.10^{-3}$	-2.63^{**}	-3.82^{*}	-6.48					
	(1.25)	(2.13)	(3.94)					
Onshore Wind $.10^{-3}$	0.18	-3.61	-1.85	-3.08	0.07	-0.41	1.55	0.46
	(2.50)	(3.78)	(3.51)	(2.81)	(1.48)	(1.20)	(0.98)	(0.69)
Gas Price	6.98^{*}	7.50	10.58^{**}	8.56^{*}	8.09^{***}	6.98^{***}	3.28^{**}	4.39^{***}
	(3.99)	(5.78)	(5.13)	(4.73)	(2.59)	(2.09)	(1.65)	(1.16)
Load	0.003^{***}	0.002^{*}	0.002^{**}	0.003^{***}	0.002^{***}	0.001^{**}	0.001	0.0004
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.0005)	(0.0004)	(0.0004)
Basis	0.69^{***}	0.58^{***}	0.75^{***}	0.27^{*}	0.64^{***}	0.62^{***}	0.04	0.57^{***}
	(0.09)	(0.13)	(0.15)	(0.16)	(0.15)	(0.12)	(0.10)	(0.09)
Var	-0.001^{**}	-0.001^{**}	0.001	-0.001^{**}	-0.001	-0.0004	0.002	-0.004^{***}
	(0.001)	(0.0004)	(0.0003)	(0.001)	(0.001)	(0.001)	(0.0003)	(0.001)
Cst.	-20.95^{*}	-9.18	-19.27	-43.88^{***}	-10.79	-5.39	-12.67^{**}	2.26
	(12.58)	(18.77)	(18.30)	(16.14)	(8.51)	(7.15)	(5.94)	(4.31)
Obs.	1,090	1,090	1,090	1,090	1,090	1,090	1,090	1,090
Adj. R^2	0.15	0.14	0.12	0.15	0.14	0.15	0.33	0.14

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 3.4: United Kingdom 00:00-08:00

	Dependent variable: $p_f^{t,T} - p_s^T$							
	Hours							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Solar $.10^{-3}$						-120.01	-19.36	-6.42
						(146.78)	(12.08)	(4.22)
Wind Off $.10^{-3}$	-1.08^{*}	-1.06^{*}	-0.26	-0.69^{*}	-1.62^{***}	-3.05^{***}	-2.54^{***}	-1.09
	(0.58)	(0.60)	(0.65)	(0.61)	(0.62)	(0.61)	(0.76)	(1.07)
Wind On $.10^{-3}$	0.33	0.29	0.11	-0.09	0.10	0.48	-0.15	0.95
	(0.39)	(0.41)	(0.45)	(0.41)	(0.45)	(0.43)	(0.54)	(0.78)
Gas Price	0.36^{***}	0.54^{***}	0.56^{***}	0.51^{***}	0.53^{***}	0.51^{***}	0.49^{***}	0.42^{***}
	(0.06)	(0.06)	(0.06)	(0.07)	(0.07)	(0.06)	(0.08)	(0.11)
Load	-0.83^{*}	-0.06	0.06	0.02	0.03	0.19	0.03	0.40^{*}
	(0.13)	(0.12)	(0.12)	(0.12)	(0.14)	(0.13)	(0.14)	(0.14)
Basis	0.75^{***}	0.88^{***}	0.93^{***}	0.81^{***}	0.81^{***}	0.70^{***}	0.83^{***}	0.77^{***}
	(0.06)	(0.07)	(0.07)	(0.07)	(0.08)	(0.07)	(0.07)	(0.08)
Var	-0.02^{***}	-0.02^{***}	-0.02^{***}	-0.03^{***}	-0.02^{***}	-0.02^{***}	-0.02^{***}	-0.01^{**}
	(0.004)	(0.003)	(0.004)	(0.005)	(0.01)	(0.01)	(0.004)	(0.003)
Cst.	42.48^{***}	13.43^{***}	9.75^{***}	8.63^{**}	6.09	8.84^{**}	10.42^{**}	24.86^{***}
	(3.96)	(3.58)	(3.70)	(3.65)	(4.02)	(3.91)	(4.29)	(5.80)
Obs.	988	988	989	989	989	989	989	989
Adj. R^2	0.22	0.21	0.21	0.16	0.15	0.18	0.17	0.18

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 3.5: United Kingdom 09:00-16:00

	Dependent variable: $p_f^{t,T} - p_s^T$							
	Hours							
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Solar $.10^{-3}$	-0.81	4.56^{***}	5.00^{***}	4.25^{*}	1.53^{*}	0.28	0.18	1.03^{*}
	(2.35)	(1.57)	(1.04)	(0.85)	(0.81)	(0.80)	(0.47)	(1.04)
Wind Off $.10^{-3}$	-2.01^{*}	-2.31^{*}	-2.85^{***}	-4.05^{***}	-2.81^{**}	-2.01^{*}	-0.63	0.21
	(1.19)	(1.24)	(1.08)	(1.10)	(1.22)	(1.28)	(0.79)	(1.65)
Wind On $.10^{-3}$	0.02	0.61	1.25	0.84	0.99	0.42	-0.01	0.77
	(0.85)	(0.88)	(0.77)	(0.76)	(0.82)	(0.85)	(0.52)	(1.09)
Gas Price	0.49^{***}	0.74^{***}	0.76^{***}	0.91^{***}	0.60^{***}	0.64^{***}	0.56^{***}	0.61^{***}
	(0.12)	(0.14)	(0.14)	(0.14)	(0.15)	(0.16)	(0.10)	(0.21)
Load	-0.07	0.46^{***}	0.52^{***}	0.03	-0.01	-0.17	-0.08	0.39
	(0.13)	(0.16)	(0.20)	(0.23)	(0.26)	(0.28)	(0.16)	(0.35)
Basis	0.71^{***}	0.80^{***}	0.93^{***}	1.25^{***}	0.80^{***}	0.85^{***}	0.69^{***}	0.74^{***}
	(0.09)	(0.10)	(0.09)	(0.09)	(0.10)	(0.12)	(0.09)	(0.16)
Var	-0.02^{***}	-0.01^{***}	-0.004^{***}	-0.02^{***}	-0.01^{***}	-0.01^{***}	-0.01^{***}	-0.002^{***}
	(0.003)	(0.003)	(0.001)	(0.001)	(0.0003)	(0.0004)	(0.001)	(0.0003)
Cst.	12.29^{*}	-12.19	-13.32	18.55	5.78	15.75	7.79	-18.13
	(6.82)	(8.34)	(10.04)	(11.43)	(12.91)	(13.67)	(7.82)	(17.40)
Obs.	989	989	989	989	989	989	989	989
Adj. R^2	0.17	0.20	0.24	0.46	0.55	0.41	0.15	0.20

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 3.6: United Kingdom 17:00-24:00

	Dependent variable: $p_f^{t,T} - p_s^T$							
	Hours							
	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
Solar $.10^{-3}$	1.08^{*}	3.23^{**}	-4.71					
	(1.21)	(1.45)	(2.37)					
Wind Off $.10^{-3}$	-3.28^{*}	-1.53^{*}	-4.52^{*}	-5.06^{***}	-2.71^{**}	-2.99^{*}	-0.87^{*}	-1.22^{*}
	(1.78)	(1.73)	(2.36)	(1.86)	(1.36)	(1.67)	(0.51)	(0.64)
Wind On $.10^{-3}$	2.41^{**}	0.52	-3.23^{**}	0.43	2.74^{***}	-0.99	-0.68^{*}	-0.33
	(1.18)	(1.16)	(1.64)	(1.29)	(0.99)	(1.18)	(0.35)	(0.43)
Gas Price	0.61^{***}	0.93^{***}	1.95^{***}	0.72^{***}	1.18^{***}	0.69^{***}	0.51^{***}	0.41^{***}
	(0.21)	(0.22)	(0.28)	(0.21)	(0.16)	(0.22)	(0.07)	(0.06)
Load	0.51	1.49^{***}	2.68^{***}	1.24^{***}	0.54^{**}	-0.02	-0.46^{***}	-0.21^{*}
	(0.37)	(0.33)	(0.42)	(0.28)	(0.21)	(0.27)	(0.10)	(0.12)
Basis	0.53^{***}	1.04^{***}	1.77^{***}	0.70^{***}	1.63^{***}	1.68^{***}	0.89^{***}	0.76^{***}
	(0.13)	(0.12)	(0.16)	(0.11)	(0.14)	(0.21)	(0.08)	(0.07)
Var	-0.004^{***}	0.0000	0.0005	-0.0004	0.05^{***}	0.01^{*}	-0.01^{***}	-0.02^{***}
	(0.0002)	(0.0003)	(0.001)	(0.001)	(0.002)	(0.01)	(0.003)	(0.01)
Cst.	-31.11	-55.64^{***}	-65.47^{***}	-26.63^{**}	5.80	55.64^{***}	38.55^{***}	21.91^{***}
	(19.02)	(18.49)	(24.49)	(13.57)	(10.62)	(12.46)	(4.01)	(4.50)
Obs.	989	989	989	989	989	989	989	989
Adj. R^2	0.39	0.25	0.19	0.18	0.47	0.18	0.18	0.16

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

present positive coefficients. With small-scale solar in the same order of magnitude as large-scale solar, the result suggests that $\sigma_K^2 < \sigma_C^2$, creating higher uncertainties for retailers than for producers, as retailers do not exactly know what is taking place behind the meter.

In terms of other specifications, we first find the basis to be one of the main explanatory variables for both markets. This relates to agents' concerns on market power and price peaks causing behavioral adaption (Bunn and Chen, 2013). In line with expectation, we find the effect to be stronger for peak hours than off-peak hours. Second, gas prices generally indicate a positive effect, especially in the United Kingdom where gas power plants are most often the marginal producer. In California, off-peak premia relate more to fuel prices than during peak hours, potentially linked to the exercise of market power (Borenstein et al., 2008). Third, the effect of load is generally positive. In line with our model, hourly differences occur as the effect is larger for peak hours. Finally, we find evidence for the forward premium to negatively correlate to the variance of spot prices. The effect decreases during peak hours, when volatile shocks may create highly skewed prices (Redl and Bunn, 2013).

3.5 Conclusions

With the growing share of sustainable energy sources, electricity markets experience increasing uncertainty and volatility. The realization of the forward premium is affected by producers and retailers' respective market understanding, information asymmetries and corresponding risk preferences. In this work, we find a technology-varying risk premium in sequential short-term power markets, related to environmental information asymmetries between renewable technologies on both sides of the market.

We find evidence for large-scale and distributed renewable energy technologies to oppositely affect the forward premium, as asymmetries arise in the ability to predict and gather information on renewable production schedules. The technology-varying forward premium reveals a balance of behavior and risk preferences among producers and retailers. In markets that are predominantly characterized by large-scale renewable production facilities, day-ahead predictions on high levels of renewable energy will negatively influence the premium as the risk related hedging pressure of producers increases. In markets with high shares of distributed 'rooftop' renewable capacity on the other hand, positive day-ahead predictions on renewable energy production will positively influence the premium, as hedging needs of retailers increase.

The findings provide important insights on the technology non-neutrality of renewable energy sources and the role of information in short-term sequential power markets. Leveraging the value of real-time information and price signals via IoT devices could potentially reduce uncertainties related to distributed renewable energy sources. Where the value of adopting smart meters and IoT devices in energy networks is often studied from a consumer perspective, this study indicates a value for better measuring and predicting of information for retailers as well. As smart meters and related IoT devices may reduce risks associated with the integration of distributed energy resources, they may ultimately enhance a market efficient integration of renewable energy sources in wholesale power markets.

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Appendix

A Derivation of the Market Equilibrium

Spot Market

We derive optimal spot positions for N_h high-cost and N_z zero-cost producers, by solving the equilibrium game with backward induction. The profit maximization problem of producer i is given by:

$$\max \Pi_i = \Big[p_f F_i + p_s Q_i - c(F_i + Q_i)\Big] \tag{A1}$$

The first-order-condition gives us the optimal quantity for high-cost producer i:

$$\forall i \in H; Q_i^* = \sqrt[a-1]{\frac{p_s}{a.e_i}} - F_i \tag{A2}$$

Zero-cost producers need to sell the realized capacity K_i in the spot market. The spot market position Q_i is determined when the forward market position F_i is given:

$$\forall i \in Z; Q_i^* = K_i - F_i \tag{A3}$$

Inserting equations (A2) and (A3) in the following market clearing condition $\sum_{i\in H} F_i + \sum_{i\in H} Q_i + \sum_{i\in Z} K_i = D - C$ renders the following optimal spot price, which is text equation (3.3):

$$p_s^* = \frac{(D - C - \sum_{i\in Z} K_i)^{a-1}}{\left[\sum_{i\in H}(\frac{1}{a.e_i})^{\frac{1}{a-1}}\right]^{a-1}} \tag{A4}$$

Forward Market

At time 1, consumer demand uncertainty D, prosumer distributed production uncertainty C, and low-cost production capacity K_i are random variables. We assume that producers and retailers are risk-averse and use a mean-variance utility function, with $\mu_i = \mu_j = \mu$ the risk-averse coefficient:

$$\max_{F_i} U(\Pi_i) = \max_{F_i}\Big[E(\Pi_i) - \mu_i \mathrm{Var}(\Pi_i)\Big] \tag{A5}$$

We next focus on the derivation for high-cost producers [2]. Inserting (3.2) in (A1) renders:

$$\forall i \in H; \Pi_i = p_f F_i - p_s^* F_i - G_i + \left(a^{\frac{-1}{a-1}} - a^{\frac{-a}{a-1}}\right) p_s^{*\frac{a}{a-1}} e_i^{\frac{-1}{a-1}} \tag{A6}$$

With $\mathrm{Var}(\Pi_i) = E(\Pi_i^2) - E^2(\Pi_i)$ and using properties of variance and covariance, we obtain for $a = 2$:

$$\begin{aligned}\forall i \in H; U(\Pi_i) = p_f F_i - E(p_s^*)F_i - G_i + \frac{1}{4e_i}E(p_s^{*2}) - \mu_i \mathrm{Var}(p_s^*)F_i^2 \\ -\mu_i\frac{1}{16e_i^2}\mathrm{Var}(p_s^{*2}) + \mu_i\frac{\mathrm{Cov}(p_s^{*2}, p_s^*)F_i}{2e_i}\end{aligned} \tag{A7}$$

We obtain optimal forward positions F_i by taking the first-order-condition:

$$\forall i \in H; F_i = \frac{p_f - E(p_s^*)}{2\mu_i \mathrm{Var}(p_s^*)} + \frac{1}{4e_i}\frac{\mathrm{Cov}(p_s^{*2}, p_s^*)}{\mathrm{Var}(p_s^*)} \tag{A8}$$

A similar process yields the optimal forward position for high-cost producers with $a = 3$:

$$\forall i \in H; F_i = \frac{p_f - E(p_s^*)}{2\mu_i \mathrm{Var}(p_s^*)} + \frac{2}{3\sqrt{3e_i}}\frac{\mathrm{Cov}(p_s^{*1.5}, p_s^*)}{\mathrm{Var}(p_s^*)} \tag{A9}$$

[2] A similar simplified derivation can be followed for zero-cost producers, as the cost term in (A1) becomes irrelevant.

Similarly, and independent of a, optimal forward positions for zero-cost producers and retailers can be found:

$$\forall i \in Z; F_i = \frac{p_f - E(p_s^*)}{2\mu_i \mathrm{Var}(p_s^*)} + \frac{\mathrm{Cov}(p_s^* K_i, p_s^*)}{\mathrm{Var}(p_s^*)} \tag{A10}$$

$$F_j = \frac{p_f - E(p_s^*)}{2\mu_j \mathrm{Var}(p_s^*)} + p_c \frac{\mathrm{Cov}(D_j - C_j, p_s^*)}{\mathrm{Var}(p_s^*)} - \frac{\mathrm{Cov}((D_j - C_j)p_s^*, p_s^*)}{\mathrm{Var}(p_s^*)} \tag{A11}$$

Finally the forward market clearing condition $\sum_{i=1}^{N_h} F_i + \sum_{i=1}^{N_z} F_i + \sum_{j=1}^{M} F_j = 0$ renders the optimal forward price for the quadratic model in text equation (3.6) and for the cubic model in text equation (3.8).

Chapter 4

Decision Strategies and Forward Pricing with Increasing Intermittent Supply [1]

4.1 Introduction

Power markets go through a series of radical transformations to achieve sustainability and liberalization targets, influencing decision making, trading strategies and price formation. The integration of renewable power introduces more low marginal costs suppliers to the market, as no fuels are needed to produce electricity and resulting decreasing power prices may significantly affect trading strategies and policy structures (Zhou et al., 2015). On the other hand, intermittent supply from wind mills and solar panels in combination with the non-storability of electricity and price inelastic

[1] This paper is currently under review at a top-ranked journal and parts of the chapter appear in the following publications and peer reviewed conference proceedings:
Koolen, D., Huisman, R., and Ketter, W. (2018). Strategic trading and hedging in sequential electricity markets with increasing renewable supply. *IAEE Energy Forum*, 27(1), 37-38.
Koolen, D., Huisman, R. and Ketter, W. (2017). The Electricity Forward Price with Increasing Intermittent Supply. *2017 International Conference on Energy Finance.* Hangzhou, China (25-27 May 2017).
Koolen, D., Huisman, R. and Ketter, W. (2016). Risk and Decision Making for Electricity Forward Markets with Volatile Resources. *2016 Annual Meeting of the Commodity & Energy Markets Association (CEMA).* Paris, France (23-24 June 2016).

demand cause spot prices to fluctuate heavily. Increased competition, lower prices and more price volatility have drastically changed decision behavior in electricity markets.

There exists extensive literature on the decision-making process in power markets, from the perspective of producers, retailers and consumers (Conejo et al., 2010). In this paper, we focus on decision making in forward and spot markets. Decisions are affected by uncertainty and risk, due to price fluctuations and spikes, intermittent production and volatile demand profiles. As agents can make more accurate predictions when time moves closer to delivery, producers and retailers face more uncertainty about volumes to deliver and spot prices when the delivery date is further away in time. This creates a demand for forward contracts, committing the producer to deliver an agreed amount of energy for a fixed price at a specific point in time in the future. Pricing forward contracts, however, is tedious and several theories have been put forward to explain differences between forward and (ex-ante) spot contracts, also called the forward premium. First, power agents engage in hedging activities to avoid risk exposure over supply and demand spot uncertainties. The forward premium as such reflects the net cost of hedging against short-term risks and may vary depending on individual needs for mitigating risks of producers and retailers (Bessembinder and Lemmon, 2002), time granularity (Longstaff and Wang, 2004) and vertical disintegration of traditional power suppliers (Aïd et al., 2011). Second, in oligopolistic markets, producers may take strategic positions in forward contracts. Allaz and Vila (1993) indicate that the existence of a forward market creates incentives for strategic commitments in forward markets, as it allows them to gain market share in the spot market. From this perspective forward markets may divide the market power of suppliers over forward and spot markets and thereby enhance total efficiency, although for power markets this has been subject to debate with respect to buyer market power (Anderson and Hu, 2008) and capacity constraints (Murphy and Smeers, 2010). No conclusive view on modeling forward price behavior has however been put forward yet, and both theories have presented their shortcomings with respect to empirical validations in power markets.

Previous empirical work on price formation of electricity forward contracts has shown various findings with no clear economic interpretations. Lucia and Schwartz (2002) find expectations over spot prices to consist out of two components; an equilibrium long-term spot price and a mean-reverting short-term price, and hence vary over time in size and sign. They successfully find empirical evidence for the model using data from the Scandinavian NordPool market. Further studies have suggested the emergence of positive ex-post risk premia, with forward prices higher than realized spot prices for example, for the German EEX market (Wilkens and Wimschulte, 2007) and the NordPool market (Botterud et al., 2010). Others find evidence for negative forward premia, for example Cartea and Villaplana (2008) indicate backwardation in the Nordic, British and PJM market. Longstaff and Wang (2004) relate time-varying premia to specific trading hours during the day for the PJM market, whereas Borenstein et al. (2002) find similar results for the Californina market, related to market inefficiencies and market power. Bessembinder and Lemmon (2002) study forward and spot price formation in electricity markets via an equilibrium approach and find mixed evidence for the Californian power market. They demonstrate that the forward risk premium depends on measures of demand uncertainty. Although they do not focus on supply uncertainty, their result shows clearly that the difference between forward and expected spot prices is a direct result of volume uncertainty. Summarizing, the sign and size of the forward premium is found to depend on market structure characteristics and demand, supply and price uncertainty. This paper contributes to this literature examining the forward risk premium in relation with uncertainty faced from an increasing market share of intermittent renewable power supply.

The economics of wind and solar power are so different from conventional power that it motivates us to study the impact that the penetration of such power sources has on decision making and prices in wholesale electricity markets. Indeed, operational constraints and the underlying technological cost structures of heterogeneous power agents may significantly affect individual bidding behavior in sequential markets (Hortacsu and Puller, 2008). Building on the rationales of hedging and strategic behavior, the production technology mix is found to influence forward and spot price formation in oligopolistic markets (Peura and Bunn, 2016) and supply function market equilibria (Al-Gwaiz et al., 2016). In terms of empirical specifications, previous work has confirmed the view that decision making and forward pricing depend on operational market characteristics and underlying production technologies, but mixed results have been presented with respect to trading decisions and (sign of the) forward premium (Bunn and Chen, 2013). Redl and Bunn (2013) indicate the impact on the forward price in the German EEX market of underlying fuel fundamentals. Huisman and Kilic (2012) discuss that significant differences may occur depending on the specific market. They find evidence for different time-varying risk premiums between the Nordpool market, with storage in the form of hydropower, and the Dutch APX market, primarily operating gas-fired power plants. This had also led to the believe that one cannot apply the same model to all markets, as specific theoretical assumptions on hedging, strategic behavior but also operational constraints and technology need careful market specific attention.

Our paper is about the impact of a technology change on the strategic behavior of agents in forward and spot markets and on respective prices. We research this in an experimental set-up as we think that this adds valuable insights related to theoretical studies, as we can allow for more variation, and empirical studies as we can rule out other effects than a change in renewable supply alone. Experiments have proven to be a promising method to analyze financial markets and individual trading behavior (Bloomfield et al., 2009; Brown and Kim, 2013), as well as testing theories related to forward trading and market competition (Le Coq and Orzen, 2006). In the context of electricity markets, experimental methods have been used to investigate market design changes (Bower and Bunn, 2000), explain system behavior (Koritarov, 2004) and analyze the effects of introducing forward trading (Brandts et al., 2008). Indeed, Ketter et al. (2016b) show that experimental modeling and agent-based simulation studies are not only an effective way to spur innovation, but also provide a flexible way to analyze decision making and price formation under various real-world conditions and test the efficacy of both analytic and strategic research ideas. The experimental design allows us to implement variations with a high degree of control and test decision making in sequential markets with a varying production technology mix under ceteris paribus conditions. As such, we are able to focus exclusively on individual decision making behavior, strategies of intermittent and non-intermittent producers and the price formation process in power markets with increasing intermittent supply.

We contribute to the emerging discussion on the efficient integration of renewable energy sources in current power systems (Cramton and Ockenfels, 2012; Kök et al., 2016). Considering an increasing market share of intermittent power sources, we find that non-intermittent power producers can retain their profits by shifting their focus towards the spot market, affecting price behavior and the premium priced in forward contracts. We find evidence for this strategic effect, evaluating price dynamics under varying market shares of intermittent renewable energy in German spot markets. As this strategic pricing effect of non-intermittent producers is often not desirable from a sustainable market point of view, the work ultimately paves the way for policy makers to examine the implications on existing market structures and their participants' strategic space, considering alternative market designs both from market and individual perspective in order to not only integrate large shares of renewable energy in existing electricity markets, but also achieve it in a sustainable manner.

The rest of the paper is organized as follows. We first discuss the experimental approach and discuss the market structure from an agent and market perspective, before elaborating on the experimental design. We next analyze the results from the experimental sessions, both from a market and decision making perspective, and relate implications of increasing intermittent renewable market capacity on pricing and decisions to the operational characteristics of power agents. We conclude by evaluating our findings empirically in German short-term power markets and discuss the contributions and implications from a market and individual perspective.

4.2 Approach

In this paper, we focus on how market agents make decisions and retain profits in forward and spot markets in light of technology change that yields operational constraints and uncertainty. Power markets wherein supply came predominantly from fuel based power plants now face a growing market share of renewable producers which burn no fuels to produce power. The inclusion of intermittent renewable power supply changes the economics of power markets. First, renewable suppliers have no fuel costs and therefore lower marginal costs of production than (traditional) fuel burning suppliers have. In competitive forward markets renewable producers undercut prices of fuel based producers because of lower marginal costs and, as a consequence, drive them out of the forward market. Secondly however, renewable sources reduce power system flexibility as their supply is intermittent depending on wind and solar radiation. Traditional fuel based supply is non-intermittent and therefore offers volume adjustment flexibility that renewable supply does not have. This leads to an advantage in spot markets, as they can more flexibly adjust their production volumes in real-time than intermittent renewable supply.

Figure 4.1 depicts price formation in power forward and spot markets, with risk neutral heterogeneous producers. The merit order curve is formed by the array of different production technologies such as renewable power, nuclear, coal, gas and peaking units forming the supply curve S. Forward demand is represented by the demand curve Q, which may be approached as inelastic (Knaut and Paulus, 2017). Following Borenstein et al. (2008), the forward price equals the expected spot price with transparent information, as market participants agree upon a price taking into account expected demand and supply in the spot market. Deviations in real time are dealt with in the spot market, resolving any mismatches between demand and supply in real time. Figure 4.1 indicates the volatile behavior of spot markets, as uncertainties

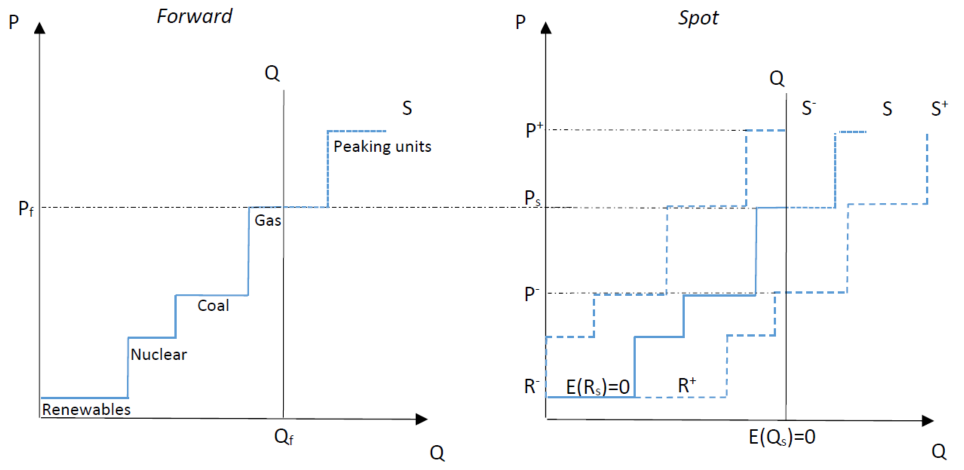

Figure 4.1: Equilibrium forward and spot pricing along the merit order of production technologies.

on demand and supply cause spot prices to fluctuate around their expected value. Where in expectation the deviations have an expected value of zero, oversupply of intermittent renewables R^+ cause the spot price to drop to p^-, where a shortage R^- would cause the spot price p^+ to be larger than its expected value. We argue that non-intermittent producers can profit from changing their focus from forward to spot markets in order to exploit their flexibility advantage in spot markets.

With respect to the terminology, classic financial decision literature defines a spot market as the market when the transaction is carried out in the same period at which the decision is made (Mulvey and Vladimirou, 1992). In this study, we consider the spot market to be such a short-term financial market. We define the forward[2] market as the place where agents trade contracts for delivery of power during future periods of time ranging from one day to several years ahead. One example is the day-ahead market where one-day forward contract are traded for next day delivery. Although energy economics literature tends to refer to the day-ahead market as a spot market as well, we define the day-ahead market as a forward market as the distinction between future and real-time delivery is of crucial importance in this paper.

We examine strategic bidding and forward price behavior with the increase of intermittent production sources in a developed experimental trading environment.

[2]For this paper, there is no need to focus on the differences between futures and forward contracts. Therefore we actually refer to both forward and futures contracts when we mention a forward contract in this paper.

The economic environment of the experiment takes into account two sets of producer agents: intermittent and non-intermittent producers. In general, agents buy and sell electricity contracts during two periods. In period 1, they trade a forward contract that delivers power in period 2. In period 2, they trade in the spot market after which delivery takes place.

4.2.1 The Agents

The first type of agent (labeled **consumer**) is an automatized power consumer that demands a volume D of power for delivery in period 2. Although modeled as a single entity, this agent represents a group of power retail companies that deliver power to households and enterprises. Typically, their demand is price in-elastic in the short run, meaning that the consumer agent purchases the demand in the market whatever the price is (price taker). Short run inelastic demand is a typical assumption for stylized short-run electricity market models. Indeed, studies examining short run markets find no significant demand elasticity (Lijesen, 2007) or only little during specific hours (Knaut and Paschmann, 2017). This behavior occurs due to energy retail companies hedging their margins with forward contracts as they typically sell power to their clients against fixed prices. We assume that consumer's demand is uncertain, but that the probability function of demand is publicly known with mean D and variance σ_D^2.

The second agent (labeled **intermittent producer** or **ip**) supplies power from intermittent power sources such as wind mills or solar panels during period 2. His supply is uncertain, depending on for instance wind speed or solar radiation. Following the work of Ito and Reguant (2016), renewable producers have zero marginal costs but are uncertain about their production realization. We assume that the supply of the intermittent producer is normally distributed with mean P_{ip} and variance σ_{ip}^2. All intermittent agents have the same production technology, with the same probability structure, and that their supply is mutually independent in order to simulate an entire market rather than a specific region. We further assume that this agent does not curtail its power supply as many countries have policies and regulation to incentivize this type of production[3]. We define n_{ip}, a treatment variable in the experiment, as the number of intermittent producers in the market.

[3]This applies to supply from subsidized renewable energy that has been integrated over the past decennia, guaranteeing renewable producers a fixed price per unit of electricity produced. The most commonly used mechanism to establish this is via feed-in tariffs, which may lead to market inefficient investment in the technology mix (Couture and Gagnon, 2010). Moreover, the loss of curtailing this type of generation is generally perceived as an unacceptable solution (Jacobsen and Schröder, 2012).

The third agent (labeled **non-intermittent producer** or **nip**) supplies (non-intermittent) power with a production capacity during delivery of P_{nip}. It converts a storable commodity in the form of chemical energy into electrical energy and can determine the amount of delivered power flexibly. We assume that non-intermittent suppliers can do so with unlimited flexibility or ramping, i.e. production volumes can be varied freely between 0 and P_{nip}. Fuel and emissions right costs are given by a variable cost efficiency parameter η_{nip}, implying the fact that production costs increase with output. We assume no other variable costs. Fixed costs are assumed zero, representing a sunk cost and not affecting the decision-making process (Pindyck, 1993). For simplicity, we assume all non-intermittent producers to have the same production cost function, where we abstract from supply issues like faults or maintenance. We define n_{nip}, a treatment variable in the experiment, as the number of non-intermittent producers present in the market.

The fourth agent (labeled **operator**) is an automatized market and system operator. The market operator collects all bids and offers and calculates the market clearing price. As soon as the actual demand and supply from the intermittent agents is revealed in period 2, this agent determines the additional amount of electricity to be purchased or sold in the spot market to balance demand and supply. As such, the market operator is a price taker.

In all sessions, we keep the total number of producers fixed, but vary the number of intermittent and non-intermittent producers such that we can examine the impact of the market share of each producer type. Market information like the number of intermittent and non-intermittent agents, cost structures and operating constraints of individual power suppliers are transparent to all market participants.

4.2.2 The Power Market and Time Periods

Trading electricity in wholesale markets can be done in different sequential markets. Where forward contracts commit a seller to deliver and a buyer to receive power for a price that is agreed upon before delivery, spot markets on the other hand serve to deal with any remaining imbalances of market agents at real time, as a perfect match between supply and demand is required to ensure grid stability. Care needs to be taken with respect to the terminology in published literature to the spot market. Electricity spot markets are typically referred to as day-ahead markets, for delivery of electricity during the period of 1 hour in the next day, or intraday markets, trading 15-minute products for the next day. Classic financial decision literature however defines a spot market as the market when the transaction is carried out in the same period at which the decision is made (Mulvey and Vladimirou, 1992). In this study, we consider the spot market to be such a short-term financial market. Indeed, in the context of electricity markets with increasing uncertainty, risk-sharing becomes more important and short-term financial instruments close to real-time, like intraday and continuous trading, gain liquidity (Knaut and Paschmann, 2017). Any remaining imbalances in real-time are solved on imbalance markets, through activation of services that are procured beforehand via the reserve market typically by flexible producers, and settled accordingly.

All (intermittent and non-intermittent) suppliers produce one homogeneous commodity, electricity. Produced power is sold in hourly contracts in two sequential stages, the forward and the spot market for physical delivery immediately after clearance of the second market.

During period 1, a forward contract is traded. The forward contract guarantees the supply of 1 entity of power in the unit MWh, in period 2 at a fixed price. All types of producers, both intermittent and non-intermittent, can submit a limit offer price and volume; i.e. they submit the minimum price against which they are willing to sell the submitted number of forward contracts. We limit intermittent producers forward trading to 115% of their nominal capacity, in line with existing policies preventing speculative behavior of inflexible power plants (Morales et al., 2010). Moreover, since the main purpose is electricity trading with physically binding contracts rather than financial arbitrage in energy markets (Knaut and Paschmann, 2017), we prevent all producers from purchasing forward contracts.

The automized consumer agent is price-taking when purchasing the expected demand for period 2 in the forward market. As we consider short-term sequential markets in this study, the market clearing volume equals the expected demand D from the consumer agent. After receiving the limit offers from the producers, the market clearing forward price is set at that price where the total supply of forwards equals the expected consumer demand. Once cleared, the forward market price is transparent to all producers and portfolio positions remaining for the spot market are updated.

During period 2, a spot contract is traded. Non-intermittent producers can submit both limit bid and offer prices; i.e. a maximum price against which they are willing to purchase power and a minimum price against they are willing to sell power. Following Knaut and Paschmann (2017), real-time markets allow only for restricted possibility of trading as market operators require assurance of supply in short-term markets. Thus although supply of intermittent power producers is incentivized, they are price-taking in the spot market. Once all bids and offers are submitted in period 2, realized consumer demand and intermittent production capacity become transparent to all producers in the market. At this point in time, the operator determines the volume needed to balance demand and supply and clears the spot market thereby setting the market clearing price. This set-up is consistent with most European imbalance markets, where power producers submit their bids and offers for specific time during the day. The system operator purchases and sells power respectively in the case of power shortage or oversupply. Therefore, at maximum 1 of the 2 limit orders of the non-intermittent producer is cleared in the spot market.

4.3 The Experimental Design

The goal of the study is to examine via a clean experimental market set-up the effects of an increase of the market share of intermittent power suppliers to volumes, bidding strategies, prices, and profits. We distinguish between three market structures:

1. The **non-intermittent** market (NI) is a market with only non-intermittent agents. The number of intermittent producers is 0% and the number of non-intermittent producers is 100%. We use this treatment as a base scenario, representing a traditional market without intermittent renewable energy supply capacity.

2. The **low market share intermittent** market (LI) is a market with both intermittent and non-intermittent producers. The market share of intermittent capacity is one third of the total capacity stalled in the market, the rest are non-intermittent producers. This represents a market in which renewable supply capacity is lower than conventional power supply capacity.

3. The **high market share intermittent** (HI) is a market with both intermittent and non-intermittent producers. The share of intermittent and non-intermittent producers is inverted compared with the LI market, representing a market that is dominated by renewable supply capacity. The share of intermittent capacity is two thirds of the total capacity stalled in the market, the remaining production capacity in the market is given by non-intermittent producers.

In order to control for ecological validity, exogenous variables defined above are set to approximate real world values[4]. The number of all (intermittent and non-intermittent) power producers is set to $n = n_{ip} + n_{nip} = 15$, as power markets typically consist out of few dominant firms representing most of the market share (Ito and Reguant, 2016). The consumer agent's demand follows a normalized distribution with $D \approx N(11500, 1150)$, which is in the same order of magnitude to that of a small country like the Netherlands, or large metropolitan area like New York. We set the maximum capacity of non-intermittent producers to $P_{nip} = 900$ MW, nominal capacity of intermittent producers to $P_{ip} = 900$ MW and their deviation to σ_{ip} to 5%. Variable costs of non-intermittent producers are set to $\eta_{nip} = 50$ euro/MWh. We allow minimum bidding prices of -300 euro/MWh and maximum bidding prices of 3,000 euro/MWh[5].

We conducted a total of 5 laboratory experiments. A single experiment consisted out of 3 sessions for each market structure, with a session being a continuous period of time where a fixed group is exposed to a single experimental treatment. Each session consisted of 30 rounds, where each round represented a sequential auction with a forward and spot market. The 3 market structures or treatments were presented in a counterbalanced order over the set of 5 experiments.

Before the start of an experimental session, participants were randomly assigned a producer role, being either an intermittent or non-intermittent producer. For the LI and HI treatment this procedure was repeated two more times to ensure that every subject participated in the three market structures as both intermittent and non-intermittent producers for an equal amount of rounds. In order to control for learning in the initial rounds, data was only collected from the rounds where market clearing prices converged and remained within a margin of 25 percent of the average over the previous 5 rounds. For all 5 experiments, convergence was achieved within 5 learning-sessions, resulting in data of 25 rounds for every market structure in every experiment.

We acknowledge that participating in the experiment requires extensive knowledge on energy finance and market design as subjects have to play different types of producers, submitting bid and offer prices, understand the probability structure of demand and intermittent supply and keep track of their results. Subjects were therefore

[4]We note that the absolute numbers in the experiment are of little importance, arbitrarily depending on the number of market participants, market technologies and production costs. Rather the results of the experiment are illustrative for relative performance of market prices in relation to the decision making behavior of intermittent and non-intermittent producers.

[5]To our best knowledge, all power markets apply minimum and maximum prices. The limits that we apply are in accordance with Dutch power markets.

recruited among graduate students that specialize in energy finance and management, with a different set of 15 market participants selected for every experiment. Subjects were provided instructions (in appendix) via e-mail before the experiment and these instructions were read aloud before the experiment. No communication between subjects was allowed and each experiment lasted about 1 hour. Participants were paid proportionally with performance, i.e. depending on their final financial position after participating in all 3 market structures and begin assigned to every producer role an equal amount of time. Cash was the only incentive offered, with an average of 25 euro. A computerized program, written in JAVA, was used to implement the experimental environment and is openly accessible via the web.

4.4 Results

We first analyze the outcomes of the experiments by analyzing market performance in terms of allocated volumes on forward and spot markets for both types of producers. Next, we elaborate on individual decision making and bidding, allowing us to study whether non-intermittent producers can retain their profits with a high market share of intermittent producers.

4.4.1 Allocated Volumes

Table 4.1 shows the allocated volumes in the forward and spot market for intermittent producers, for the two treatment set-ups where intermittent producers are active. In the first experiment of the LI market, intermittent producers sell on average 892 MWh forward (median 900 MWh). They sell 5 MWh on average on the spot market (median 4 MWh), however when looking at absolute numbers they sell or buy on average 55 MWh. This indicates the balancing behavior of the spot market, where both shortage and oversupply imbalances are settled in order to ensure market and grid stability. Indeed, over all the experiments of the LI market, the intermittent producers sell almost all of their expected output (900 MWh) on the forward market. Spot market trade is characterized by dealing with variations between realized and expected volume. We observe the same behavior in the HI market, with a larger share of intermittent producers active. This is in line with expectation, where intermittent producers move as close to real time in order to follow more accurate production predictions, but restricted participation in the real-time spot markets prevents them from strategic behavior.

Although the average and median allocated volumes do not differ between the LI and HI markets, we observe differences between the LI and HI standard errors for the forward market in Table 4.1. In all experiments, the standard error of the allocated volumes is higher in the HI market than in the LI market. We attribute the higher dispersion of allocated volumes in the HI market to the increased market share of intermittent producers. Some intermittent producers seem to deviate from the nominal bidding procedure and are allocated only very low volumes as indicated by the column representing minimum values for the HI market. This is mainly due to high bidding prices, which result in the risk of not being cleared in the market.

Table 4.2 shows the allocated volumes of non-intermittent producers. In the first experiment, producers sell 750 MWh on average (median 890 MWh) in the forward market. They purchase on average 20 MWh (median 0 MWh) in the spot market, however absolutely speaking we find that on average 56 MWh is bought or sold. Moving from market NI via LI to HI, we clearly observe a decreasing pattern in the allocated conventional volumes in the forward market. The higher the market share of intermittent producers, the lower the volumes allocated to non-intermittent producers. This is in line with the negative effect of intermittent producers on electricity prices up to a day-ahead level as low marginal cost producers replace conventional production capacity (Sensfuß et al., 2008). The opposite pattern is apparent in the spot market as it becomes more liquid from NI to HI. The null-values for minimum allocated volumes in the forward market and median allocated volumes in the spot market indicate that some bids of the non-intermittent producers however do not get cleared.

We observe that standard errors are higher than those of intermittent producers, indicating more risk-seeking behavior. Moreover, larger standard errors are observed with increasing intermittent market share, both for the forward and the spot market. This indicates a larger discrepancy in sequential decision making between individual non-intermittent producers. The view that we obtain from this table is that a non-intermittent producer sells less on the forward market and more on the spot market when the share of intermittent producers increase.

4.4.2 Strategic Decision Making Non-intermittent Producers

Non-intermittent producers (are forced to) move from the forward market to the spot market when the share of intermittent producers increases. In other words, conventional power producers trade less on the forward market and more on the spot market when the production capacity of renewable energy sources increases. This results in more uncertainty in the profits and losses of non-intermittent power plants,

Table 4.1: Allocated market volumes intermittent producers

	forward				**spot**				
experiment	mean(se)	median	min	max	mean(se)	|mean|(se)	median	min	max
Market: LI									
1	892(1)	900	890	920	5(7)	55(5)	4	-142	610
2	906(1)	900	890	930	-2(5)	41(3)	-2	-118	107
3	889(1)	890	870	910	3(4)	39(2)	12	-114	80
4	896(1)	900	840	930	14(5)	40(3)	11	-89	131
5	891(2)	890	840	940	24(5)	47(3)	25	-90	125
Market: HI									
1	893(4)	900	269	930	-6(6)	56(4)	-29	-164	634
2	894(5)	900	152	940	-23(7)	62(6)	-38	-176	777
3	878(2)	880	342	910	27(5)	55(3)	18	-105	575
4	884(3)	890	307	930	0(4)	36(3)	-3	-118	604
5	891(3)	900	210	950	-4(4)	40(3)	3	-120	642

Table 4.2: Allocated market volumes non-intermittent producers

experiment	forward				spot				
	mean(se)	median	min	max	mean(se)	|mean|(se)	median	min	max
					Market: NI				
1	750(15)	890	0	900	-20(10)	56(9)	0	-900	900
2	750(14)	880	0	900	-25(10)	58(9)	0	-900	765
3	758(15)	880	0	900	8(10)	58(10)	0	-900	900
4	751(14)	890	0	900	-8(9)	48(8)	0	-900	900
5	753(15)	880	0	900	-17(11)	74(10)	0	-900	900
					Market: LI				
1	687(19)	830	0	900	4(14)	88(13)	0	-870	900
2	683(21)	845	0	900	-43(17)	110(16)	0	-900	900
3	706(19)	840	0	900	-34(15)	90(14)	0	-900	900
4	692(19)	830	0	900	-25(15)	86(14)	0	-871	900
5	691(20)	840	0	900	-32 (16)	104(15)	0	-880	900
					Market: HI				
1	489(25)	620	0	880	-3(34)	237(26)	0	-840	900
2	476(24)	610	0	870	40(34)	251(25)	0	-810	900
3	533(24)	640	0	840	-84(30)	216(24)	0	-810	773
4	523(23)	610	0	840	-39(28)	194(23)	0	-800	900
5	485(23)	580	0	890	24(28)	181(22)	0	-850	900

however not necessarily in reduced profits since non-intermittent producers determine prices in the spot market whereas intermittent producers are price takers, obliged to trade away remaining imbalances resulting from variation in realized production volumes.

Table 4.3 presents the average profits of non-intermittent producers for the different experiments. In the first experiment, average profits of non-intermittent producers were 16758 euro in the forward market (median 18900 euro), 1949 euro in the spot market (median 0 euro) and 18707 euro in total (median 19800 euro). We find evidence for the merit order effect in the forward market, resulting in lower profits and the subsequent market push-out of conventional power plants. Non-intermittent producers however do seem to gain from trading in the spot market, with higher profits made with more intermittent sources on the market. This indicates that there is a demand for flexible spot production with more intermittent production in the market, i.e. a convenience yield for flexibility in the producer's portfolio. Moreover, Table 4.3 shows null median values in the spot market for NI and LI but positive median values for HI, indicating that most non-intermittent producers are profitable in the HT spot market. Some non-intermittent producers even only profit from trading in the spot market as maximum total profit values for HI are equal to maximum spot profits in some cases.

We find that the well-known merit order effect is only dominant in the NI to LI market with low share of intermittent production. The increase in spot market profits seems to be the dominant factor moving from LI to HI, when there is a significant market share of intermittent producers. To verify, we run a multilevel mixed-model extension of the Mann-Whitney test, allowing to test for differences between the three market set-ups while taking into account the nested group structure. Z-scores are reported in Table 4.3, calculated by comparing ranks between treatment levels, while p-values are obtained by comparing the Z-score against a distribution of Z-scores calculated by bootstrapping ranks with no treatment interference. We find that with increasing intermittent market share, forward profits decrease and spot profits increase significantly, and as a result total profits significantly decrease from NI to LI and significantly increase again from LI to HI. Interestingly however, no significant differences were found in total profits between the NI and HI market for non-intermittent producers. This indicates a strategic move from non-intermittent producers, moving from the forward market to the spot market, exploiting the convenience yield for flexibility.

Table 4.3: Market profits non-intermittent producers

	forward			**spot**			**total**		
exp	mean(se)	median	max	mean(se)	median	max	mean(se)	median	max
				Market: NI					
1	16758(342)	18900	24300	1949(420)	0	83959	18707(457)	19800	83959
2	24667(499)	27390	36900	2045(329)	0	53950	26712(552)	28500	65700
3	23656(488)	26400	37800	3290(611)	0	91304	26946(608)	27000	94340
4	16975(335)	18630	27900	1979(412)	0	90900	18954(456)	18920	90900
5	23256(538)	25800	36000	2943(516)	0	93600	26199(607)	28560	93600
				Market: LI					
1	10937(323)	12390	18270	4683(801)	0	91872	15620(757)	14280	90900
2	13394(450)	15160	24920	4901(889)	0	96300	18295(903)	16332	96300
3	13973(446)	14400	31320	4091(683)	0	82800	18064(742)	16175	82800
4	14456(436)	16600	24360	4060(697)	0	74160	18516(738)	17920	77940
5	12331(389)	13920	21120	4751(746)	0	74700	17082(745)	15132	75110
				Market: HI					
1	6147(366)	6300	14250	19398(2545)	5382	132240	25545(2534)	12920	132240
2	4747(263)	4960	10360	17465(1875)	10179	88560	22212(1837)	14793	89280
3	4791(284)	4970	14760	16041(1830)	5977	85650	20832(1879)	10349	85650
4	7216(367)	7300	16800	13590(1832)	465	115200	20806(1815)	12640	117600
5	6537(368)	6480	17000	16190(2148)	2178	122400	22727(2147)	12150	122400
				Nested multilevel Z-scores					
NI-LI		0.412***			0.598***			0.213**	
LI-HI		0.589***			0.843***			0.145**	
NI-HI		0.735***			0.975***			0.032	

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$

Table 4.4: Forward bid volumes and prices of non-intermittent producers

	volumes					**prices**			
exp	mean(se)	disagreement	median	min	max	mean(se)	median	min	max
				Market: NI					
1	870(2)	51	900	710	900	66(0)	67	52	81
2	864(3)	71	900	600	900	68(1)	68	51	97
3	875(2)	42	900	760	900	71(0)	71	50	95
4	857(3)	79	900	580	900	64(0)	63	51	88
5	877(2)	33	900	760	900	70(0)	69	51	94
				Market: LI					
1	840(2)	31	840	760	900	60(0)	60	51	77
2	857(2)	45	860	760	900	61(0)	60	49	82
3	850(2)	35	850	770	900	60(1)	56	51	95
4	842(3)	52	845	640	900	64(0)	64	45	85
5	851(1)	26	850	790	900	61(0)	60	50	84
				Market: HI					
1	671(6)	74	670	480	880	59(1)	57	48	74
2	653(7)	85	640	450	870	57(0)	57	51	69
3	692(6)	72	690	530	880	56(1)	55	33	74
4	672(7)	83	670	490	840	59(1)	59	49	74
5	660(8)	96	650	460	900	59(1)	58	50	75

The shift in strategic sequential market decision making of non-intermittent producers is interesting to observe from a bidding perspective in the forward market. Table 4.4 shows the bidding volumes and prices of non-intermittent producers in the forward market. In the first experiment, non-intermittent producers offered to sell on average 870 MWh (median 900 MWh) against an average price of 66 euro per MWh (median 67 euro per MWh). We find that non-intermittent producers are willing to sell against lower prices on average in the forward market, approaching the marginal production cost of 50 euro per MWh in the HI market. Minimum prices even fall below marginal production costs for some producers.

The standard error of the bidding volumes increases from NI to HI, indicating that possibly not all producers follow the same strategy. We define this form of disagreement as the mean of the individual producers' variances, resembling on average how different the strategies are of the individual non-intermittent producers. Indeed, highest levels of disagreement are found for the HI market, with some producers clearly bidding forward volumes around half of their capacity (450 MWh), while others remain risk-averse and mainly try to hedge against uncertainties in the spot market.

To conclude, we observe that non-intermittent producers try to strategically enter the spot market, even at the risk of making a loss in the forward market. Thus, our experiments show that non-intermittent producers are not only pushed out of the market due to the merit order effect, they also strategically decide themselves to bid lower volumes in the forward market, as they expect they can profit from changing their focus from forward to spot markets in order to exploit their flexibility advantage.

4.5 Forward and Spot Price Dynamics in Relation to Supply Uncertainty

We next focus whether the shift in focus of non-intermittent producers from forward to spot markets affects forward and spot price dynamics and therefore also the behavior of the forward premium. Table 4.5 provides summary statistics of market clearing prices in the forward and spot market. We observe a decline in forward prices for power markets with more intermittent capacity, related to the merit order effect. Clearly, spot prices become more volatile from NI to HI. The range of spot prices increases, with a clear decline in minimum prices and even reaching negative values for HI. The well-known positive skewness of power spot prices seems to disappear for markets with more intermittent production, in line with recent empirical results from the German spot market (Gianfreda and Bunn, 2018). Realized forward premiums

Table 4.5: Forward and spot clearing prices and resulting forward risk premium

	forward						**spot**						**premium**	
exp	mean	sd	median	min	max	skew	mean	sd	median	min	max	skew	mean	sd
							Market: NI							
1	72	2	72	69	77	0.2	83	44	88	34	163	0.45	-11	43.94
2	83	4	83	75	91	0.22	64	42	43	16	133	0.41	19	41.73
3	81	4	80	74	92	0.81	75	51	84	15	163	0.88	6	50.01
4	73	3	73	67	81	0.5	76	45	94	29	151	0.24	-3	44.71
5	81	6	82	69	90	-0.1	80	48	44	35	154	0.35	1	50.01
							Market: LI							
1	66	2	66	62	71	0.2	86	47	102	22	154	-0.13	-20	46.56
2	70	4	69	63	78	0.22	60	47	40	12	157	0.82	10	46.32
3	70	5	69	63	86	1.4	77	52	99	6	148	-0.1	-7	51.52
4	71	4	71	64	78	0.01	74	52	34	11	153	0.48	-3	51.30
5	68	4	67	62	74	0.11	70	50	32	11	171	0.53	-2	50.56
							Market: HI							
1	63	4	62	57	70	0.42	70	78	21	-20	202	0.47	-7	77.46
2	60	2	60	56	64	0	73	65	101	-27	158	0.1	-13	64.02
3	59	4	59	54	68	0.44	49	78	7	-45	200	-0.63	10	77.82
4	64	4	63	59	74	0.97	65	70	17	-10	194	0.46	-1	68.50
5	63	5	63	57	74	0.46	83	79	113	-49	189	-0.3	-20	78.30

experience large variations over rounds and markets. As a result from the merit-order effect, the forward risk premium seems to drop from NI to LI. The change in the forward premium is however less clear from LI to HI, where the above described strategic effects seems to play a role.

Figure 4.2 visualizes bidding price density distributions of non-intermittent producers in forward and spot markets for all market treatments. The plot indicates that across all experiments, bidding prices shift to the left in the forward market from NI to HI, as producers try to remain competitive. This leads to more similar distributions in the HI forward market across experiments, indicating smaller margins for strategic bidding in this market. Bidding price density distributions in the spot market appear to present a bimodal distributions, which can be explained by the fact that producers need to bid two prices; one for selling power and one for buying back power. The bimodal behavior in spot price distributions is confirmed by a Hartigans dip test. We further observe bidding spot prices to be more volatile with increasing market share of intermittent producers. Although it is line with expectation that cleared spot price would be more volatile with more intermittent market capacity, as expected imbalances would increase, we argue that a similar trend for bidding prices in the spot market indicates strategic behavior.

Summarizing, we find that with a increasing market share of intermittent renewable energy producers, non-intermittent producers are able to retain their profits by moving their focus from the forward to the spot market. In order to do so, non-intermittent producers bid lower volumes against lower prices in the forward market, in order to have in expectation higher profitable positions in the spot market. This is in accordance with Allaz and Vila (1993), who show that in oligopolistic market settings, strategic producers engage in forward trading in order to gain spot market share. We however also observe that, apparently irrespective of the realized demand for power in the spot market, non-intermittent producers strategically enlarge the difference between spot prices for buying back power and selling extra power. Non-intermittent producers thus have market power to strategically make use of their convenience yield for flexibility in the spot market. As most non-intermittent producers in current power markets burn fossil fuels to produce power, our findings imply that it is important for renewable policies to adequately evaluate the product flexibility, in relation to achieving a sustainable increase of intermittent renewable energy sources in wholesale power markets.

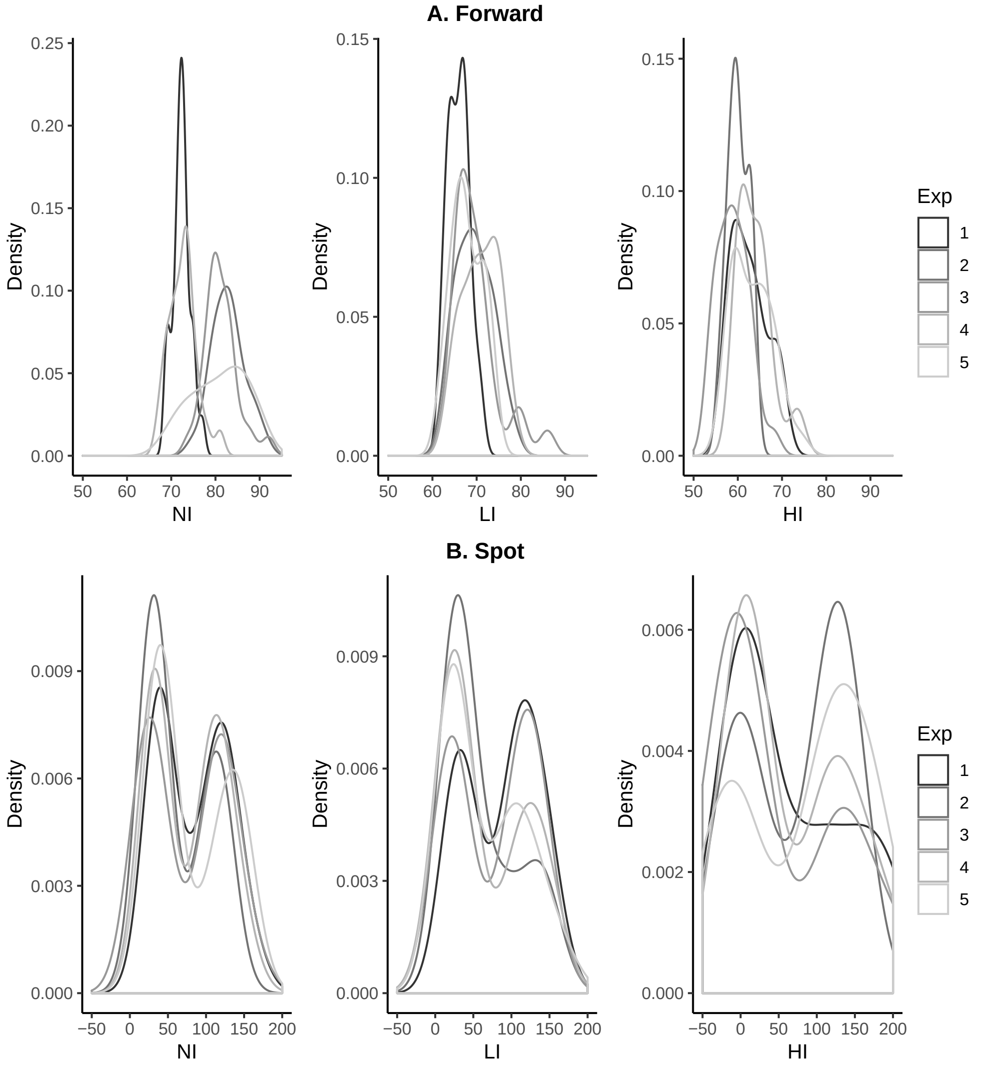

Figure 4.2: Bidding prices of non-intermittent producers in non intermittent market (NI), low intermittent market (LI) and high intermittent market (HI) for the (A) forward market and (B) spot market.

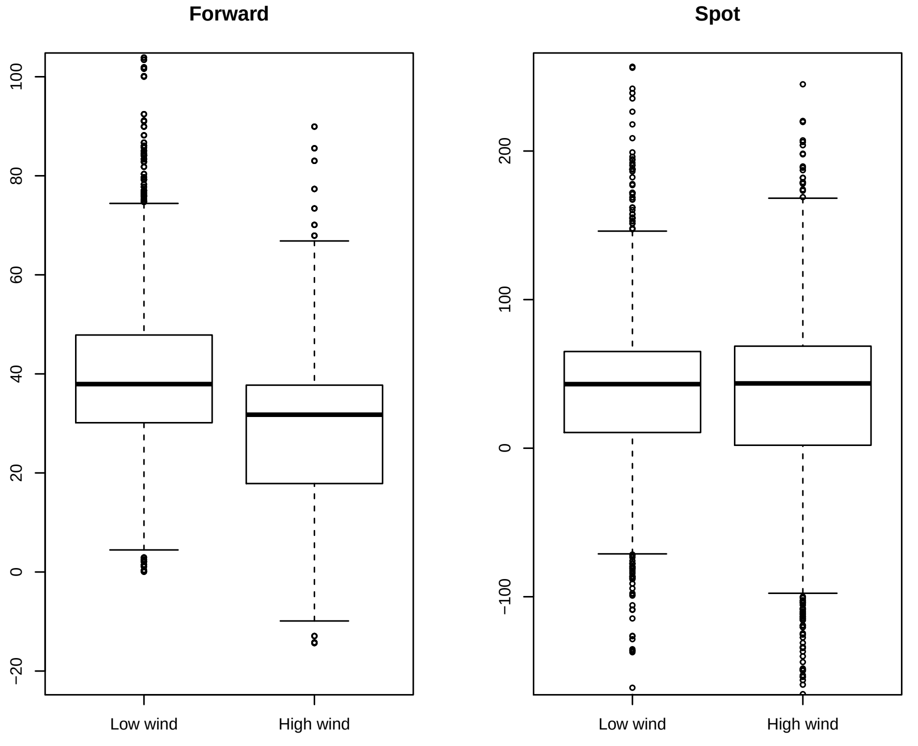

Figure 4.3: Boxplots of German forward (day-ahead) and spot (real-time) prices [EUR/MWh] for the 10% least windy days (Low wind) and the 10% most windy days (High wind) in 2017. Data from ENTSO-E (2018).

4.5.1 Empirical Validation in German Short-term Power Markets

We validate the above experimental findings empirically, using data from short-term sequential day-ahead and real-time power markets in Germany. German power markets provide us an ideal setting to study the effect of intermittent renewable energy sources on power pricing, as the main reference in European power markets with a recent sharp increase in the market share of solar and wind power. With the outspoken objective to achieve a share of renewable energy in power production of 35% by 2020 and 80% by 2050, Germany's renewable energy share has boosted through massive subsidies. With rapid expansions in wind and photo voltaic power, intermittent supply creates increasing uncertainties in German short-term markets.

We collect data on forward (day-ahead) predictions on wind generation and spot prices in the German control area in 2017[6]. Figure 4.3 illustrates the intuition on the effects of technology and renewables on German forward and spot trading. The figure depicts forward (day-ahead) and spot (imbalance) prices for the predicted 10% least and the 10% most windy days in 2017. Note the different scale for both markets, indicating higher spot price volatility in general. The merit order effect is observed in the forward market, as prices drop on more windy days. The decreasing pattern is less clear for the spot market, as prices are more scattered in both the positive and negative direction. The simple illustration nicely demonstrates the impact of intermittent production sources on price formation in short-term electricity forward and spot markets. In the following, we examine whether we can find empirical evidence in German spot markets for the strategic effect indicated by the experimental sessions. In order to find evidence for this effect, we estimate the effect of forward (day-ahead) wind prediction levels on the ex-post forward premium, using the following Two-Stage Least Squares regression:

$$p_f^{t,T} - p_s^T = \alpha_v + \beta_1 \text{Wind}_{t,T} + \beta_2 \text{Vol}_T + \beta_3 \text{Gas}_t + \beta_4 \text{Margin}_t + \epsilon_T \tag{4.1}$$

Where the term on the left-hand side resembles the realized forward premium, $p_f^{t,T}$ is the forward price at time t for delivery in T and p_s^T is the spot price at delivery. We control for fundamental price drives like fuels costs of non-intermittent producers, using day-ahead NCG gas spot prices, and the reserve margin, which is modeled as the ratio of generation over production at t (Redl and Bunn, 2013). All predictive variables are day-ahead predictions, with the natural exception of actual realized imbalance volumes, and thus closely relate to our experimental design by controlling for any information gains between forward market closing and spot market decision making.

[6]We represent the spot price by the reBAP imbalance price, which incorporates the price for activating secondary and tertiary imbalance reserves close to real-time. The price presents some further interesting characteristics that motivates the reBAP price as a good representation for the spot price. First, the reBAP price is symmetric per time interval, i.e. the same price is applied for both positive and negative imbalances. This is similar to our experiment, where irrespective of the individual imbalance, the cleared spot price is the same for all market participants. Second, European imbalance markets are in general regulated markets, where the auction design differs slightly per region and country. The reBAP price is one of the only imbalance prices partially based upon (energy) bids that are made day-ahead. As we make use of day-ahead predictions levels for wind generation, this feature is particularly interesting with regards to our experimental set-up as no additional information on generation levels is available to market participants on the spot market. As a consequence, prediction accuracy between the forward and spot market does not change and hence does not affect the results.

The main variables of interest are $\text{Wind}_{t,T}$ representing the predicted volume of wind production at t for delivery in T and Vol_T, which is the spot demand for power or imbalance volume at T. As suggested by the experiment, a higher market share of intermittent production leads to strategic behavior of non-intermittent producers and subsequently higher absolute forward premiums. In order to illustrate this effect in other words, consider two respective days A and B in a power market where wind generation is responsible for a substantial part of the supply curve. Day-ahead predictions for day A indicate wind mills produce at maximum capacity, whereas it is predicted to be windstill on day B: $\text{Wind}_t^A > \text{Wind}_t^B$. Consider now on the day itself an equal positive spot demand (imbalance) in hour 1 for both days and an equal negative spot demand for hour 2: $\text{Vol}_T^{A1} = \text{Vol}_T^{B1} = -\text{Vol}_T^{A2} = -\text{Vol}_T^{B2}$. In that case, the indicated strategic behavior of non-intermittent power producers would lead for comparing day A to day B to a more negative premium in hour 1 and a more positive premium in hour 2, or also: $\left|p_f^A - p_s^A\right| > \left|p_f^B - p_s^B\right|$.

We estimate the model with log-transformed price differences as the impact of the explanatory variables on the electricity prices is likely to be non-linear (Mulder and Scholtens, 2013). Our main interest is to find evidence for the indicated (strategic) bimodal effect of intermittent production on spot prices. We therefore split the data and analyze the effects separately for positive and negative imbalances. Note that spot prices in general tend to be higher(lower) than forward prices for positive(negative) imbalances, resulting in a negative(positive) forward premium in order to compensate for ramping-up(ramping-down) capacity. We remove the about 10 % of the data where this was not the case and log-transform the absolute value of the premium in order to compare results between positive and negative imbalances. The estimates for equation (4.1) are given in Table 4.6.

Results largely follow our expectation. Absolute positive and negative imbalances naturally create a larger demand for spot balancing, thus positively influencing the absolute forward premium. Controlling for the actual imbalance, we find evidence for the positive effect of day-ahead wind predictions on the absolute premium. Thus, when high shares of intermittent production are predicted day-ahead, non-intermittent producers seem to bid more negative spot prices to balance negative demand and more positive spot prices for positive imbalances. In other words, irrespective of the actual spot demand to balance the market, high day-ahead predictions on wind generation will result in more extreme spot prices. This is in line with the intuition of the experimental results, where non-intermittent producers engage in strategic behavior with high share of intermittent production.

Table 4.6: Regression results on absolute premium for positive and negative spot market volumes, Germany 2017. Robust standard errors in parentheses.

	Dependent variable: log $\left\|p_f^{t,T} - p_s^T\right\|$	
	Positive Imbalance	Negative Imbalance
	(1)	(2)
$\|\mathrm{Vol}_T\|$ $.10^{-3}$	0.27***	0.06*
	(0.02)	(0.03)
Wind_t $.10^{-6}$	7.19***	4.16***
	(1.25)	(1.18)
Gas_t	0.18***	-0.02**
	(0.003)	(0.008)
Margin_t	0.19	0.93***
	(0.12)	(0.11)
Constant	-0.13	2.83***
	(0.15)	(0.13)
Observations	18,397	10,705
Adjusted R^2	0.18	0.12
Note:	*p<0.1; **p<0.05; ***p<0.01	

4.6 Conclusions

In this paper, we study decision making and price formation in short-term forward and spot power markets with increasing supply uncertainty via an experimental approach. The developed trading environment allows us to isolate the effects of volume uncertainty via three market structures representing a non-intermittent market, low intermittent market share and high intermittent market share. It is well-known that with increasing intermittent capacity, non-intermittent producers are pushed out of the forward market as they have higher costs to produce power. We observe however an alternative explanation, as bidding volumes of non-intermittent producers decrease as well. This indicates that non-intermittent producers bid strategically in power markets with increasing intermittent capacity to obtain profitable spot market positions, capitalizing their convenience yield for flexibility.

The results indicate how behavior and decisions of power agents can significantly differ with changing technology and operational market constraints. We find the notions of hedging pressure and strategic behavior to depend on the market share of intermittent production as well as vary according the preferences and beliefs of individual power agents. As such, the present study constitutes a first step in using experiments to investigate the impact of increasing supply uncertainties on established rationales for forward trading. Further experiments could be helpful in understanding a number of related issues, disentangling strategic behavior (Murphy and Smeers, 2010), hedging (Bessembinder and Lemmon, 2002) and convergence bidding (Li et al., 2015). As mixed empirical results have been found for these rationales when applied to markets operating under different operational constraints, experiments could investigate the desired variations with a high degree of control.

Analyzing these systems, relationships between market participants, technology adaption and changes to market behavior provide key ingredients for devising a robust well-functioning electricity market, its design and its governing policies. We find that producer technologies affect commodity trading and thereby affect market prices, often not desirable from a sustainable efficient market point of view. This work paves the way for policy makers to examine the implications on existing market structures and their participants' strategic space, considering alternative market designs both from market and individual perspective in order to not only integrate large shares of renewable energy in existing electricity markets but also achieve it in a sustainable manner.

Appendix

A Instructions of the Portfolio Management Game

Instructions

This is an experiment in the economics of strategic decision making in energy wholesale markets. The instructions are simple. If you follow them carefully and make appropriate decisions, you can make a substantial amount of money. Your earnings will be paid to you in euro at the end of the experiment. In the experiment we use the (virtual) euro as well. The average amount of earnings is put on 20 euro, this can go up to 50 euro if you make appropriate decisions.

In this experiment, you will participate in a market as a producer of the fictitious commodity electricity and exchange it on the wholesale market. The end consumers, or demand side, of the market are simulated. All participants will represent a different producer type and you will be every producer type at least once. It is important that you remain silent and do not communicate with other people while the experiment is running. Do not log in before the experimenter tells you to log in. This is very important because if you log-in at another time, you might end up with a wrong portfolio. You can register to the game by going to `http://xlarge.rsm.nl/hedging_game2/faces/register`. Use your student number as your user name. Passwords can be chosen freely. If for some reason you lose connection to the internet or the game play does not automatically load, do not refresh the page! You can log-in again by using your log in credentials at `http://xlarge.rsm.nl/hedging_game2/faces/login.xhtml`. If you have any questions, or need assistance of any kind, please indicate this to the experimenter and he will come to you. We expect and appreciate your cooperation.

Please make sure you go through the full documentation. It will help you significantly in getting higher earnings. *The clarification of the gameplay will be written in italic.* Reading this should help you to understand the basic gameplay. We will use numerical examples in the instructions. These are only meant to be an illustration and are irrelevant for the experiment itself. The experiment consists of 3*30 different rounds with each 2 decision periods, a forward and a spot market. The whole experiment will take about 90 minutes. You will represent one player in every market setting. After 10 or 20 rounds, your player (or producer) type may be switched. The experimenter will announce at the beginning of each period that a new period has begun. If for some reason your screen does not update automatically, please go to the address bar and press enter. Do not press F5 to refresh as this might introduce errors!

An example is used to explain the basic game play, written throughout this document in italic. You can log-in to this example by going to http://xlarge.rsm.nl/hedging_game2/faces/login.xhtml. The example consists out of a market of 6 players with Username: 1 to 6. and respectively the same Password. Thus, for logging in to player 1, submit '1' in the Username and Password field. In this way, you can log in to all 6 players and look at their playing and bidding strategy. You will find the game is currently in round 5. By going to the Bids tab, you can find all the previous

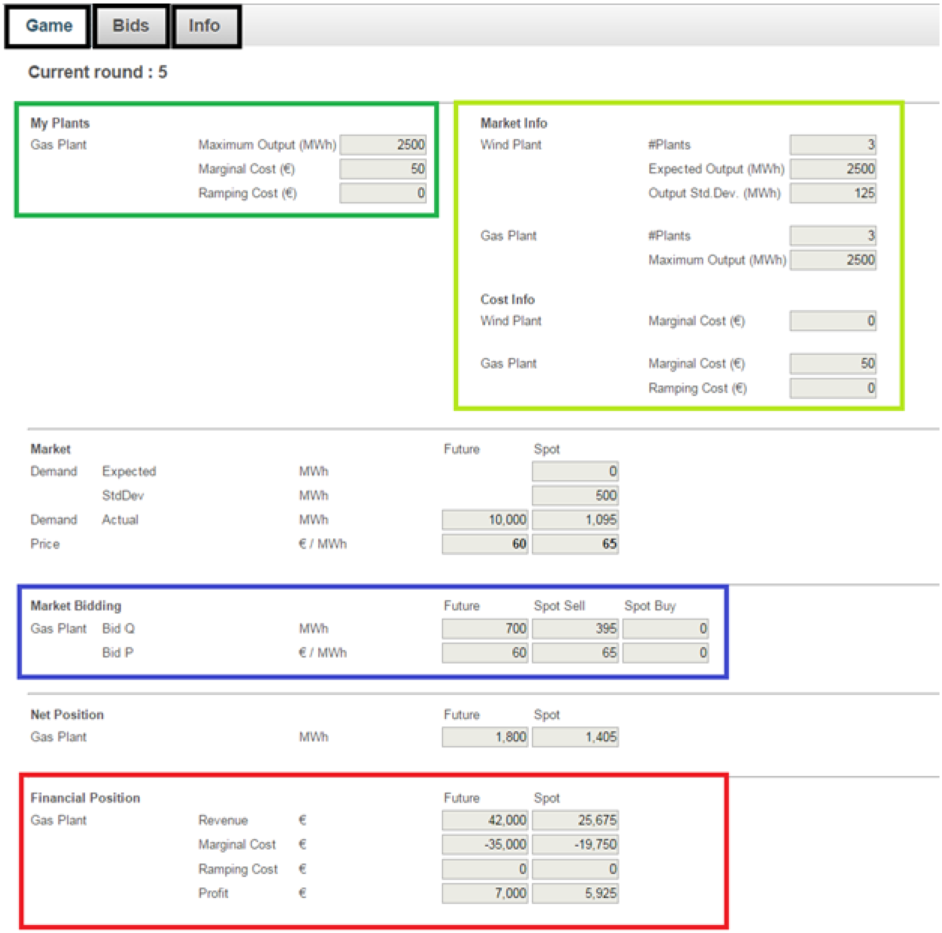

Figure A1: Overview game tab example.

bids of the respective player. Unless mentioned otherwise we will use player 1 in the explanation. An overview of this player his game tab is found in Figure A1.

Market Setting

When you log-in, you will be automatically directed to the 'game' tab of the game. In this tab you get an overview of what your portfolio looks like under my plants. Market information will be presented to you (shown in light green), indicating how the supply side of the market is established. The remaining fields in this tab show the financial overview of your activities in the market and are discussed below. Next, there is a tab called 'bids', giving you an overview of your bid history and the cleared market results in all previous rounds and a tab 'info' where general background information on the portfolio management game can be found. The different tabs are shown in black in Figure A1.

At the beginning of the game you can see the producer type of your personal portfolio in the game tab under my plants. During each period, you can sell units of the fictitious commodity. If you sell a unit you will have to incur that unit's production cost (though these are zero for some production types), this info can be found under cost info.

Player 1 his portfolio consists out of 1 wind plant with an expected output of 2500 MWh and a standard deviation of 125 MWh. In this round his actual output was 2503 MWh. Further you can find under market info that the market consists out of 3 wind plants with the same characteristics and 3 gas plants with a maximum output of 2500 MWh and a marginal cost of 50 euro/MWh.

Market

This field shows you the properties of the demand side of the market. Expected demand and the standard deviation are given at the beginning of each period to give an indication of expected demand. This is depending on historical data and the current market profile. Once the period is closed, the actual demand and the cleared market price are filled in.

Player 1 is currently at the end of round 5. The demand in the forward market is 10.000 MWh and a clearing price of 60 euro/MWh was established. In the spot market expected demand was 0, but due to a standard deviation of 500 on this expected demand, an actual demand of 1095 was observed. A clearing price of 65 euro/MWh was found.

Market Bidding

Under market bidding, you will have to place your bids for which volume and price you would like to sell or buy electricity. Each period you will have to make decisions on the offer price and the offer volume for the commodity. The two decisions periods are called the forward and the spot market, explained further below. Each bid represents an offer to sell or buy the fictitious good on the wholesale market. Depending on the market demand and the bids of the other players in the game, you will see whether your bid got executed or not after each period. It may happen that a bid only gets partially executed. If your bid gets executed, then you will make a revenue which can be consulted under Financial Position in the 'game' tab.

Player 1 made a bid to sell 2500 MWh for a price of 60 euro/MWh in the forward market. He was forced to sell his remaining position of 3 MWh in the spot market, this will be explained further below.

Rounds and Periods

Each round of the experiment consists of 2 subsequent periods: the forward market and the spot market. Both markets get cleared via a uniform pricing auction.

Forward Market

When the forward market is open, the market bidding fields below forward market will appear in white, meaning that you can now place your bids in the forward market. All producer types can participate. In the forward market you can only sell electricity. This can be done for positive and negative prices. Make sure that once your bids are placed, you hit enter or click on the save button in the upper right corner to submit them to the market. Once every player has done this, the market gets cleared and the spot market is opened. You can then consult whether your personal bid got executed or not.

By going to the 'bids' tab, you get an overview of the bidding history. For player 1 you can see the last 5 playing rounds. Player 1 his bid always got fully cleared, except for round 2. Here only a part got cleared (1556 MWh of 2600 MWh), due to his higher bidding price which was also the marginal clearing price.

Spot Market

When this market is open the fields below spot market will appear in white, meaning that you are allowed to place bids in the spot market. You can make two bids here, one to sell electricity in the spot market and one to buy back electricity in the spot market. Only one market gets cleared, depending on the market demand which is set after closure of the market. In the spot market 'sell' you can sell your remaining position and in the spot market 'buy' you can decide to buy back electricity that you sold in the forward market. For renewable producers these fields are already filled in, as they cannot make any bids in the spot market. Make sure that once your bids are placed, you click on the save button in the upper right corner to submit them to the market. Once every player has done this, the market is closed and cleared. You will be able to see whether your bid got executed and consult the cash position.

For the understanding of the spot market, log-in to player 4 and go to the bids tab to get an overview of his bids. In round 2, player 4 sold 2000 MWh in the forward market. He thus decides to sell his remaining of 500 MWh for a price of 60 euro/MWh or buy back his sold 2000 MWh for a price of 40 euro/MWh, depending on the total market demand. After submitting his bids and closure of the market, it was found that there was an oversupply in the market, therefore the spot 'buy' market gets cleared and player 4 sells 65 MWh.

Producer Types

There are 2 different producer types with differing properties:

- Renewable producers. These power plants produce electricity based upon a renewable energy resource. This makes these sources intermittent as no perfect predictions can be made of weather forecasts. Therefore an expected output with standard deviation is given. You can bid up to 115% of the expected output in the forward market. Actual output of your power plants is shown once the spot market is opened. Remaining positions are automatically dealt with by the game. You will therefore not be able anymore to make bids in the spot market.
- Conventional producers. These power plants produce electricity based upon a fossil fuel, which can be seen as a non-sustainable resource. Utilities have to buy in the primary energy resource and indicated by the marginal cost price field. These power plants are however much more flexible in producing electricity and are only limited by their maximum output capacity. Once scheduled in the forward market, power plants are allowed to still deviate from this position in the spot market.

Player 4 has a gas plant, thus being a conventional producer. He can sell up to his maximum output in the forward and spot market but is not obliged to do this. In round 2, player 4 decides to only sell 2000 MWh of his 2500 maximum output in the forward market. In this way, he can sell the reminder of 500 MWh in the spot market sell or buy back 2000 MWh in the spot market buy. In case the player sells everything or nothing in the forward market, the player will only be able to make a bid in one of both spot markets. This is the case for player 6 in round 2 (Did not sell in forward market so cannot buy anything back).

Financial Position

The financial position can be found at the end of the page of the 'game' tab and in the 'bid' tab for previous rounds. These can be split up into different parts for each period and are shown per power plant and in total. Your earnings in euro's will depend on the total profit you make over the different rounds. Some further player rationales are discussed in the example. Good luck!

To get an overview of the bidding strategy of player 1, go to his bid tab. In Round 1, player 1 bids 2200 MWh for a price of 48 euro/MWh. He knows that the conventional producers have a cost price of 50 euro, so he expects his bid will get cleared as it is likely that they will bid higher. The clearing price is 58 euro and he sells his total bid, generating a revenue of 127.600 euro. In the spot market he has a remaining position of 545 MWh which he has to sell. Market demand is negative however in the spot market (case of oversupply) and cleared spot price is 45 euro, thus generating a loss of 24.525 euro in the spot market. Next, observe how player 1 differs his bidding behavior over the next couple of rounds and compare it to player 2 and 3 which are also wind producers. The strategy renewable producers try to pursue is to not have a remaining portfolio in the spot market. This is because if they produce more than expected, they could have sold this for a higher price in the forward market and if they produce less than expected they will have to buy in expensive energy. Driving the bid price up in the forward market may thus end up generating a loss in the spot market.

To get an overview of the bidding strategy of player 4, go to his bid tab. In Round 2, Player 4 his bid of 2000 MWh gets cleared for a price of 58 euro/MWh. He thus generates a revenue of 116.000 euro but has a cost of 100.000 euro for buying in the gas, leaving him with a revenue of 16.000 euro. It is logical that the conventional producer will always place a bid with a price higher than his marginal cost price for producing. In the spot market player 4 has to make two decisions. The player is willing to sell his remaining position of 500 MWh, but only for a higher price as he knows he is only bidding against other conventional power plants. His bid on the buy side of the spot market is to buy back his sold quantity of the forward market. He will do this for a lower price than his marginal cost price in order to generate an extra profit, in this case 40 euro. The buy side of the market gets cleared and player 4 makes a profit of 650 euro. The strategy conventional producers follow is to not sell everything in the forward market and make a profit by selling for higher prices or by buying back for lower prices in the spot market. In order to make a profit, the bid price in spot sell will thus always be higher than the marginal cost price, bid prices in the spot buy market will always be lower.

Chapter 5

Conclusions

With the ongoing decarbonization, it is key for markets to provide adequate price signals for assets and investments in order to ensure an efficient and sustainable energy transition. In this dissertation, we have investigated the influence of an increasing market share of intermittent renewable energy resource on sequential pricing in short-term power markets. We find the increasing share of intermittent renewable energy sources to present some pronounced challenges for producers and retailers, decentralized prosumers, network operators, financial traders and power systems and markets as a whole. To summarize, the three chapters make the following main contributions in relation to an increasing market share of intermittent renewables in short-term sequential power markets:

[1] identify a technology-varying forward premium in relation to risk preferences of heterogeneous producers and retailers and evaluate its non-monotonic behavior in terms of demand uncertainty and (flexible) trading opportunities (Chapter 2).

[2] propose a multi-factor model incorporating various renewable technologies and provide empirical evidence for the effect of resulting information asymmetries between market participants on short-term sequential pricing (Chapter 3).

[3] indicate a convenience yield for flexibility in a developed experimental trading environment and empirically evaluate strategic bidding of non-intermittent producers in spot markets (Chapter 4).

Table 1.1 puts these contributions into context in terms of the main differences between the chapters.

5.1 Discussion

Power markets transitioned from a regulated to a market-based paradigm, with the liberalization of the power sector in the beginning of this century. The process transformed traditional monopolies with very few stakeholders to an industry where generators enter new business fields and final customers can source their own electricity. Moreover, public concerns about the negative environmental effects of using conventional carbon-intensive power sources to generate electricity have globally motivated policies to support the increase of renewable energy sources that are inherently variable and uncertain. Consequently, power markets face unprecedented challenges that require a thorough understanding of market mechanisms and pricing in order to achieve productive and allocative market efficiency.

In this dissertation, we study the effect of intermittent renewable energy sources on trading behavior and price formation in short-term sequential markets. Forward markets provide information about future prices and may improve the efficiency of the final allocation for commodities facing uncertainty on future prices or volumes (Ito and Reguant, 2016). Price differences between forward and spot prices have primarily been explained to reflect risk preferences of producers and retailers with the forward premium corresponding to the net hedging cost of all market agents (Bessembinder and Lemmon, 2002). Strategic behavior (Allaz and Vila, 1993) and trading inefficiencies (Borenstein et al., 2008) have further been indicated to play a role, although for power markets this has been subject to debate with respect to buyer market power (Anderson and Hu, 2008) and capacity constraints (Murphy and Smeers, 2010). No conclusive view on modeling forward price behavior has however been put forward yet, and both theories have presented their shortcomings with respect to empirical validations. Mixed empirical evidence for these rationales across markets and maturities has put forward the role of technology and operational characteristics in analyzing forward and spot price formation (Bunn and Chen, 2013; Huisman and Kilic, 2012).

With the ongoing decarbonization of production sources in global power markets, in this dissertation we address via a multi-method approach the role of heterogeneous production technologies and intermittent renewable power in short-term sequential power markets. The first five propositions attached to this dissertation indicate how the different chapters relate to the notions of risk preferences and decision strategies in short-term sequential power markets. In chapter 2, we analyze risk related hedging behavior of producers and retailers in markets with an increasing share of intermittent capacity via an equilibrium model. We observe a tipping point in the forward risk premium with increasing intermittent market capacity, reflecting variations in individual risk preferences. Chapter 3 builds on this work, empirically validating market participants' risk related behavior with both large-scale and distributed renewable energy sources. The more comprehensive experimental approach in chapter 4 allows to implement variations with a high degree of control and test decision making in sequential markets with a varying production technology mix. The results from the experimental trading platform show evidence for strategic behavior of non-intermittent producers and a convenience yield for flexibility in power markets with an increasing share of renewable energy.

Our work relates to two major streams within the management science literature. First, there is an emerging stream of work on sustainable Operations Management (OM), studying the relationship between operational drivers on the one hand and profitability, people and the planet on the other hand, linked to the triple bottom line reporting (Kleindorfer et al., 2005). With operational and financial interactions clearly linked in the decision making of the firm (Birge, 2014), sustainable OM plays a crucial role in delivering solutions for sustainability and enabling production and supply chains to operate more efficiently with respect to their environmental and social impact. In this dissertation, we relate to the key active themes as identified by Drake and Spinler (2013), by addressing the role of production technology and information asymmetries in efficient sustainable supply chains. Besides addressing differences between production technologies their environmental performance, it implies considerations between sustainable production technologies and their impact on sequential market efficiency.

Second, the field of Green Information Systems (IS) also applies sustainability notions by action levels, being individual, organization and societal (Watson et al., 2010). Green IS can be seen as a wicked problem (Rittel and Webber, 1973), bridging research and ideas from many fields, by having an impact through innovative use of IS in transportation, energy, manufacturing, buildings and elsewhere (Dedrick, 2010). Sustainable transformations in energy systems are seen as such complex transitions (Ketter et al., 2016a), where issues involve a plethora of different dimensions, from market, commercial and financial to environmental and political issues. In this work, we approach one of the core questions of Green IS, finding the association between information systems and supply chain performance from an efficiency and environmental perspective (Melville, 2010; Loock et al., 2013). We address these issues in relation to environmental transparency, as the specific nature of supply and demand uncertainties may cause asymmetries between market agents' ability to gather and predict information. Furthermore, we contribute to the economics of IS focusing on pricing structures of low-cost goods. IS literature typically focuses on digital product settings, as with the growth of the internet, pricing structures changed for information and other digital goods, such as cable television, digital music and news and journal articles, where goods are modeled as information goods with zero marginal cost (Hitt and Chen, 2005). Note that IS artifacts for pricing low marginal goods in most digital industries are self-sustaining. This is at odds with power markets, ensuring grid stability and security of supply by requiring availability and flexibility, therefore necessarily involving various technological products.

The influence of electricity on our society is undeniably widespread, being closely related to issues on national security, economic and sustainable development, and environmental awareness. This complex of issues makes the world faces one of its biggest challenges ever in meeting the needs for sustainable and reliable energy. The future of the energy sector will, to a large extent, be formed transformation in the power sector. With the electrification of heating and transport, large scale integration of renewable energy sources and increased overall energy efficiency associated with new appliance standards and more industrial technologies powered by electricity, markets are in a state of uncertainty and flux. The work ultimately engages policymakers to adequately evaluate the implications of intermittent renewable energy sources on existing power market structures and their participants' strategic space. Considering alternative market structures from both market and individual perspectives, it allows to devise key ingredients for well-functioning sustainable power markets, its design and governing policies.

5.2 Summary of Main Findings and Implications

In this section, we briefly revisit the main findings and implications of the individual chapters in this dissertation, discuss limitations and provide an outlook for future research.

5.2.1 Main Findings Chapter 2

In Chapter 2, we study how an increasing market share of intermittent renewable energy sources affects risk preferences of producers and retailers in forward markets via a general equilibrium approach. Where sequential markets help with efficient allocation of resources for commodities facing market uncertainty, operational constraints affect producers' ability to trade and hence cause different market behavior from producers with different production technologies. We analyze how market conditions define risk behavior of heterogeneous market participants and influence the ability of forward prices to predict spot prices.

Combining analytic modeling and numerical simulations, we find evidence for non-monotonic behavior of the forward premium in relation to increasing intermittent market capacity, driven by varying risk-related hedging pressure of producers and retailers. Depending on the systematic risk and the net hedging pressure of all market participants, we find the risk premium to vary and reach a tipping point along the increasing share of intermittent market capacity. We further explore the technology-varying risk premium in relation to power demand and find evidence for hourly varying fluctuations of the forward premium, oppositely affected by the level of wind penetration and demand. Lastly, we analyze the notion of flexible arbitrage in the form of cooperatives and speculative trading, and give evidence for a first-mover advantage to integrate flexible assets in the portfolio.

Influenced by market conditions as flexibility, producer set up and risk aversion, relative performance of spot and forward markets is bound by the markets' operational constraints. We find that the various operational characteristics of producer technologies affect trading behavior and thereby affect market prices, often undesirable from a sustainable efficient market point of view. It is key for policy makers to adequately evaluate the need for flexibility in renewable power markets, in order to motivate the increase of renewable energy source in a sustainable manner.

5.2.1.1 Limitations and Future Work Chapter 2

Weron (2014) discusses in his review on electricity price forecasting models a set of limitations of equilibrium and multi-agent models. Although such models offer valuable insights in understanding price formation and overall market behavior, they have limitations in the way in which the competition between market participants can be represented, especially with regards to short-term volatility. Indeed, where most literature considers equilibrium in expectations and risk aversion, notions on strategic behavior and convergence bidding are often left out or modeled under specific assumptions. Although our primary focus is on the relation between heterogeneous production technologies and risk aversion among market players, market specific implications require further specifications and assumptions in order to price formations and behavior on a more granular level.

A central theme in addressing the effect of renewable power on efficient market functioning is to identify metrics and the needs for flexibility. Although, our model is simplified with no curtailment of intermittent supply or market power, we believe the main insights on forward price behavior are robust to such extensions. Another avenue for future research may be to explore the role of non-convexities in the supply curve (Paschmann, 2017), as well as the notion of flexibility or flexible cooperatives with respect to issues related to transactions costs, financial constraints and market power.

5.2.2 Main Findings Chapter 3

In Chapter 3, we investigate renewable technology information asymmetries and the effect on risk preferences of producers and retailers in sequential short-term power markets. Across the world, the integration of renewable energy sources in power systems is taking place in various ways and paces, resulting in a fierce ongoing political combat between the various technologies (Hiroko, 2017). The forces at play are driven by the decarbonization of generation portfolios, moving conventional power plants toward intermittent renewable technologies, as well as the decentralization of demand and control. Moreover, digital advances in the form of smart meters and IoT devices have created opportunities for tech-savvy end-consumers and prosumers to become increasingly, but not entirely, independent from the grid. In this work, we study related risks of retailers and producers in these new volatile and uncertain market environments.

We propose a multi-stage competitive equilibrium model, including intermittent production on both sides of the market, to analyze price formation with different renewable technologies in sequential power markets. We validate the model by analyzing data in short-term forward and spot power markets in California and the United Kingdom. Both markets have recently experienced a significant increase in the share of renewable energy, respectively predominantly in terms of utility scale and distributed sources. We find evidence for large-scale and distributed renewable energy technologies to oppositely affect the forward premium, as asymmetries in the ability to predict and gather information on renewable energy supply heterogeneously influence risk preferences of producers and retailers, providing important insights on the technology non-neutrality of renewable energy sources.

5.2.2.1 Limitations and Future Work Chapter 3

New forms of dynamic trading on electricity markets can be enabled by information systems research, using real-time information streams and price signals to predict, analyze and steer bidding behavior. Therefore, one main direction for future work is to benchmark the indicated value for information to the cost of IoT devices. The indicated value for visibility of information should motivate retailers to stimulate, at least partly, a more widespread roll-out of smart meters. This may ameliorate their ability to predict and gather information, lowering risk-associated costs, and enhance an efficient integration of decentralized renewable energy resources.

The main limitations of the study relate to the data quality and statistical method. Forecasting accuracy depends on the numerical efficiency of the method employed, but also on the ability to include important fundamental factors. Although we motivate the model via an extensive multi-factor propositional framework, future work could enhance the explanatory power of the model by including factors related to scarcity, market power, spikes and higher moments of the spot price (Redl and Bunn, 2013). Furthermore, we suppose measured data on predicted renewable generation to be a good proxy for all available generation of a specific renewable technology in the market. Wind and solar measurements are however often based on a combination of computation, measurements and extrapolations, and are thus only assumed to be representative for the respective entire generation portfolio. Lastly, whilst forward price models focus on ex-ante expectations of spot price and premium realizations, empirical analyses focus on an ex-post analyses of realized premiums. In future work, this may be addressed by controlling for shocks to spot price expectations as well as for the endogeneity of the premium with realized spot prices (Bunn and Chen, 2013).

5.2.3 Main Findings Chapter 4

In this chapter, we developed an experimental trading platform to analyze decision making and price formation in short-term forward and spot power markets with increasing supply uncertainty. The experimental approach allows us to exploit the fact that in the laboratory one can implement the desired variations with a high degree of control. Laboratory control has several virtues proven particularly useful when studying electric power markets (Brandts et al., 2008). Where an empirical comparison of the effects of production technologies on market pricing requires to be done over an extensive period of time in order to collect sufficient high-quality data, there are typically many other variables that change over time. Experimental control allows us to isolate the effects of volume uncertainty via three market structures representing a non-intermittent market, low intermittent market share and high intermittent market share.

We focus on the decision making of non-intermittent producers in forward and spot markets and provide evidence for them to strategically shift focus from the forward to the spot market. With increasing intermittent capacity, non-intermittent producers bid lower volumes in the forward market in order to gain market share and profitable positions in the spot market, as expected spot profits rise with increasing uncertainty, indicating a convenience yield for flexibility. Moreover, we find that irrespective of the actual demand for power in the spot market, i.e. imbalances occurring in real-time, spot market power allows flexible non-intermittent producers to strategically bid higher prices in spot markets. Analyzing these systems, relationships between market participants, technology adaption and changes to market behavior provide key ingredients for devising a robust well-functioning electricity market, its design and its governing policies (Koolen et al., 2018).

5.2.3.1 Limitations and Future Work Chapter 4

The limitations in this chapter mainly relate to the experimental design of the developed trading platform. The exploitative power of such models often reduces the ecological validity, as Weron (2014) indicate that a number of exogenous variables need to be defined; the number of players, the payoff and the operational market structure next to the potential strategies and the way players interact. Although we control for ecological validity and approximate variables with real-world values, some design issues are difficult to overcome in our experimental setting. Follow-up work could consider the implementation of multi-unit bidding, as risk and strategic preferences vary across quantities and prices. Moreover, further experiments with experienced traders could further strengthen the ecological validity of our results.

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Summary

Energy businesses are going through a series of swift and radical transformations to meet the growing demands for sustainable energy. The integration of wind and solar introduces more low marginal costs suppliers to power markets, as no fuels are needed to produce electricity. Most power produced by renewable energy sources is however variable and difficult to predict by nature, putting current power system operations under pressure and causing prices to fluctuate heavily. Increased competition, new production technologies and volatile prices completely changed operations in todays power markets.

In this dissertation, we assess the integration of intermittent renewable energy sources in relation to agents' risk preferences and decision strategies in short-term sequential power markets via a multi-method approach. First, we analytically identify a technology-varying forward risk premium in relation to hedging needs of heterogeneous producers and retailers. Second, we empirically validate a multi-factor propositional framework, incorporating various renewable technologies, and provide evidence for market non-neutralities between these technologies. Third, we indicate a convenience yield for flexibility in a developed experimental trading environment and empirically evaluate strategies of intermittent and non-intermittent producers in forward and spot markets.

With the ongoing decarbonization, power markets should provide adequate price signals for assets and investments to ensure an efficient and sustainable energy transition. The work paves the way for policymakers to investigate the implications of intermittent renewable energy sources on existing market structures and their participants' strategic space. It further devises key ingredients for well-functioning sustainable power markets, its design and governing policies.

Nederlandse Samenvatting (Summary in Dutch)

Energiemarkten doorgaan wereldwijd een radicale transformatie om te voldoen aan de groeiende vraag naar duurzame energie. De integratie van wind- en zonne-energie introduceerde meer producenten met lage marginale kosten in elektriciteitsmarkten, aangezien deze geen (fossiele) brandstoffen nodig hebben. Hernieuwbaar gegenereerde elektriciteit is echter meestal variabel en van nature moeilijk te voorspellen. In combinatie met factoren zoals beperkte opslag en variable consumptie zorgt dit ervoor dat huidige elektriciteitssytemen onder druk komen te staan en prijzen zeer volatiel worden. Toegenomen competitie, nieuwe technologieën en volatiele prijzen hebben elektriciteitsmarkten drastisch veranderd.

In dit proefschrift bestuderen we via meerdere methodes het effect van de integratie van hernieuwbare energiebronnen op marktspelers hun risiscogedrag en beslissingstrategieën in korte termijncontracten. Eerst identificeren we analytisch een technologisch-afhankelijke prijspremium tussen termijnmarkten, afhankelijk van de mate waarin producenten en leveranciers hun risico afdekken. Ten tweede stellen we een model voor met verscheidene hernieuwbare technologieën en tonen empirisch het effect aan van de ontstane informatieasymetrieën tussen marktspelers. Ten derde tonen we het nut van flexibiliteit aan in een experimentele handelsomgeving en evalueren empirisch het strategische biedingsgedrag van flexibele producenten in spot markten.

Het is van groot belang dat markten correcte prijssignalen geven om het decarboniseren van elektriciteitsmarkten te bewerkstelligen. Dit werk zet beleidsmakers ertoe aan om de implicaties van variabele hernieuwbare energiebronnen in bestaande marktstructuren te evaluaren vanuit zowel het perspectief van de markt als het individu. Het bespreekt verder enkele belangrijke concepten om het verwezenlijken van een efficieënte en duurzame energietransitie mogelijk te maken.

About the Author

Derck Koolen was born in 1991 in The Hague, the Netherlands. He obtained his Bachelor of Science in Mechanical Engineering and Master of Science in Energy Engineering *cum laude* from the University of Leuven in Belgium. Derck further studied Power Systems and Markets at the Institut Polytechnique de Grenoble in France and worked as an energy economist for a German grid operator, before starting his PhD research in 2014 at the Department of Technology and Operations Management of the Rotterdam School of Management, Erasmus University.

In his research, Derck focuses on a quantitative analysis of strategic decision making, risk preferences and sequential pricing in electricity markets with an increasing share of intermittent renewable energy sources. Derck presented his research widely at top peer-reviewed conferences and won the Best Student Paper Award at the International Association for Energy Economics (IAEE) conference. The work also gained broad media coverage and has been presented to relevant practitioners and policy makers. During his PhD, Derck spent time as a visiting scholar at London Business School in the United Kingdom and the Haas School of Business, University of California Berkeley in the United States.

Derck has been involved in teaching courses for MBA and MSc students and has supervised over 25 master thesis projects with practical relevance. He further served as an advisor for RSM teams in international business case competitions and has experience as freelance writer and consultant offering expertise in energy systems and markets, power economics, and technology and innovation policy.

Author's Portfolio

Publications

Peer-Reviewed Publications

- Koolen, D., Sadat-Razavi, N. and Ketter, W. (2017). Machine Learning for Identifying Demand Patterns of Home Energy Management Systems with Dynamic Electricity Pricing. *Applied Sciences*, 7(11), 1160.

Professional Publications

- Koolen, D., Huisman, R., and Ketter, W. (2018). Strategic Trading and Hedging in Sequential Electricity Markets with Increasing Renewable Supply. *IAEE Energy Forum*, 27(1), 37-38.

Papers Under Review

- "The Sustainable Electricity Tipping Point: The Value of Flexibility in Sequential Markets", with W. Ketter, L. Qiu and A. Gupta, *under review*.
- "Decision Strategies and Forward Pricing with Increasing Intermittent Supply", with R. Huisman and W. Ketter, *under review*.

Peer-Reviewed Conference Proceedings

- Koolen, D., Bunn, D.W., Ketter, W. and Gupta, A. (2018). Effect of Technology Non-Neutrality and Information Transparency on Sequential Pricing in Decarbonizing Power Markets. *29th Workshop on Information Systems and Economics (WISE).* San Francisco (CA), United States (17-18 December 2018).

- Koolen, D. (2018). Forward Trading and the Value of Flexibility in Sequential Electricity Markets with Increasing Intermittent Supply. *Proceedings of the 41st International Association for Energy Economics (IAEE) International Conference.* Groningen, Netherlands (10-13 June 2018).

- Koolen, D., Ketter, W., Qiu, L. and Gupta, A. (2017). The Sustainability Tipping Point in Electricity Markets. *38th International Conference on Information Systems (ICIS).* Seoul, South Korea (10-13 December 2017).

- Koolen, D., Huisman, R. and Ketter, W. (2017). The Electricity Forward Price with Increasing Intermittent Supply. *2017 International Conference on Energy Finance.* Hangzhou, China (25-27 May 2017).

- Koolen, D., Ketter, W., Qiu, L. and Gupta, A. (2017). Market Efficiency and Design in Electricity Markets Integrating Renewable Energy: Theory and Simulation. *2017 Winter Conference on Business Analytics (WCBA).* Snowbird (UT), United States (2-4 March 2017).

- Koolen, D., Huisman, R. and Ketter, W. (2016). Risk and Decision Making for Electricity Forward Markets with Volatile Resources. *2016 Annual Meeting of the Commodity & Energy Markets Association (CEMA).* Paris, France (23-24 June 2016).

- Koolen, D., Qiu, L. and Ketter, W. (2016). Decision Making under Information Revelation Policies in Electricity Markets. *2016 Winter Conference on Business Intelligence (WCBI).* Snowbird (UT), United States (3-5 March 2016).

Teaching

- Co-Instructor for the MBA courses *Sustainable Smart Energy Business*, 2014-2015 and *Energy Analytics for Sustainability*, 2015-2016.

- Co-Instructor for the MSc elective course *Next Generation Business Applications*, 2014-2016.

- Guest lecturer and teaching assistant for the New York University MSBA courses *Energy Analytics*, 2014-2015 and *Analytics for Sustainability*, 2015-2016.

- Coach 25 Master Theses, MSc Business Information Management, 2014-2018.

- Adviser Case Society, BSc International Business Administration, 2016-2018.

Invited Talks and Seminars

Practice

- Renewable Energy's Dark Secret: Risk and Strategies in Decarbonizing Power Markets. *Strategy&, PwC.* Amsterdam, the Netherlands (8 February 2019).
- Macroeconomic perspectives on Integrating Intermittent Renewable in Power Systems. *Tennet TSO.* Arnhem, the Netherlands (12 October 2017).
- Issues, Economic Trends and Policies for Decarbonizing European Electricity Markets. *European Commission, Directorate-General for Energy.* Brussels, Belgium (12 September 2017).

Academic Seminars

- Renewable Technology Non-Neutrality and Sequential Pricing in Decarbonizing Power Markets. *Massachusetts Institute of Technology (MIT) - Energy Initiative.* Cambridge (MA), United States (1 November 2018).
- Decision Strategies in Sequential Power Markets with Increasing Intermittent Power Supply. *Department of Economics, University of Cologne.* Cologne, Germany (3 July 2018).
- The Sustainability Tipping Point and the Value of Flexibility in Electricity Markets. *Energy Economics Institute, University of Cologne.* Cologne, Germany (9 November 2017).
- The Sustainability Tipping Point and the Value of Flexibility in Electricity Markets. *Lorentz Center workshop on Applied Mathematics Techniques for Energy Markets in Transition.* Leiden, the Netherlands (18 September 2017).
- Forward Risk Premiums in Heterogeneous Electricity Markets under the Influence of Volatile Resources. *House of Energy Markets & Finance, University of Duisburg-Essen.* Essen, Germany (26 October 2016).
- Trading Strategies for Balancing Electricity Markets. *Energy Economics Institute, University of Cologne.* Cologne, Germany (29 January 2015).

Conferences

- Information Transparency, Intermittent Sustainable Production and Pricing in Short-term Sequential Power Markets. *2018 INFORMS Annual Meeting.* Phoenix (AZ), United States (4-7 November 2018).
- Hedging and Operational Decision Strategies with Renewable Energy in Electricity Supply Chains. *29th European Conference On Operational Research (EURO).* Valencia, Spain (8-11 July 2018).
- Market Design Challenges for Sustainable Electricity Markets. *27th Annual Conference Production and Operations Management Society (POMS).* Orlando (FL), United States (6-9 May 2016).
- An Agent-Based Approach for Intelligent Decision Making on Electricity Future Markets. *2015 INFORMS Annual Meeting.* Philadelphia (PA), United States (1-4 November 2015).

Research Visits

- Research Assistant Energy Markets Group. Department of Management Science and Operations, London Business School (February-May 2018).
- Visiting Scholar Energy Institute. Haas School of Business, University of California Berkeley (March-June 2017).

Services and Activities

- Ad-hoc Reviewer
  - Journals: Energy Economics, Journal of the Association for Information Systems (JAIS), Business & Information Systems Engineering (BISE).
  - Conferences: International Conference on Information Systems (ICIS), Hawaii International Conference on System Sciences (HICSS), Workshop on Information Technologies and Systems (WITS).
- Session Chair: POMS conference, Orlando (FL), United States (6-9 May 2016).
- Board Member External Relations, Erasmus PhD Association Rotterdam (EPAR), 2016.

Media

News

- Het Nederlandse energiebeleid kan een stuk efficiënter en schoner. *Het Financieele Dagblad*. 26 February 2018. https://fd.nl/opinie/1243301/het-nederlandse-energiebeleid-kan-een-stuk-efficienter-en-schoner
- Wie van grijs houdt, moet vooral groen stimuleren. *Energeia*. 25 August 2017. https://energeia.nl/nieuws/40059777/wie-van-grijs-houdt-moet-vooral-groen-stimuleren
- Explosieve groei aantal elektrische auto's in Rotterdam. *Algemeen Dagblad*. 16 August 2017. https://www.ad.nl/rotterdam/explosieve-groei-aantal-elektrische-auto-s-in-rotterdam-br~a95da14a/
- Aantal elektrische auto's in Randstad groeit explosief. *nu.nl*. 16 August 2017. https://www.nu.nl/economie/4881932/aantal-elektrische-autos-in-randstad-groeit-explosief.html

Radio

- Hoe Trump zijn kolencentrales het beste openhoudt. *BNR News Radio*. 13 July 2017. https://www.bnr.nl/radio/wetenschap-vandaag/10326391/hoe-trump-zijn-kolencentrales-het-beste-openhoudt

RSM Discovery

- How the current electricity market design may keep fossil fuel alive (over 1,500 views on Youtube). https://discovery.rsm.nl/articles/detail/290-how-the-current-electricity-market-design-may-keep-fossil-fuel-alive/

Awards and Accomplishments

- European Energy Exchange (EEX) Trader Certification 2019
- International Association Energy Economics Best Student Paper Award 2018
- Erasmus Trustfund Grant for Research Visit London Business School 2017-2018
- Finalist United Nations Global Energy Essay Contest 2013

The ERIM PhD Series

The ERIM PhD Series contains PhD dissertations in the field of Research in Management defended at Erasmus University Rotterdam and supervised by senior researchers affiliated to the Erasmus Research Institute of Management (ERIM). All dissertations in the ERIM PhD Series are available in full text through the ERIM Electronic Series Portal: http://repub.eur.nl/pub. ERIM is the joint research institute of the Rotterdam School of Management (RSM) and the Erasmus School of Economics (ESE) at the Erasmus University Rotterdam (EUR).

Dissertations in the last four years

Akemu, O., *Corporate Responses to Social Issues: Essays in Social Entrepreneurship and Corporate Social Responsibility*, Promotors: Prof. G.M. Whiteman & Dr S.P. Kennedy, EPS-2017-392-ORG, https://repub.eur.nl/pub/95768

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Alserda, G.A.G., *Choices in Pension Management*, Promotors: Prof. S.G. van der Lecq & Dr O.W. Steenbeek, EPS-2017-432-F&A, https://repub.eur.nl/pub/103496

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Avci, E., *Surveillance of Complex Auction Markets: a Market Policy Analytics Approach*, Promotors: Prof. W. Ketter, Prof. H.W.G.M. van Heck & Prof. D.W. Bunn, EPS-2018-426-LIS, https://repub.eur.nl/pub/106286

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Bouman, P., *Passengers, Crowding and Complexity: Models for Passenger Oriented Public Transport*, Prof. L.G. Kroon, Prof. A. Schöbel & Prof. P.H.M. Vervest, EPS-2017-420-LIS, https://repub.eur.nl/

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Hollen, R.M.A., *Exploratory Studies into Strategies to Enhance Innovation-Driven International Competitiveness in a Port Context: Toward Ambidextrous Ports,* Promotors: Prof. F.A.J. Van Den Bosch & Prof. H.W. Volberda, EPS-2015-372-S&E, http://repub.eur.nl/pub/78881

Hurk, E. van der, *Passengers, Information, and Disruptions,* Promotors: Prof. L.G. Kroon & Prof. P.H.M. Vervest, EPS-2015-345-LIS, http://repub.eur.nl/pub/78275

Jacobs, B.J.D., *Marketing Analytics for High-Dimensional Assortments,* Promotors: Prof. A.C.D. Donkers & Prof. D. Fok, EPS-2017-445-MKT, https://repub.eur.nl/pub/103497

Kahlen, M. T., *Virtual Power Plants of Electric Vehicles in Sustainable Smart Electricity Markets*, Promotors: Prof. W. Ketter & Prof. A. Gupta, EPS-2017-431-LIS, https://repub.eur.nl/pub/100844

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Karali, E., *Investigating Routines and Dynamic Capabilities for Change and Innovation*, Promotors: Prof. H.W. Volberda, Prof. H.R. Commandeur and Dr J.S. Sidhu, EPS-2018-454-S&E, https://repub.eur.nl/pub/106274

Keko. E, *Essays on Innovation Generation in Incumbent Firms*, Promotors: Prof. S. Stremersch & Dr N.M.A. Camacho, EPS-2017-419-MKT, https://repub.eur.nl/pub/100841

Kerkkamp, R.B.O., *Optimisation Models for Supply Chain Coordination under Information Asymmetry*, Promotors: Prof. A.P.M. Wagelmans & Dr. W. van den Heuvel, EPS-2018-462-LIS

Khattab, J., *Make Minorities Great Again: a contribution to workplace equity by identifying and addressing constraints and privileges*, Promotors: Prof. D.L. van Knippenberg & Dr A. Nederveen Pieterse, EPS-2017-421-ORG, https://repub.eur.nl/pub/99311

Kim, T. Y., *Data-driven Warehouse Management in Global Supply Chains*, Promotors: Prof. R. Dekker & Dr C. Heij, EPS-2018-449-LIS, https://repub.eur.nl/pub/109103

Klitsie, E.J., *Strategic Renewal in Institutional Contexts: The paradox of embedded agency*, Promotors: Prof. H.W. Volberda & Dr. S. Ansari, EPS-2018-444-S&E, https://repub.eur.nl/pub/106275

Krämer, R., *A license to mine? Community organizing against multinational corporations*, Promotors: Prof. R.J.M. van Tulder & Prof. G.M. Whiteman, EPS-2016-383-ORG, http://repub.eur.nl/pub/94072

Kysucky, V., *Access to Finance in a Cros-Country Context*, Promotor: Prof. L. Norden, EPS-2015-350-F&A, http://repub.eur.nl/pub/78225

Lee, C.I.S.G., *Big Data in Management Research: Exploring New Avenues*, Promotors: Prof. S.J. Magala & Dr W.A. Felps, EPS-2016-365-ORG, http://repub.eur.nl/pub/79818

Legault-Tremblay, P.O., *Corporate Governance During Market Transition: Heterogeneous responses to Institution Tensions in China*, Promotor: Prof. B. Krug, EPS-2015-362-ORG, http://repub.eur.nl/pub/78649

Lenoir, A.S. *Are You Talking to Me? Addressing Consumers in a Globalised World,* Promotors: Prof. S. Puntoni & Prof. S.M.J. van Osselaer, EPS-2015-363-MKT, http://repub.eur.nl/pub/79036

Li, D., *Supply Chain Contracting for After-sales Service and Product Support*, Promotor: Prof. M.B.M. de Koster, EPS-2015-347-LIS, http://repub.eur.nl/pub/78526

Liu, N., *Behavioral Biases in Interpersonal Contexts*, Supervisors: Prof. A. Baillon & Prof. H. Bleichrodt, EPS-2017-408-MKT, https://repub.eur.nl/pub/95487

Ma, Y., *The Use of Advanced Transportation Monitoring Data for Official Statistics*, Promotors: Prof. L.G. Kroon & Dr J. van Dalen, EPS-2016-391-LIS, http://repub.eur.nl/pub/80174

Maira, E., *Consumers and Producers*, Promotors: Prof. S. Puntoni & Prof. C. Fuchs, EPS-2018-439-MKT, https://repub.eur.nl/pub/104387

Mell, J.N., *Connecting Minds: On The Role of Metaknowledge in Knowledge Coordination*, Promotor: Prof. D.L. van Knippenberg, EPS-2015-359-ORG, http://hdl.handle.net/1765/78951

Meulen,van der, D., *The Distance Dilemma: the effect of flexible working practices on performance in the digital workplace*, Promotors: Prof. H.W.G.M. van Heck & Prof. P.J. van Baalen, EPS-2016-403-LIS, http://repub.eur.nl/pub/94033

Micheli, M.R., *Business Model Innovation: A Journey across Managers' Attention and Inter-Organizational Networks*, Promotor: Prof. J.J.P. Jansen, EPS-2015-344-S&E, http://repub.eur.nl/pub/78241

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Energy businesses are going through a series of swift and radical transformations to meet the growing demands for sustainable energy. The integration of wind and solar introduces more low marginal costs suppliers to power markets, as no fuels are needed to produce electricity. Most power produced by renewable energy sources is however variable and difficult to predict by nature, putting current power system operations under pressure and causing prices to fluctuate heavily. Increased competition, new production technologies and volatile prices completely changed operations in today's power markets.

In this dissertation, we assess the integration of intermittent renewable energy sources in relation to agents' risk preferences and decision strategies in short-term sequential power markets via a multi-method approach. First, we analytically identify a technology-varying forward risk premium in relation to hedging needs of heterogeneous producers and retailers. Second, we empirically validate a multi-factor propositional framework, incorporating various renewable technologies, and provide evidence for market non-neutralities between these technologies. Third, we indicate a convenience yield for flexibility in a developed experimental trading environment and empirically evaluate strategies of intermittent and non-intermittent producers in forward and spot markets.

With the ongoing decarbonization, power markets should provide adequate price signals for assets and investments to ensure an efficient and sustainable energy transition. The work paves the way for policymakers to investigate the implications of intermittent renewable energy sources on existing market structures and their participants' strategic space. It further devises key ingredients for well-functioning sustainable power markets, its design and governing policies.

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