

Strategic Aspects of Forward Trading on the German Electricity Market

Consequences for Volatility, Competition, and
Investment

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List of Variables

a	Prohibitive Price for a Linear Demand Function
a^B	Prohibitive Price for a Linear Demand Function during a Boom
a^R	Prohibitive Price for a Linear Demand Function during a Recession
A	Cross Sectional Area of a Wind Converter
A_1	Cross Sectional Area Passed by Wind Stream in Front of a Wind Converter
A_2	Cross Sectional Area Passed by Wind Stream behind a Wind Converter
c	Marginal Costs
c_P	Power Coefficient of a Wind Converter
CO_2	Carbon Dioxide
D	Demand Function
D_{Spec}	Demand Function (from Speculators)
D^E	Remaining Demand Function
δ	Discount Factor
δ^*	Critical Discount Factor
$\delta_{F=0}^*$	Critical Discount Factor without Forward Contracts
Δt	Time Intervall
e	Price Elasticity of Demand
E	Expectation
E_{Wind}	Kinetic Energy of a Wind Stream
\tilde{E}	Inelastic Demand for Electricity for Numerical Example
ϵ	Infinitesimal Small Unit
η_{flow}	Flow Losses of a Wind Converter
η_{mec}	Mechanical Losses of a Wind Converter
η_{electr}	Cable Losses of a Wind Converter
η_{Betz}	Coefficient of Betz for the Maximal Extrable Power from a Wind Stream
f	Probability Density Function of a Random Variable
f_V	Probability Density Function of Wind Velocity
\tilde{f}	Forward Contracts Traded by a Single Firm in a Short Position
\underline{f}	Forward Contracts Traded by a Single Firm in a Long Position
F	Cumulative Distribution Function of a Random Variable
F_V	Cumulative Distribution Function of Wind Velocity
\tilde{F}	Forward Contracts Traded by All Firms
γ	Scale Parameter of the Modified Weibull Distribution
$\tilde{\gamma}$	Difference of Prohibitive Price and Marginal Costs (Spread)
Γ	Gamma Function
h	Hours

List of Variables

i	Firm Index
j	Firm Index
kg	Kilogram
k	Shape Parameter of the Weibull Distribution
κ	Shape Parameter of the Modified Weibull Distribution
λ	Scale Parameter
$\tilde{\lambda}$	Scale Parameter of a Exponential Distributed Spread
λ_e	Scale Parameter of the Exponential Distribution
λ_W	Scale Parameter of the Weibull Distribution
m	(Air) Mass
μ	Empirical Mean
μ_{LN}	Location Parameter of the Log-Normal Distribution
$\tilde{\mu}$	Recession Probability in a Two State Model
n	Number of Firms
N	Newton
Ω	Firms Payment Obligation to Speculators
p^M	Monopoly Price
p^{RM}	Monopoly Price after Forward Contracts
$p_{i,j}$	Price Charged by Firm i or j
p^{SM}	Spot Market Price
p_*^{SM}	Equilibrium Spot Market Price
p^{FM}	Forward Market Price
p_B^M	Monopoly Price During a Boom
p_R^M	Monopoly Price During a Recession
P_{Ext}	Power Really Extractable from a Wind Converter
P_{Real}	Effectively Extracted Power from a Wind Stream
P_{Total}	Power Supplied by All Windmills in Germany
P_{Wind}	Power of a Wind Stream
Π^M	Monopoly Profit
Π^C	Collusive Profit
Π_{Day}	Daily Total Profit on the German Electricity Market
$\Pi_{i,j}$	Profit Function for Firm i or j
$\Pi_{i,j}^{SC}$	Semi-Collusive Profit of firm i,j
$\Pi_{e \rightarrow 0}^D$	Deviation Profit for a Price Inelastic Demand Function
$\Pi_{e \rightarrow 0}^C$	Collusive Profit for a Price Inelastic Demand Function

List of Variables

q^M	Monopoly Quantity
q_B^M	Monopoly Quantity During a Boom
q_R^M	Monopoly Quantity During a Recession
R_{Day}	Daily Revenue on the German Electricity Market
ρ	Density of Air
s	Seconds
σ	Empirical Standard Deviation
σ^2	Empirical Variance
σ_{LN}	Scale Parameter of the Log-Normal Distribution
t	Time Variable
T	Thrust of a Wind Stream
θ	Deterministic Factors of a Representative Windmill
v	Wind Speed
v_1	Wind Velocity in Front of the Wind Converter
v_2	Wind Velocity Behind of the Wind Converter
v'	Wind Velocity in the Stream Level of the Wind Converter
\tilde{v}	Coefficient of Velocity Behind and in Front of the Wind Converter ($:= \frac{v_2}{v_1}$)
\dot{V}	Volume Stream
Var	Variance
W	Watt (Unit of Power)
kW	Kilowatt (Unit of Power)
MW	Megawatt (Unit of Power)
GW	Gigawatt (Unit of Power)
TW	Terrawatt (Unit of Power)
Wh	Watt-hour (Unit of Energy)
MWh	Megawatt-hour (Unit of Energy)
GWh	Gigawatt-hour (Unit of Energy)
TWh	Terrawatt-hour (Unit of Energy)
$x_{i,j}^{SM}$	Output Traded on the Spot Market

List of Abbreviations

AT	Austria
CH	Swiss Confederation
BpB	Bundeszentrale für politische Bildung
BMWi	Bundesministerium für Wirtschaft und Energie
BDEW	Bund der Energie- und Wasserwirtschaft
BNetzA	Bundesnetzagentur
CZ	Czech Republic
DEN	Denmark
DIW	Deutsches Institut für Wirtschaftsforschung
DSO	Distribution System Operator
EC	European Commission
ECC	European Commodity Clearing
EEG	Erneuerbares Energien Gesetz
EEX	European Energy Exchange (Electricity Forward Market)
EPEX SPOT	European Power Exchange (Electricity Spot Market)
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EUR (€)	Euros: European Currency
FR	French Republic
IFM	Industry Funds Management: Australian Pension Fund
LUX	Grand Duchy of Luxembourg
MC	Marginal Generation Costs of Electricity
MEAG	Munich Ergo Asset Management GmbH
MS&RS	Municipal and Regional Supplier
NL	Kingdom of the Netherlands
NPV	Net Present Value
OTC	Over the Counter Trading of Two Parties Without an Exchange

List of Abbreviations

Pears.	Pearson product-moment correlation coefficient
PHELIX	Physical Electricity Index
PL	Republic of Poland
Spear.	Spearman's rank correlation coefficient
Stat.	Electricity Operator Statkraft
SWM	Stadtwerke München
P&T	Electricity Producers and Electricity Traders
FSP&FI	Financial Service Providers and Financial Institutions
CC	Commercial Costumers
R&D	Research and Development
TGC	Total Generation Costs of Electricity
TSO	Transmission System Operators
SWE	Sweden

Chapter 1

Introduction

Electricity markets are different! They significantly differ from common markets, since technical and economical aspects fundamentally differ. There exists an uncountable number of special technical and economical features on electricity markets. However, at least the following five central aspects can be identified as main drivers for the special market structure of most electricity markets.

Large investments are necessary to generate electricity, which leads to economies of scale and a oligopolistic structure on the electricity market. Moreover, investments decisions, for example, about generation capacities or the structure of the electricity grid mostly have a very long time horizon. This combination of large investments with long term time horizons leads to large uncertainties.

To manage these uncertainties precise forecasts are of major importance for the electricity market. Based on these forecasts market participants can engage in financial derivatives. On liberalized electricity markets the most popular financial derivatives are forward and futures contracts. Market volumes of these contracts often exceed the spot market volumes.

Electricity supply always has to match electricity consumption exactly. Whenever feed-in of electricity exceeds consumption or feed-in of electricity is below consumption, serious technical problems occur for the electricity network. In extremal cases blackouts may occur.

Developed economies heavily rely on electrical power! The economic costs associated with a blackout lasting for one hour are estimated by Simon Piaszeck (2013, p.23). A

blackout, that is taking place at 12:00 pm noon leads to costs of 22.74 million euros in the city area of Berlin, 19.10 million euros in the city area of Hamburg and 16.00 million euros in the city area of Munich. These estimations clearly illustrate the importance of balancing electricity generation and consumption as well as the high dependence of households and industry on electrical power in developed economies.

Distribution networks are highly relevant for electricity markets. They can be seen as natural monopolies, since competition between different networks would be much too costly and the existing network is the only way to deliver electricity to consumers. Therefore, investment decisions into the distribution networks play a crucial role for the total electricity market.

In particular the combination of a distribution network, the technological need of balancing demand and supply in every second and oligopolistic firms leads to various externalities and strategic interactions. The aim of the presented thesis is to analyze strategic effects of forward trading on the German electricity market. By doing so it adds to economic research in three different ways:

Firstly, **Chapter 2** gives an empirical analysis of the German electricity market. This analysis of the German power market consists of an overview about market structure and conditions for electricity trading, an empirical evaluation of stochastic renewable energies feed-in, and an empirical evaluation of the demand for electricity generated by conventional power plants.

Secondly, in **Chapter 3** a theoretical model based on the market characteristics of the German electricity market is presented. This model contributes to economic research, since it adds volatile market conditions to the existing literature about forward trading and collusive behavior of firms. It is shown that for power-generating firms a large incentive exists to collude on a price far above marginal costs.

Thirdly, in **Chapter 4** a theoretical model, which helps to analyze the strategic effect of forward trading on investment incentives, is presented. A multi-stage game, in which firms face an investment decision followed by a decision about forward trading, is compared to a multi-stage game, in which firms face a decision about forward trading followed by an investment decision. It is shown that, depending on the time horizon of an

investment, the incentive to invest fundamentally differs. Finally, **Chapter 5** gives a brief summary of the most important findings of this thesis and concludes it.

Analysis of the German Electricity Market

Chapter 2 is dedicated to a detailed analysis of the German electricity market. Until electricity generated in a power plant flows out of the socket of a consumer three different market stages with totally different competitive settings can be identified. Firstly, the market for electricity generation, which is dominated by four electricity generators (E.ON, RWE, Vattenfall, EnBW and Vattenfall) and which can be seen as an oligopolistic market with strategic interaction. Secondly, the transmission of electricity from plants to regional suppliers, which is organized in a regulated regional monopoly. These regulated regional monopolies are operated by the following four Transmission System Operators: Tennet, 50 Hertz, Amprion and TransnetBW. Thirdly, the market for electricity supplied to households and industrial consumers, which is characterized by interaction of many electricity sellers and buyers and quite effective competition.

In principle, electricity can either be traded on an electricity exchange or by bilateral contracts. Trading electricity on bilateral contracts, which is often called over-the-counter-trading (OTC), is not based on standardized rules, whereas for trading electricity on an exchange clear rules have to be applied. An overview about the most important contracts traded on the European Energy Exchange (EEX) as well as one about the most important contracts traded over-the-counter bilaterally is given. The four most important markets are the day-ahead spot market, the futures market, the intraday spot market and the options market. For each of these markets the most important participants, trading rules, trading volumes, and prices are presented.

In Germany electricity is generated mainly out of one of the following five energy sources: Soft coal, hard coal, nuclear energy, natural gas, and renewable energies. The composition of this electricity generating mix is shown for all the years between 1990 and 2013 and explanations for fundamental changes in the generating mix are given. Electricity generated by renewable energy sources is subsidized by feed-in tariffs, which lead to a compensation for the supplier. This compensation is calculated in the way that a constant amount of money is earned by a supplier. Thus, electricity generated by solar power and

wind power feeds power into the German grid independent of market conditions. Renewable energies feed-in data is collected by the four German Transmission Operators and provided by the European Energy Exchange. I will use it to quantify feed-in fluctuations. More precisely, fluctuations of solar power and wind power as well as fluctuations coming from simultaneous feed-in of wind and solar power are quantified.

Demand for electricity is fluctuating, too. Data provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) is used to account for demand fluctuations. Demand for electricity shows a clear pattern. During nights and morning hours demand for electricity is rather small. Demand for electricity increases until noon. After a decrease during the afternoon an increase occurs in the early evening hours. Then demand for electricity decreases until next morning. This pattern is generally the same for all weekdays, even though on business days total demand is larger than on Saturdays or on Sundays. Differences between working days, Saturdays and Sundays shift this pattern, but do not lead to fundamental changes of the corresponding pattern.

In order to estimate the amount of electricity that has to be generated by conventional power plants, the demand data set provided by ENTSO-E is combined with the renewable energy supply data set provided by the European Energy Exchange. More precisely, renewable energy supply is deducted from demand for electricity to find the necessary conventionally generated load for Germany in 2013. This necessary conventional load can be seen as the total amount of electricity that has to be supplied by all electricity providers. Again a clear daily pattern emerges, since during night and in the early morning hours demand is rather low. However, the former demand peak at noon is normally compensated by an increasing solar feed-in. Thus, the necessary conventional load has a peak in the afternoon, since during the afternoon the supply of solar energy is decreasing much faster than the demand for electricity.

In order to show the effect of the necessary conventional load on day-ahead spot prices scatter plots are illustrated. For most combinations of day-ahead spot prices and necessary conventional load a clear linear relationship emerges. However, for extremely low or high realizations of the necessary conventional load this linear relationship breaks down.

Forward Trading and Competitive Pressure

On the basis of the analysis of the German electricity market a micro-economic model is presented. It investigates the relationship between forward contracts and competitive pressure. It adds to the economic research about forward trading and (anti-)competitive behavior, since (up to my very best knowledge) it is the first theoretical model that allows for a simultaneous analysis of forward-trading, (anti-) competitive behavior and volatile market conditions.

Each firm serving a certain market has to take two sources of profits into account: Current profits as well as future profits. For oligopolistic firms this rather trivial fact leads to more complicated consequences, since for any price that exceeds marginal costs a clear trade-off between undercutting or adapting prices emerges. Undercutting the market price leads to a significant increase of short term profits. In turn this may induce a price war between competitors, which leads to a significant decrease of long-term profits. Indeed, there is a coordination problem of firms, since a firm that matches a (tacitly) fixed price has to rely on identical behavior of its competitor. Firms are not allowed to agree on prices and are under the supervision of antitrust authorities. In Germany three government institutions (Bundeskartellamt, Bundesnetzagentur and Monopolkommission) have a close look on the electricity market. Thus, firms cannot easily fix a certain price. However, they can try to balance collusive and competitive profits in such a way that collusive profit exceeds profit gained by undercutting the tacitly fixed price.

The analytical model shows that trading forward contracts increases incentives for price matching behavior and decreases incentives to undercut a certain price under volatile market conditions. It is shown, that firms theoretically can collude for any discount factor on a price above marginal costs. Firms can do so by selling a very large amount in forward contracts while setting a price between monopoly prices and marginal costs during booms. However, under volatile market conditions firms that rely on stabilizing a collusive agreement by forward trading face another problem. They never know the profit-maximizing quantity in advance and always have a threat of involuntarily having traded forward more than the optimal quantity. Thus, profitability of a collusive agreement is reduced by (excessive) forward trading.

Forward Trading and Strategic Investment

On commodity markets and especially on the electricity market investment decisions play a crucial role in strategic competition. There are long-lasting investments such as constructing a plant or introducing a cost-reducing new technology. Other investments such as building up capacities in an existing plant, distributing, or advertising the product have a shorter time horizon. The importance of investment decisions can particularly be illustrated by estimations for the German "Energiewende". The annual investment costs for this ongoing turnaround to a sustainable energy supply are estimated by The German Institute for Economic Research (DIW Berlin) (Blazejczak, Diekmann, Edler, Kemfert, Neuhoff, and Schill, 2013) for up to 38 billion euros. From this total amount of 38 billion euros approximately 26 billion euros are needed for investments in power and heating supply and 7 billion euros for investments in the electricity network.

A theoretical model is presented that incorporates two important strategic decisions simultaneously: The decisions on investment and on forward trading. As mentioned before, for investment decisions different time horizons matter. Thus, long-term investment decisions and short-term investment decisions are modeled separately. A long-term investment decision is modeled by a three-stage game, in which firms firstly decide about their investments, secondly decide about the forward-traded amount, and thirdly compete on a spot market. A mid-term investment decision is modeled by a three-stage game, in which firms firstly decide about their forward-traded amount, secondly decide about their investments and thirdly compete on a spot market.

From a welfare point of view the desirability of forward trading critically depends on the time horizon of an investment decision. For investment decisions that have a rather short time horizon forward trading strongly increases social welfare, since in equilibrium a high forward-traded volume, moderate investments, and rather low prices evolve. For investment decisions that have a rather long time horizon forward trading decreases social welfare, since in equilibrium a small forward-traded volume, moderate investments and higher prices evolve. This is bad news for the efficiency of electricity markets, since a lot of investment decisions on the electricity market have a rather long time horizon.

Chapter 2

Analysis of the German Electricity Market

There have been fundamental changes on the German electricity market during the last 15 years. These changes were mostly driven by political decisions. Two main objectives of these political decisions can be identified. Firstly, the objective of making the German electricity market more efficient and decreasing electricity prices. Secondly, the objective of transforming electricity generation currently based on fossil fuels and nuclear energy into electricity generation based on renewable energies.

In order to increase competition on the German electricity market a law, which is called "*Gesetz zur Neuregelung des Energiewirtschaftsrechts*", came into force in 1998. This law made an end to the regional monopolies for electricity supply and liberalized the German electricity market. Another important step for the liberalization of the electricity market was made in 2009: Energy supply companies were forced by a common directive of the European Commission, the European Parliament and the European Council (European-Union, 2009) to unbundle electricity generation from electricity distribution.

In order to phase out electricity generation based on nuclear power the federal government of Germany negotiated with German energy supply companies. These negotiations led to a common solution in the year 2000, which is called "*Vereinbarung zwischen der Bundesregierung und den Energieversorgungsunternehmen vom 14. Juni 2000*." In order to replace these capacities and to support electricity generation from renewable energy sources a law, which is called "*Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG) sowie zur Änderung des Energiewirtschaftsgeset-*

zes und des Mineralölsteuergesetzes", came into force at the same time. The main tool of this law is the introduction of a feed-in tariff for electricity generated from renewable energy sources. This law has been quite successful in increasing electricity generated by renewable energy sources. Another important tool for cleaner electricity is the European Union Emissions Trading System, which tries to assign a price to the emission of CO_2 and came into force in 2005.

The upcoming analysis of the German electricity market focuses more on the objective of market efficiency and less on the objective of increasing electricity generation from renewable energy sources. However, market efficiency provides the essential element for an affordable transformation of the German electricity market. Therefore, the focus on market efficiency should not be seen as a disregard of the importance of sustainable electricity generation, but rather as a step to control its costs.

The analysis of the German electricity market consists of three parts. The first part gives a comprehensive analysis of conditions for electricity supply in Germany. The second part illustrates fluctuations of renewable energies feed-in and quantifies important stochastic properties of renewable energy supply. The third part analyzes the weekly pattern of demand for electricity and presents calculations for the amount of electricity that has to be generated by conventional power plants. Following this, scatter plots are used to determine a relationship between conventionally generated electricity and day-ahead spot prices on the European Energy Exchange (EEX).

Additionally, economic literature that may help to explain strategic aspects of forward trading on the German electricity market is presented. Unfortunately all presented models have at least one black spot, which means they are not suitable to explain strategic aspects of forward trading on the German electricity market in detail. Models that are presented in **chapter 3** and **chapter 4** try to fill this gap.

2.1 Electricity Supply in Germany

In order to get an overview about important aspects of the supply side of the German electricity market three different properties of electricity supply are analyzed in a more detailed way: Firstly, the vertical and horizontal market structure of electricity supply. Secondly, the organization of electricity trading either on the European Energy Exchange (EEX) or by bilateral negotiation and trading of over-the-counter (OTC) contracts. Thirdly, the composition of energy sources used for electricity generation in Germany (energy mix).

2.1.1 Market Structure

Vertical Structure of the electricity market: From the Plant to the Socket

In general the supply chain of electricity from a plant to the socket of a consumer can be separated into following three different stages:

1. Generation of Electricity
2. Transmission of Electricity
3. Distribution of Electricity

In a first step the market structure of Power Generation is analyzed more deeply. Then the economic situation on the second stage of Network Transmission is considered. Finally, the degree of competition on the third stage of Power Distribution is figured out.

Generation of Electricity

Figure 2.1 illustrates the net electricity generation of the main operators in Germany for the years 2008 and 2013. Net electricity generation is found by deducting the electricity being necessary to operate a plant from its gross electricity production. This data is provided by RWE (2014a) and based on information coming from the "Bundesverband der Energie- und Wasserwirtschaft (BDEW)" as well as data coming directly from the operators.

RWE has been the operator with the largest electricity generation in Germany in 2008 (179.7 TWh) as well as in 2013 (151.1 TWh). E.ON is the operator with the second

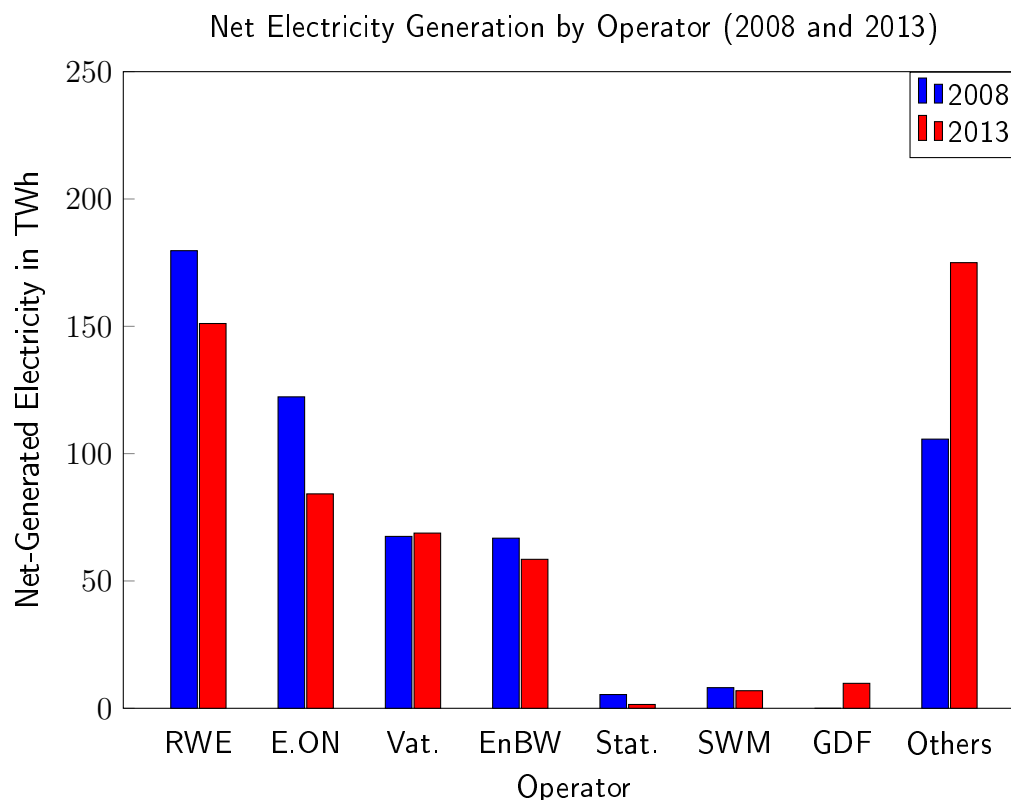


Figure 2.1: Net Electricity Generation by Operator (2008 and 2013)

largest electricity generation. The decrease of its electricity generation from 122.3 TWh in 2008 to 84.2 TWh in 2013 can mainly be explained by the sale of generation capacity due to an arrangement with the EU Commission. Vattenfall (abbreviated as Vat. in figure 2.1) is the third largest operator in Germany. It generated 67.5 TWh electricity in 2008 and 68.8 TWh electricity in 2013. It is followed by EnBW Energie Baden-Württemberg, which generated 66.8 TWh in 2008 and 58.5 TWh in 2013. The decrease of 8.3 TWh electricity generation can mainly be explained by the shut-down of the nuclear plants Neckarwestheim 1, with a capacity of 840 MW and Philippsburg 1, with a capacity of 890 MW, in 2011. Due to their large common share in electricity generation, these four operators are sometimes called "the big four", since in 2008 they generated about 78% and in 2013 65% of the electricity traded on the German power market. Additionally, there exist three other minor electricity producers in Germany. First, there is Statkraft (abbreviated as Stat. in figure 2.1), which is a Norwegian electricity operator and focuses on renewable energies. In Germany statkraft holds plant capacities for gas, water and biomass. Second, there is Stadtwerke München (abbreviated as SWM. in figure 2.1),

which holds an 25% interest in the nuclear power plants "Isar 1 and Isar 2". Additionally SWM owns hydroelectric power stations as well as combined heat and power plants. Third, there is GDF Suez (abbreviated as GDF in figure 2.1) purchased hard coal as well as water electricity generation capacities from E.ON in 2009. The political promotion of renewable energy sources in Germany led to a growing contribution of rather small operators in German electricity generation (others in figure 2.1), since in 2008 103.2 TWh and in 2013 174.2 TWh of electricity were generated by "other" operators.

As shown above there exists an oligopolistic market structure on the wholesale electricity market. The strategic interaction of the four largest firms seems to be very relevant for the electricity market. Even though they are asymmetric in terms of generation capacity, market shares and regional focus, they are able to exercise at least together a certain level of market power and to affect wholesale electricity prices. However, it should be mentioned that the market shares of the big four electricity operators have decreased and will probably keep decreasing in the next years.

Transmission of Electricity

There exist four Transmission System Operators (TSO) in Germany. Each operator is as a regional (regulated) monopolist and is therefore responsible for transmission in a clearly defined control area.

1. Tennet TSO GmbH: Operates in Schleswig Holstein, Lower Saxony, Hamburg as well as broad areas of Hesse and Bavaria.
2. 50 Hertz Transmission GmbH: Operates in the former East Germany federal states Mecklenburg Western Pomerania, Brandenburg, Berlin, Saxony-Anhalt, Thuringia, Saxonia as well as in Bremen.
3. Amprion GmbH: Operates in broad areas of North Rhine-Westphalia, Rhineland Palatinate, Saarland as well as in few areas of Hesse and Bavaria.
4. TransnetBW GmbH: Operates solely in the federal state of Baden-Württemberg.

Figure 2.2, which has been provided by the "Bundeszentrale für politische Bildung (BpB)", shows control areas for each Transmission System Operator. In order to unbundle the electricity production from the electricity transmission the European Commission, the

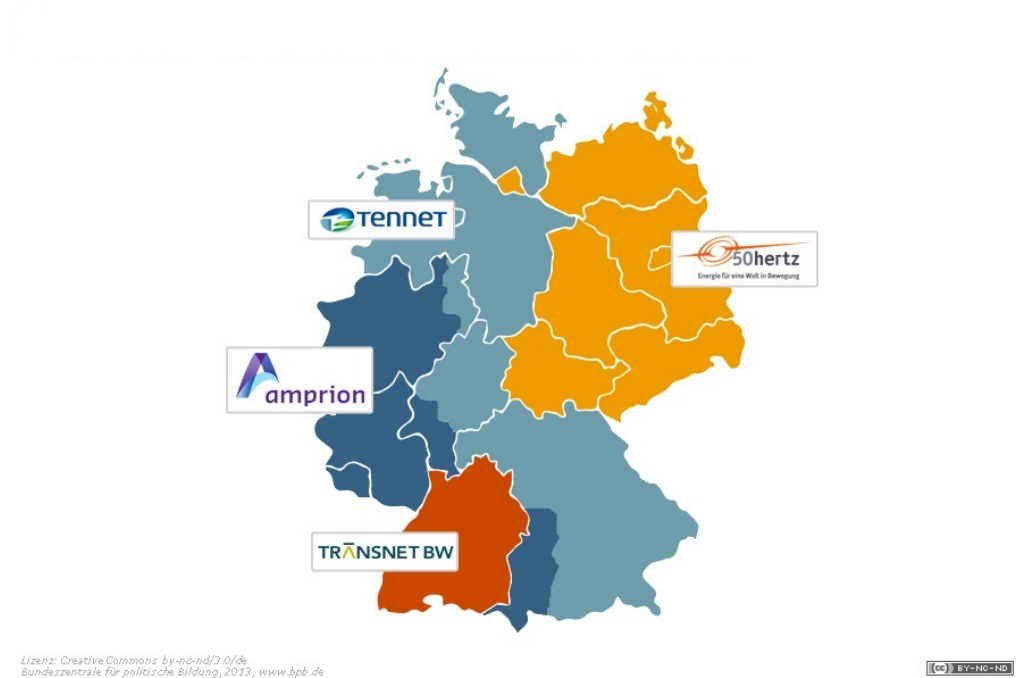


Figure 2.2: Control Areas of German Transmission System Operators

European Parliament, and the European Council passed a Directive in 2009 (European-Union, 2009). This Directive forced plant operators with integrated electricity transmission to significantly reduce their control on the transmission of electricity. As motivation and justification for this EU directive in particular non-discriminatory market access is given ("Without effective separation of networks from activities of generation and supply (effective unbundling), there is an inherent risk of discrimination not only in the operation of the network but also in the incentives for vertically integrated undertakings to invest adequately in their networks" (European-Union, 2009, p.56)). Avoidance of social unfavorable (investment) incentives is given as another reason for this directive ("Ownership unbundling, which implies the appointment of the network owner as the system operator and its independence from any supply and production interests, is clearly an effective and stable way to solve the inherent conflict of interests and to ensure security of supply." (European-Union, 2009, (p.56))). The big four German plant operators, all of which owned transmission units, implemented this EU Directive in different ways.

E.ON sold its entire subsidiary transpower stromübertragungs GmbH (transpower) to the Dutch transmission system operator TenneT holding B.V.. For this German Transmission System Operator the TenneT Holding founded the TenneT TSO GmbH, which can

be seen as a completely independent Transmission System Operator, since its owner neither runs power plants in Germany nor distributes electricity to consumers. See the press release of E.ON (2010) for further details.

Vattenfall firstly renamed its subsidiary Vattenfall Europe Transmission as "50Hertz Transmission" and two months later sold 60% of this subsidiary to the Belgian Transmission System Operator ELIA, which already operated the entire Transmission System in Belgium. The remaining 40% were sold to the Australian infrastructure fund "Industry Funds Management (IFM)". 50Hertz can be also seen as a completely independent Transmission System Operator, since both owners do not own power plants or distribute electricity to consumers in Germany. See the press release of Vattenfall Europe (2010) for further details.

RWE owned the subsidiary RWE Transportnetz Strom GmbH, which worked as Transmission System Operator. In 2009 the subsidiary was renamed as Amprion GmbH. In 2011 the Commerz Real, which is a subsidiary of the Commerzbank, bought 74,9% of Amprion GmbH and set up an infrastructure fund for institutional investors. Known institutional investors of this fund are MEAG (Munich ERGO Assetmanagement GmbH), which is controlled by the German Reinsurance company Munich Re and its subsidiary ERGO Versicherungsgruppe Aktiengesellschaft, the insurance company Swiss Life, the insurance company Talanx, as well as the pension funds for medical doctors of Westphalia-Lippe and Brandenburg (Ärzteversorgung Westfalen-Lippe and Ärzteversorgung Land Brandenburg). RWE still holds a participation of 25,1% in Amprion. The answer to what extent RWE uses this participation to influence decisions of Amprion to its own advantage cannot be answered easily. However, a full ownership unbundling did not take place. See the press releases of CommerzReal (2011) and CommerzReal (2012) for further details.

EnBW Energie Baden-Württemberg AG owned the Transmission System Operator EnBW Transportnetze AG. In March 2012 it renamed it as TransnetBW GmbH. There have been several organizational changes to both firms to satisfy the unbundling rules. However, EnBW still holds 100% of Transnet BW. Therefore, for EnBW and TransnetBW the highest economic interdependence exists. See the press release of EnBW (2012) for further details.

The German Transmission System Operators are regulated by the Bundesnetzagentur

(BNetzA). BNetzA regulates transmission fees as well as investments in the network of the Transmission System Operators for a regulation period of five years. Price regulation is done by a revenue cap. The investment regulation is done by setting efficiency targets. The way a network operator fulfills an efficiency target is not prescribed. If a network operator beats an efficiency target, it can retain additional profits in the corresponding five-year regulation period. If a network operator fails to fulfill an efficiency target, it suffers a loss. For a detailed overview about regulation of the German Transmission System Operators and a first evaluation see Bundesnetzagentur (2015).

Summarizing the analysis, it can be stated that transmission is organized via regional (regulated) monopolists, which in general work independently from plant operators as well as electricity distributors. However, the level of effective independence of Amprion and TransnetBW might be doubted.

Distribution of Electricity

The Bundesnetzagentur is the German regulatory authority for the network-related markets for electricity, gas, telecommunication, postal services and railway services. The Bundeskartellamt, which is the general German competition protection office, publishes together with the Bundesnetzagentur an annual report about the German electricity and gas markets, which is called Monitoringbericht. The aim of this report is to analyze the competitiveness of the corresponding markets and if necessary to propose legislative measures.

Their Monitoringbericht counted more than 50 active providers for more than 75% of the service areas (Bundesnetzagentur and Bundeskartellamt, 2013, p.124). The services areas with a large amount of service providers have significantly increased over the last years, since in 2007 more than 50 active providers were counted only in about 25% of the service areas. This vast number of providers can be seen as a high degree of competition. However, the Bundesnetzagentur and the Bundeskartellamt (2013) point out that some providers can only be seen as formally active, since they supply only very few households in some service areas.

As a competition restraining factor the lacking willingness of consumers to change their providers is often mentioned. Therefore, data for end-consumers that changed their

suppliers has been collected by the Bundesnetzagentur and the Bundeskartellamt (2013, p.125). In table 2.1 the amount of electricity that changed supplier in 2012 is shown, whereas table 2.2 shows the number of end-consumers that changed their suppliers in 2012. The category " ≤ 10 MWh/Year" refers to households as end-consumers, the category " > 10 MWh/Year ≤ 2 GWh/Year" mainly refers to trade, commerce and small industry as consumers and the category " > 2 GWh/Year" refers to big industry as consumers. Classical household consumers show the least willingness to change their electricity suppliers, since only 7.8% of the electricity amount in this category changed suppliers and only 5.7% of consumers in this category changed their suppliers in 2012. Trade, commerce and small industry show a higher willingness to change their suppliers. This is reflected in 11.6% of the total electricity amount that changed suppliers in this category and 8.2% of consumers which changed their suppliers in this category in 2012.

Category of End-Consumer	Electricity Extraction from TSO and DSO in TWh	Supplier Change in TWh	Supplier Changed Electricity as Percentage of Extracted Electricity
≤ 10 MWh/Year	124.5	9.7	7.8 %
> 10 MWh/Year ≤ 2 GWh/Year	134.8	15.6	11.6 %
> 2 GWh/Year	242.4	27	11.1%
Total	501.7	52.3	10.4%

Table 2.1: Quantity of Electricity that Changed Suppliers in 2012

Large industrial companies show the highest willingness to change their suppliers, since 14.7% of consumers changed their suppliers. Even though for this category the largest number of consumers changed supplier the amount of electricity that changed supplier was with 11.1% a bit smaller than for trade commerce and small industry in 2012. A

Category of End-Consumer	Number of Consumers of TSO and DSO	Number of Supplier Changes	Supplier Changes as Percentage of End-Consumers
≤ 10 MWh/Year	46 221 649	2 617 745	5.7%
> 10 MWh/Year ≤ 2 GWh/Year	2 474 295	204 092	8.2%
> 2 GWh/Year	18 707	2 743	14.7%
Total	48 714 651	2 824 589	5.8%

Table 2.2: Number of Consumers that Changed Suppliers in 2012

reason for this result might be that the largest consumers in this category (e.g. Deutsche Bahn) either cannot easily change their suppliers from a technical perspective or already get favorable contracts without changing the suppliers.

The heterogeneity of households and industrial consumers is additionally reflected in contracts they choose. Therefore, the Bundesnetzagentur and the Bundeskartellamt (2013) provide data for the type of contract for households and industrial consumers.

Figure 2.3 shows purchased electricity for households and industrial consumers depending on whether they have a basic contract with the regional provider (Basic contract), a special contract with the base provider (Special Contract with Base Provider) or a special contract with another provider (Other Provider). The highest amount of electricity is purchased by industrial consumers from other providers (184.9 TWh). The second highest amount of electricity is purchased by industrial consumers from their base providers in a special contract (124.1). Only 6.6 TWh of electricity are purchased by industrial consumers from their base providers in a basic contract.

The data base for households looks a bit different. Most electricity is purchased from base providers in special contracts (55.7 TWh). More households purchase electricity from their base providers in a basic contract than from other providers. 47.3 TWh were

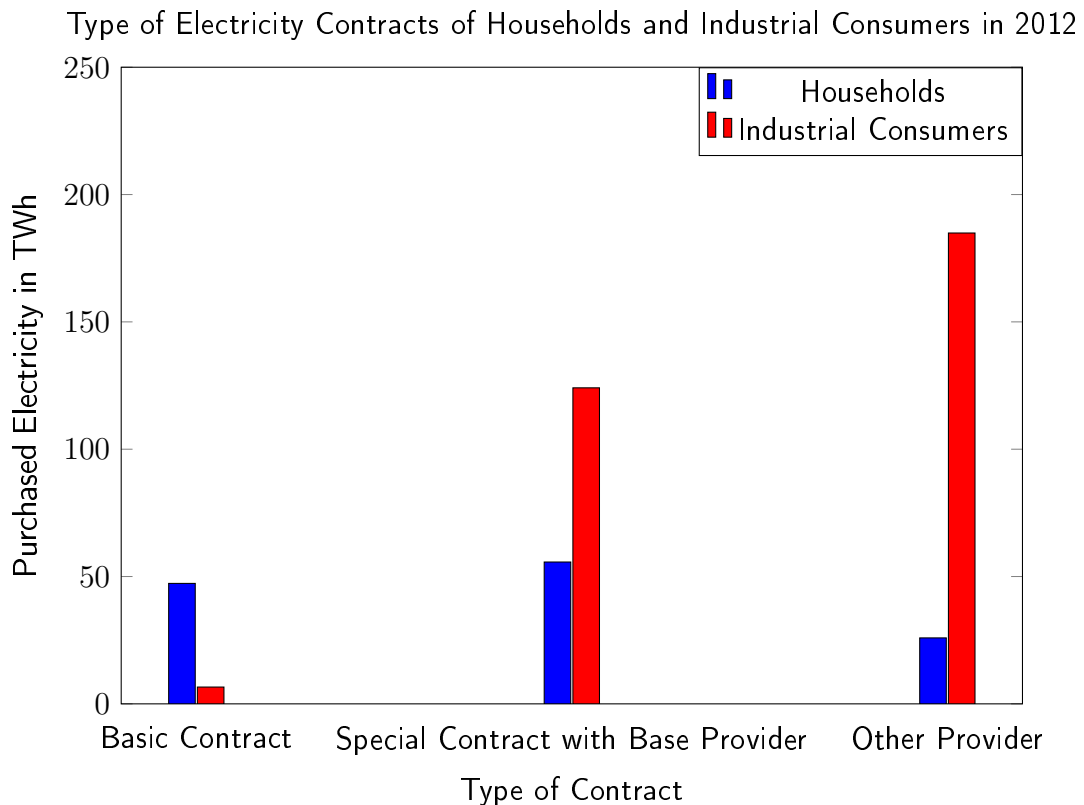


Figure 2.3: Type of Electricity Contracts of Households and Industrial Consumers

purchased from base providers at basic conditions and only 25.9TWh were purchased from other providers in 2012. This clearly illustrates that the willingness to change the contract or even providers for households is lower than for industrial consumers. Probably this comes from the effect that households estimate the changing costs due to bureaucratic procedures, the fear of being potentially unplugged etc. as rather large, whereas the savings from a more favorable contract are estimated to be rather small. In general firms focus more on costs issues. For a lot of firms energy costs are an important item on their balance sheet and consequently cutting energy costs is (compared to other cost-cutting measures) a rather easy way to increase competitiveness.

From this data one can conclude that the willingness (and the ability) to change suppliers exist for large groups of consumers. However, consumers differ in their required amount and their short-run as well as long-run elasticity. Another important consumer characteristic especially for large electricity consumers is the time when electricity is needed. See section 2.3 for details about the time patterns of demand and the resulting load profile for Germany.

Due to consumers' possibility to change suppliers and the large number of suppliers on the end-consumer market one can conclude that no serious deficits in competition exist on this last stage of the market. From a theoretical point of view, competing price-setting firms that supply heterogeneous consumers seem to be the adequate model for the end-consumer market. However, as shown above many consumers do not use the possibility to change their supplier.

Stage	Supply	Demand	Market Structure
1) Generation	Plant Operators	Electricity Trader	Oligopoly with Strategic Interaction
2) Transmission	Transmission System Operators	Electricity Provider	Regulated Regional Monopoly
3) Distribution	Electricity Provider	End-Consumers	Polypoly with Heterogenous Consumers

Table 2.3: Form of Competition on the Three Stages of the Electricity Market

For each stage of the German electricity market table 2.3 summarizes the main actors and its competitive structure.

From a strategic perspective the first stage of the German electricity market is most relevant, since only four considerable plant operators compete and strategic interaction occurs. Thus, the focus of the following analysis is on the electricity wholesale market.

2.1.2 Electricity Trading

In principle two different distribution channels for power-generating firms in Germany exist: Firstly, trading electricity on the European Energy Exchange (EEX). Secondly, trading electricity contracts bilaterally. Bilateral contracts that are traded without involvement of an exchange are called over-the-counter contracts (OTC). These OTC contracts have the advantage of being precisely tailored to people's own requirements. However, they have the disadvantage of counterpart risk and a lack of liquidity.

The following pages about electricity trading takes a look at the most important market participants, the most important contracts on the electricity market and prices of these contracts.

Registered Market Participants at the European Energy Exchange

In 2008 POWERNEXT, which had been the energy exchange foremost for the French market, started a cooperation with with the European Energy Exchange (EEX), which had been the energy exchange for the German and Austrian market. Both exchanges founded the European Power Exchange (EPEX SPOT) to organize the spot markets for Germany/Austria, for Switzerland and for French. Future contracts for all three market areas can be traded on the European Energy Exchange (EEX).

EPEX SPOT and EEX put market participants into the following 5 categories:

1. Electricity Producers and Electricity Traders (P&T)
2. Municipal and Regional Supplier (MS&RS)
3. Financial Service Providers and Financial Institutions (FSP&FI)
4. Commercial Costumers (CC)
5. Transmission System Operators (TSO)

Figure 2.4 illustrates the registered participants at the EPEX SPOT as well as at the EEX. Registered participants at the EPEX SPOT can be seen as actors with spot market access, whereas registered participants at the EEX can be seen as actors with futures market access. Of course, simultaneous registration at both exchanges is possible and usual. The presented data about registered market participants is taken from the report of the

Bundesnetzagentur and Bundeskartellamt (2014, p.117).

Participants Registered at the Spot and Forward Market by Trader Category (2013)

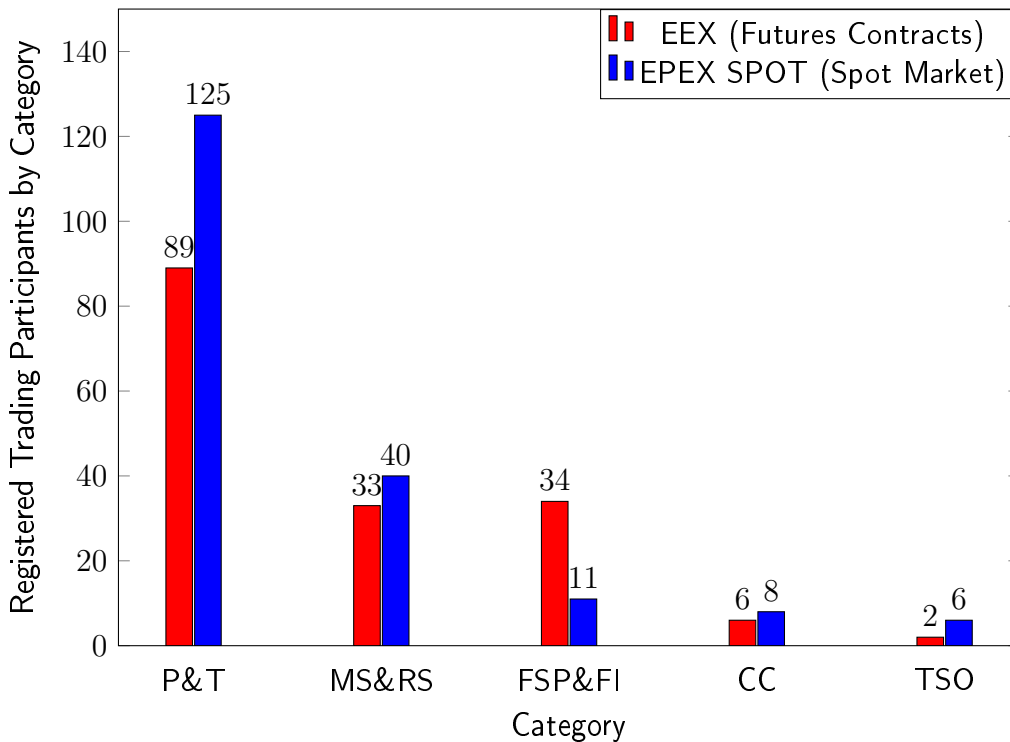


Figure 2.4: Participants Registered at the Spot and Forward Market by Category (2013)

The largest number of registered market participants can be found in the category of Electricity Producers and Electricity Traders (P&T). 89 participants have access to the futures market and 125 participants have access to the spot market. The category with the second largest number of registered participants refers to Municipal and Regional Suppliers (MS&RS), where 33 suppliers have futures market access and 40 suppliers have spot market access. Another important category of market participants are Financial Service Providers and Financial Institutions (FSP&FI). About the same number of financial institutions as regional and municipal suppliers are trading on the futures market (33), whereas on the spot market considerably less financial institutions are trading (11). This crucial role on the futures, but not on the spot market, can be explained by the fact, that futures contracts can be settled financially on the EEX, whereas spot market obligations are normally fulfilled physically. Only a few Commercial Customers (CC) choose to register at the energy exchanges (EEX 6, EPEX SPOT 8). It seems that even for large customers direct exchange trading is too impracticable and expensive in comparison to purchasing

electricity from Distribution Operators. Of course, the German/Austrian Transmission Operators are registered. One interesting detail is given by the fact that some of the Transmission System Operators are not registered at the futures market. Therefore, only 2 TSO are registered at the EEX, whereas 6 TSO (50Hertz, Amprion, Tennet, TransnetBw, Austrian Grid and Vorarlberger Übertragungsnetze GmbH) are registered at the spot market. One explanation might be that for the aim of network stability foremost short-term measures are important. Thus, futures contracts are not necessary for this aim.

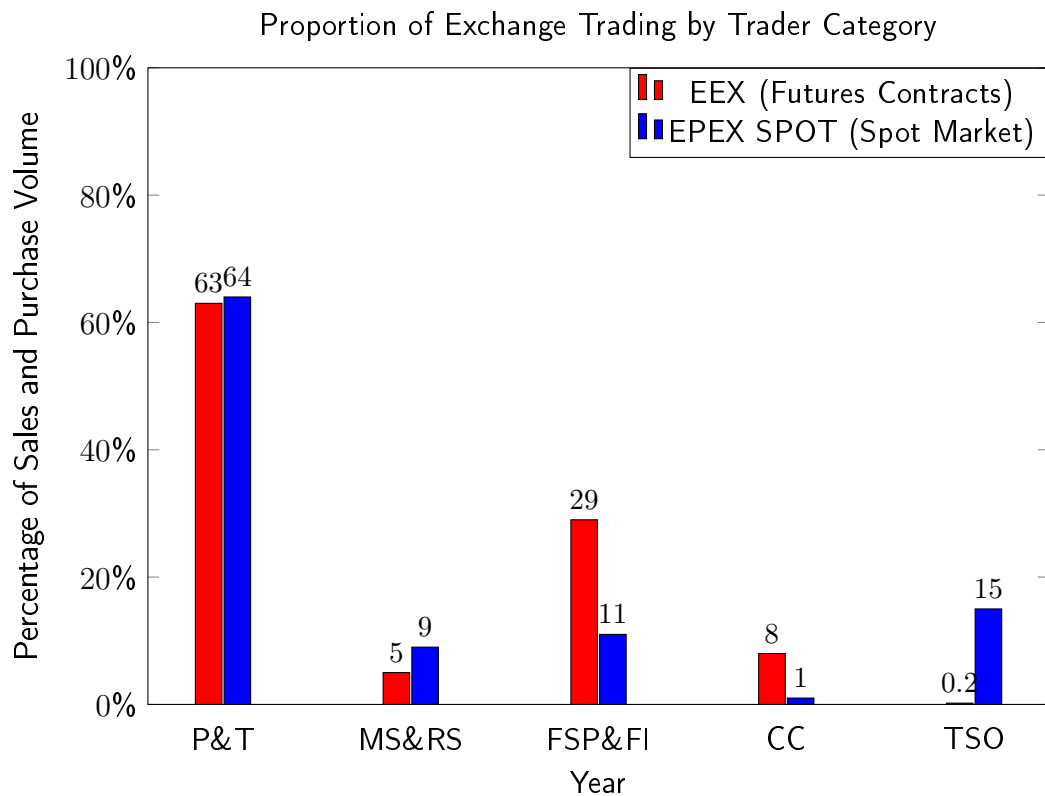


Figure 2.5: Proportion of Exchange Trading by Trader Category

Figure 2.5 illustrates the sales and purchases volume on the spot market (EPEX SPOT) as well as on the futures market (EEX) by category of traders. This data is taken from the report of the Bundesnetzagentur and the Bundeskartellamt (2014, p.131). The largest volume is traded by Electricity Producers and Electricity Traders (P&T), since on the spot market 64% and on the forward market 63% of the market volume is traded by Electricity Producers and Electricity Traders. Financial Service Providers and Financial Institutions (FSP&FI) follow at considerable distance with a proportion of 29% of the traded forward market volume. However, on the spot market Financial Service Providers and Financial

Institutions only play a minor role, since they only have a proportion of 11% of the spot market volume. Probably they foremost trade on the spot market to equalize their forward market positions, since Financial Service Providers and Financial Institutions take no direct interest in physical electricity that is traded on the spot market. Thus, for the futures market the 34 registered Financial Service Providers and Financial Institutions play an important role, whereas their role on the spot market seem to be of less importance. The opposite trading strategy applies for the registered Transmission System Operators (TSO), since they account for the second largest spot market volume of 15%, whereas they account for less than 1% of the forward market volume. This strengthens the argumentation that for network stability, which can be seen as the principal objective of Transmission System Operators, long-term forward contracts are of minor importance. Even though Municipal and Regional Supplier (MS&RS) account for the second largest category of traders, the volume traded by suppliers is rather low. On the spot market Municipal and Regional Supplier account only for 9% of the market volume and the proportional forward volume with 5% is even lower. The difference between both proportional market volumes might be explained by a principally physical need of electricity. This need can be satisfied on the spot market. Commercial Costumers (CC) are in numbers as well as in proportionally traded market volumes of lower significance on the electricity wholesale market, since they only account for a proportion of 1% spot market volume and a proportion of 3% forward market volume. The slightly higher participation on the forward market might be explained by the hedging focus of Commercial Costumers. Hedging, which is an financial motivation, can be ensured by forward market participation more efficiently than by spot market participation.

The analysis of the registered market participants together with the analysis of the market structure in section 2.1.1 leads to following conclusion: The most significant role on the German electricity exchange is played by Electricity Producers and Electricity Traders. The big four energy suppliers in Germany (RWE, EON, Vattenfall and ENBW) have a dominant role in electricity generation. Unfortunately, for Electricity Traders no data that shows proportional market shares is publicly available (up to my best knowledge). However, it can be assumed that from the registered Electricity Producers and Electricity Traders (89 at EEX and 125 at EPEX SPOT) a significant amount are pure

trading firms, since compared to the electricity generation the barriers to electricity trading seem to be rather low. Therefore, in the group of Electricity Traders significant dominance of certain traders seems to be unlikely. Hence, it is reasonable that the behavior of Electricity Producers influences (at least when behaving the same way) the market outcome of the wholesale market, since they play a dominant role in the group of Electricity Producers and Electricity Traders, which in turn seems to be the most powerful group on the wholesale market.

Important Contracts Traded on the European Energy Exchange

On the energy exchange the following four important markets, on which different products for the German market zone exist, are traded:

1. Day-Ahead Spot Market
2. Intraday Spot Market
3. Futures on Phelix (Physical Electricity Index) Market
4. Derivatives Market (European Put and Call Options on Phelix Base)

Detailed conditions of the spot market products traded can be found in EPEX-SPOT (2014) and detailed conditions of the future contracts traded at the EEX can be found in the contract specifications of the European-Energy-Exchange (2015). The most important conditions for trading on the exchanges are summarized at this point.

Important for the spot markets is the fact that physical delivery takes place. Therefore, article 5.1 in EPEX-SPOT (2014, p.21) states: "The Contracts admitted to trading on EPEX SPOT are commercial contracts on commodities for the physical Delivery (Injection or Withdrawal) of electrical power within the Austrian, French, German or Swiss transmission systems". For this physical delivery a detailed time and date is defined and no right to withdraw from the contract exists, since article 5.2 in EPEX-SPOT (2014, p.21) states: "The execution of an Order in the market entails the firm and irrevocable commitment at a set date and time: [This means] for the buyer to take Delivery of (Withdraw) and to settle the Underlying at the set Price [and] for the seller to deliver (Inject) and to receive settlement of the Underlying at the set Price".

The conditions for intraday and day-ahead trading are quite similar. However, some

Contract Type	Delivery Hour	Days
Base	0 to 24	Monday to Sunday
Peak	8 to 20	Monday to Friday
Peak Weekend	8 to 20	Saturday to Sunday
Off Peak	0 to 8 and 20 to 24 0 to 24	Monday to Friday Saturday to Sunday

Table 2.4: Delivery Hour and Delivery Days of Future Contracts on the EEX

important differences exist. Table 2.5 shows these similarities and differences of the intraday and the day-ahead spot markets. A first difference is given by the detail that on the intraday spot market electricity is traded for intervals of 15 min, whereas on the day-ahead spot market electricity is traded in blocks of 1 hour. The smallest trading volume for both spot markets is given by 0.1 MW, which means that a seller commits to feed in at least 0.1 MW for the corresponding time interval. Therefore, on the intraday spot market a volume per bid of at least 0.025 MWh is sold, whereas on the day-ahead spot market a volume per bid of at least 0.1 MWh is sold. The range of prices that can be set is larger for the intraday market and extends from -9999 €/MWh to + 9999 €/MWh, whereas on the day-ahead spot market negative prices are not allowed to fall below -500 €/MWh and positive price peaks cannot exceed 3000 €/MWh. The place of delivery is defined as either one of the five TSOs zones of the German/Austrian Market Zone, which means more precisely feed-in in one of the transmission zones of Amprion, Tennet TSO, 50Hertz Transmission, TransnetBW or Austrian Power Grid. The most important difference is given by the deadline for trading. For the intraday spot market trading can take place until 45min before delivery. For the day-ahead spot market all bids have to be submitted until 12 p.m. (noon) the day before delivery.

For the futures market it depends on the market area whether physical and/or financial settlement is possible, since article 2.1.2.1 and article 2.1.2.2 of European-Energy-Exchange (2015, p.5) state: "Futures with physical fulfillment within the respective control area can be traded for the following market areas: Belgium, France, and The Netherlands. Futures with financial fulfillment can be traded for the following market areas:

	Intraday Spot Market	Day-Ahead Spot Market
Underlying	Electricity traded the same or following day in 15 min Periods	Electricity traded for delivery the following day in 24 hour intervals
Size	Min. volume of 0.1MW	Min. volume of 0.1MW
Price Range	-9999 to 9999 €/MWh	-500 to 3000 €/MWh
Place of Delivery	One TSO Zone in the German/Austrian Market Zone	One TSO Zone in the German/Austrian Market Zone
Latest Trading	45 min before delivery	12 pm at the day before delivery

Table 2.5: Properties of the Intraday and Day-Ahead Spot Market

Germany/Austria, France, and Italy." Thus, for the German market zone futures cannot be settled physically and therefore all futures contracts have to be settled financially.

The underlying of a financially settled power futures contract is the Physical Electricity Index (Phelix). The pay-off for this futures contract is given by the difference of the price fixed in the futures contract and the Phelix in the corresponding period. Strictly speaking, there exist two indices, which are called Phelix Base and Phelix Peak. Phelix Base and Phelix Peak are calculated on a daily as well as on a monthly basis. Phelix Base and Phelix Peak are simply calculated by on average prices. For the Phelix base all hours of a day are taken into account, since article 2.2 of European-Energy-Exchange (2012, p.4) states: "Phelix Day Base is the average price of the hours 1 to 24 for electricity traded on the spot market. The PHELIX is calculated for all calendar days of the year as the simple average of the auction prices for the hours 1 to 24 in the market area Germany/Austria disregarding power transmission bottlenecks". For the Phelix peak solely the time between 8 a.m. and 8 p.m. is taken into account, since article 2.3 of European-Energy-Exchange (2012, p.4) says: "Phelix Day Peak is the average price of the hours 9 to 20 for electricity traded on the spot market. It is calculated for all calendar days of the year as the simple average of the auction prices for the hours 1 to 20 in the market area Germany/Austria disregarding power transmission bottlenecks". A peak-weekend futures-contract as well as an off-peak

futures-contract can be traded additionally since 2012. Table 2.4 gives an overview for the delivery hour and day for futures contracts of types Base, Peak, Peak Weekend and Off Peak.

A (physical) futures contract is defined by article 1.1.1 of the European-Energy-Exchange (2015, p.6) as "delivery or acceptance of delivery of electricity with a constant output of 1 MW into the maximum voltage level of the respective market area during the delivery time on every delivery day during the delivery period". Thus, the 1 MW year base load futures contract binds the owner to purchase for every hour in the next year 1 MW of electricity, which implies purchasing 8760 MWh of total electricity in the corresponding year (365 days times 24 h times 1 MW). This is in contrast to other commodity exchanges, where e.g. a 1 ton year wheat futures contract binds the owner to purchase 1 ton wheat in August, when the year futures had been bought in August the year before.

Delivery Period of Futures	Tradable Maturities
Day Futures	The respective next 34 days
Weekend Futures	The respective next 5 weekends
Week Futures	The current and the next 4 weeks
Month Futures	The current and the next 9 months
Quarter Futures	The respective 7 full quarters
Year Futures	The respective next 6 full years

Table 2.6: Delivery Periods and Tradable Maturities for EEX Futures

Table 2.6 shows the different tradable futures contracts with their corresponding maturities. At a certain day, day-futures can be traded for each of the next 34 days, weekend-futures can be traded for the next 5 weekends, week-futures for the next 4 weeks, month-futures for the next 9 months, quarter-futures for the respective 7 full quarters and year-futures for the respective next 6 full years. Thus, with a combination of futures a trader can purchase or sell electricity individually for each and every day in the next month, but not in the current year. However, it is possible to purchase or sell electricity futures over a longer period by monthly, quarterly or yearly contracts.

Article 4.1 in the European-Energy-Exchange (2015, p.14) defines the rights associated with the acquisition of a Put and Call Option at the EEX. All options at the EEX are European Put or Call Options with financial fulfillment, since they can only be exercised on the last trading day and give a right to purchase or sell the corresponding financially fulfilled futures contract, since article 4.1 of European-Energy-Exchange (2015, p.14) states: "The buyer of a call option (call) is entitled to receive a long position in the corresponding future at the exercise price of the option on the last trading day". There has been an increase in volume for Phelix options. However, the futures and the day-ahead spot market show significantly higher trade volumes for the years 2009 to 2013.

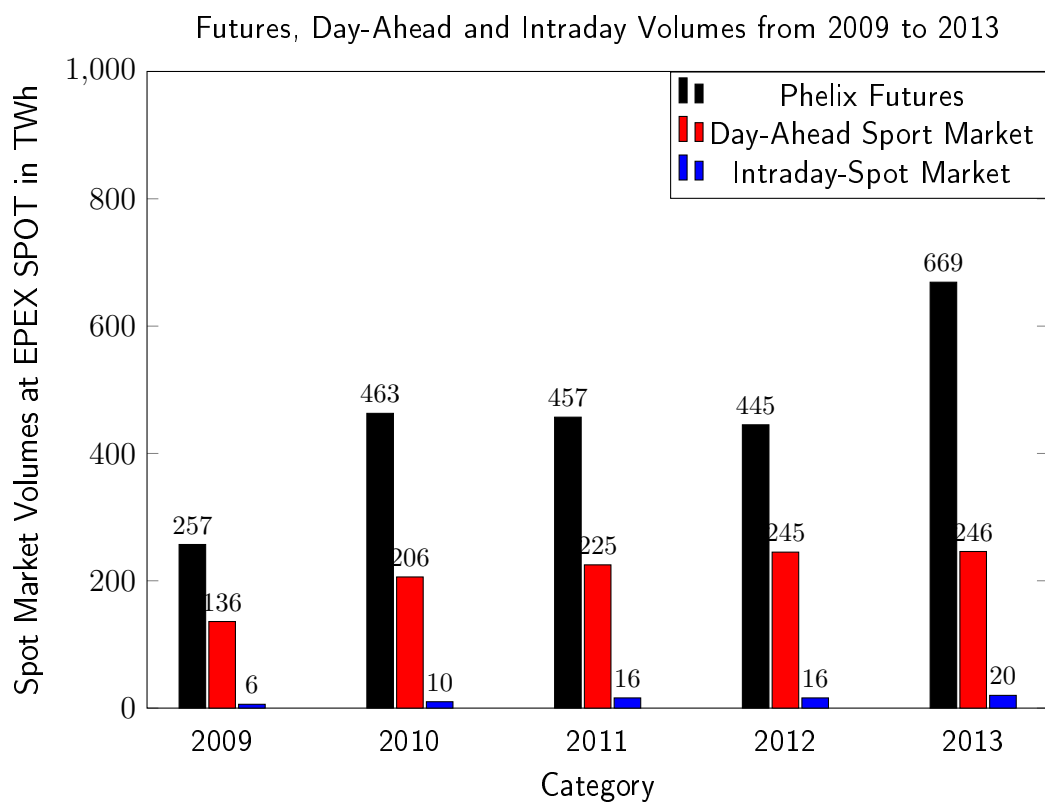


Figure 2.6: Futures, Day-Ahead and Intraday Volumes from 2009 to 2013

Figure 2.6 illustrates market shares for futures, day-ahead and intraday trading for the years 2009 to 2013. The data is taken from the report of the Bundesnetzagentur and the Bundeskartellamt (2014, p.119 and p.125). All three markets have been growing since 2009. However, the market volumes for the different markets significantly differ. The largest volumes are traded for all years on the EEX futures market. In 2009 257 TWh and in 2013 629 TWh electricity were traded forward. The second largest market volume is

traded at the day-ahead spot market. In 2009 136 TWh and in 2013 246TWh were traded forward. The intraday spot market is of minor relevance for the electricity wholesale market. In 2009 only 6 TWh and in 2013 20 TWh were traded forward. Market volumes increased for all three markets from 2009 to 2013.

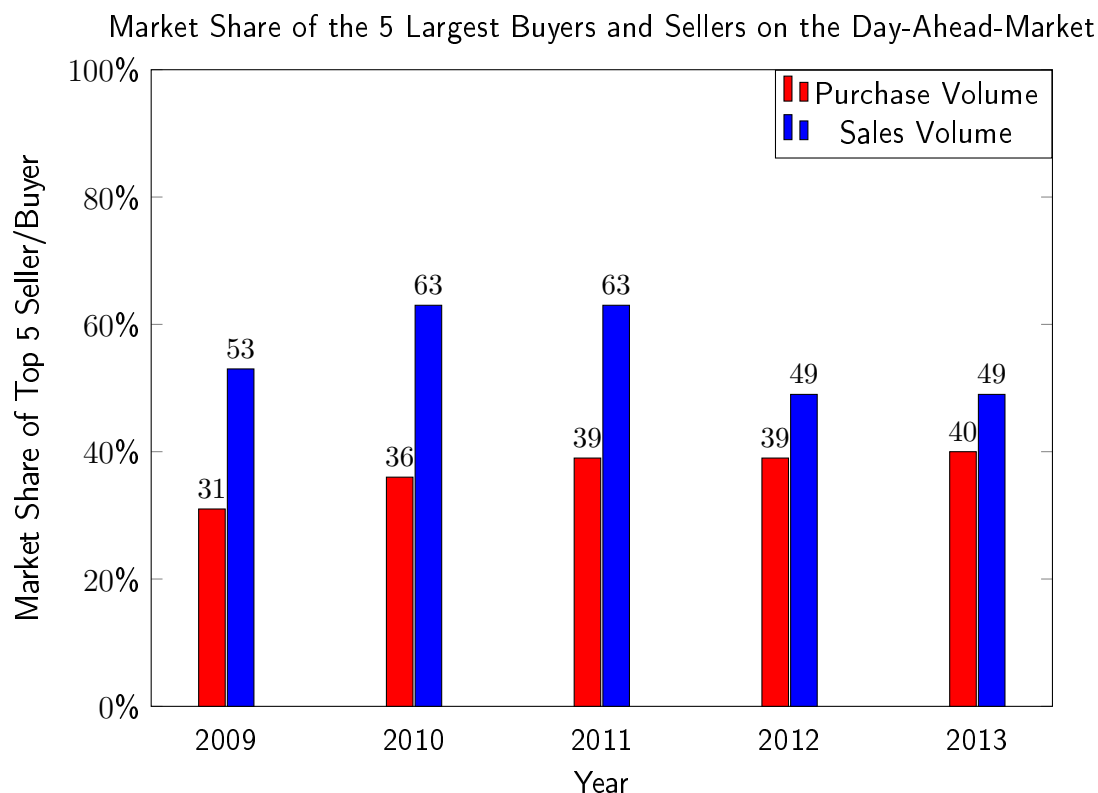


Figure 2.7: Market Shares of the 5 Largest Buyers and Sellers on the Day-Ahead-Market

For the years 2009 to 2013 figure 2.7 shows the proportions sold and purchased on the day-ahead spot market by the 5 largest traders. For all the years about 50% or more of the electricity has been sold on the day-ahead market by the 5 largest traders. Due to the large capacities of RWE, E.ON, Vattenfall, and ENBW for electricity generation, this volume mainly comes from the German big four supply firms. For all the years about 30% or more of the electricity has been purchased by the 5 largest traders. This corresponds to the guess above that a larger number of traders purchases electricity from these suppliers.

Figure 2.8 presents the proportions sold and purchased for the years 2009 and 2013 for the 5 largest traders on the futures market. Similar to the spot market a high proportion of sold and purchased market volume is traded by those 5 largest traders. However, in contrast to the spot market market concentration seems to be similar for sold and purchased

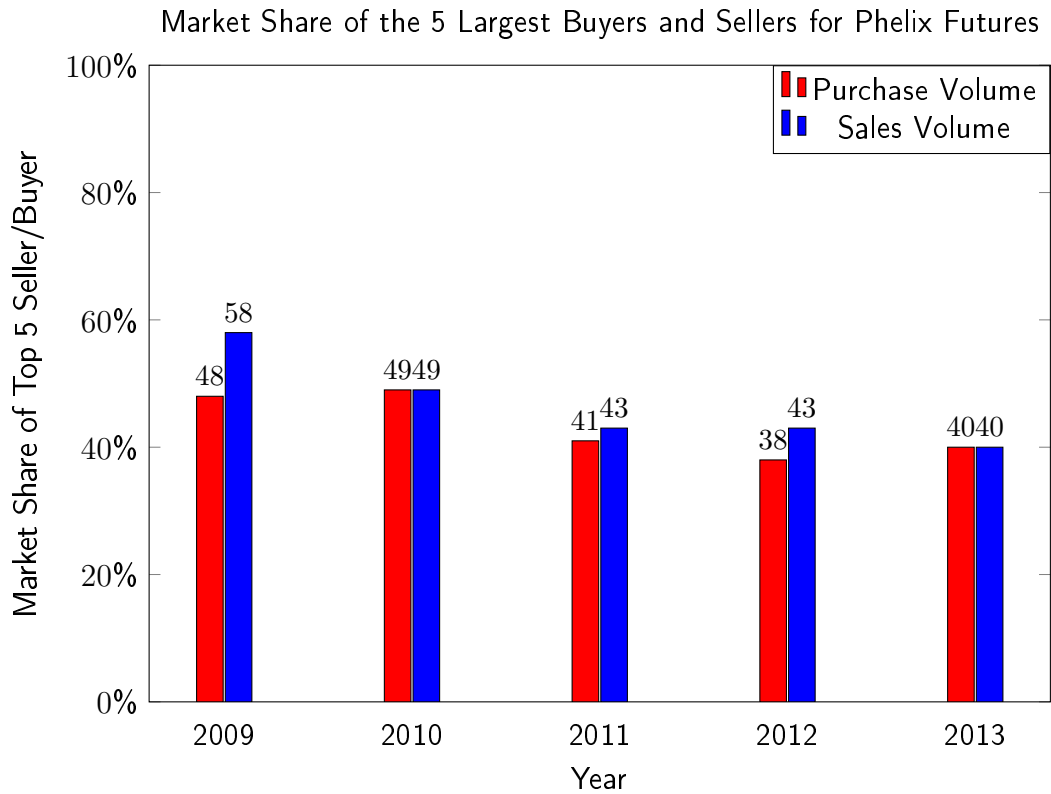


Figure 2.8: Market Share of the 5 Revenue largest Buyers and Sellers for Phelix Futures

volume, since for both between 40% and 60% of the market volume is traded by the 5 largest traders. One explanation might be that positions taken in futures are either settled by cash or by other contracts. If a trader settles his long position in a futures contract, he has to take a short position in another contract. This effect could explain the effect that the group of the 5 largest traders purchase and sell approximately equal volumes.

Figure 2.9 shows the histogram of the EPEX SPOT Day-Ahead Spot Market Price in 2013. The mean of the day-ahead spot price was 37.78 €/MWh and the standard deviation of the day-ahead spot price was 16.46 €/MWh in 2013. A normal distribution, which parameters are chosen to match these first two empirical moments ($\mu = 37.78$ €/MWh, $\sigma = 16.46$ €/MWh) approximately describes the distribution of the EEX day-ahead spot market price. However, the real distribution of the EEX day-ahead spot market price is more leptokurtic, since prices between 25 €/MWh and 40 €/MWh are more often realized than a normal distribution would suggest, whereas prices between 15 €/MWh and 25 €/MWh and prices between 40 €/MWh and 55 €/MWh are realized less often. Negative day-ahead spot market prices are an existing but rare phenomenon, since it occurred

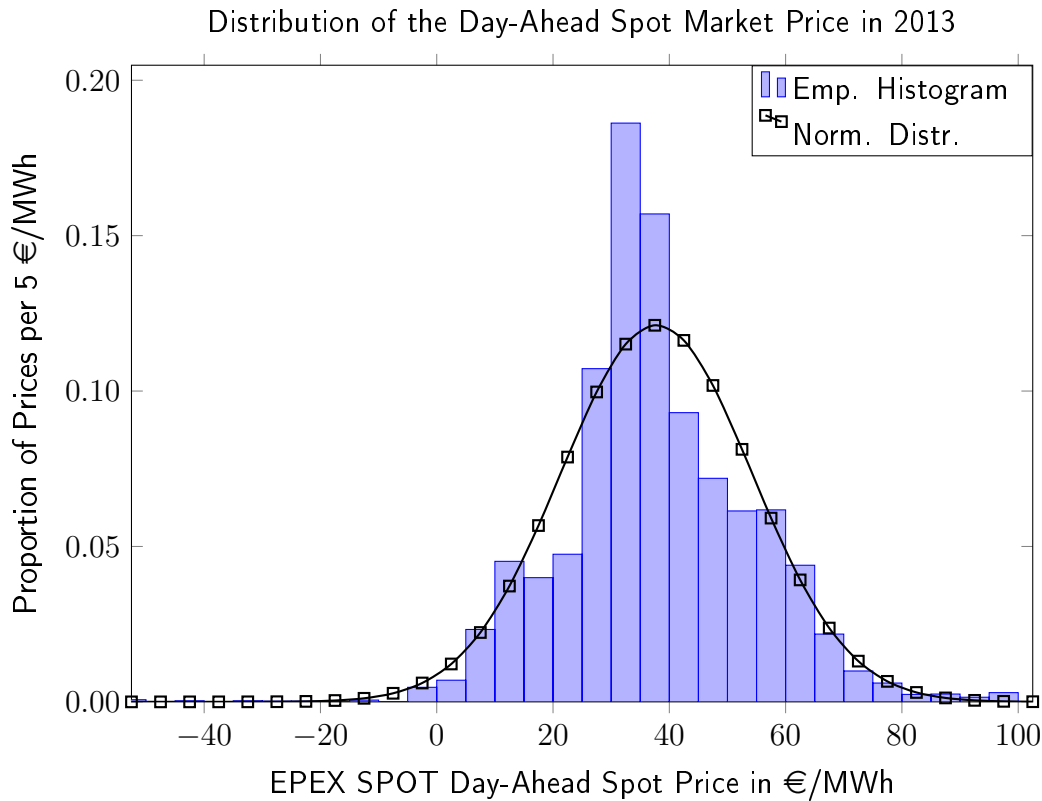


Figure 2.9: Histogram of the EPEXSPOT Day-Ahead Spot Market Price in 2013

only in 0.74 % of the trading blocks or in 65 h in 2013.

Another interesting detail about the EPEX SPOT spot market is mentioned by report of the Bundesnetzagentur and the Bundeskartellamt (2014, p.120). On the demand as well as on the supply side price-inelastic orders dominate bidding behavior, since 72% of the EPEX SPOT spot market volume in 2013 was ordered by price-inelastic bids. Interestingly this exactly holds true for demand and supply side. Therefore, only 28% of the market volume has been traded by price-elastic bids. This leads to the interesting effect that only a very small amount of bids actually sets the price, since in the end the highest supply meeting demand, sets the market-clearing price for all bids. From a strategic perspective this detail is very interesting for collusive behavior. If a firm undercuts this market-clearing price, it does not serve the total demand, since price-inelastic bids from this firm as well as from all competitors are firstly served. Therefore, the additional profit by undercutting a given market clearing price is rather small. This weakens the incentive for aggressive pricing strategies in the electricity wholesale market and makes profits from tacit collusion easier to sustain.

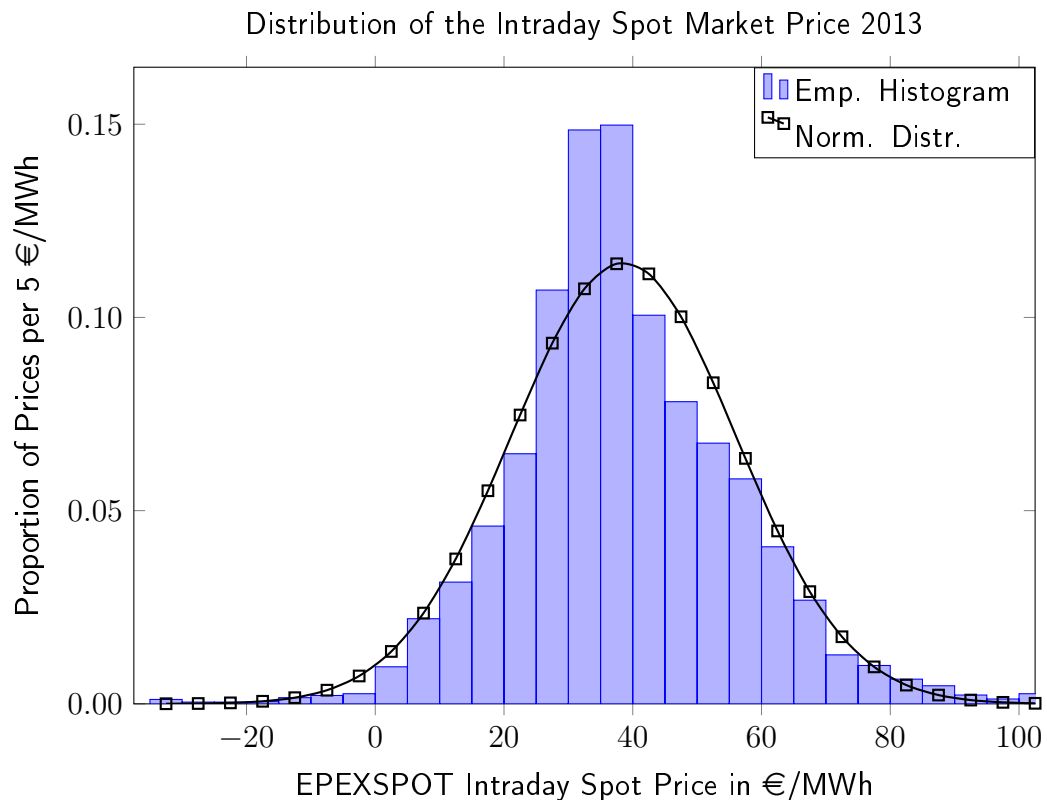


Figure 2.10: Histogram of the EPEXSPOT Intraday Spot Market Price 2013

Figure 2.10 illustrates the distribution of the EPEX SPOT intraday spot market price in 2013. Therefore, a histogram with a class size of 5 €/MWh and a normal distribution with the average intraday spot market price in 2013 ($\mu = 38.58 \text{ €/MWh}$) and the standard deviation of the intraday spot market price in 2013 ($\sigma = 17.48 \text{ €/MWh}$) as parameters is drawn. In general, this histogram is similar to that of the day-ahead spot market price and the normal distribution seems to approximately fit the data. Nevertheless real distribution seems to be more leptokurtic, since prices between 25€/MWh and 40€/MWh seem to be overrepresented, whereas spot market prices between 40 €/MWh and 60€/MWh are less often realized than a normal distribution would suggest.

Figure 2.11 shows the market volume of futures contracts with different maturities in 2013. The data is provided by the the Bundesnetzagentur and the Bundeskartellamt (2014, p.126), which additionally show that the market volumes for different maturities were quite similar in the years 2010, 2011 and 2012. The 1-year-futures contract has been traded most, since 362 TWh of electricity were traded with maturity in 2014, whereas the market volume of contracts with maturity in 2015 has only been about one third (119

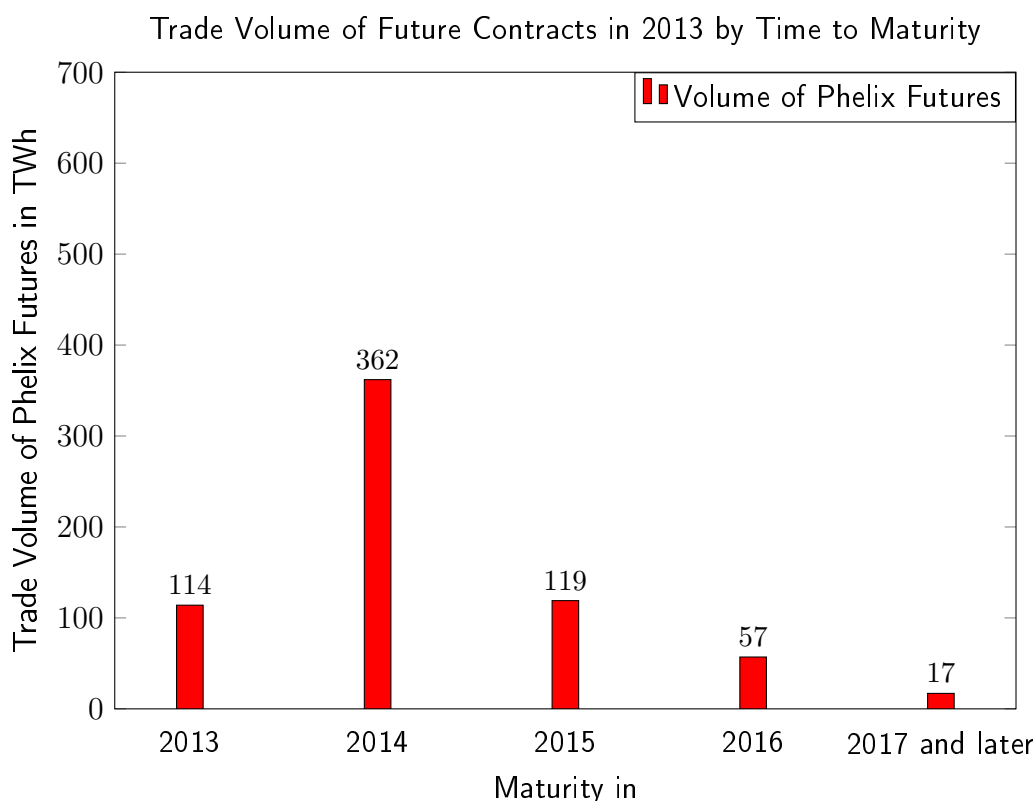


Figure 2.11: Trade Volume of Future Contracts in 2013 by Time to Maturity

TWh). Futures contracts that became due in 2013 account for the third-largest market volume of 114 TWh. Futures contracts that mature in 2016 and 2017 are from less relevance for the futures market, since they only account for a market volume of 57 TWh and 17 TWh of electricity.

Figure 2.12 illustrates the price of the Phelix with maturity in 2014. As mentioned before with a 1-year-futures contract electricity is sold or purchased "for the delivery time on every delivery day during the delivery period" (European-Energy-Exchange, 2015, p.6). Therefore, with a Phelix 2014 Base futures electricity for every hour of the 8760 hours in 2014 was traded. With a Phelix 2014 Peak futures electricity for every peak hour (trading blocks 9 to 20, which means from 08.00 to 20.00 hours) in 2014 was sold or purchased. Thus, electricity for 4380 hours (12 hours a day times 365 days) was sold or purchased. With a Phelix 2014 Off Peak futures contract electricity for every off-peak hour during the week (20.00 to 24 hours and 0.00 to 08.00 hours) and during the weekend (00.00 to 24.00 hours) was sold or purchased. Thus, electricity for 5628 hours (12 hours a week day times 261 week days and 48 hours a weekend times 52 weekends) was sold or

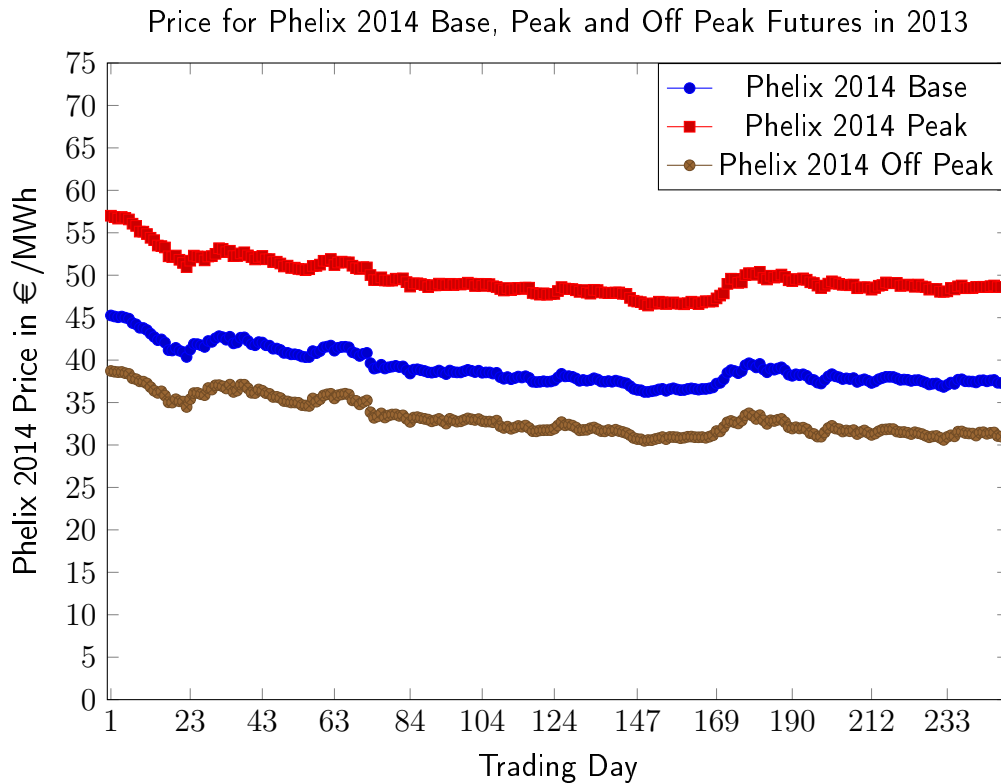


Figure 2.12: Price for Phelix 2014 Base, Peak and Off Peak Futures in 2013

purchased. However, the futures price presented at EEX is not given by the sum of prices for all hourly deliveries, but it is presented as the associated mean price in €/MWh. The trading days marked on the x-axis are the first trading days of each month.

Most expensive was electricity between 08.00 and 20.00 hours. This was reflected in the Phelix 2014 Peak futures price between 57.01 €/MWh on the first trading day (02. January) and 46.63 €/MWh on trading day 150 (05. August) in 2013. The price of the Phelix 2014 Base futures was between 45.26 €/MWh on the first trading day and 36.25 €/MWh on trading day 150. The price of the Phelix 2014 Off Peak futures was between 38.72 €/MWh on the first trading day and 30.49 €/MWh on trading day 149 (02. August). The prices of all three futures on the Phelix followed a very similar pattern, had rather constant prices and show only little volatility. For an excellent analysis of electricity forward prices traded on the German electricity see Mueller-Merbach (2009).

Over-the-Counter Electricity Trading

Contracts that are traded directly and bilaterally between two contracting parties without involvement of an exchange are called over-the-counter (OTC) trades. Over the-counter-traded contracts have a significant relevance for the wholesale electricity market. To get an rough overview about these transactions the Bundesnetzagentur and the Bundeskartellamt (2014) implemented a survey of OTC clearing. Therefore several market participants and broker platforms as well as the European Commodity Clearing AG (ECC), which works as clearing house for all exchange traded contracts as well as for voluntarily registered over the counter contracts, were interviewed.

Over the Counter Traded Volume by Maturity (2013)

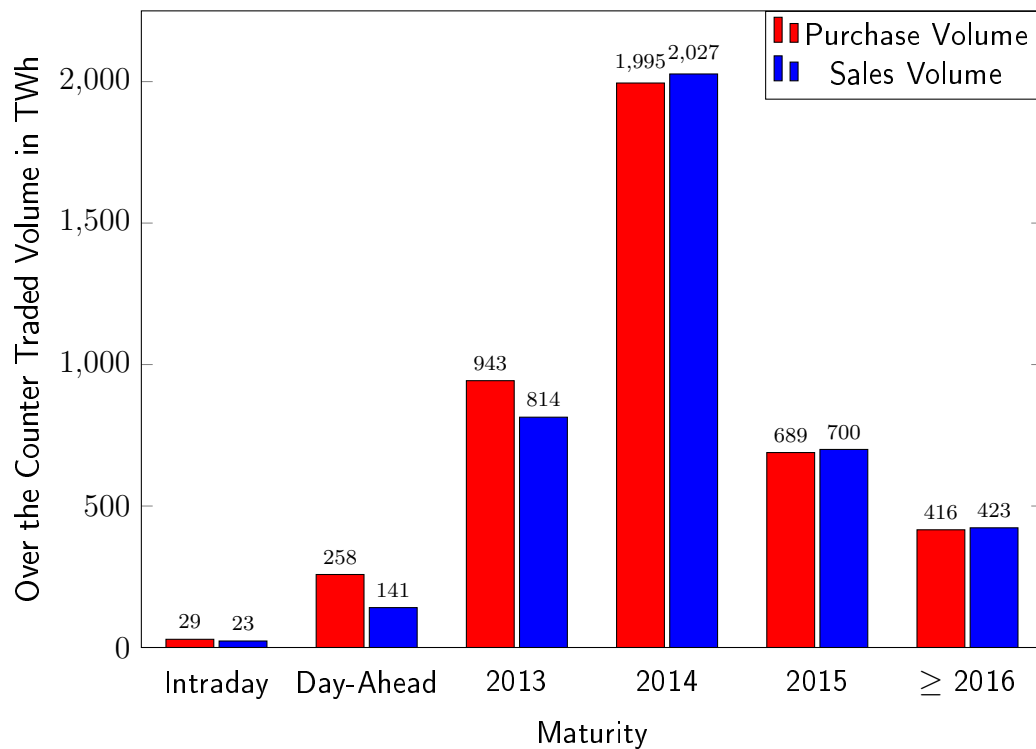


Figure 2.13: Over the Counter Traded Volume by Maturity (2013)

For different maturities figure 2.13 shows contract volumes of OTC trades in 2013. The original data of this survey is presented on page 134 of the Bundesnetzagentur and the Bundeskartellamt (2014). In general the OTC market volumes for different maturities are quite similar to that presented above for EEX. The highest market volume results for contracts that expire in 2014 (around 200 TWh for sales and purchases). Forward contracts with maturity in 2013 and 2015 have a rather low market volume and longer

lasting contracts that mature in 2016 or latter are traded less often (about 420 TWh). For the intraday as well as for the day-ahead spot market OTC traded contracts have a low relevance. This is reasonable, since the time for all necessary trade processes (contract, payment and especially delivery) cannot be handled that easily under time pressure that necessarily exists for contracts that expire the same or the next day. Hence, it can be concluded that the general structure of OTC trading does not systematically differ from the trading structure on the exchange.

From the analysis of the different products traded on energy exchanges as well as over-the-counter two contracts show a particularly relevance for the wholesale market: The day-ahead contracts and the futures contracts with a maturity of exactly one year, since both account by far for the largest market volume. For both contracts for short as well as long positions, a high market concentration exists.

Prices for 1-year-futures contracts have a rather small volatility, since their price is given by the average price for electricity sold for the entire year. This contract specification additionally leads to the effect that a 1-year-futures contract reduces the market volume for the spot market for the total year. As theoretical considerations will show, this leads to strategic important implications for firms incentives to relax prices and competitive pressure. In contrast the day-ahead spot price shows a much higher volatility, since its price directly corresponds to hourly trading blocks.

2.1.3 Important Energy Sources in Germany

In general electricity can be generated from a lot of different energy sources. Each country in the world uses a different composition of energy sources to generate electricity. The following pages are dedicated to the composition of energy sources used for electricity generation in Germany from 1990 until 2013. Then, cost estimates for electricity generation from different energy sources, which are provided by literature about the German electricity market, are combined with my own calculation of the probability distribution function for day-ahead spot prices in 2013. This leads to an estimation for the amount of hours in 2013, in which each energy source could profitably supply electricity on the German day-ahead spot market. There has been a discussion about effects of German feed-in tariffs for renewable energies on electricity imports and exports of Germany. Therefore,

the development of German electricity exports and imports from 1990 until 2013 is presented.

Energy Sources used for Electricity Generation in Germany

The time series of gross electricity production of the reunified Germany is illustrated in figure 2.14. This data has been published by *Energiebilanzen* (2014) for the years 1990 to 2014. The contribution of each energy source to gross electricity production can be summarized as follows:

1) Soft Coal: Soft coal had a decreasing contribution to the gross electricity production from 170.9 TWh in 1990 to 136 TWh in 1999. At the beginning of the century coal again became a more important energy source and in 2004 158 TWh of electricity were generated by soft coal power plants. After a period of a decreasing contribution soft coal filled the supply gap that came from the sudden shut-down of 6 nuclear power plants in 2011. Additionally soft coal profited from the price erosion of CO_2 certificates. This led to a comeback of soft coal resulting in a gross electricity production of 160.9 TWh in 2013. Thus, after the decision to close down nuclear power generation soft coal became the largest contributor to the German energy mix. This development has led to an ongoing political controversy, since it increases CO_2 emissions and Germany is likely to miss its Kyoto CO_2 reduction target.

2) Nuclear Energy: Nuclear energy had a fluctuating but rather stable contribution to the German electricity production. The sharp decrease from 160.4 TWh in 2006 to 140.5 TWh in 2007 can be mainly explained by technical problems of two plants (Brunsbüttel and Krümmel) as well as a plant being offline due to regulatory issues (Biblis A). The next considerable decrease from 140.6 TWh in 2010 to 108.0 TWh in 2011 can be explained by the political decision to close 6 of the 17 German nuclear plants after the nuclear disaster of Fukushima. Electricity generation from nuclear power will decline further and the last German nuclear plants will be shut down in 2022.

3) Hard Coal: Hard coal had a steady contribution to the German electricity production until 2007. In 2008 a sharp increase of the hard coal price led to a decreasing contribution of hard coal to the German energy mix. Therefore, the gross electricity production of hard coal decreased from 142.0 TWh in 2007 to 107.9 TWh in 2009. At this level the gross

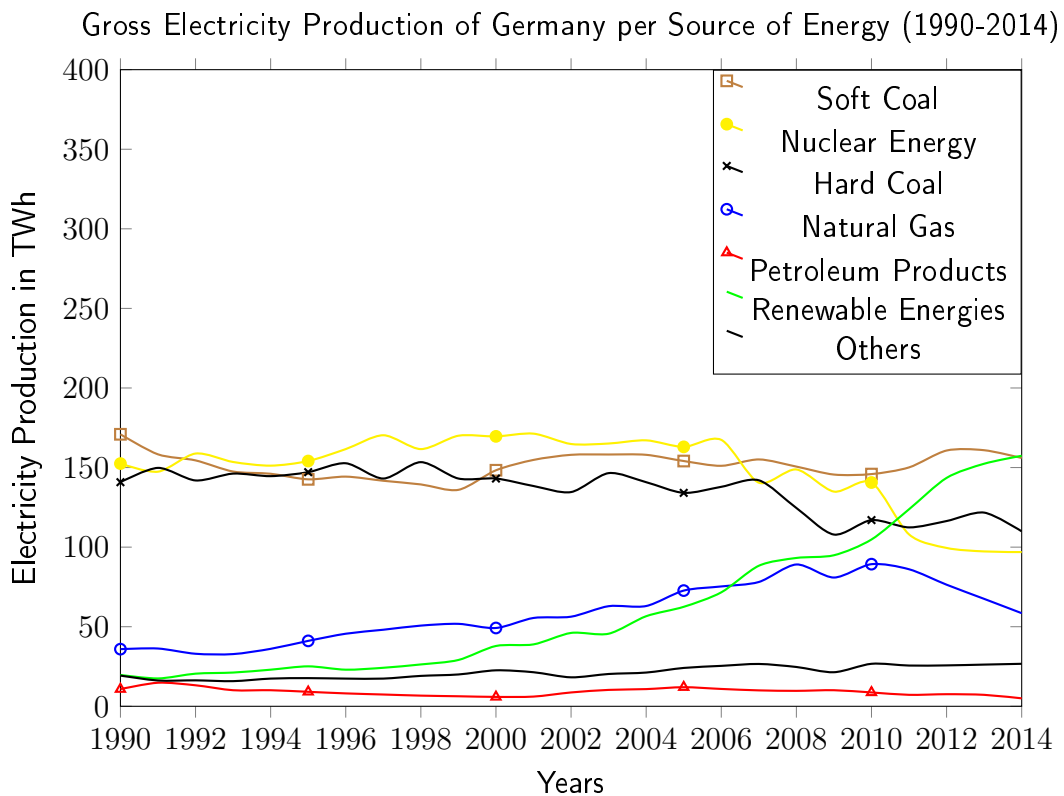


Figure 2.14: Gross Electricity Production of Germany per Source of Energy (1990-2014)

production of electricity generated by hard coal was stabilized and in 2014 109.9 TWh were contributed.

4) Natural Gas: Natural gas plants are seen as the perfect complement to fluctuating renewable energies due to their fast adaptability to the load profile. Therefore natural gas had a increasing contribution to the gross electricity production until 2008. In 2008 the price of CO_2 certificates dropped as a consequence of the world financial crisis. This price drop and an additional price drop in 2011 significantly decreased the price of coal power generation. Therefore, the large existing capacities of coal-based electricity generation are crowding out gas-based electricity generation at the moment.

5) Petroleum Products: Petroleum-based products have a small, but constant, contribution to the German electricity production of about 10 TWh. Petroleum products are mainly used in combined heat and power plants to generate electricity. However, electricity production from petroleum products does not play a significant role in the German energy mix and decreased from 14.8 TWh in 1991 to 5.0 TWh in 2014.

6) Renewable Energy Sources: Renewable energies have a rising contribution to the

German electricity production. In 1990 renewable energies had a very small contribution of only 19.7 TWh, coming completely from hydropower. In the following years the contribution of renewable energies grew constantly. In 2014 157.4 TWh of renewable energies were fed-in and renewable energies became the second largest contributor to the German energy mix. The increased contribution of renewable energy sources leads to an increased volatility of electricity supply, since electricity cannot easily be stored and especially feed-in of wind and solar power depends on stochastic weather conditions. Therefore in section 2.2 timely patterns and stochastic effects of renewable energies feed-in will be analyzed in a more detailed way.

Renewable Energy Sources used for Electricity Generation in Germany

In figure 2.15 renewable energies gross electricity production is decomposed into the several sources of energy for the years 1990 to 2013. This data was also published by *Energiebilanzen* (2014).

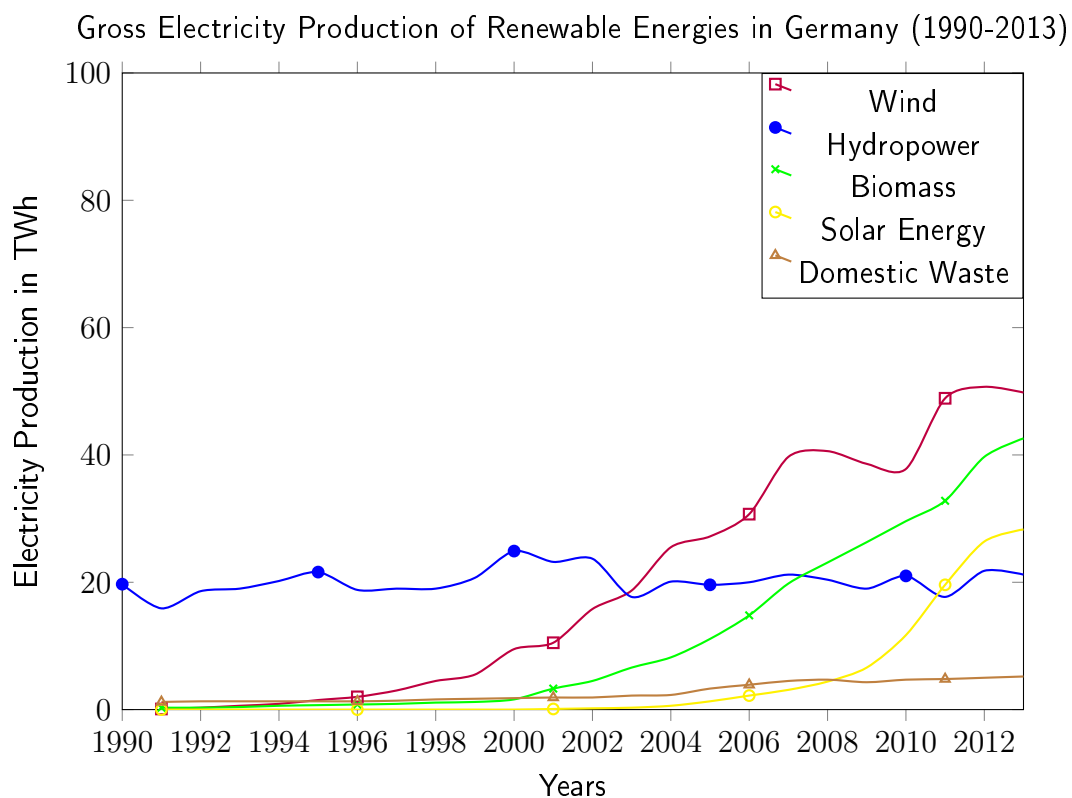


Figure 2.15: Gross Electricity Production of Renewable Energies in Germany (1990-2013)

1) Wind: For a long time wind had no significant contribution to the German electricity production. The "Stromeinspeisungsgesetz" that placed an obligation on the network operators to feed in all electricity from renewable energies entered into force in 1991. This law led only to a small increase from 0.1 TWh renewably-generated electricity in 1991 to 5.5 TWh in 1999, since a rather low compensation for supplying renewable energies had been fixed. In 2000 the "Erneuerbare-Energien-Gesetz (EEG)" passed the German Bundestag which fixed higher prices and differentiated between the renewable energy sources. In the following years an almost exponential increase occurred and in 2014 52.4 TWh of electricity were generated by wind power. Onshore wind generation clearly dominates the total wind generation, since offshore wind generation only contributed 0.9 TWh in 2014 and 1.2 TWh in 2014 to the annual wind-generated electricity. Wind has become the largest contributor to electricity generation of all renewable energies.

2) Hydropower: Hydropower benefited most from the "Stromeinspeisungsgesetz". However, this did not lead to a significant increase in electricity generation from hydropower, since most attractive locations for hydropower generation had already been used. Therefore, the "Stromeinspeisungsgesetz" led foremost to windfall profits for hydropower instead of an expansion of hydropower. This led to a rather constant electricity generation of hydropower of about 20 TWh per year with cyclical fluctuations.

3) Biomass: Until the "Erneuerbare-Energien-Gesetz" biomass had a rather small contribution to the German electricity generation, since e.g. in 1999 it only contributed 1.6 TWh to the German electricity production. In the following years an almost exponential increase occurred and in 2014 42.8 TWh electricity were generated by biomass. Biomass is the second-largest contributor to electricity generation of all renewable energies.

4) Solar Energy: Until the "Erneuerbare-Energien-Gesetz (EEG)" solar energy had no contribution to German electricity generation at all, since with the fixed price from the "Stromeinspeisungsgesetz" the costs of electricity generation by solar energy could not be covered. The feed-in tariff of the EEG supported electricity generation massively. It increased from 2000 to 2014 almost exponentially and in 2014 35.2 TWh electricity were generated by solar cells. Thus, solar energy is the third-largest contributor to electricity generation from renewable energies at the moment.

5) Domestic Waste: A rather small contribution to the gross electricity in Germany comes from domestic waste or more precisely from the biogenic proportion of domestic waste. The electricity is mainly generated by garbage incineration plants with power heat coupling. In 1991 1.2 TWh of electricity were generated by (the biogenic proportion) of domestic waste. The electricity generated by (the biogenic proportion) of domestic waste was increased to 6.1 TWh in 2014.

Estimation of Costs for Different Energy Sources

Table 2.7 presents estimated electricity generation costs and marginal costs for different energy sources. The data for estimated electricity generation costs is provided by Kost, Mayer, and Thomsen (2013), the data for estimated marginal costs is provided by Graichen (2014), and the rather complicated calculation for the electricity generation costs for a nuclear plant comes from Panos (2013).

For all conventional energy sources electricity generation from nuclear power has the lowest marginal costs (about 20 €/MWh or 0.02 €/KWh). However, even without full internalization of all external costs the total cost of electricity production is estimated by Panos (2013) for a newly-built nuclear power plant by 74€/MWh or 0.074 €/KWh. However, it is reasonable that for the existing nuclear power plants in Germany total electricity generation are considerably lower, since e.g. the capital service, which is the largest cost block of the estimated electricity generation costs (about 67%), has already been done.

Power plants operated by soft coal have marginal costs comparable to nuclear power plants (about 20 €/MWh or 0.02 €/KWh). These marginal costs mainly depend on coal prices as well as prices for CO_2 certificates and therefore are at the moment on a rather low level. Total generation costs are estimated to be between 38 €/MWh and 53 €/MWh. Power plants operated by hard coal have higher marginal costs than power plants operated by soft coal, since hard coal is a more expensive fuel and this price difference is not compensated by the reduced costs of CO_2 emission rights at the moment. Total generation costs are estimated to be between 63 €/MWh and 80 €/MWh. The highest marginal and total costs of conventional electricity generation can be made out for power plants operated with natural gas. The cost structure of a natural gas plant is mainly determined by

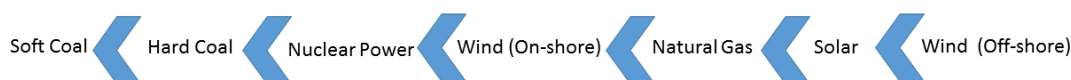
Energy Source	Estimated Total Generation Costs (TGC)	Estimated Marginal Costs (MC)
Nuclear Power	74 €/MWh	20 €/MWh
Soft coal	38 to 53 €/MWh	18 to 21 €/MWh
Hard Coal	63 to 80 €/MWh	35 to 41 €/MWh
Natural Gas	75 to 98 €/MWh	53 to 65 €/MWh
Solar (South)	98 to 121 €/MWh	0 €/MWh
Solar (North)	115 to 142 €/MWh	0 €/MWh
Wind (On-shore)	45 to 107 €/MWh	0 €/MWh
Wind (Off-shore)	119 to 194 €/MWh	0 €/MWh

Table 2.7: Cost of Electricity Production for Different Energy Sources

fuel costs and marginal costs are estimated to be between 53 €/MWh and 65 €/MWh. Investment costs are comparatively low and total costs of electricity production are estimated to be between 75 €/MWh and 98€/MWh.

For wind and solar energy, marginal costs are very close to zero, since solely additional abrasion, depreciation and maintenance charges that can be directly linked to (additional) energy generation could be taken into account. However, normally these costs can be neglected. In Germany on-shore wind generation is the cheapest renewable energy source and it is at least in windy locations competitive with hard coal, since its total costs of electricity generation are estimated to be between 45 €/MWh and 107€/MWh. Solar energy in southern Germany is estimated to have total electricity generation costs of between 98€/MWh and 121€/MWh, whereas for northern Germany costs of solar electricity generation are estimated to be between 115 €/MWh and 142€/MWh. At the moment the most expensive way to generate electricity is given by using off-shore wind, since total generation costs of off-shore wind power plants are estimated to be between 119 €/MWh and 194 €/MWh. They are roughly twice as high as on-shore total generation costs.

Order of Total Generation Costs for Different Energy Sources



Order of Marginal Generation Costs for Different Energy Sources



Figure 2.16: General Order of Costs for Different Energy Sources

Figure 2.16 summarizes the analysis of generation costs for different energy sources graphically. Therefore it presents the ascending order of total generation costs (TGC) and marginal generation costs (MC). The lowest TGC is associated with electricity generation from soft coal. It is followed by electricity generation from hard coal, nuclear power, wind energy (on-shore), natural gas, solar energy and wind energy (off-shore). The lowest MC can be found for wind and solar energy, since they are very close to zero. It is followed by nuclear power, soft coal, hard coal and natural gas.

Figure 2.17 shows an estimation for the merit order curve of electricity generation in

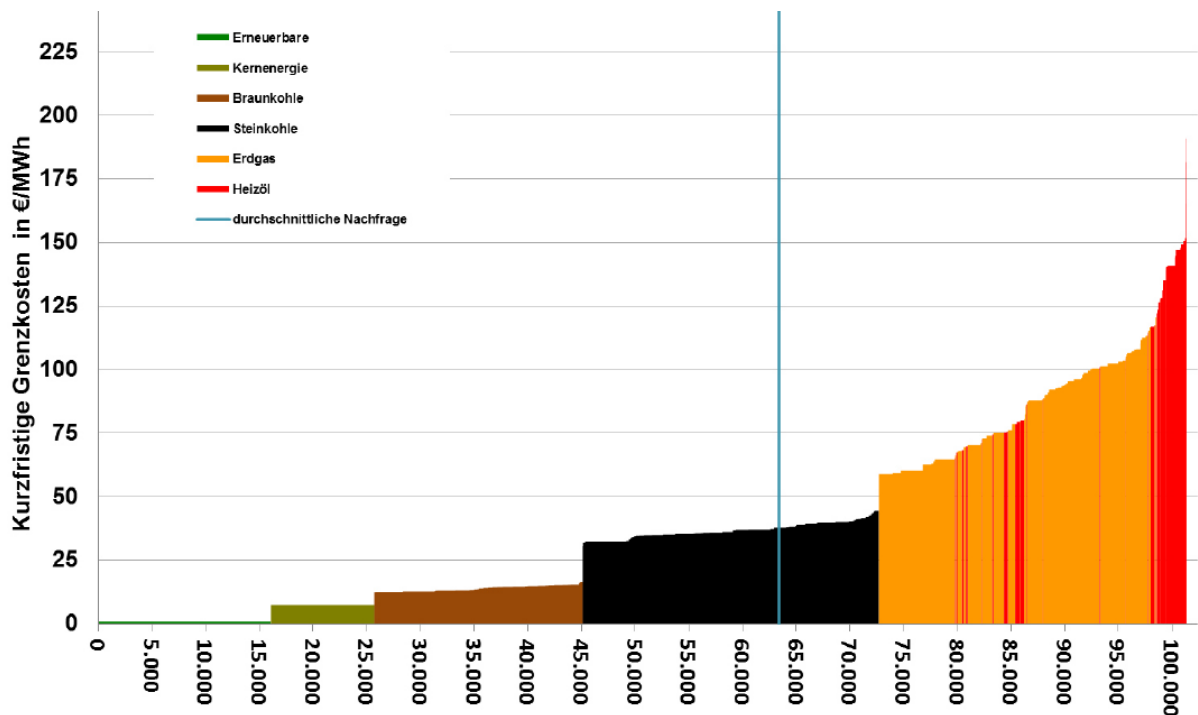


Figure 2.17: Merit Order Curve of Electricity Generation in Germany

Germany, that has been calculated by Haller, Hermann, and Loreck (2013, p.45). The merit order curve is very important for the electricity market. It determines the wholesale market price. All power plants, which are able to cover their marginal costs, will generate electricity. The marginal costs of the last power plant, that is necessary to meet current demand, sets the price for all market participants. Figure 2.17 illustrates the convex shape of marginal costs of electricity production in Germany. There are two main drivers for this convexity. The most obvious driver is given by the different marginal costs of different energy sources. Thus, electricity is generated in following order to meet demand: Firstly by renewable energies, secondly by nuclear power plants, thirdly by soft coal, fourthly by hard coal and fifthly by natural gas. Another driver for the convexity is, that power plants have to some extent different marginal costs when using the same energy sources. This can be explained by constructional differences or age differences of the German power plants.

It should be noticed, that Haller, Hermann, and Loreck (2013) assume a price for CO_2 certificates of 3 euros per ton, which is rather low. Thus, prices for electricity generated by brown coal are rather low, since their financial compensations for their rather large CO_2 emissions are (assumed to be) low. If the price for CO_2 certificates was (assumed

to be) higher, two main effects could be identified. Firstly, generation becomes more expensive for all energy sources that emit CO_2 . Secondly, the differences in marginal costs between power plants using soft coal, hard coal and natural gas decrease, since the higher fuel costs of hard coal or natural gas are compensated by higher savings for CO_2 certificates. Thus, *ceteris paribus* a higher (lower) price for CO_2 certificates leads to a more flat (more steep) merit order curve. It should be noticed additionally that Haller, Hermann, and Loreck (2013) estimate the marginal costs of nuclear power plants lower than Graichen (2014).

Perhaps from a cost perspective the integration of the renewable energy sources into the German grid seems to be a solvable task. However, the lack of dispatchability, which means that especially for renewable energy sources it is scarcely possible to increase and/or decrease their generation quickly, leads to severe problems for the German electricity grid.

Estimation of Profitable Feed-in of Different Energy Sources in 2013

Energy Source	$P_{Day-Ahead} > TGC$		$P_{Day-Ahead} > MC$	
	In Percent	Hours	In Percent	Hours
Nuclear Power	1.5 %	135 h	87.7 %	7683 h
Soft coal	37.9 %	3322 h	87.7 %	7683 h
Hard Coal	6.7 %	413 h	53.6 %	4697 h
Natural Gas	1.5 %	135 h	15.3 %	1339 h
Solar (South)	0 %	0 h	99.3 %	8695 h
Solar (North)	0 %	0 h	99.3 %	8695 h
Wind (On-shore)	28.7 %	2507 h	99.3 %	8695 h
Wind (Offshore)	0 %	0 h	99.3 %	8695 h

Table 2.8: Estimation of Profitable Feed-in of Different Energy Sources in 2013

Table 2.8 gives my own estimation for the (proportional) time in 2013, at which the day-ahead spot price exceeded the cost of electricity generation based on total electricity generation costs and marginal electricity generation costs. This estimation is found by combining the distribution of the 2013 EPEX SPOT day-ahead spot prices, which is illustrated in figure 2.10 with the cost estimates that have been presented in table 2.7.

For this purpose the second column with the headline $P_{Day-Ahead} > TGC$ presents my

own estimation for the proportional time (in %) as well as for the trading hours (Hours) in 2013, when estimated total electricity generation costs for a certain energy source were below the EPEX SPOT day-ahead spot price. The third column of table 2.7 with the headline $P_{Day-Ahead} > MC$ gives my own estimation for the proportional time (In Percent) as well as for the trading hours (Hours) in 2013, at which the day-ahead spot price exceeded the estimated marginal costs of electricity generation for a certain energy source.

This is done by summing up all histogram classes of the EPEX SPOT day-ahead spot price that strictly exceed the lower bound of estimated electricity generation costs or the lower bound of estimated marginal electricity generation costs respectively. For instance, a nuclear power plant may have estimated total generation costs of 74€/MWh. Therefore, the first class of the spot price histogram that exceeds 74€/MWh is the class between 75€/MWh and 80€/MWh. Summing up the class frequencies of all classes exceeding 75€/MWh leads to a frequency of 1.5%. This means, that nuclear plants could only finance their estimated total electricity generation costs in 1.5% of all cases or about 131h in 2013 (1.5% of 24 hours times 365 days). However, for the existing nuclear power plants it is reasonable that they could cover their total costs more often, since Panos (2013) estimated total costs for a nuclear power plant that is built nowadays. For instance for existing nuclear power plants most of the capital service, which is the largest cost block of the estimated electricity generation costs (about 67%), has already been done. Therefore, the total profitability for existing nuclear power plants seems to be much higher. For the short-run market outcome marginal electricity costs are more important, since the decision whether to generate electricity or not depends foremost on the marginal costs of each power plant. The marginal costs of electricity generated by nuclear plants are about 20€/MWh and are rather low. Therefore, nuclear plants generated positive contribution margins in about 88.6 % of trading blocks or in approximately 7762 hours of the 8760 hours in 2013.

Soft coal power plants have lower fix costs than nuclear power plants. This leads to total cost of electricity generation of between 38€/MWh and 53€/MWh. Therefore, total electricity generation costs were covered for soft coal plants in 37.9 % of the trading blocks or in 3322h in 2013. The marginal costs of a soft coal plant of 20€/MWh are approximately the same ones as for nuclear power plants. Therefore, soft coal plants

generated positive contribution margins also in about 88.6 % of trading blocks or in approximately 7762 hours of the 8760 hours in 2013, too.

Hard coal plants have, due to their technology, higher investment costs than soft coal plants. Additionally the fuel costs of hard coal are higher than that of soft coal, but there is lower CO_2 emission. At the moment the costs of lower CO_2 emissions do not compensate the higher investment and fuel cost, due to the rather low price of CO_2 certificates. In 2013 the EPEX SPOT day-ahead spot price exceeded total generation costs of hard coal plants only in 6.7 % of the trading blocks or 413 hours. Positive contribution margins were generated in 53.6 % of trading blocks or in 4697 hours by hard coal plants.

Natural gas plants are often seen as the perfect complement of renewable energies, since they can easily be dispatched. However, they have severe problems to cover their costs at the moment. Total generation costs have only been covered in 1.5 % of the trading blocks or 135 hours. Marginal costs of electricity production have been covered in 15.3 % of the trading blocks or in 1339 hours respectively.

For electricity generation by wind and solar power marginal costs are very close to zero. Therefore, even without the subsidies of the feed-in tariff electricity generation would lead to positive contribution margins as long as the EPEX SPOT price is not negative. This has been the case in 99.3 % of the trading blocks or in 8695 hours respectively. On-shore wind generation is the only one, that would be able to cover its total electricity costs in 2013 for 29.7 % of the trading blocks and 2507 hours. However, as for wind and solar electricity generation there exists a guaranteed and fixed premium per MWh they do not have to cover total or marginal costs by day-ahead spot market prices. Therefore, all electricity from solar and wind generation is fed into the German grid irrespective of the spot market price.

It can be summarized that for most trading hours the day-ahead spot price is high enough to cover the marginal costs for most sources of electricity generation. Only plants generating electricity from hard coal or gas have problems to cover their marginal costs, since for hard coal in 46.4% and for natural gas in 84.7% of trading blocks the day-ahead spot price is below their estimated marginal costs. However, except for soft coal plants the day-ahead spot market price is not sufficient to cover total production costs. This effect can mainly be attributed to the capacities of renewable energies that entered into

the market. This has led to excess generation capacities in the German market, since the conventional capacities, which could satisfy German electricity demand event without renewable energies, are still present. Due to the fixed feed-in tariff for every MWh of renewably-generated electricity, renewable energies do not have the pressure to finance their total costs on the spot market, but they decrease the electricity demand that has to be met by conventional energy sources. Therefore, conventional power plants have problems to cover their total electricity generation costs. However, this effect cannot easily be taken as an argument for high competitiveness, since the exogenous shock of additional renewable capacities could as well lead to a spot market price even closer to marginal costs. Therefore, the high concentration on the wholesale market still raises the question whether strategic interaction between the big suppliers leads to price increasing and competition softening effects.

German Electricity Exports and Imports

The problems associated with the lack of dispatchability are partly "solved" by electricity imports and exports. German electricity net-exports and net-imports are illustrated in figure 2.18. Data is provided by the German Federal Ministry of Economic Affairs and Energy (BMWi, 2014b).

From 1990 to 2002 annually about 40 TWh of electricity were exported and imported and the net export of electricity was rather small. The expansion of renewable energy sources led to an increase in electricity net export since 2002. This development remained even when 6 nuclear power plants were shut down in 2011. Therefore, one might argue that the shut-down of conventional capacities is more than compensated by renewable energies and everything is fine. However, a more detailed analysis of the German exports with each bordering country is necessary, to get the complete picture.

For this purpose figure 2.19 illustrates the exported and imported electricity production of Germany and its bordering countries for 2013 (Energiebilanzen, 2014). Analyzing the decomposed export and import data the increase of net exported electricity can be mainly explained as follows: The expansion of renewable capacities came on top of the existing power generating capacities. In times of high wind or solar feed-in and a rather low demand the German electricity grid cannot absorb all of this power due to rather inflexible

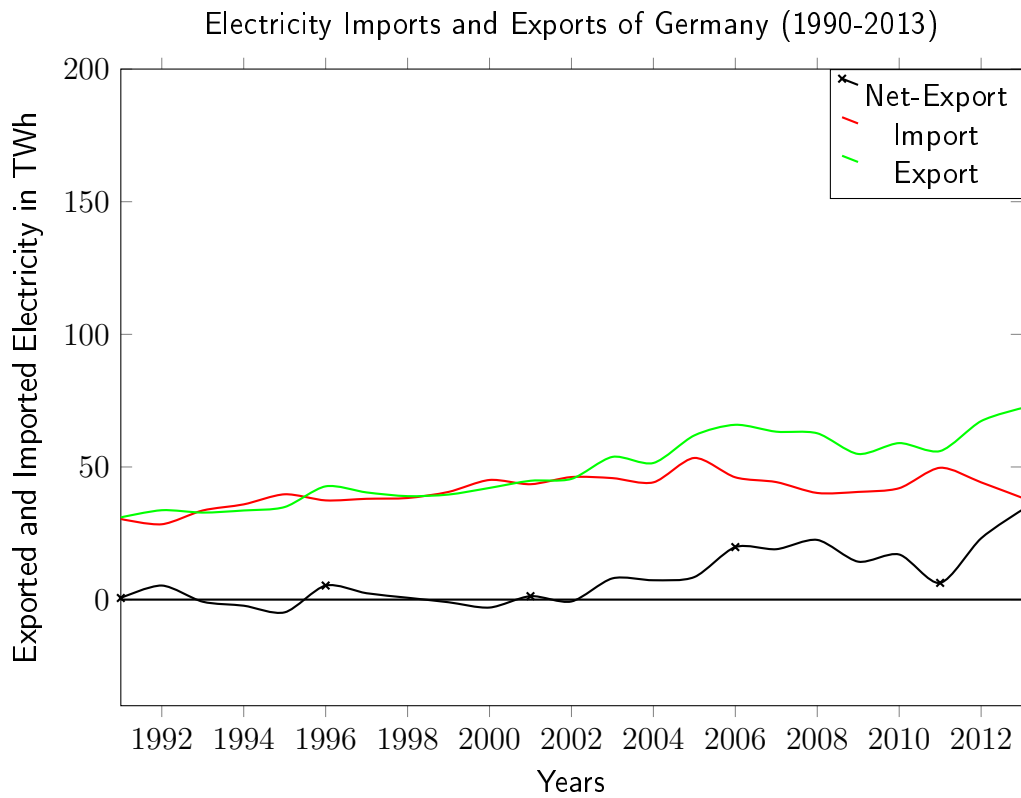


Figure 2.18: Electricity Imports and Exports of Germany(1990-2013)

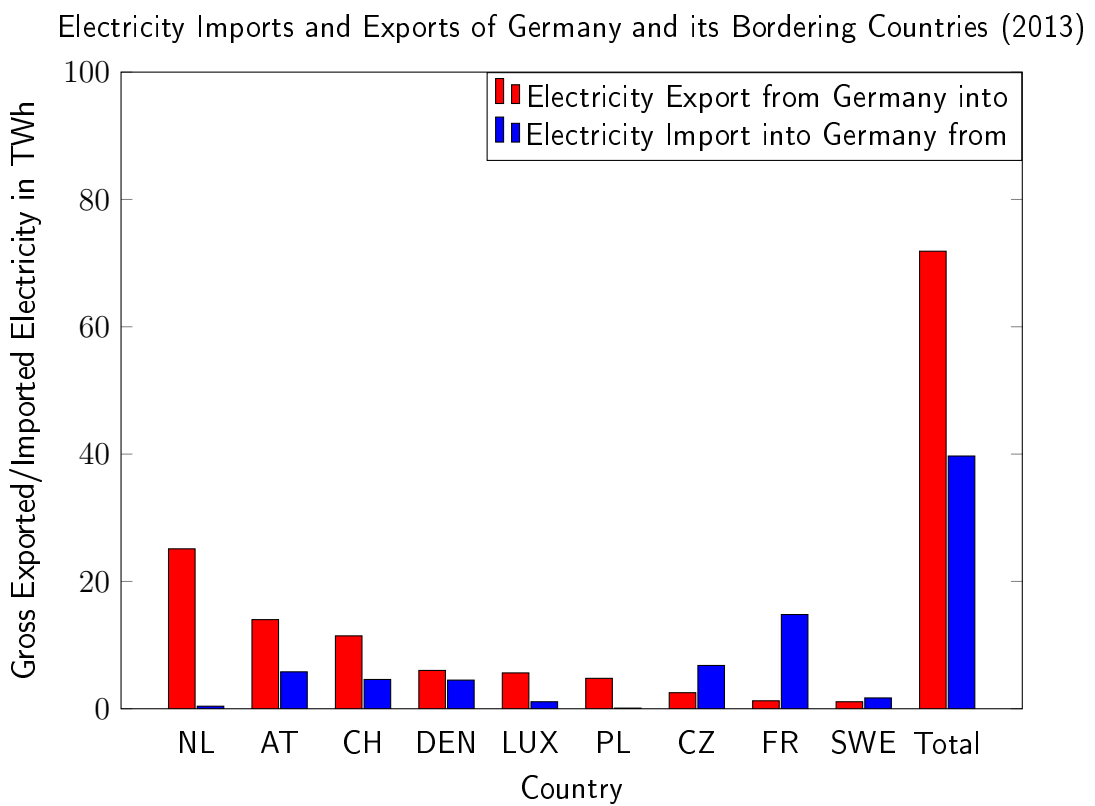


Figure 2.19: Electricity Imports and Exports of Germany and its bordering countries (2013)

nuclear and coal power plants. Therefore, electricity has to be exported for example to the Netherlands. In the Netherlands an important source of electricity are gas plants, which can be immediately shut down. Austria and Switzerland are other attractive countries for electricity exports, since they have a lot of pump storage hydro power stations, which can use the power to fill their upper reservoirs. Therefore, the Netherlands, Switzerland, and Austria can absorb a lot of the German voltage peaks.

The electricity imports of Germany mainly come from France and Czechia, where nuclear plants and coal plants (Czechia) deliver reliable electricity at low marginal costs. When electricity generation is not sufficient to meet demand in Germany, their nuclear and coal plants firstly step in due to the low marginal costs (merit-order-effect). In conclusion it can be stated that Germany exports parts of the non-dispatchable electricity mainly from subsidized renewable energy sources but imports rather cheap load coming from conventional power plants, which in total leads to a net-export of electricity. In section 2.2 the direct effect of renewable energy feed-in on German electricity exports and imports is analyzed more deeply.

In a nutshell the actual German energy mix can be characterized as follows: It is mainly based on soft coal, renewable energy sources and nuclear power. The energy mix of renewable energies is mainly based on wind power, solar power and biomass. This leads to a volatile supply of electricity, since except for biomass all of the mainly used energy sources cannot be easily dispatched, and additionally the feed-in of solar power and wind power depends on (stochastic) weather conditions. Problems for the energy grid associated with this actual energy mix are partly "solved" by electricity exports and imports.

2.2 Electricity Supply from Renewable Energies

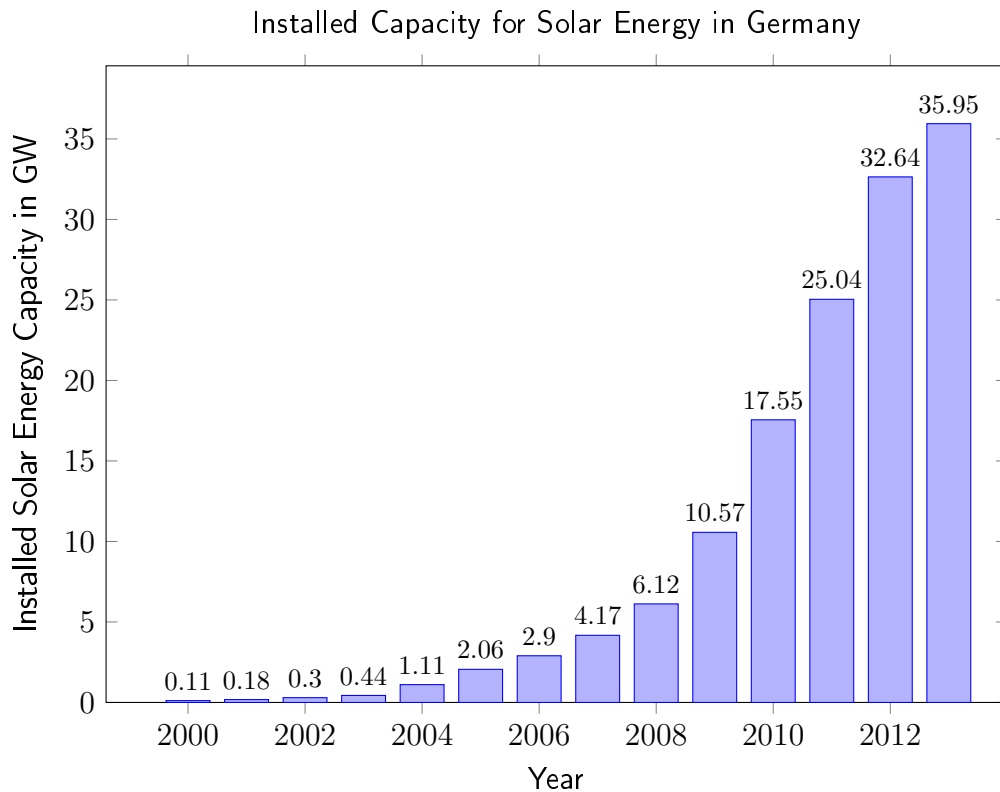


Figure 2.20: Installed Capacity for Solar Energy in Germany

There has been an enormous political will to increase electricity generation by renewable energies. Therefore in the year 2002 the German Bundestag passed the "Erneuerbare Energien Gesetz" (EEG) to increase the feed-in of electricity generated by solar and wind energy. The main policy instrument is given by a constant price for electricity from renewable energies that are fed into the German grid. Whenever the wholesale market price is below this a priori fixed price, the so-called EEG apportionment compensates for the price difference. To cover costs associated with EEG apportionment a charge on the end-consumer price for electricity is set conjointly by all four Transmission System Operators for each year.

This highly significant effect of the EEG can be seen by looking at the installed capacity for electricity generation by renewable energy sources. Figure 2.20 illustrates the exponential growth of capacity for electricity generated by solar energy from the year 2000 to 2013. Figure 2.21 illustrates the linear but nevertheless enormous growth of capacity for electricity generated by wind energy from the year 2000 to 2013. However,

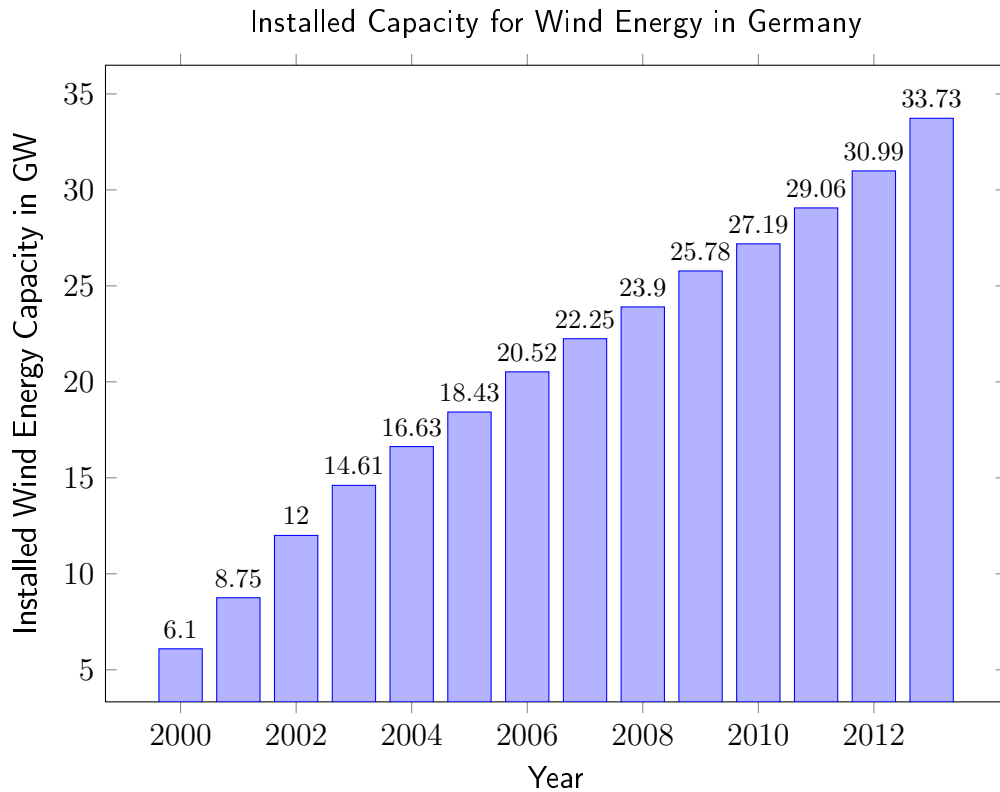


Figure 2.21: Installed Capacity for Wind Energy in Germany

for the electricity market the generated electricity not the installed capacity is of relevance, since electricity and not capacity is traded. At night or on cloudy days no electricity can be generated by solar energy, whereas on a windless day no electricity can be generated by wind energy. Even on windy days the total wind capacity cannot be exploited, since this would mean that each wind mill in Germany is exactly exposed to the maximum wind stream it is designed for, and even on a sunny day total solar capacity can hardly be exploited. Therefore, the capacity gives - if at all - only an approximation of the electricity generated by solar or wind energy.

The enormous difference between capacity for solar energy and electricity generation can be seen, when calculating the theoretically extractable electricity from solar and wind energy. If the total of all the installed solar energy capacity of 35.948 GW in 2013 had been used for electricity generation 24 hours and 365 days, 314,9 TWh electricity could have been generated by solar energy ($35.948 \text{ GW} \times 24\text{h} \times 365 = 314904.48 \text{ GWh}$). This would be more than half of the total German electricity generation in 2013, given by 633.2TWh. However, only 31.00 TWh of electricity were generated by solar energy. If

analogously all the installed wind energy capacity of 33.730 GW in 2013 had been used for electricity generation 24 hours and 365 days, 295.47 TWh electricity could have been generated by wind energy ($33.730 \text{ GW} \times 24\text{h} \times 365 = 295474.8 \text{ GWh}$). This would be a bit less than half of the total German electricity generation in 2013, given by 633.2TWh. Even though the installed wind capacity is below installed capacity for solar energy wind accounts for 51.7 TWh of electricity in 2013.

Large capacities for electricity generation depending on weather conditions lead to volatile conditions for all market participants. The following pages are dedicated to a detailed analysis of fluctuations of renewable energy supply. To increase market transparency Transmission System Operators are obliged to publish a day-ahead forecast for electricity generated by wind and solar energy. These forecasts are available on the homepage for market transparency of the EEX (www.eex-transparency.com) and are provided for the transmission zones of each operator on a daily basis. In order to analyze the feed-in of renewable energies in Germany data for day-ahead forecast and actually feed-in of wind and solar energy into the grid of each Transmission System operator is used. All this data is integrated within one large data file.

2.2.1 Feed-in of Solar Power

In order to give an overview of the extent of volatility coming from solar energy, the histogram of the day-ahead forecast of electricity generated by solar energy in 2013, the week profile of the day-ahead forecast, the histogram of the electricity actually generated by solar energy, the week profile of the electricity actually generated by solar energy, and a histogram of the forecast error of day-ahead forecast errors are presented.

Day-Ahead-Forecast of Solar Energy Feed-in

In figure 2.22 a histogram with a range of 1 GW, an exponential distribution with the mean solar feed-in of 5.8963 GW is plotted. Whenever day-ahead forecast of solar feed-in as well as the realized solar feed-in is zero, the observation is skipped, since then observation (most likely) refers to night and is consequently not stochastic. The parameter of the exponential distribution (λ_e), that describes its expectation as well as its standard deviation

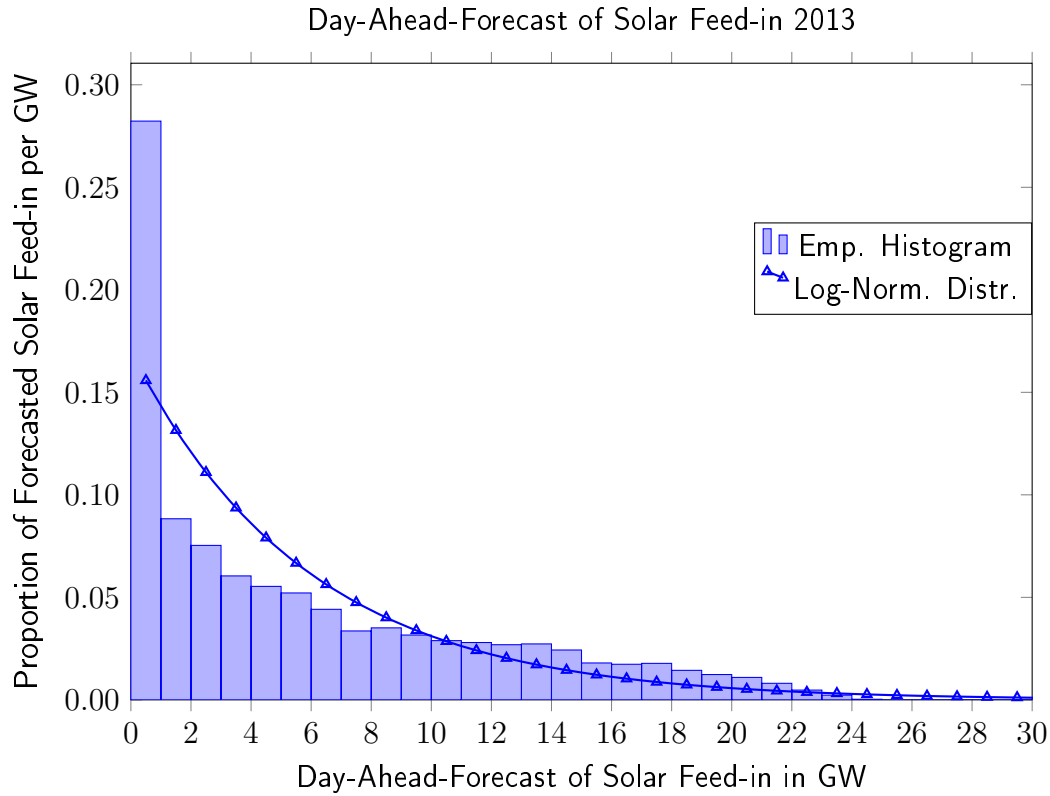


Figure 2.22: Histogram of Day-Ahead-Forecast of Solar Feed-in 2013

($\lambda_e = \frac{1}{E(x)} = \frac{1}{\sqrt{Var(x)}}$), is found by equalizing the expectation of the distribution and the empirical mean of solar energy feed-in in 2013.

$$f(x) = \lambda_e e^{-\lambda_e x}, \quad \forall x \geq 0, f(x) = 0 \quad \forall x < 0$$

$$\lambda_e = \frac{1}{E(x)} = \frac{1}{5.8963} = 0.17 \quad (2.1)$$

At a first glance one can see, that an exponential distribution fits the feed-in data of solar power quite well. Choosing the scale parameter to match average solar power feed-in, a value of 0.17 is found for the scale parameter λ_e . Taking this value to calculate the corresponding variance, a value for the variance of 34.77 ($Var(x) = \frac{1}{\lambda_e^2} = \frac{1}{0.17^2} = 34.7663$) can be found. This calculation shows, that the degree of dispersion is approximately the same for the exponential distribution and the original data set, since the variance of the fitted exponential distribution differs by only about 3% from the variance of the feed-in data ($\frac{34.7663}{35.8576} = 0.9696$). A log-normal distribution was fitted to the data, too. It is not shown in 2.22, since its fit was very poor.

In 28.23% of the cases the solar feed-in lies in the class between 0 GW and 1 GW. The

next class, which is between 1 GW and 2 GW, only accounts for 8.83% of the cases. For all upcoming histogram classes the percentage is constantly decreasing. The highest solar energy feed-in of 24.101 GW had been forecasted for the 21.07.2013 at 13:15hrs, which means that even at the highest peak of solar energy feed-in German capacity of 35,95 GW was only exploited for two-thirds ($\frac{24.101}{35.95} \Rightarrow 67\%$).

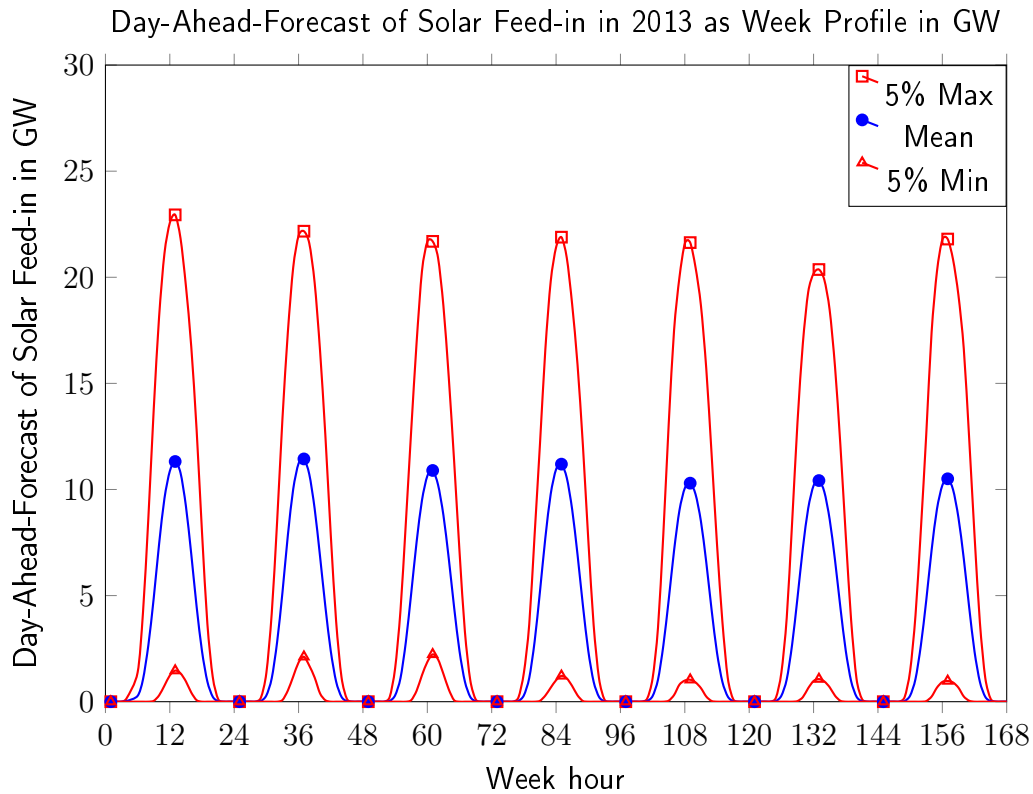


Figure 2.23: Forecasted Solar Feed-in in 2013 as Week Profile

Figure 2.23 shows the weekly pattern of solar energy feed-in in 2013. The red upper curve illustrates the threshold for the highest 5% of forecasted solar feed-in, the blue curve in the middle illustrates the mean forecasted solar feed-in and the red lower curve illustrates the threshold for the lowest 5% of forecasted solar feed-in. The x-axis represents the hour on a weekly basis, which means that for example hour 60 represents Wednesday 12 noon. The principal pattern for all three curves is very similar. Before sunrise, whose exact time depends on the season, no solar energy is fed in. From sunrise (between 6 hrs and 8 hrs) until noon (between 12 hrs and 13 hrs) the solar feed-in rises, afterwards it falls until sunset (between 18 hrs and 20hrs). Repetition of this daily pattern leads to the weekly pattern presented in figure 2.23. Interesting is the range of possible values, since

e.g on Monday noon in 90% of the cases a solar feed-in between 1.46 GW and 22.94 GW has been forecasted. This means that the mean forecasted solar feed-in of 11.31GW does not always provide a good approximation of forecasted solar feed-in. In 90% of the cases it could either be doubled (22.94 GW) or reduced to a tenth (1.46 GW). Thus, there is some volatility associated with the feed-in of solar energy. However, a clear pattern of solar feed-in exists and day-ahead forecasts are important for all market participants.

Realized Solar Energy Feed-in

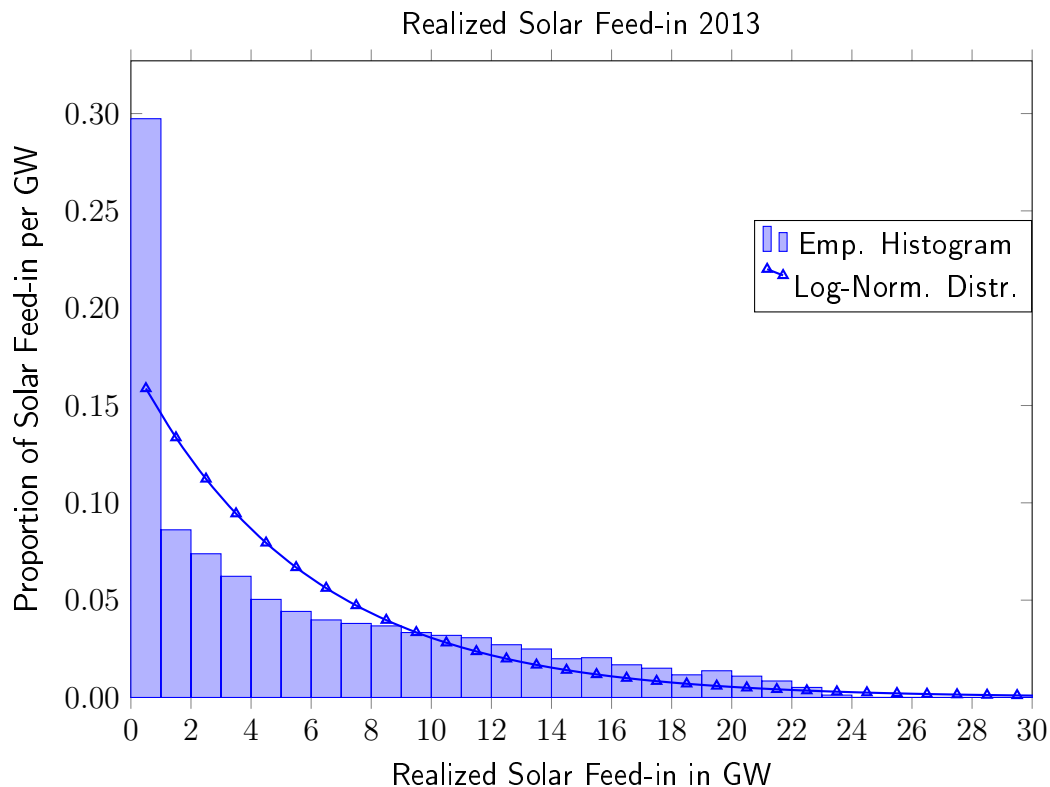


Figure 2.24: Histogram of Realized Solar Feed-in 2013

In figure 2.24 a histogram with a range of 1 GW, an exponential distribution with the mean realized solar feed-in of 5.77 GW ($\lambda_e = \frac{1}{5.77}$) is plotted. This histogram of realized solar feed-in (figure 2.24) is quite similar to the histogram for forecasted solar feed-in (figure 2.22), since in 29.74 % of the cases the solar feed-in lies in the class between 0 GW and 1 GW. The next class, which is between 1 GW and 2 GW, only accounts for 8.61 % of the cases. For all upcoming histogram classes the percentage is constantly decreasing (with the exception of the class between 19 GW and 20 GW). The highest solar energy feed-in of 24.00 GW was realized on 21.07.2013 at 13:30hrs.

Figure 2.25 shows the weekly pattern of solar energy feed-in in 2013. Again, the red upper curve illustrates the threshold for the highest 5% of the realized solar feed-in, the blue curve in the middle illustrates the mean realized solar feed-in and the red lower curve illustrates the threshold for the lowest 5% of realized solar feed-in. The x-axis represents the hour on a weekly basis, which means that, for example, hour 60 represents Wednesday 12 noon. The principal pattern for all three curves again is very similar. Before sunrise, whose exact time depends on the season, no solar energy is fed in. From sunrise (between 6 hrs and 8 hrs) until noon (between 12 hrs and 13 hrs) the solar feed-in rises, afterwards it falls until sunset (between 18 hrs and 20hrs). Repetition of this daily pattern leads to the weekly pattern presented in figure 2.25. Interesting is the range of possible values, since e.g. on Monday noon in 90% of the cases a solar feed-in between 1.44 GW and 22.71 GW was realized. This means that the mean realized solar feed-in of 11.20 GW does not provide a good approximation of the realized solar feed-in, since in 90% of the cases it is either doubled (22.72 GW) or almost reduced to a tenth (1.44 GW). Thus, there is a high volatility associated with the feed-in of solar energy even if in general a clear pattern of solar feed-in exists.

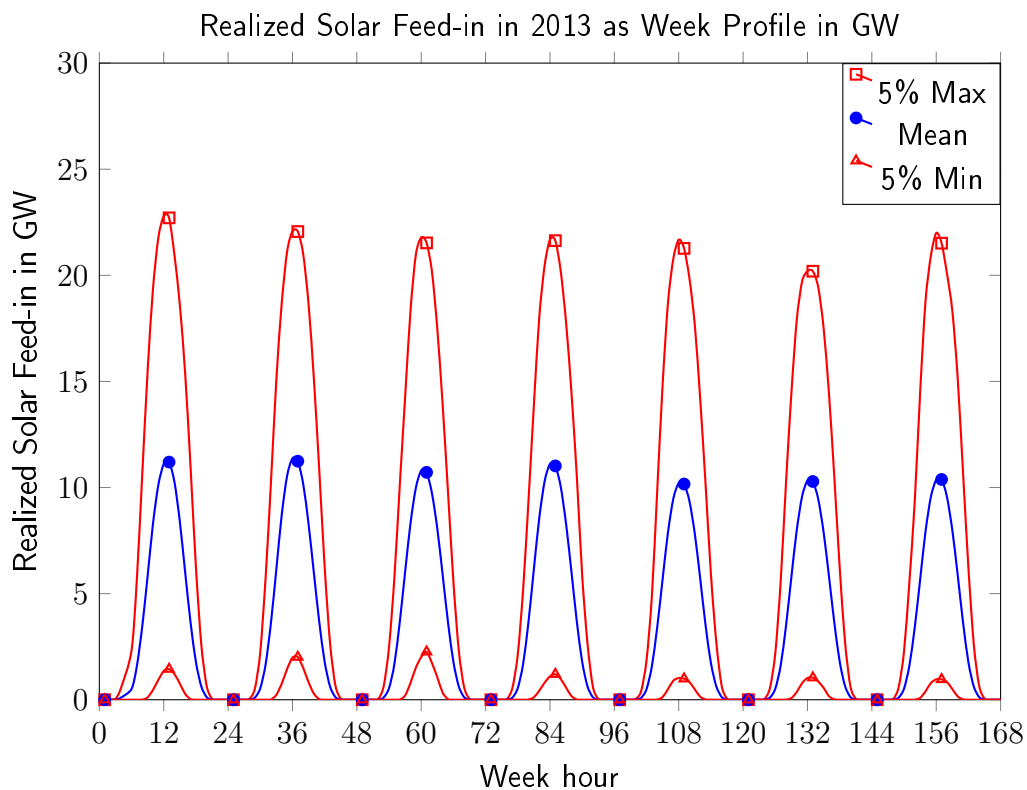


Figure 2.25: Realized Solar Feed-in in 2013 as Week Profile

Forecasting Quality

Comparing the histogram and the week profile for realized and forecasted solar feed-in there seems to be no big difference between both. However, when directly comparing day-ahead forecasted and realized solar feed-in, one can see that even for the short length of one day, larger differences between both do exist.

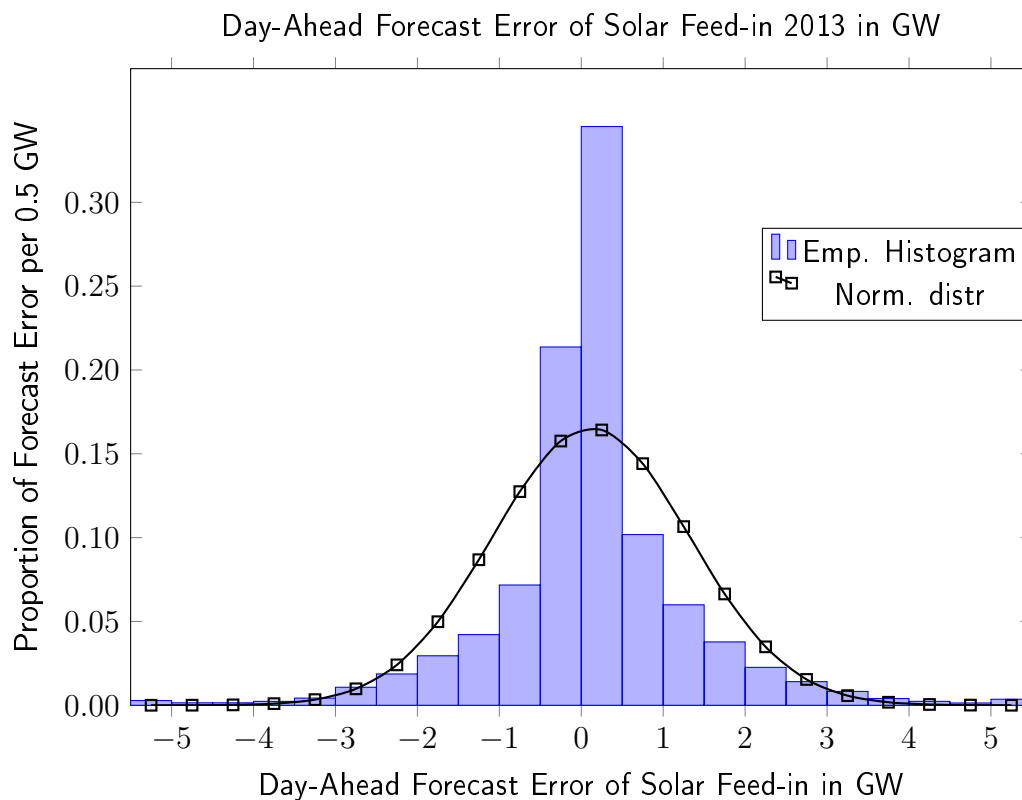


Figure 2.26: Day-Ahead Forecast Error of Solar Feed-in 2013

Figure 2.26 presents a histogram of the difference between the day-ahead forecast and the realized solar feed-in in 2013. Positive values are associated with electricity from solar energy that was forecasted but not realized. Negative values are associated with electricity from solar energy that was realized but not forecasted. Additionally, a normal distribution with the mean day-ahead forecast error of 0.12 GW and the standard deviation of the day-ahead forecast of 1.21 GW is plotted and a class size of 0.5 GW is chosen. In principle the day-ahead forecast estimates the solar feed-in quite well, since in 56% of the cases the day-ahead forecast is, according to amount, below 0.5 GW. This good forecasting quality leads to a more leptokurtic shape than a normal distribution would suggest. However, in few cases forecast errors that are according to amount larger than 3 GW can occur.

2.2.2 Feed-in of Wind Power

The scope of the next pages is to find a suitable distribution for wind energy feed-in. This is done by firstly looking at the physical process of converting kinetic energy from wind into electricity. This process can be found in engineers standard reference works such as Hau (2014). Therefore the next pages give a short summary how to derive, for a certain windmill, the electrical power that can be extracted from the wind. Using the resulting formula for power generation my own calculations to find a stochastic distribution for wind energy supply will follow. Then the empirical histogram of wind energy supply in 2013 is compared to a log normal distribution, a Weibull distribution and the wind energy distribution that has been derived before. The presented overview on the energy supply of a wind converter mainly refers to the standard engineer reference work of Hau (2014).

Physical Background of Wind Power

The kinetic energy of a certain air mass (m), that moves with a steady speed (v), is given by:

$$E_{wind} = \frac{1}{2}mv^2 \quad \left(W = \frac{kg \ m^2}{s^2} \right) \quad (2.2)$$

The volume (V) which passes a certain cross sectional area with a steady velocity (v) per unit of time is called volume stream (\dot{V}). This volume stream is given by the velocity of the air multiplied by the cross sectional area (A),

$$\dot{V} = vA \quad \left(\frac{m^3}{s} \right) \quad (2.3)$$

The mass (m) which passes a certain cross sectional area with a steady velocity v per unit of time is called mass stream (\dot{m}). This mass stream is given by multiplying the volume stream with the density of air (ρ)

$$\dot{m} = \rho vA \quad \left(\frac{kg}{s} \right) \quad (2.4)$$

With the general formula of kinetic energy and the mass stream (\dot{m}) one can calculate the kinetic energy that passes the cross sectional area per unit of time, which physically is equivalent to the power of the wind stream (P_{wind}).

Note: The velocity is assumed to be constant and therefore to be independent of time.

$$P_{wind} = \frac{\partial E_{wind}}{\partial t} = \frac{1}{2} \dot{m} v^2 = \frac{1}{2} \rho A v^3 \quad \left(W = \frac{kg \ m^2}{s^2} \right) \quad (2.5)$$

The kinetic energy that passes the cross sectional area per unit of time ($P_{wind} = \frac{\partial E_{wind}}{\partial t}$) gives a good starting point. However, the aim is to calculate the power that can be extracted by the energy converter (in our case a wind mill). Extracting mechanical power necessarily reduces the kinetic energy that is contained by the stream of wind, which leads to a reduction of the wind velocity behind the energy converter. For a constant mass stream this leads to an expansion of the cross sectional area. To find the extractable power, the state in front of the converter should be compared to the state behind the converter. The mechanical power that the converter extracts from the mass stream is equal to the difference of the power that the air stream contains in front and behind the converter. The wind velocity in front of the converter is denoted by v_1 , whereas the wind velocity behind the converter is denoted by v_2 . The cross sectional area that is passed by the wind stream in front of the converter is denoted by A_1 , and the cross sectional area that is passed by the wind stream behind the converter is denoted by A_2 . This leads to:

$$P_1 = \frac{1}{2} \rho A_1 v_1^3 - \frac{1}{2} \rho A_2 v_2^3 = \frac{1}{2} \rho (A_1 v_1^3 - A_2 v_2^3) \quad (W) \quad (2.6)$$

The mass stream cannot change. Therefore,

$$\rho v_1 A_1 \stackrel{!}{=} \rho v_2 A_2 \quad \left(\frac{kg}{s} \right) \quad (2.7)$$

Using this relationship leads to following expression for the mechanical energy that can be extracted by the converter:

$$\begin{aligned} P_1 &= \frac{1}{2} \rho (A_1 v_1 v_1^2 - A_1 v_1 v_2^2) && (W) \\ &= \frac{1}{2} \rho A_1 v_1 (v_1^2 - v_2^2) && (W) \\ &= \frac{1}{2} \dot{m} (v_1^2 - v_2^2) && (W) \end{aligned} \quad (2.8)$$

This relationship leads to the conclusion that from a theoretical point of view the extracted power is maximized when the air stream is totally decelerated, since then the speed behind the converter equals zero ($v_2 = 0$). However, from a physical point of view this cannot

be the solution. When the wind speed behind the converter is zero the speed in front of the converter has to be zero, too, and as a consequence there would be no stream at all. Thus, the search is for the relationship between the velocity in front (v_1) and behind the converter (v_2) that maximizes the extractable power.

There exists another way to derive the mechanical power of the converter. The force that is exerted by the wind to the converter can be found by the conservation of momentum.

$$T = \dot{m}_1 v_1 - \dot{m}_2 v_2 = \dot{m}(v_1 - v_2) \quad \left(N = \frac{kg \ m}{s^2} \right) \quad (2.9)$$

It can be said that this force, more specifically this thrust, moves the volume of air with the velocity, which appears in the stream level of the converter (v'). The power that is needed for this (P_2) can be calculated by multiplying the force that is exerted by the wind to the converter (equation 2.9) with the flow velocity at the converter (v').

$$P_2 = T v' = \dot{m}(v_1 - v_2)v' \quad \left(W = N \frac{m}{s} \right) \quad (2.10)$$

There are two ways of calculating the mechanical power that is extracted from the air stream. Firstly, by calculating the difference of the power in front and behind the converter. Secondly, by calculating the thrust and the flow velocity at the converter. In order to find a relationship between the flow velocity in front of the converter, through the converter, and behind the converter, both expressions for the extracted mechanical power are equalized:

$$\begin{aligned} P_1 &\stackrel{!}{=} P_2 && (W) \\ \frac{1}{2} \dot{m} (v_1^2 - v_2^2) &= \dot{m}(v_1 - v_2)v' && (W) \\ v' &= \frac{1}{2}(v_1 + v_2) && \left(\frac{m}{s} \right) \end{aligned} \quad (2.11)$$

Consequently, the flow velocity through the converter is given by the mean of the the velocity in front and behind the converter. The cross sectional area is given by A. Therefore the mass stream at the converter can be calculated as:

$$\dot{m} = \rho A v' = \frac{1}{2} \rho A (v_1 + v_2) \quad \left(\frac{kg}{s} \right) \quad (2.12)$$

The mechanical power really extracted by the converter can be stated as:

$$P_{Ext} = \frac{1}{2} \dot{m}(v_1^2 - v_2^2) = \frac{1}{4} \rho A (v_1 + v_2)(v_1^2 - v_2^2) \quad (W) \quad (2.13)$$

This real mechanical power extracted by the converter is compared to the power of the air stream when no mechanical power is extracted (P_{wind}). The coefficient of the mechanical power of the converter and the mechanical power of the air stream is called power coefficient (c_p) and is given by:

$$\begin{aligned} c_p &:= \frac{P_{ext}}{P_{wind}} = \frac{\frac{1}{4} \rho A (v_1 + v_2)(v_1^2 - v_2^2)}{\frac{1}{2} \rho A v^3} \quad (-) \\ &= \frac{1}{2} \frac{(v_1 + v_2)(v_1^2 - v_2^2)}{v_1^3} \quad (-) \end{aligned} \quad (2.14)$$

In order to find the optimal relationship between the wind velocity in front and behind the converter the power coefficient is stated as a function of the coefficient of velocities ($\tilde{v} = \frac{v_2}{v_1}$)

$$\begin{aligned} c_p &= \frac{1}{2} v_1 \frac{\left(1 + \frac{v_2}{v_1}\right)(v_1^2 - v_2^2)}{v_1^3} \quad (-) \\ &= \frac{1}{2} \left(1 - \left(\frac{v_2}{v_1}\right)^2\right) \left(1 + \frac{v_2}{v_1}\right) \quad (-) \\ &= \frac{1}{2} (1 - \tilde{v}^2) (1 + \tilde{v}) \quad (-) \end{aligned} \quad (2.15)$$

The power coefficient (c_p), which gives the relationship between the extractable mechanical power and the total mechanical power that is contained in an air stream is solely dependent on the velocity in front of the converter and the velocity behind the converter. The maximum of the power coefficient is found by maximizing the power coefficient with respect to the coefficient of velocities ($\tilde{v} = \frac{v_2}{v_1}$)

$$\begin{aligned} \frac{\partial c_p}{\partial \tilde{v}} &= \frac{1}{2} (-2\tilde{v}(1 + \tilde{v}) + (1 - \tilde{v}^2)) \stackrel{!}{=} 0, & \frac{\partial c_p^2}{\partial \tilde{v}^2} &= -2 - 4\tilde{v} - 2\tilde{v} < 0 \\ \tilde{v}_{1,2} &= \frac{-2 \pm \sqrt{4 + 4 * 3 * 1}}{6} & \tilde{v}_1 &= -1 \quad \tilde{v}_2 = \frac{1}{3} \end{aligned} \quad (2.16)$$

The coefficient of velocities is maximized for $\tilde{v} = \frac{1}{3}$. Thus, the wind velocity behind the converter has to be a third of the wind velocity in front of the converter ($v_2 = \frac{1}{3} v_1$). This

leads to an optimal power coefficient of:

$$\begin{aligned} c_p \left(\tilde{v} = \frac{1}{3} \right) &:= \eta_{Betz} & (-) \\ &= \frac{1}{2} \left(1 - \left(\frac{1}{3} \right)^2 \right) \left(1 + \frac{1}{3} \right) = \frac{16}{27} = 0,593 & (-) \end{aligned} \quad (2.17)$$

This relationship of the wind velocities of a converter was first found by Albert Betz in 1926. Therefore the optimal power coefficient is often called coefficient of Betz (η_{Betz}). For further details see the reprint of his book "Wind-Energie und ihre Ausnutzung durch Windmühlen" (Betz, 1982). The flow velocity at the converter is given by:

$$v' = \frac{1}{2} \left(v_1 + \frac{1}{3}v_1 \right) = \frac{2}{3}v_1 \quad \left(\frac{m}{s} \right) \quad (2.18)$$

Thus, the highest mechanical power, that can be theoretically extracted from a wind stream is given by:

$$P_{Ext} = \eta_{Betz} * P_0 = \eta_{Betz} \frac{1}{2} \rho A v^3 \quad (W) \quad (2.19)$$

Any wind mill has additional losses of efficiency. Flow losses coming from the friction part of the Navier-Stokes-equation, mechanical losses coming from friction in the transmission units as well as cable losses. Therefore the mechanical power that really can be extracted from a windmill (P_{real}) is given by the theoretically extractable power multiplied by the efficiency factors resulting from the flow losses η_{flow} , from the mechanical losses η_{mec} as well as from the cable losses η_{electr} :

$$\begin{aligned} P_{real} &= P_{extr} \cdot \eta_{flow} \eta_{mec} \eta_{electr} & (W) \\ &= \eta_{flow} \eta_{mec} \eta_{electr} \cdot \eta_{Betz} \frac{1}{2} \rho A v^3 & (W) \end{aligned} \quad (2.20)$$

If the wind velocity is constant for a time interval Δt , the energy supplied by a windmill in this time interval is solely given by the power resulting from the wind velocity (v) the cross sectional area (A) the efficiency factors ($\eta_{flow} \eta_{mec} \eta_{electr} \cdot \eta_{Betz}$) multiplied by the time interval (Δt)

$$E_{real} = P_{real} * \Delta t = \eta_{flow} \eta_{mec} \eta_{electr} \cdot \eta_{Betz} \frac{1}{2} \rho A v^3 \Delta t \quad (Wh) \quad (2.21)$$

Whenever wind speed exceeds the maximum wind speed, for which a certain wind power

plant is designed for, electricity generation has to be stopped. This can be done by three different ways: Firstly, a wind power plant can be constructed so that the air flow separates whenever wind speed exceeds a certain threshold (stall). Secondly, all rotor can be turned (pitch). Thirdly, by turning the nacelle of the generator away from the wind. Neglecting this shutdown for very high wind speeds does not seem to be critical, since, as the evaluation of wind power feed-in will show, no severe differences for tail values occur.

There are three important findings resulting from this short physical explanation. Firstly, the power as well as the energy that can be converted from a wind stream varies with the cube of the wind speed (v^3). Secondly, the power as well as the energy that can be converted from a wind stream are linearly raised by the cross sectional area (A) and logically raised to the second power by the the length of a rotor blade ($A = \pi r^2$). Last but not least, even a perfectly engineered windmill cannot extract more than about 60 % of the energy of the wind stream it is exposed to.

Deriving a Distribution for Wind Energy

Electricity is traded at the European Energy Exchange in trading blocks of quarter of an hour. Under the assumption of a constant wind velocity during each quarter of an hour a distribution for power supplied by all German windmills can be found by using the derived power supply function of a certain wind turbine and summarizing efficiency factors ($\eta_{Betz}\eta_{reib}\eta_{mec}\eta_{electr}$) as well as other deterministic factors ($\frac{1}{2}\rho A$) in a common variable θ .

$$P_{real} = \eta_{flow}\eta_{mec}\eta_{electr}.\eta_{Betz} \frac{1}{2} \rho A v^3 \quad (W)$$

$$P_{Total} = \theta v^3 \quad (W) \quad (2.22)$$

Of course, all wind converters in Germany differ from each other in cross sectional areas (A), in their efficiency factors (η), and, depending on their locations, they additionally differ in air density (ρ) as well as in the exact wind velocity (v) they are exposed. However, to analyze stochastic properties of wind energy supply in Germany all these factors are summarized in the variable θ , which can be seen as the product off all factors for something like a "representative windmill". In general velocity of wind is said to follow

a Weibull distribution. Therefore, the cumulative distribution function of the velocity of wind (F_V) and the corresponding density function (f_V) look as follows:

$$F_V = 1 - e^{-(\lambda v)^k} \quad f_V = \lambda^k k v^{k-1} e^{-(\lambda v)^k} \quad (2.23)$$

Using equation 2.22 and the property of wind velocity being Weibull distributed, the distribution function of stochastic supply of wind energy can be derived. The energy supplied to the market is given by the energy of the representative windmill $E_{market} = \theta v^3$. Two steps have to be taken to derive the distribution for this stochastic variable θv^3 . The first step is to determine the distribution of the random variable $y = v^3$, where the velocity v follows a Weibull distribution. The second step is to determine the distribution for the random variable $x = \theta y$.

Proposition 2.2.1. *For any exponent larger than zero ($\tau > 0$) the distribution of a continuous random variable V with $F_V(0) = 0$ and $Y := V^{1/\tau}$ the corresponding cumulative distribution function $F_Y(y)$ and the corresponding density function $f_Y(y)$ are given by:*

$$F_Y(y) = F_V(y^\tau) \quad \text{and} \quad f_Y(y) = \tau y^{\tau-1} f_V(y^\tau) \quad \forall y > 0$$

Proof:

$$\begin{aligned} F_Y(y) &= P(Y \leq y) = P(V \leq y^\tau) = F_V(y^\tau) \\ f_Y(y) &= \frac{\partial F_Y(y)}{\partial y} = \frac{\partial F_V(y^\tau)}{\partial y} = \tau y^{\tau-1} f_V(y^\tau) \end{aligned} \quad (2.24)$$

Using Proposition 2.2.1 for the underlying Weibull distribution leads to:

$$\begin{aligned} F_Y(y) &= 1 - e^{-\lambda^k y^{\frac{k}{3}}} \\ f_Y(y) &= \frac{1}{3} k y^{\frac{k}{3}-1} \lambda^k e^{-\lambda^k y^{\frac{k}{3}}} \end{aligned} \quad (2.25)$$

Proposition 2.2.2. *For any multiplicand larger than zero ($\theta > 0$) the distribution of a continuous random variable $X := \theta Y$ the corresponding cumulative distribution function $F_X(x)$ and the corresponding density function $f_X(x)$ are given by:*

$$F_X(x) = F_Y\left(\frac{x}{\theta}\right) \quad \text{and} \quad f_X(x) = \frac{1}{\theta} f_Y\left(\frac{x}{\theta}\right)$$

Proof:

$$F_X(x) = P(X \leq x) = P(\theta Y \leq x) = P\left(Y \leq \frac{x}{\theta}\right) = F_Y\left(\frac{x}{\theta}\right) \quad (2.26)$$

Using Proposition 2.2.2 for the underlying transformed distribution leads to:

$$\begin{aligned} F_X(x) &= 1 - e^{-\lambda^k \left(\frac{x}{\theta}\right)^{\frac{k}{3}}} \\ f_X(x) &= \frac{1}{3} k x^{\frac{k}{3}-1} \lambda^k \theta^{-\frac{1}{3}k} e^{-\lambda^k \left(\frac{x}{\theta}\right)^{\frac{k}{3}}} \end{aligned} \quad (2.27)$$

The original scale parameter λ and the multiplicand θ can be summarized in a new scale parameter $\gamma = \frac{\lambda}{\theta^{1/3}}$, since they influence the cumulative distribution and the corresponding density function the same structural way. In the upcoming analysis the shape parameter of this modified Weibull distribution is henceforth denoted by κ to avoid confusion with the shape parameter of the classical Weibull distribution.

$$\begin{aligned} F_X(x) &= 1 - e^{-\left(\frac{\lambda}{\theta^{1/3}}\right)^k x^{\frac{k}{3}}} = 1 - e^{-\gamma^\kappa x^{\frac{\kappa}{3}}} \\ f_X(x) &= \frac{1}{3} k x^{\frac{k}{3}-1} \left(\frac{\lambda}{\theta^{1/3}}\right)^k e^{-\left(\frac{\lambda}{\theta^{1/3}}\right)^k x^{\frac{k}{3}}} = \frac{1}{3} \kappa x^{\frac{\kappa}{3}-1} \gamma^\kappa e^{-\gamma^\kappa x^{\frac{\kappa}{3}}} \end{aligned} \quad (2.28)$$

Day-Ahead Forecast of Wind Feed-in

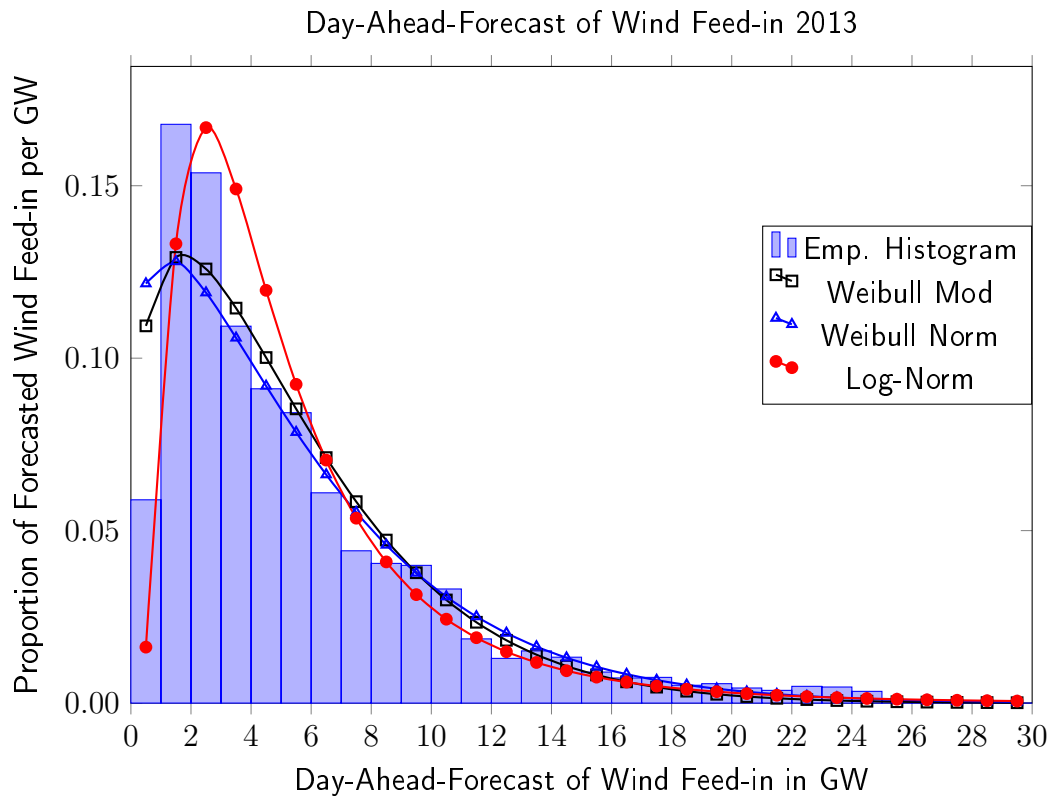


Figure 2.27: Histogram of Day-Ahead-Forecast of Wind Feed-in 2013

Figure 2.27 shows the empirical histogram of the day-ahead forecast of wind power

feed-in in 2013. Additionally, a log normal distribution, a Weibull distribution as well as the modified Weibull distribution, that has been derived on the pages before, are plotted. A class size of 1 GW is chosen. The mean of wind power feed-in in 2013 was 5.5849 GW, whereas variance of wind power feed-in was 22.6314 GW^2 . The parameters of the log normal distribution $(\mu_{LN}, \sigma_{LN}^2)$ are found by equalizing theoretical and empirical moments.

$$\begin{aligned}
 f(x) &= \frac{1}{\sqrt{2\pi}\sigma_{LN}} e^{-\frac{(\ln(x)-\mu_{LN})^2}{2\sigma_{LN}^2}} & \forall x \geq 0, f(x) = 0 & \forall x < 0 \\
 \mu_{LN} &= \ln\left(E^2 \sqrt{\frac{1}{Var + E^2}}\right) = 1.45, & E &\stackrel{!}{=} 5.5849 \text{ GW} \\
 \sigma_{LN}^2 &= \ln\left(1 + \frac{Var}{E^2}\right) = 0.74, & Var &\stackrel{!}{=} 22.6314 \text{ GW}^2
 \end{aligned} \tag{2.29}$$

Parameters of the log normal distribution are chosen to reflect the values of empirical mean and are given by $\mu_{LN} = 1.45$ and $\sigma_{LN}^2 = 0.74$. Parameters of the Weibull distribution are chosen to reflect mean and variance of wind feed-in by numerically equalizing theoretical and empirical moments.

$$\begin{aligned}
 E(x) &= \frac{1}{\lambda_W} \Gamma\left(1 + \frac{1}{k}\right) \stackrel{!}{=} 5.5849 \text{ GW} \\
 V(x) &= \frac{1}{\lambda_W^2} \left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right) \right] \stackrel{!}{=} 22.6314 \text{ GW}^2 \\
 \implies & k = 1.18, \quad \lambda_W = 0.17
 \end{aligned} \tag{2.30}$$

Parameters of the modified Weibull distribution are chosen to reflect mean and variance of wind feed-in, too. However, this is done by fitting the distribution as well as possible to the empirical 0.1, 0.3, 0.5, 0.7, 0.9 quantile, since no closed form solution for mean and variance of the modified Weibull distribution is known. This is done by choosing parameters so that the sum of mean square errors for all five quantiles is minimized. This minimum is found by a grid search for all values of γ and κ with two digits. The minimum sum of mean square error is found for $\gamma = 0.56$ and $k = 3.83$.

A wind power feed-in forecast of less than 1 GW is realized in only 5.9% of the cases. The interval with highest frequency of wind feed-in is the interval between 1 GW and 2 GW (16.8%). For all forecasts of wind feed-in larger than 2 GW the frequency is strictly decreasing until a maximum forecasted wind feed-in of 26.35 GW.

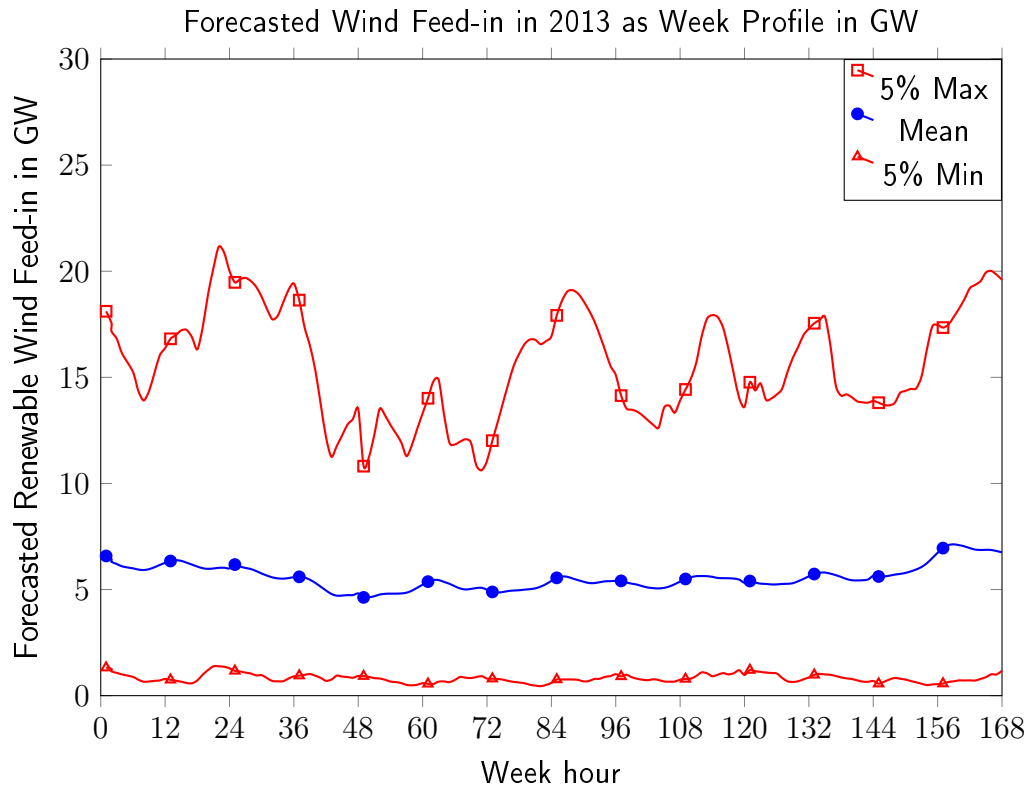


Figure 2.28: Forecasted Wind Feed-in in 2013 as Week Profile

Figure 2.28 illustrates the weekly pattern of forecasted wind feed-in in 2013. For all 168 hours of the week the mean, the highest 5% and the lowest 5% forecasted wind feed-in are plotted. The mean forecasted wind feed-in is fluctuating around 5.6 GW, with a maximum mean forecasted wind feed-in of 7.1 GW and a minimum forecasted wind feed-in of 4.6 GW. Even though the mean forecasted wind feed-in is not perfectly stable, fluctuations seem to be rather stochastic without any trend, structure or pattern. The lowest 5% of forecasted wind feed-in is fluctuating around 0.8 GW with an absolute (relative) lower (higher) amplitude. The minimum is given by a forecasted wind feed-in of 0.4 GW and the maximum is given by 1.4 GW. The highest 5% of the forecasted wind feed-in are fluctuating around 15.6 GW, with a rather high amplitude in absolute terms, since the minimum of 5% highest forecasted wind feed-in is given by 10.6 GW and the maximum 5% of the forecasted wind feed-in is given by 21.2 GW. For all three plots fluctuation seem to be stochastic without a clear trend, structure or pattern. This is not surprising, since wind velocity, which is the main determinant of wind power feed-in, does not follow a daily or weekly pattern.

Realized Wind Feed-in

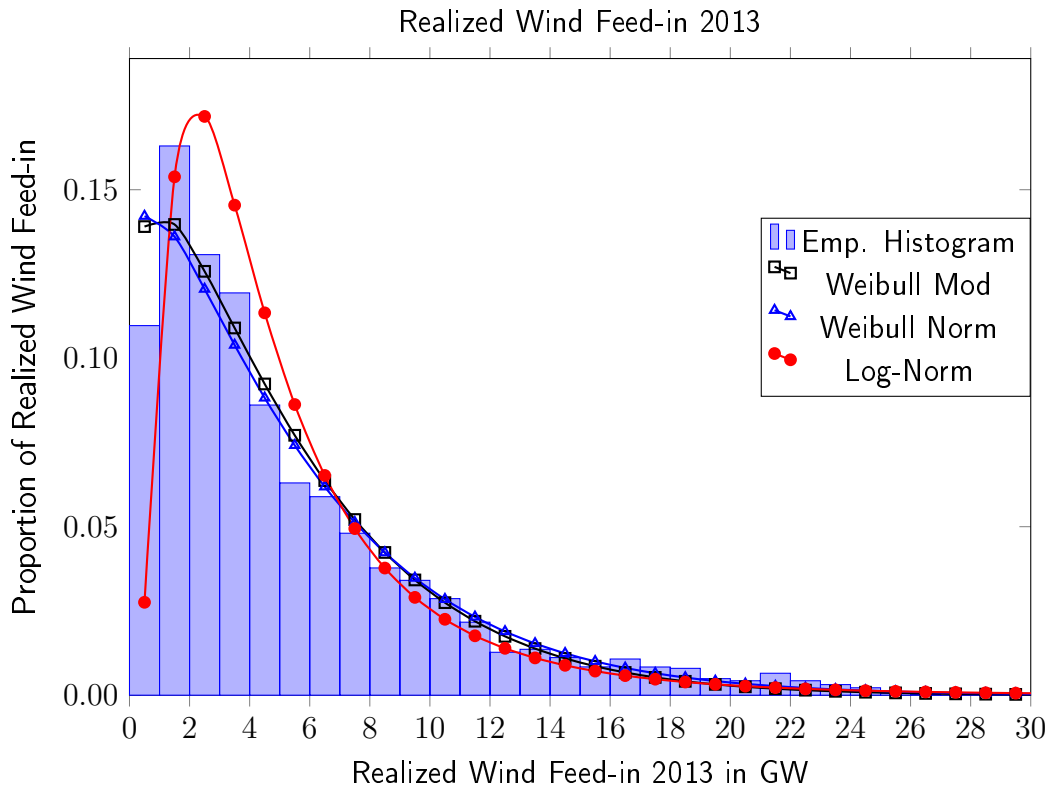


Figure 2.29: Histogram of Realized Wind Feed-in 2013

Figure 2.29 presents the empirical histogram of the actually realized wind power feed-in in 2013. Again, a log normal distribution, a Weibull distribution as well as the modified Weibull distribution are plotted additionally. As class size of 1 GW is chosen. The mean of the realized wind power feed-in was 5.39 GW and the variance of wind power feed-in was 23.67 GW^2 in 2013. Parameters of the log normal distribution are chosen to reflect the values of the empirical mean and variance, analogue to the procedure in equation 2.29, and are given by $\mu_{LN} = 1.38$ and $\sigma_{LN}^2 = 0.77$. Shape and scale parameter of the Weibull distribution are chosen to reflect the mean and variance of wind feed-in by numerically equalizing theoretical and empirical moments and are given by $\lambda_W = 0.18$ and $k = 1.11$. For the modified Weibull distribution parameters are found by a grid search, which leads to $\gamma = 0.57$ and $\kappa = 3.46$. All parameter values for realized wind power feed-in do not fundamentally differ from the estimates for the forecasted wind power feed-in. This leads to basically similar histograms and distributions. The histogram class with the highest frequency of realization is given by class between 1 GW and 2 GW (16.2 %). For all

histogram classes above 2 GW the frequency of realization is strictly decreasing.

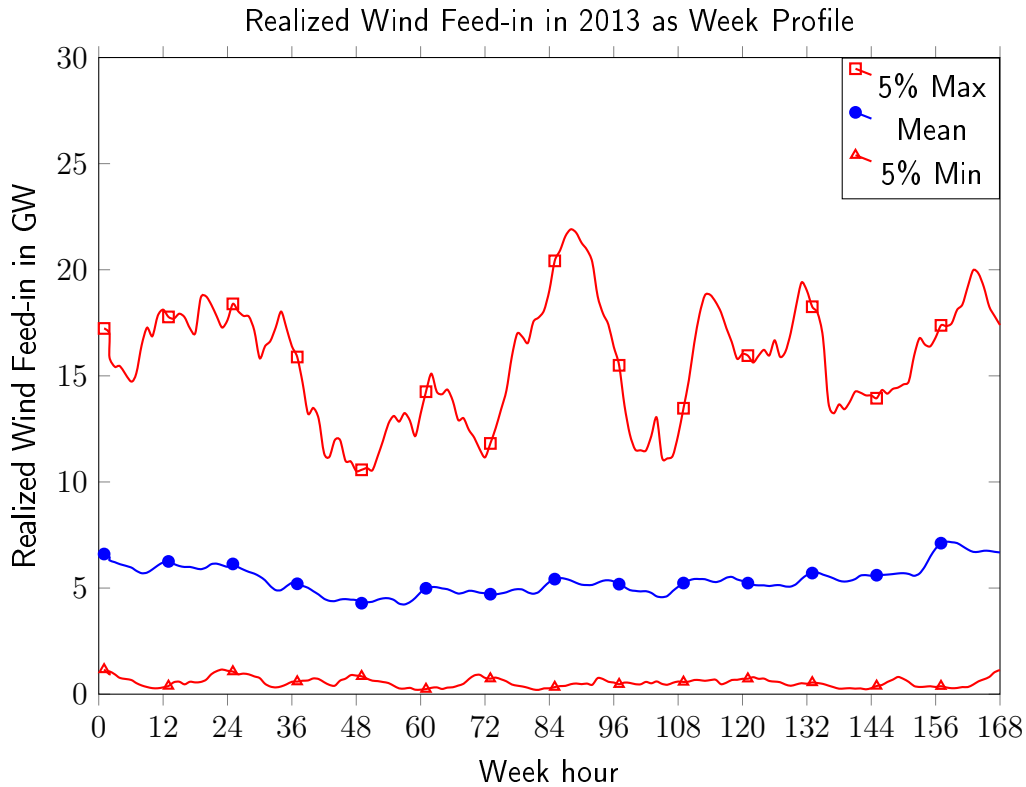


Figure 2.30: Realized Wind Feed-in in 2013 as Week Profile

Figure 2.30 illustrates the weekly pattern of realized wind power feed-in in 2013. Again, for all 168 hours of a week mean, the highest 5% and lowest 5% realized wind power feed-in is plotted. The mean realized wind power feed-in is fluctuating around 5.4 GW, with a maximum mean realized wind-feed-in of 7.2 GW and a minimum realized wind power feed-in of 4.2 GW. The lowest 5% of realized wind feed-in is fluctuating around 0.6 GW with an absolute lower amplitude, since the minimum is given by a realized wind feed-in of 0.2 GW and the maximum is given by 1.2 GW. The highest 5% of the forecasted wind feed-in are fluctuating around 15.7 GW, with, in absolute terms, a rather high amplitude. On a weekly basis, the minimum 5% of the highest forecasted wind feed-in is given by 10.5 GW and the maximum 5% of the forecasted wind feed-in is given by 21.9 GW. Similar to fluctuations of forecasted wind power feed-in fluctuations of realized wind power feed-in seem to be stochastic without a clear trend, structure or pattern.

Forecasting Quality

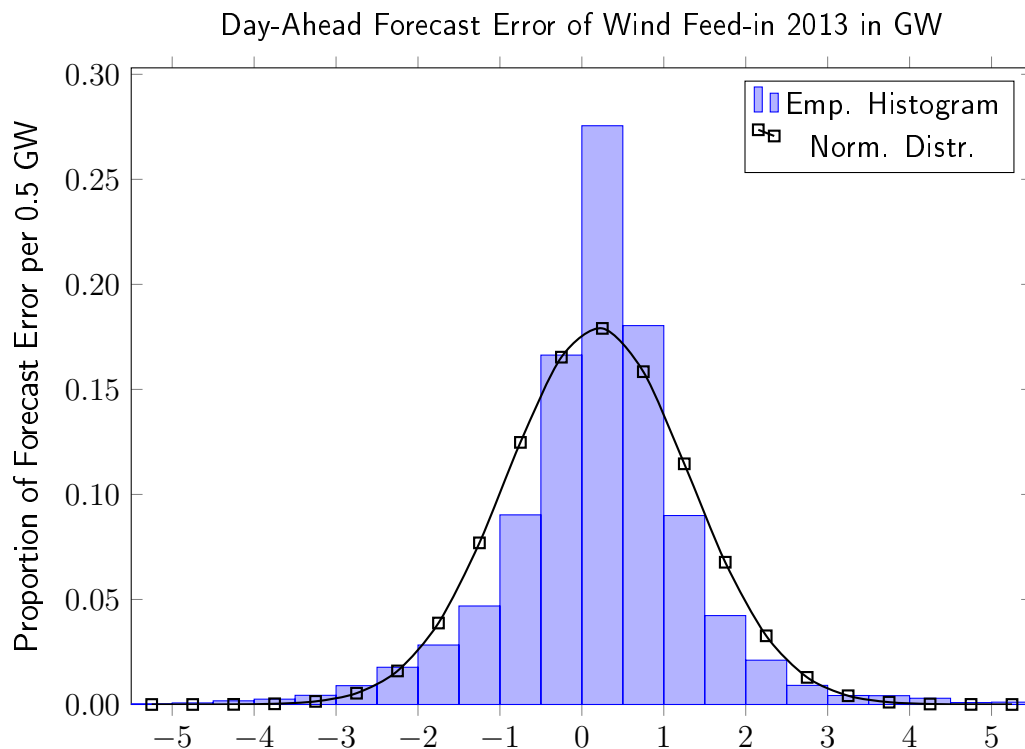


Figure 2.31: Day-Ahead Forecast Error of Wind Feed-in 2013

Figure 2.31 illustrates the empirical histogram of day-ahead forecast error of wind power feed-in. The actually realized wind power feed-in is deducted from its day-ahead forecast. Thus, a positive value is associated with a day-ahead forecast of wind power feed-in that is exceeding its realization. A negative value is associated with a day-ahead forecast of wind power feed-in that falls behind its realization. Additionally, the mean day-ahead forecast error of wind power feed-in of 0.20 GW in 2013 and the standard deviation of day-ahead forecast error of wind power feed-in of 1.11 GW in 2013 are taken as parameters for a normal distribution. In general, day-ahead forecasts help to estimate realizations of wind power feed-in quite well, since 44.1% of day-ahead forecast errors fall into histogram classes between -0.5 GW and 0.5 GW. This high forecast quality leads to a more leptokurtic shape of day-ahead forecast errors than a normal distribution would suggest. However, some bias towards positive forecast error with (forecasts exceeding) realization can be seen. Large forecast errors that, according to amount, are above 2 GW account for 8.01 % of realizations, since in 3.64 % of the cases forecast error is below -2 GW and in 4.37 % of the cases forecast error exceeds 2 GW.

2.2.3 Feed-in of Renewable Energies

Even though some interesting insights can be gained by analyzing solar power feed-in and wind power feed-in separately, common feed-in effects are more relevant for the German electricity grid. Therefore, solar power feed-in and wind power feed-in should be analyzed simultaneously, too. For further analysis this feed-in is referred to as renewable energies feed-in. This means renewable electricity generation from biomass or hydropower are neglected, which is in some way semantically imprecise. However, to analyze volatility that is associated with the feed-in of electricity from renewable energy sources, this does not seem to be a critical point, since power feed-in from other renewable energy sources like hydropower, biomass or biogenic waste can be controlled and dispatched without larger problems.

Fluctuations of renewable energies feed-in are often accused of large electricity exports and imports. The argumentation of this criticism is as follows: Whenever feed-in of renewable energy sources is small, Germany has to import electricity. This imported electricity is often generated by nuclear power plants or soft coal power plants. Thus, renewable energies feed-in indirectly leads to a support of fossil fuels in other countries. Whenever feed-in of renewable energy sources is large, Germany has to export electricity. These exports lead to problems for the grid of neighbouring countries and a crowding-out flexible gas plants. In contrast countries such as Austria and Switzerland benefit from peaks, since the renewable energy, which was highly subsidized in Germany, can be used to fill pump storage lakes cheaply. Whenever a negative electricity price occurs even a direct payment is received by filling a pump storage plant.

Data for German exports and imports of electricity, that is provided by ENTSO-E are combined with data for renewable energy feed-in. This gives the possibility to evaluate effects of renewable energies feed-in on German exports and imports of electricity.

Day-Ahead Forecast of Renewable Energies Feed-in

Figure 2.32 shows the histogram of forecasted common feed-in of solar and wind power into the German electricity grid. Additionally a logarithmic normal distribution, a classical Weibull distribution as well as modified Weibull distribution, which was originally

derived for wind power feed-in, is plotted. All three distributions are parameterized to have an expectation as close as possible to 9.04 GW and a variance as close as possible to 44.49 GW^2 , which are the empirical moments of renewable energies feed-in. All parameters for renewable power feed-in are calculated analogous to the parameters derived for wind power feed-in. Parameters for logarithmic normal distribution are estimated to be $\mu_{LN} = 1.99$ and to be $\sigma_{LN} = 0.66$. For Weibull distribution shape parameter is estimated to be $k = 1,37$ and scale parameter is estimated to be $\lambda = 0.10$. For modified Weibull distribution shape parameter is estimated to be $\kappa = 3.81$ and scale parameter is estimated to be $\gamma = 0.47$.

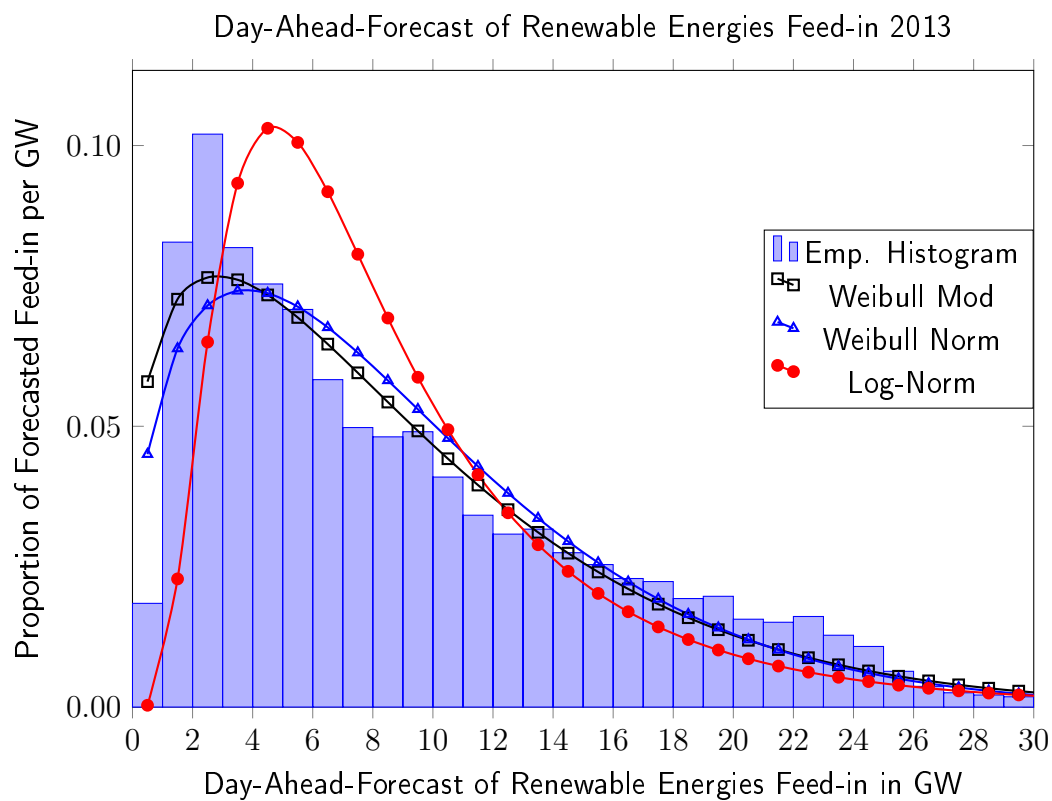


Figure 2.32: Histogram of Day-Ahead-Forecast of Renewable Energies Feed-in 2013

A renewable energies feed-in of less than 1 GW was forecasted for only 1.8 % of cases in 2013. A renewable energies feed-in between 1 GW and 2 GW was forecasted for 8.3% of realizations in 2013. A renewable energies feed-in between 2 GW and 3 GW has been most frequent and has been forecasted for 10.2 % of cases. The frequency is falling for all larger histogram classes in direction with some histogram classes having a slightly higher frequency than smaller histogram classes. Therefore, the frequency of realization can

be said to fall in tendency until the maximum forecasted power feed-in from renewable energies of 33.8 GW that was realized on 18.04.2013 at 13:15 hrs.

All three distributions have some problems to fit the histogram data properly. The biggest problems exist for a logarithmic normal distribution, since it heavily underestimates realizations between 1 GW and 3 GW and heavily overestimates realizations between 3 GW and 13 GW. Additionally it underestimates frequency for extremal realizations, since it does not have enough mass in its tail. A normal Weibull distribution as well as a modified normal distribution have a better, but not at all perfect, fit to the data. They underestimate forecasts between 1 GW and 3 GW and overestimate forecasts between 6 GW and 14 GW. Both distributions slightly underestimate extremal forecasts between 17 GW and 25 GW. Even though a modified Weibull distribution is not able to perfectly fit the data it seems to be most appropriate to describe the distribution of renewable energy forecasts in 2013.

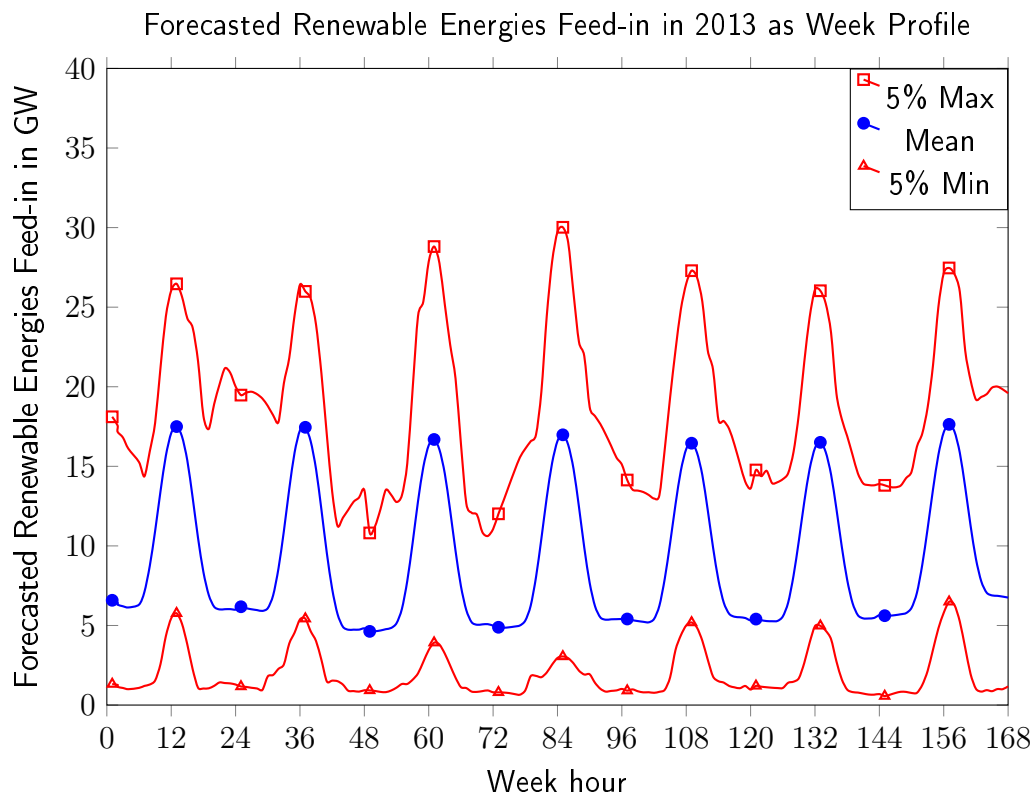


Figure 2.33: Forecasted Renewable Energies Feed-in in 2013 as Week Profile

Figure 2.33 shows the weekly pattern of forecasted power feed-in of renewable energy sources. Therefore for each of the 168 week hours mean feed-in from renewable energy

sources, the highest 5% of the forecasted feed-in from renewable energy sources as well as the lowest 5% of the forecasted feed-in from renewable energy sources, is plotted. The general pattern can mainly be explained by overlapping the profile for solar energy feed-in with the profile for wind energy feed-in. Wind energy feed-in, which basically has a time-stable pattern during the entire week, on average leads to a feed-in of about 5.5 GW. During sunshine hours that occur approximately between 06 00 hrs and 18 00 hrs (depending on seasons), on top of this solar energy is fed into the German grid. Thus, a strong hourly pattern can be identified. For a whole-year the correlation coefficient of feed-in of wind and solar energy is very close to zero (0.01). However, due to the hourly pattern of solar energy feed-in it seems to be appropriate to determine the coefficient of correlation for distinct hours of a day separately. Then the coefficient of correlation lies between -0.31 at 7:00 hrs and -0.39 at 9:00 hrs. High realizations of wind and solar feed-in are rather unlikely to occur simultaneously, since sunny, but windy, days are less likely, which is reflected in these calculated negative correlations. Looking at maximum values supports this negative correlation, since maximum forecast of feed-in of renewable energies was 33.8 GW, whereas maximum forecast of feed-in from wind power was 26.4 GW and maximum forecast of feed-in of solar power was 24.1 GW, which would theoretically amount to 50.5 GW. 5 % of the smallest values fluctuate between a feed-in of round about 1 GW for night hours and round about 5 GW at noon.

Realized Renewable Energies Feed-in

Figure 2.34 shows the empirical histogram of common feed-in of solar and wind power into the German grid in 2013. Again a logarithmic normal distribution, a classical Weibull distribution as well as a modified Weibull distribution, which was originally derived to describe wind power feed-in, is plotted. All three distributions are parameterized to have an expectation as close as possible to 8.77 GW and a variance as close as possible to 46.27 GW^2 , which are the empirical moments of the renewable energies feed-in. Parameters for logarithmic normal distribution are estimated to be $\mu_{LN} = 1.94$ and to be $\sigma_{LN} = 0.69$. For Weibull distribution shape parameter is estimated to be $k = 1.11$ and scale parameter is estimated to be $\lambda = 0.11$. For modified Weibull distribution shape parameter is estimated to be $\kappa = 3.53$ and scale parameter is estimated to be $\gamma = 0.47$.

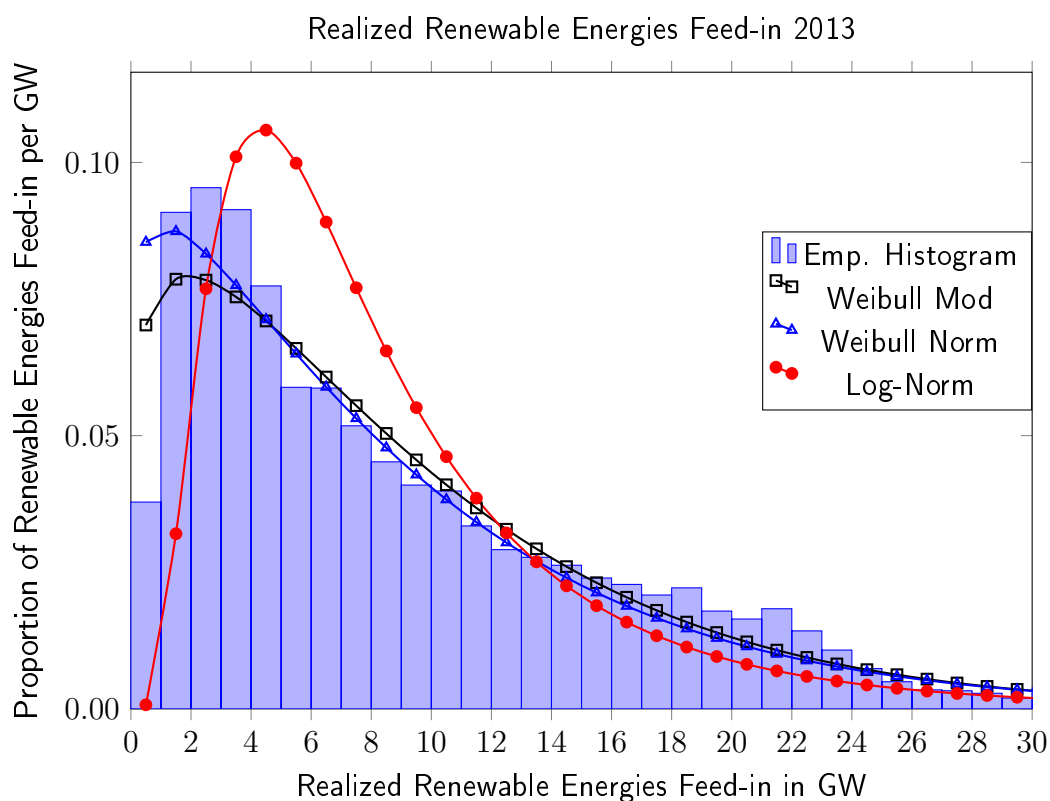


Figure 2.34: Histogram of Realized Renewable Energies Feed-in 2013

A renewable energies feed-in of less than 1 GW was realized for only 3.8 % of cases in 2013. A renewable energies feed-in between 1 GW and 2 GW was realized for 9.1% of cases in 2013. A renewable energies feed-in between 2 GW and 3 GW was most frequent and was realized for 9.5 % of cases. The frequency is falling for all larger histogram classes in direction with some histogram classes having a slightly higher frequency than smaller histogram classes. Therefore, frequency of realization can be said to fall in tendency until the maximum realized power feed-in from renewable energies of 36.1 GW, which was realized on 18.04.2013 at 14:15 hrs.

Again, all three distributions have some problems to fit the histogram data properly. The biggest problems exist for a logarithmic normal distribution, since it heavily underestimates realizations between 1 GW and GW 3 and heavily overestimates realizations between 3 GW and 13 GW. Additionally it underestimates frequency for extremal realizations, since it has too little mass in its tail. A normal Weibull distribution as well as a modified normal distribution have a better fit to the data. The modified Weibull distribution fits to the data, especially for realizations between 6 GW and 16 GW.

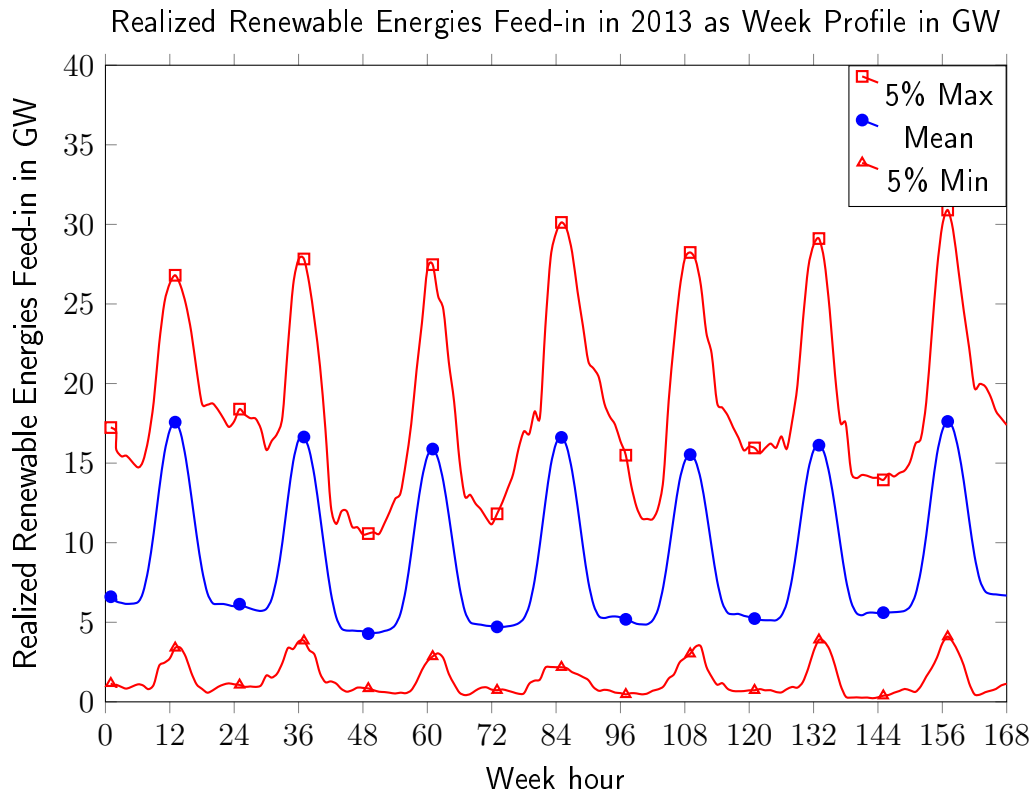


Figure 2.35: Realized Renewable Energies Feed-in in 2013 as Week Profile

Figure 2.35 shows the weekly pattern of realized power feed-in from renewable energy sources. Again, for each of the 168 week hours mean feed-in from renewable energy sources, the highest 5% forecasted feed-in from renewable energy sources as well as the lowest 5% forecasted feed-in from renewable energy sources, is plotted. The general pattern can mainly be explained by overlapping the profile for solar energy feed-in with the profile for wind energy feed-in. Wind energy feed-in, which basically has a time-stable pattern during the entire week, on average leads to a feed-in of about 5.5 GW. During sunshine hours that occur approximately between 6 hrs and 18:00 hrs (depending on seasons), on top of this solar energy is fed into the German grid. Thus, a strong hourly pattern can be identified. The whole-year correlation coefficient of feed-in for wind and solar energy is given by -0.12. However, due to the hourly pattern of solar energy feed-in it seems to be appropriate to determine the coefficient of correlation for distinct hours of a day separately. Then, the coefficient of correlation lies between -0.23 at 14:00 hrs and -0.37 at 9:00 hrs. Looking at maximum values supports this negative correlation, since the maximum realized feed-in of renewable energies was 36.1 GW, whereas the maximum

realized feed-in from wind power was 26.3 GW and the maximum realized feed-in of solar power was 24.0 GW, which would theoretically amount to 50.3 GW.

Forecasting Quality

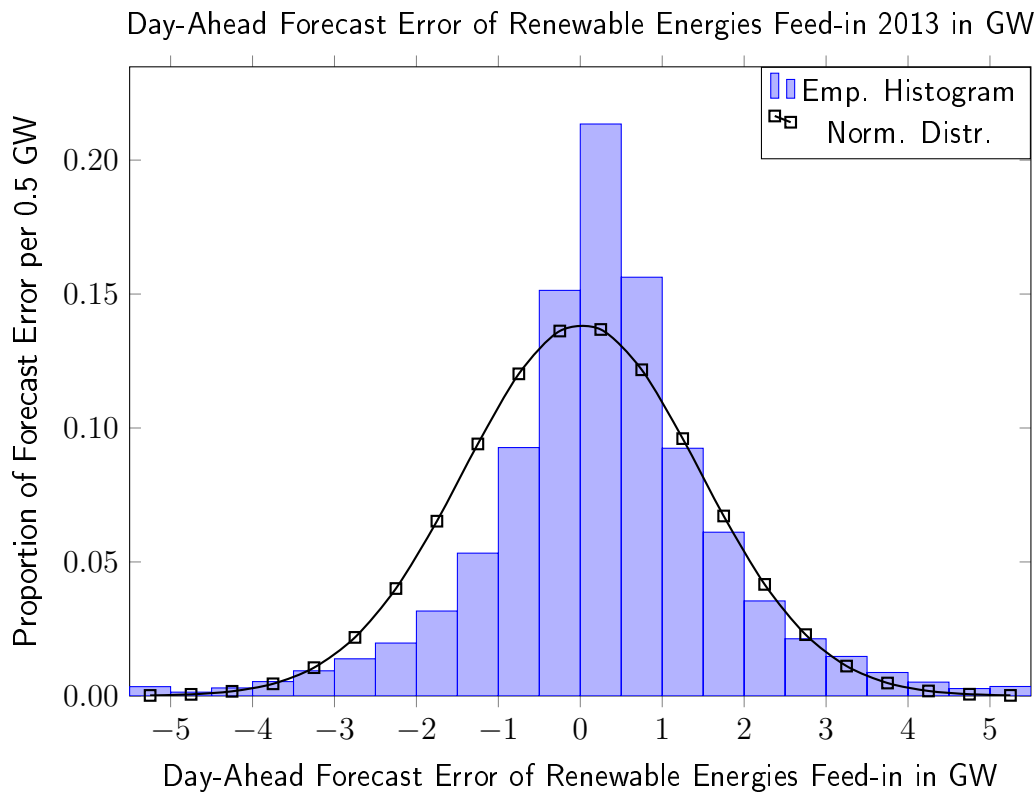


Figure 2.36: Histogram of Day-Ahead Forecast Error of Renewable Energies Feed-in 2013

Figure 2.36 shows the empirical histogram of renewable energies day-ahead forecast error in 2013. For a positive value day-ahead forecasted feed-in is exceeding realized feed-in, whereas for a negative value realized feed-in exceeds its day-ahead forecast. On average day-ahead forecast of renewable energies feed-in exceeds realized renewable energies feed-in, since on average day-ahead forecast error in 2013 was given by 0.26 GW. Standard deviation of day-ahead forecast error is given by 1.44 GW. This empirical moments are used as parameters for normal distribution plotted in figure 2.36. Day-ahead forecast quality seems to be good, since 36.5% day-ahead forecast errors lie in a histogram class between -0.5 GW and 0.5 GW. The highest frequency is given for a day-ahead forecast error between 0 GW and 0.5 GW (21.3 %). Day-ahead forecast bias can additionally be demonstrated by the fact, that positive day-ahead forecast errors account for 61.5 %

of realizations. The highest negative forecast error of -7.1 GW was made for 29.06.2013 12:45 hrs and the highest positive forecast error of 8.3 GW was made for 03.04.2013 13.16 hrs. The high forecast quality leads to a more leptokurtic shape than a normal distribution would suggest. However, drastic forecast error may occur.

Effect of Renewable Energy Feed-in on Electricity Exports

To determine the degree of volatility on the German electricity market associated with feed-in of renewable energies electricity, exports and imports should be taken into account. For this purpose, cross-border physical flow data, which is provided by the European Network of Transmission System Operators (ENTSO-E) for all European countries are used. For each hour in 2013 the flow from Germany into each border country and the flow from each border country into Germany can be taken from this data. Using this information a net cross-border physical flow for Germany and each border-country can be calculated.

In order to get an overview to what extent feed-in of solar, wind and renewable energies are exported, table 2.9 presents for each country Pearson's (column Pears.) product-moment correlation coefficient and Spearman's rank correlation coefficient (column Spear.) for solar (column Solar), wind (column Wind) and renewable energies (column Renew) feed-in for Germany and each of its border countries.

On the one hand the net-exports and energy feed-in will not necessarily follow a linear relationship, which provides a serious argument for using rank correlation to analyze the data. On the other hand for the relationship between energy feed-in and exports magnitudes and not only ranks are of importance, which gives a justification for analyzing Pearson's correlation. Thus, using each of these correlation coefficients has its own justification.

First column of table 2.9 gives Pearson's and Spearman's correlation coefficients for energy feed-in from solar energy and net-exports. For the feed-in of solar energy and net-export to all countries except for Switzerland a positive Pearson's correlation coefficient is found. Thus, in general higher feed-in of solar energy leads c.p. to higher net-exports. However, correlation coefficients between 0.09 (Czechia and France) and 0.13 (Poland and Total) should be interpreted as a rather small relationship. Looking at the rang correla-

tion according to Spearman draws a slightly different picture, since correlation, according to amount. is smaller and for five countries (Austria, Switzerland, France, Netherlands and Sweden) correlation becomes negative, whereas for three countries (Czechia, Denmark and Poland) a small positive value occurs. In total a small negative correlation is found. Thus, according to Spearman's correlation no monotone relationship can be found. One explanation might be that the feed-in of solar energy takes place between 10:00hrs and 17:00hrs, when demand is high. Therefore, to the most extent solar energy feed-in can be used in the German grid.

The second column of table 2.9 gives Pearson's and Spearman's correlation coefficients for energy feed-in from wind energy and net-exports. For the feed-in of wind energy and net-export to all countries a positive correlation coefficient according to Pearson and Spearman is found. A rather small Pearson correlation is found for exports to France, Czechia, Netherlands and Sweden (between 0.01 and 0.14). For exports to Switzerland, Austria and Poland larger Pearson correlations are realized (between 0.24 and 0.60). For total net-export a correlation of 0.39 is found, which indicates a weak or moderate linear relationship between net exports and feed-in of wind energy. Comparable values of the correlation coefficient according to Spearman are calculated. This indicates a weak or moderate monotone relationship for net-exports and wind energy feed-in.

The third column of table 2.9 gives Pearson's and Spearman's correlation coefficients for energy feed-in from solar as well as from wind energy and net-exports. Comparable to the pattern of wind energy feed-in and net-exports linear correlation according to Pearson and rank correlation according to Spearman lie close together. For France, Czechia, Switzerland and Netherlands a rather small correlation is found (between 0.04 and 0.12). For Sweden, Denmark, Austria and Poland higher correlations are found (between 0.19 and 0.53). For the feed-in of wind and solar energy and total net exports a Pearson correlation of 0.39 is found, which indicates a small or moderate linear positive relationship. A Spearman correlation coefficient of 0.36 is determined, which indicates again a small or moderate relationship.

Summarizing it can be said that there exists a positive relationship between electricity net-exports and renewable energies feed-in. However, according to the analysis of Pearson's and Spearman's correlations coefficients, any direct linear or monotone relationship

Net Exports to	Solar		Wind		Renew	
	Pears.	Spear.	Pears.	Spear	Pears.	Spear
Austria	0.09	-0.08	0.46	0.42	0.41	0.38
Switzerland	-0.10	-0.16	0.24	0.20	0.10	0.06
Czechia	0.09	0.03	0.06	0.03	0.12	0.14
Denmark	0.12	0.003	0.21	0.21	0.25	0.21
France	0.09	-0.03	0.01	0.01	0.08	0.04
Netherlands	0.11	-0.02	0.04	0.07	0.12	0.11
Poland	0.13	0.04	0.60	0.55	0.53	0.53
Sweden	0.12	-0.05	0.14	0.23	0.19	0.19
Total Net Export	0.13	-0.09	0.39	0.41	0.39	0.36

Table 2.9: Correlation According to Spearman and Pearson for Net-Export and Feed-in

between electricity exports and renewable energies feed-in seems to be rather small. Thus, electricity generated by renewable energy sources is mainly fed into the German grid and used by German consumers.

2.3 Electricity Demand in Germany

Fluctuations on the German electricity market cannot solely be attributed to fluctuations coming from renewable electricity supply. Therefore the next pages are dedicated to fluctuations in electricity demand.

European Network of Transmission System Operators for Electricity (ENTSO-E) provides data for day-ahead forecast of demand for electricity as well as for realized demand for electricity. Day-ahead forecasts of demand for electricity are very important, since power station schedules are made the day before delivery. Consequently the day-ahead spot market has a dominant role for electricity allocation. Using this data weekly patterns of forecasted and realized demand for electricity are illustrated. Furthermore day-ahead forecast error of demand for electricity is evaluated.

Conventional load that is necessary to meet demand is computed by deducting data of renewable energies supply from demand data. Weekly pattern and day-ahead forecast errors are illustrated again. Furthermore serial correlation of necessary conventional load as well as effects of necessary conventional load on the day-ahead spot price are evaluated.

For the years 2011, 2012, 2013 figure 2.37 shows electricity consumption separated into following four sectors: Industry, households, commerce trade and services, and transportation. Data is provided by RWE (2014b). The highest demand for electricity comes from industrial consumers. For the last three years industrial demand was decreasing from 249.6 TWh in 2011 to 240.09 TWh in 2013. By a clear margin households and commerce, trade and services have the second highest demand for electricity. In 2011 households consumed 136.8 TWh, in 2012 136.1TWh and in 2013 136.5 TWh of electricity. Commerce, trade and services in 2011 consumed 136.8 TWh, in 2012 136.1 TWh and in 2013 136.5 TWh of electricity. Transportation in general and railways in particular consumed a stable amount of 12.2 TWh in 2011, 12.1 TWh in 2012 and 12.1 TWh in 2013.

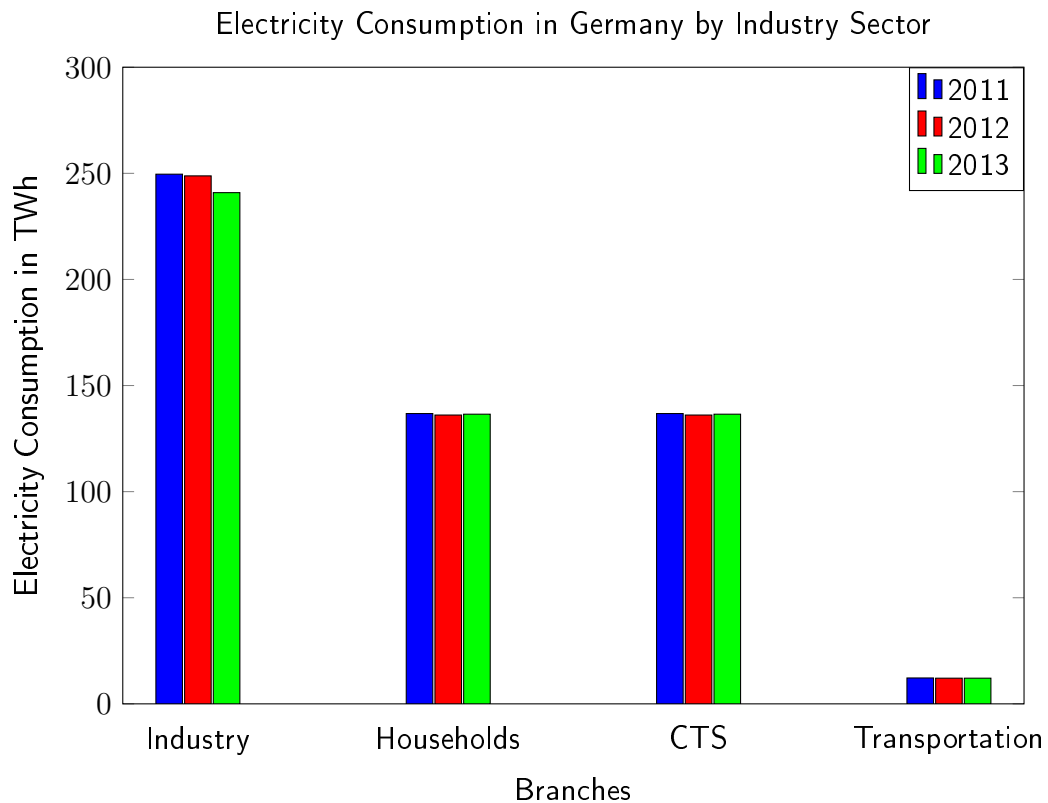


Figure 2.37: Electricity Consumption in Germany by Industry Branches

In a nutshell a stable electricity consumption for Germany that is mainly driven by industry, households and trade, commerce and services can be seen as the main insight of figure 2.37. Having these different groups of electricity consumers in mind, lots of features of the German electricity demand, such as the weekly load profile, can be easily explained.

2.3.1 Weekly Load Profile

To analyze demand for electrical load a time factor has to be considered, since electrical load cannot directly be stored. For all possible storage technologies electricity firstly has to be converted into other forms of energy and when electricity is needed this energy has to be reconverted into electricity. At the moment this energy conversion leads to high energy losses, a lack of efficiency and henceforth cannot be offered in a cost-covering manner. Pump storage power plants give the only exception. However, pump storage is heavily restricted by geographic factors. Even if respective geographical factors are given, political problems in landscape transformation often occur. Thus, no profitable

storage of large amounts of electricity is possible. From a technical perspective electricity generation and consumption have to be equal at every single moment. From an economic perspective electricity sold and bought has to be equal at every single moment. Thus, the timely pattern of demand is of particularly importance.

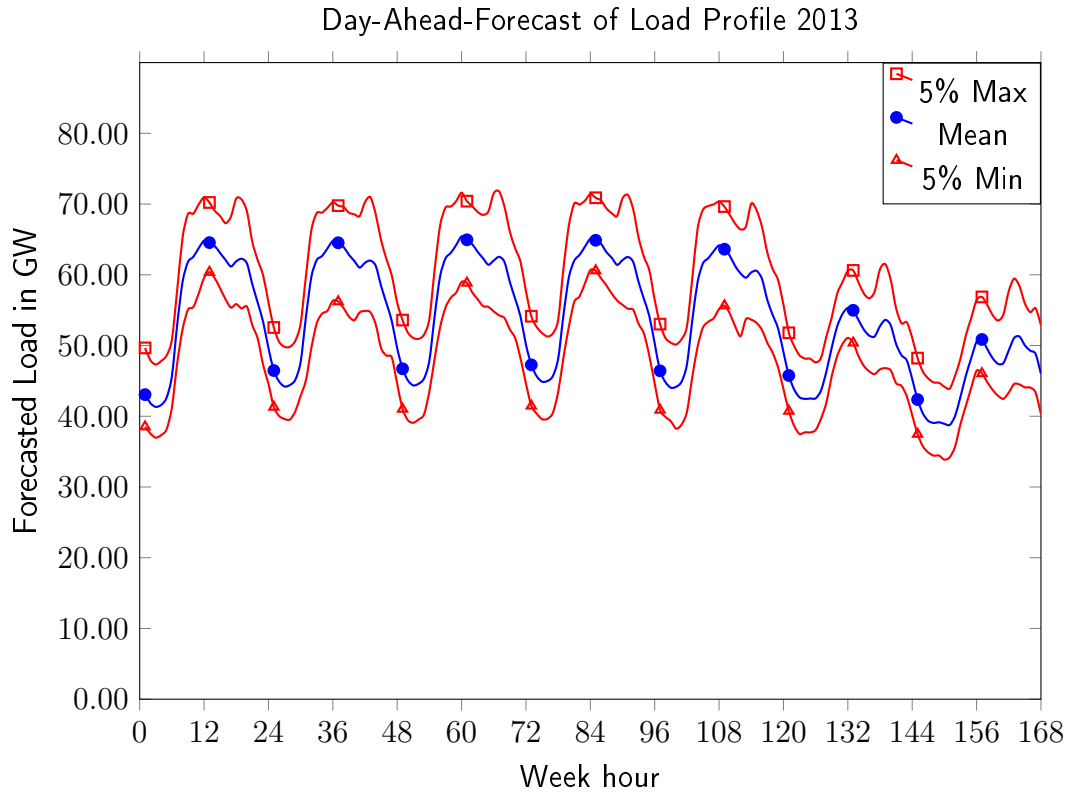


Figure 2.38: Day-Ahead-Forecast of Week Load Profile 2013

Figure 2.38 gives for each of the 168 hours of a week the load profile for demand for electricity in 2013. The mean demand for load is plotted as a blue line, whereas the highest 5% of demand and the lowest 5% of demand are plotted as a red line. In general the pattern for each weekday is very similar.

On average the lowest demand for load is given by round about 41 GW between 02:00 hrs and 05:00 hrs. Then the average demand for electricity increases considerably to its maximum of round about 65 GW between 12:00 hrs and 14:00 hrs. Afterwards the demand for electricity decreases (interrupted by a smaller increase to about 62 GW between 17:00 hrs and 19:00 hrs) until the next daily minimum between 02:00 hrs and 05:00 hrs. Having in mind the four main consumers of electricity (industry, households, commerce, trade and services) this pattern can be easily explained. During night hours only industry

with production based on shift work demands electricity, which adds to basic consumption. In the morning between 06:00 hrs and 08:00 hrs production is started and households demand for electricity additionally. Afterwards commerce, trade and services start their work, which implies additional desire for electricity. The peak between between 12:00 hrs and 14:00 hrs can be explained by food preparation of staff restaurants and households, which implies additional demand for electricity. After this peak demand for electricity decreases, since economic activity for many branches decreases. The small increase between 17.00 hrs and 19:00 hrs is mainly explained by household activities that mainly take place after work, such as washing and drying clothes, food preparation and washing dishes etc. After this local peak of electricity consumption demand for electricity falls sharply, since neither households nor commerce, trade and services nor industry that does not rely on shift work asks for electricity apart from basic consumption.

On Saturdays a lot of industrial producers as well as a lot of branches of the commerce, trade and service sector do not operate their business activities. This leads to a significant shift of demand for electricity. On Sundays additional companies of the service sector (e.g. stores) do not ask for electricity. This leads to a further decrease in demand for electricity.

The pattern for extremal values, which are visualized in figure 2.38 by a line for the highest and lowest 5 % of demand for each hour, generally follows the same trend. However, the interval that results from this upper and lower boundary is rather large. The highest difference can be made out for week hour 67 (Wednesday 18:00 hrs to 19:00 hrs), where both boundaries have a difference of 17.5 GW. The lowest difference results for week hour 129 (Saturday 08:00 hrs to 09:00 hrs), where both boundaries have a difference of 8.4 GW. This is nevertheless rather a large difference of about 17 % of mean demand at this time (49.7 GW). Thus, it can be stated that demand fluctuations are of particular importance.

Figure 2.39 shows the realized demand as load profile for all 168 hours of a week in 2013. This profile of actually realized demand does not fundamentally differ from its forecast illustrated in figure 2.38, since the daily pattern for realized electricity demand is generally quite similar. However, all demand values are mean or 5% boundary values. Thus, to analyze forecast qualities direct differences of day-ahead forecast of demand and

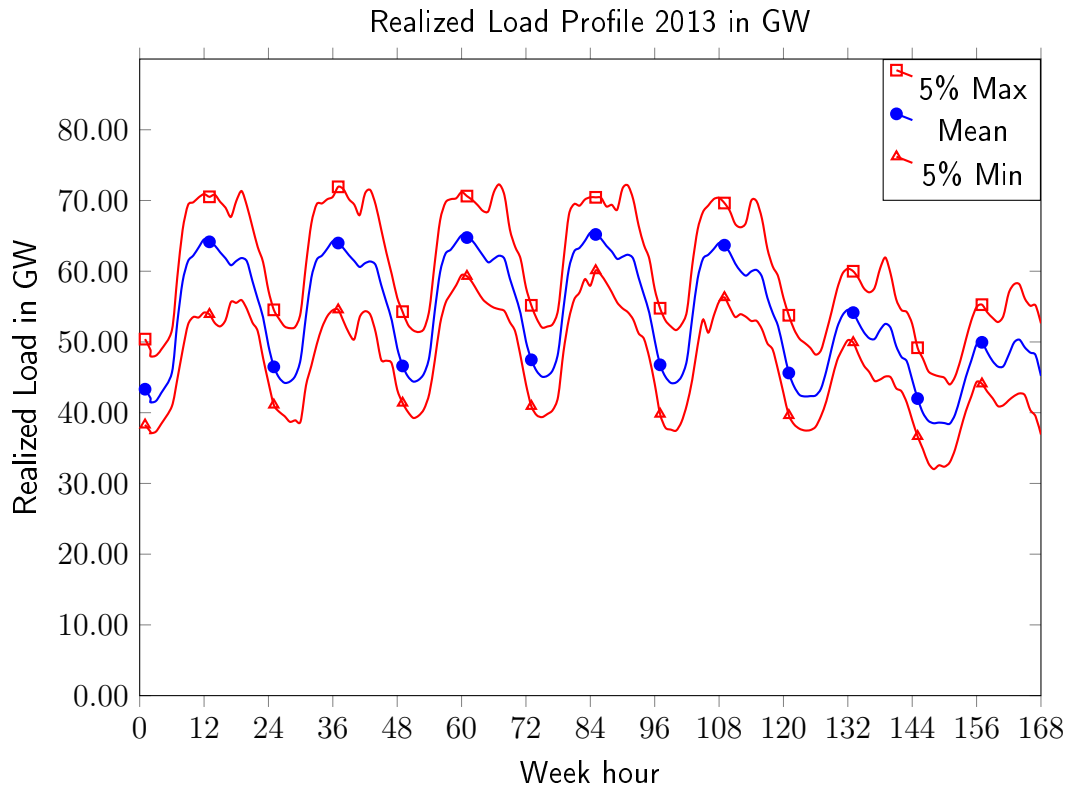


Figure 2.39: Realized Week Load Profile 2013

actually realized demand for every hour and day in 2013 have to be computed. The qualities of day-ahead forecasts is evaluated by analyzing histograms for weekdays, weekends and total weeks separately, since due to heterogeneous demand levels a separate evaluation might be necessary.

Figure 2.40 gives a histogram of day-ahead forecast error of load for all weekdays in 2013. Mean day-ahead forecast error was 0.34 GW, which means that on average day-ahead forecasted demand exceeded realized demand in 2013. Standard deviation of day-ahead forecast error was 2.21 GW. A normal distribution that uses these values as parameters is plotted additionally. Day-ahead-forecast error seems to be (approximately) normally distributed, since no fundamental differences of the histogram and a normal distribution can be found. Nevertheless, two interesting points can be seen: Firstly, there are more realizations between -0.5 GW and 0.5 GW than a normal distribution would suggest, which could be seen as a consequence of good forecast quality. However, day-ahead forecast error of demand has rather a large standard deviation, which for 4.5% of all the observations leads to a day-ahead forecast error of more than 4 GW and for 1.5%

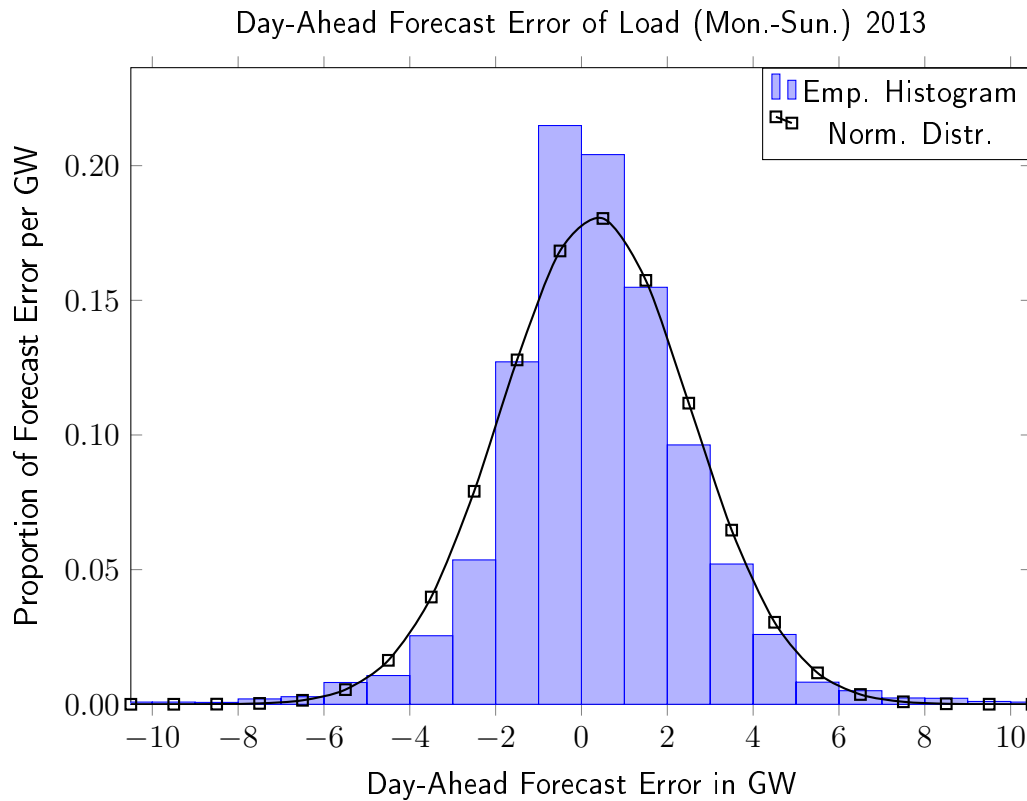


Figure 2.40: Day-Ahead Forecast Error of Load (Mon.-Sun.) 2013

for a day-ahead forecast error of more than -4 GW. Compared to the day-ahead forecast errors of feed-in from renewable energies extremal forecast errors rather often emerge.

Figure 2.41 presents the histogram of weekday day-ahead forecast error in 2013. On average day-ahead forecast error was 0.09 GW and standard deviation was 2.07 GW. This means, day-ahead forecast was better for weekdays than for a total week, since mean and standard deviation of day-ahead forecast error were lower for weekdays than for all days of the week. Again a normal distribution with mean and standard deviation of day-ahead forecast error is plotted additionally. Large positive day-ahead forecast errors exceeding 4 GW were realized for 4.1% of all observations, while large negative day-ahead forecast errors, exceeding -4 GW in amount, were realized for only 1.0% of all observations. Realizations between -0.5 GW and 0.5 GW more often occurred than a normal distribution would suggest. This leads to a more leptokurtic shape of the distribution for day-ahead forecast error.

Figure 2.42 shows the histogram of day-ahead forecast error for weekend days in 2013. On average day-ahead forecast error was 0.84 GW and standard deviation was 2.39 GW.

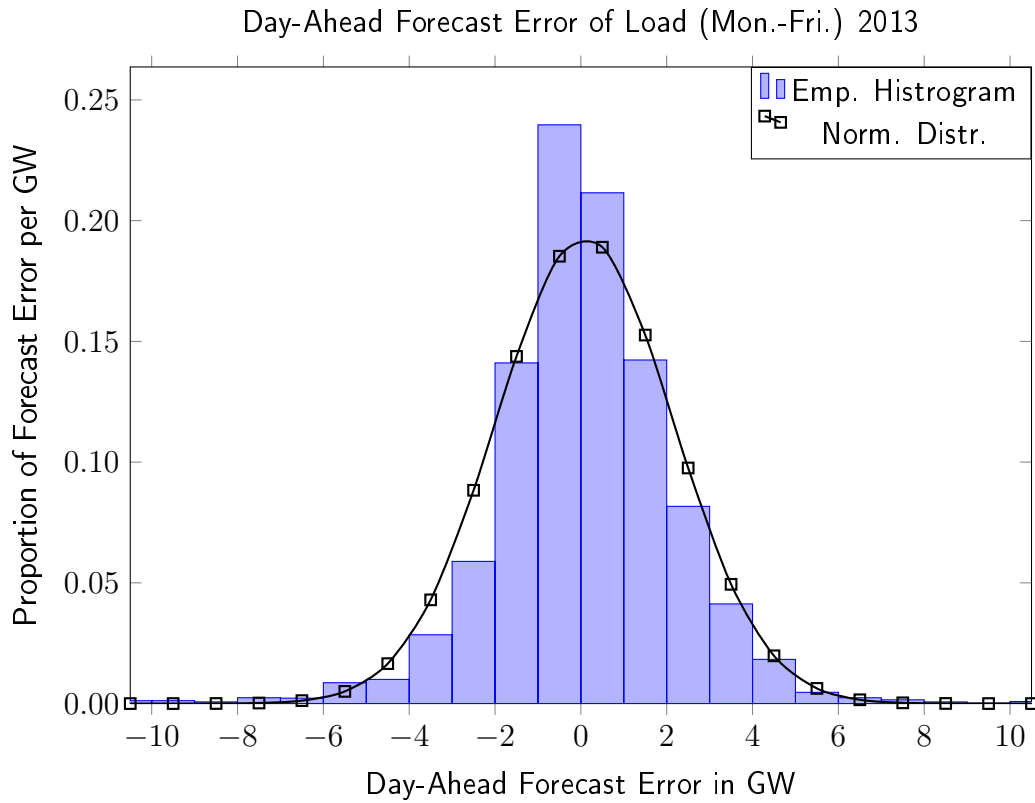


Figure 2.41: Day-Ahead Forecast Error of Load (Mon.-Fri.) 2013

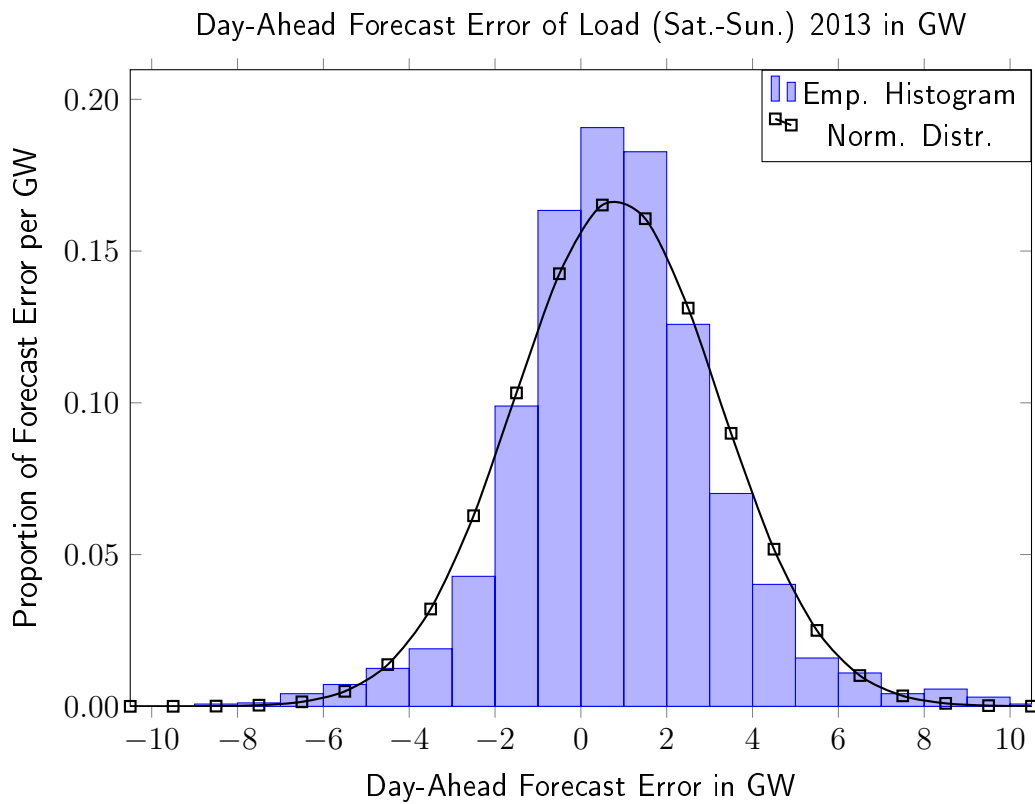


Figure 2.42: Day-Ahead Forecast Error of Load for Weekends 2013

Again normal distribution with the corresponding mean and standard deviation is plotted. Large positive day-ahead forecast errors exceeding 4 GW were realized for 8.1% of observations, while large negative day-ahead forecast errors exceeding in amount -4 GW occurred for 2.5% of realizations. All this shows that day-ahead forecast quality for demand on weekends was rather low compared to forecasts for workdays. Its mean forecast and standard deviation exceeded corresponding values calculated for workdays. Day-ahead forecast errors, which exceeded in amount 4 GW, were realized more often, too.

The analysis of the load profile for demand on a weekly basis mainly leads to two insights: Firstly, for each workday on average a similar pattern of demand is realized, with an increase of demand in the morning and a decrease of demand in the evening. On weekends the similar pattern is realized on a lower level. Secondly, on average day-ahead forecasts of demand may give a good estimation of actually realized demand. However, relatively large forecast errors can occur for individual forecasts.

2.3.2 Weekly Demand for Conventional Load

Electricity generated by solar and wind energy is fed into the German grid irrespective of the wholesale price, since according to the "Erneuerbare Energien Gesetz" subsidies for renewable energies lead to a total remuneration for suppliers, which is completely independent of the wholesale price. Thus, demand that has to be served on the wholesale market is reduced by exactly the same amount of wind and solar feed-in into the German grid. The difference of electricity demand and feed-in of renewable energies can be seen as the load, which has to be generated by conventional power plants. It determines the wholesale electricity price by meeting its supply curve. This necessary conventional load is calculated by deducting feed-in data for renewable energies provided by German transmission system operators and European Energy Exchange from demand data provided by ENTSO-E.

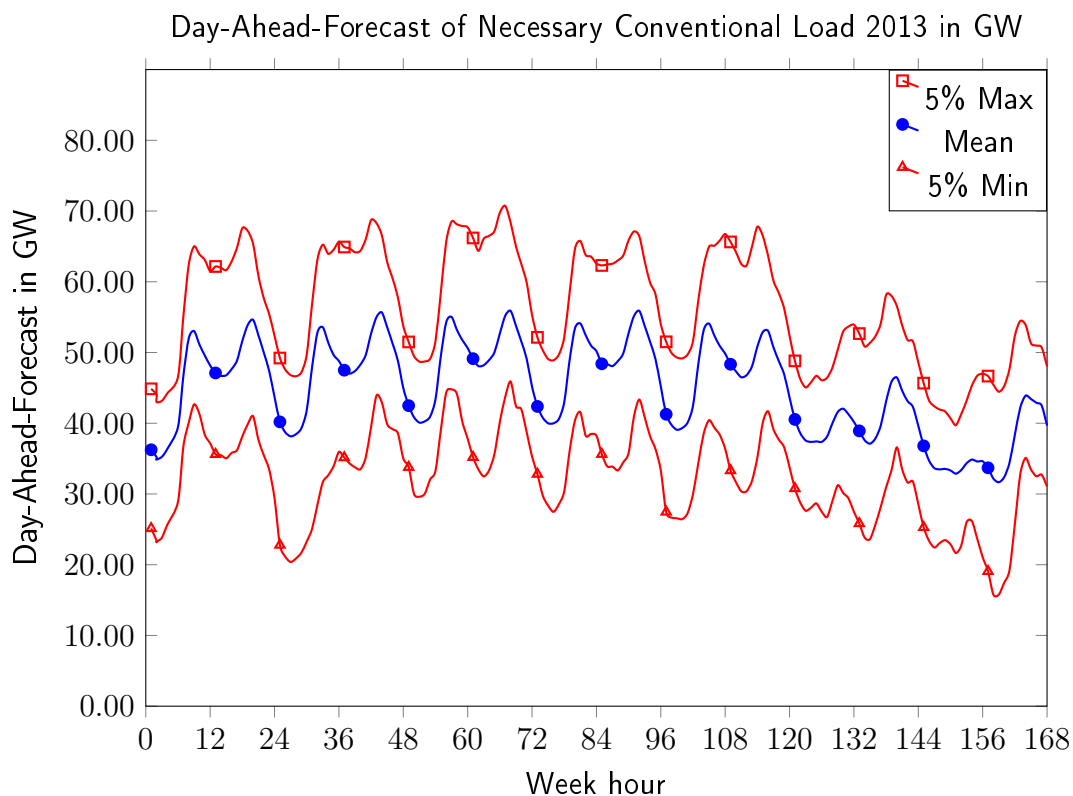


Figure 2.43: Day-Ahead-Forecast of Necessary Conventional Load 2013

Figure 2.43 shows day-ahead forecast of necessary conventional load in 2013, which is calculated by deducting day-ahead forecast of renewable energies supply from day-ahead forecast of electricity demand. Comparing this forecast for necessary conventional load

to the demand profile plotted in figure 2.38 three important findings should be pointed out:

Firstly, on average feed-in of renewable energies leads to a down-shift of necessary conventional load compared to the classical demand profile. As shown in figure 2.28 for example feed-in of electricity generated by wind turbines does not follow any time pattern. On average this leads to a constant downshift of necessary conventional load of round about 5.5 GW.

Secondly, the daily pattern of necessary conventional load is different from a classical demand profile, since feed-in of electricity generated by solar energy does follow a clear pattern as has been shown for example in figure 2.23. This pattern eliminates noon demand peak between 12:00 hrs and 14:00 hrs, since at this time the feed-in of solar energy has its maximum. However, this pattern of solar energy feed-in leads to two new daily peaks for necessary conventional load, which occur in the morning between 09:00 hrs and 10:00 hrs as well as in the evening between 19:00 hrs and 20:00 hrs. The explanation can easily be given, since in the early morning hours feed-in of solar energy is increasing more slowly than demand for electricity. Thus, the former noon peak is shifted for round about 3 hrs. In the evening between 19:00 hrs and 20:00 hrs solar feed-in does not significantly contribute to renewable energy feed-in. Thus, solar feed-in does not significantly reduce the evening peak and only (time independent) the feed-in of wind energy reduces the necessary conventional load. This leads to a daily maximum of necessary conventional load between 19:00 hrs and 20:00 hrs.

Thirdly, the interval, which is stretched by maximum 5 % and minimum 5 % necessary conventional load, is considerably increased. In order to explain the pattern of these extremal values it is very helpful to keep the weekly pattern of renewable energy feed-in presented in figure 2.33 in mind. For 5 % of observations calm and windless night hours lead to a renewable energies feed-in of round about 1 GW only. At noon renewable energy feed-in for 5 % of observations results in round about 5 GW or less. Thus, the 5 % upper bound of necessary conventional load is time-dependent shifting between 1 GW and 5 GW. In contrast, during windy nights for 5 % of the observations a renewable energy feed-in of between 12 GW and 20 GW can be found. At noon, common feed-in for 5 % of the observations leads to a renewable energy feed-in of between 25 GW and 30 GW.

Thus, the 5 % lower bound of necessary conventional load is time-dependent shifting by between 12 GW and 30 GW. The interval stretched by the maximum and minimum 5% of necessary conventional load is enlarged asymmetrically.

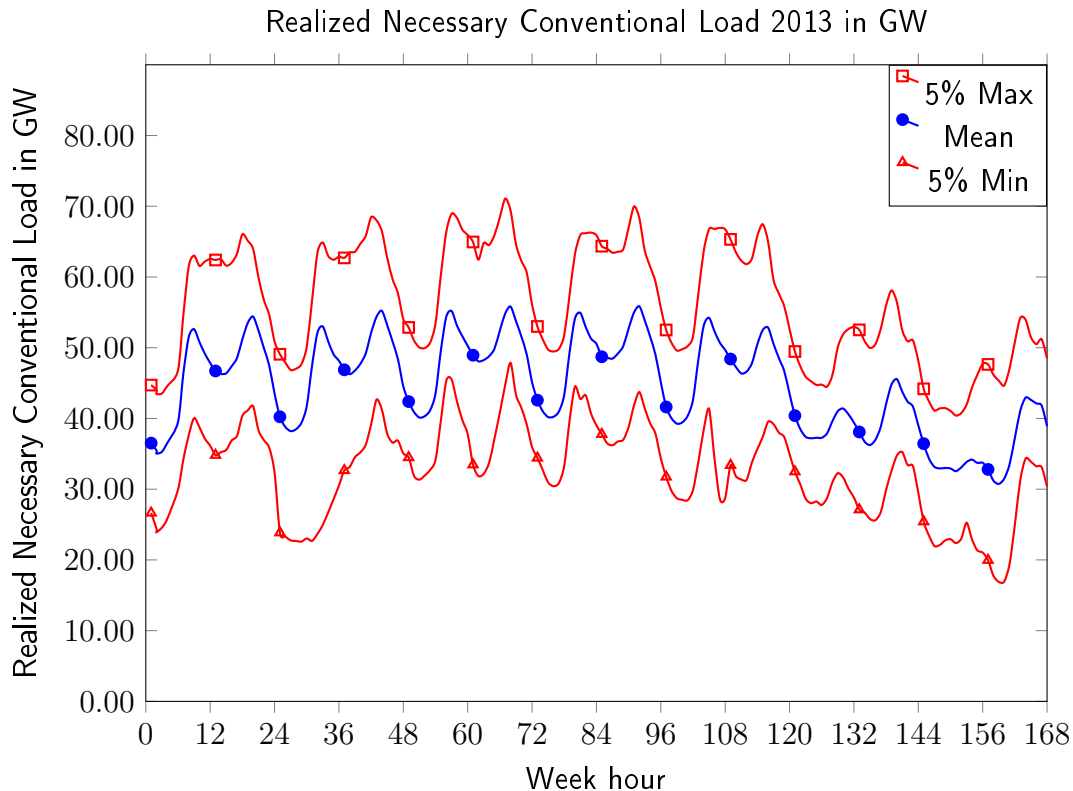


Figure 2.44: Realized Necessary Conventional Load 2013

Figure 2.44 shows the actually realized necessary conventional load in 2013, which is calculated by deducting realized renewable energies supply from realized demand for electricity. This profile of the actually realized necessary conventional load does not fundamentally differ from its forecast illustrated in figure 2.43. However, all values for necessary conventional load are mean or 5% boundary values. Thus, to analyze forecast quality direct differences of day-ahead forecast of necessary conventional load and the actually realized conventional load for every hour and day in 2013 have to be computed. The quality of day-ahead forecast is evaluated by analyzing histograms for weekdays, weekend and a total week separately, since due to heterogeneous demand levels separating evaluation might be necessary.

Figure 2.45 shows the empirical histogram of day-ahead forecast error for necessary conventional load, which is found by deducting realized necessary conventional load from

day-ahead forecast of necessary conventional load. Data for all days of a week is taken into account. In 2013 the mean day-ahead-forecast error was close to zero (-0.005 GW) and standard deviation of day-ahead forecast error has been 2.50 GW. Thus, on average forecast of conventional necessary load is good. However, high forecast errors of more than 4 GW account for 4.8 % and high forecast errors leading to less than -4 GW account for 5.1%. The highest positive day-ahead forecast error in 2013 was 17.6 GW and the highest negative forecast error was -12.3 GW. Hence, in few cases forecasted and realized necessary conventional load differ distinctly. A normal distribution that has a mean and standard deviation according to values estimated in 2013 is plotted. Comparing the empirical histogram to this normal distribution suggests a more leptokurtik distribution for day-ahead forecast errors, since day-ahead forecast errors between -1 GW and 1 GW are more often realized than a normal distribution would suggest.

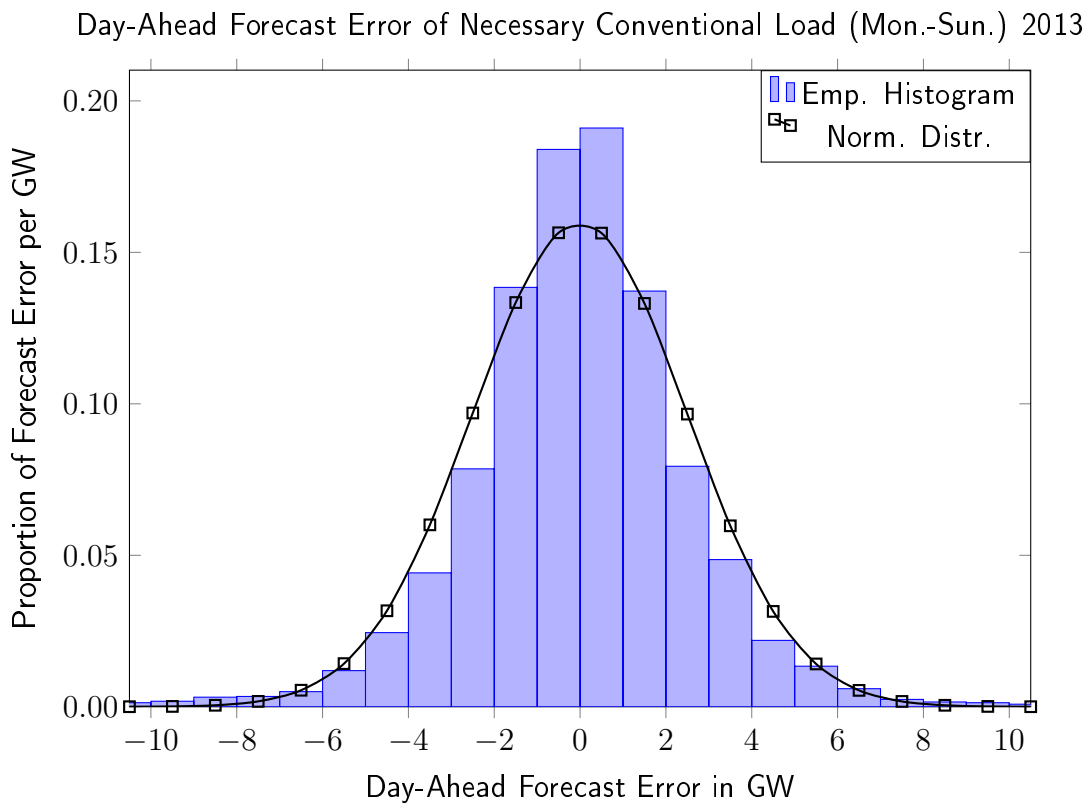


Figure 2.45: Day-Ahead Forecast Error of Necessary Conventional Load (Mon.-Sun.) 2013

Figure 2.46 shows the empirical histogram of day-ahead forecast error for necessary conventional load, which is found by deducting realized necessary conventional load from day-ahead forecast of necessary conventional load. Only data for working days (Mon.

-Fri.) is taken into account. In 2013 mean day-ahead forecast error has been negative (-0.22 GW) and standard deviation of day-ahead forecast error has been 2.46 GW for work days. Thus, on average the forecast of necessary conventional load was below actual realization of necessary conventional load. Large positive day-ahead forecast errors of more than 4 GW are realized for 4.0 % of observations and large negative day-ahead forecast errors are realized for 5.8% of observations. The highest positive day-ahead forecast error was 17.57 GW and the highest negative day-ahead forecast error was -12.3 GW. Again, large differences of day-ahead forecast error and realized necessary conventional load can occur.

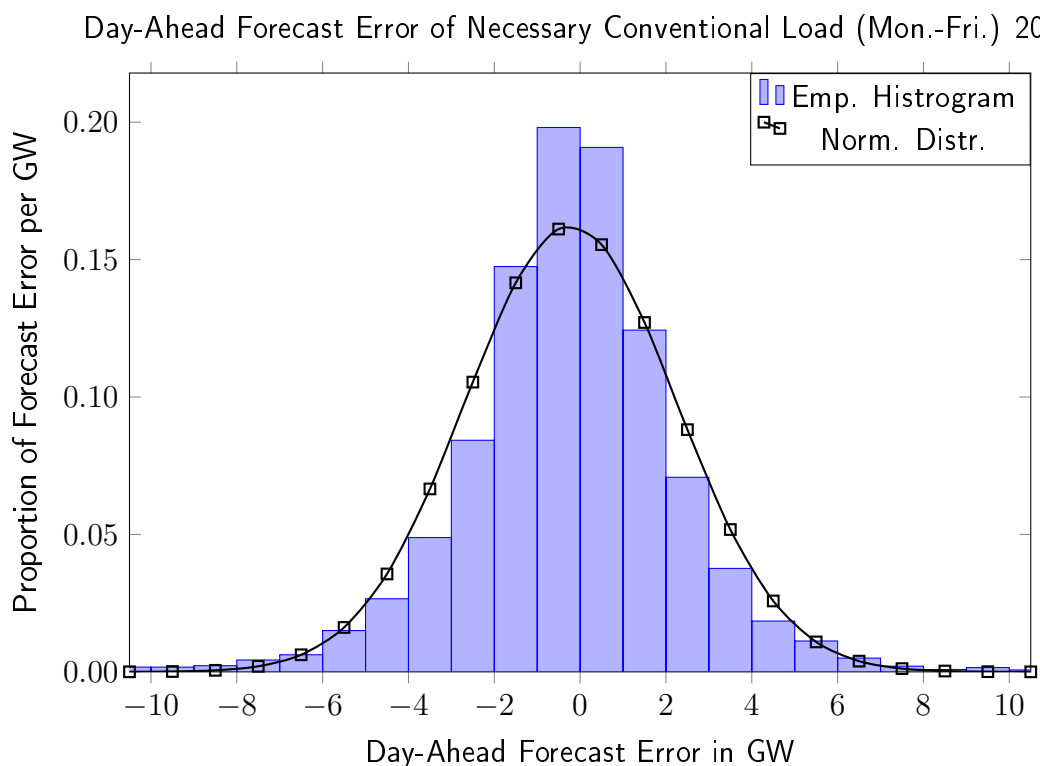


Figure 2.46: Day-Ahead Forecast Error of Necessary Conventional Load (Mon.-Fri.) 2013

Figure 2.47 shows the empirical histogram of day-ahead forecast error for necessary conventional load. This is found by deducting realized necessary conventional load from day-ahead forecast of necessary conventional load. Only data for weekend days (Sat. - Sun.) is taken into account. In 2013 the mean day-ahead forecast error was positive (0.5 GW) and standard deviation of day-ahead forecast error has been 2.522 GW for work days. Thus, on average forecast of necessary conventional load was above actual real-

ization of necessary conventional load. Large positive day-ahead forecast errors of more than 4 GW are realized for 3.5 % and large negative day-ahead forecast errors are realized for 6.6 % of all observations. The highest positive day-ahead forecast error was 16.6 GW and the highest negative day-ahead forecast error was -10.3 GW. Again, large differences of day-ahead forecast error and realized necessary conventional load can occur.

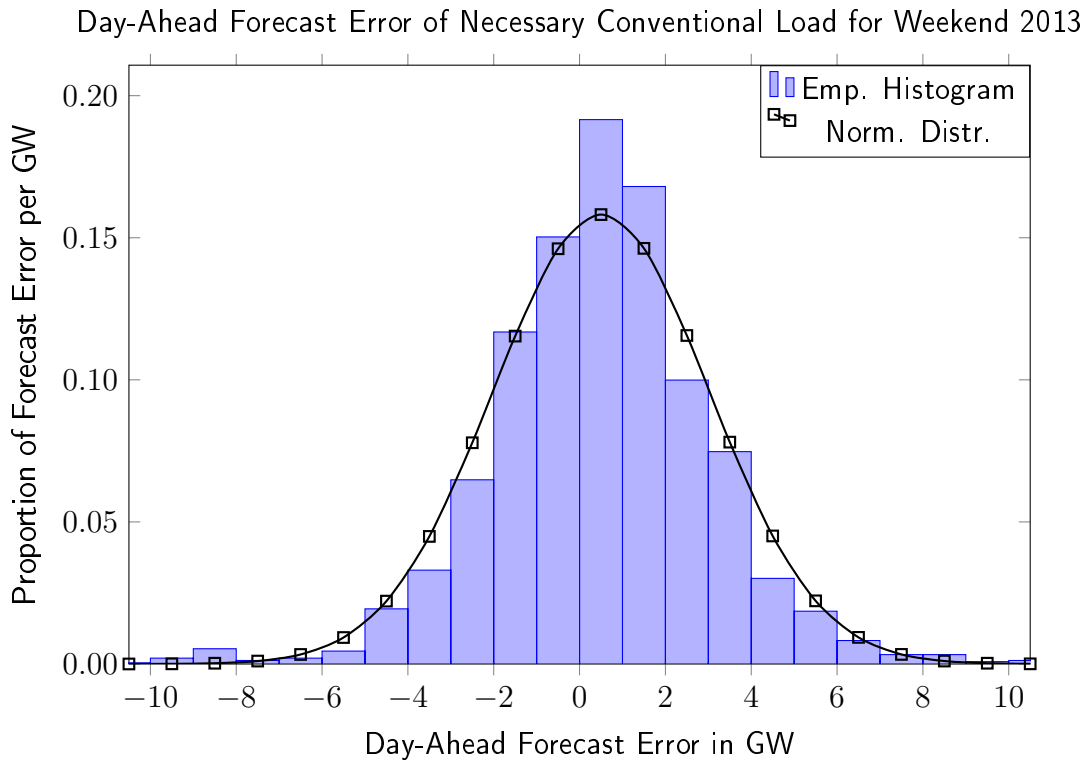


Figure 2.47: Day-Ahead Forecast Error of Necessary Conventional Load for Weekend 2013

The analysis of day-ahead forecast errors of necessary conventional load can be summarized as follows: On average day-ahead forecasts give a good estimation of electricity demand that has to be generated by conventional (coal, nuclear or gas) power plants. However, even on preceding days this necessary conventional load cannot be estimated exactly, which for few days leads to severe coordination problems. Transmission system operators approach this problem by using control energy. If the feed-in of electricity is too high, transmission operators forbid suppliers to deliver electricity and compensate their losses by market prices. If on the other hand feed-in of electricity is too low, e.g. gas plants are forced to supply electricity and are compensated for their costs. The costs for controlling feed-in fluctuations are financed by a levy that is added to the price paid by

the end-consumers.

Serial Correlation of Demand for Conventional Load

When analyzing strategic pricing on the German electricity market, it is important to keep in mind the three most important properties of demand for electricity. Firstly, demand for electricity shows a clear daily pattern. Secondly, demand for electricity differs significantly for working days and weekends. Thirdly, due to weather conditions and consumer behavior demand for electricity is likely to be serially correlated over time.

To answer the question to what extent demand for electricity is serially correlated over time, one must remember the trading rules of the day-ahead auction on the EPEX SPOT. As presented in table 2.5 prices and quantities offered for trading have to be registered until 12:00 (noon) for each trading block of the next day into the EPEX SPOT order system. After that EPEX SPOT sets up for each trading block a day-ahead spot market price to clear the market and the highest price bid, which is just suitable to meet demand, is taken as the market price for the corresponding trading block. Thus, market participants have to give their offer for a vector of 24 prices and quantities until 12:00 (noon) of the previous day. Thus, for strategic price decisions on the day-ahead spot market implications of daily patterns are less important than implications coming from serial correlation for different days.

The time series of demand for conventional electricity is taken to analyze serial correlation, since renewable energy feed-in does decrease demand for electricity available for price setting firms. For each of the 24 trading blocks a separate time series for 2013 is computed, since otherwise calculations of correlation would be misleading due to the deterministic daily pattern. This is done for day-ahead forecasted demand for conventional load, which is given by ENTSO-E day-ahead forecast for demand less EEX day-ahead forecast of renewable energies feed-in. This is done for the actually realized demand for conventional load, which is given by ENTSO-E realized demand less realized feed-in of renewable energies additionally. For each of the 48 time series of demand for conventional serial correlation for the first three lags is computed. For example, correlation of the first lag means the correlation for a realization in t and $t - 1$ for all t (except for first day and last day due to missing predecessor and successor). Correlation of second lag

means the correlation for a realization in t and $t - 2$ for all t (except for first two days and last two days due to missing predecessors and successors).

Table 2.10 shows serial correlation for morning hours on a weekday as well as the mean of all correlations of the morning, whereas table 2.11 shows serial correlation for weekday evening hours. For the first lag of the forecasted necessary conventional load time series serial correlation for hours one to six, when due to the daily pattern demand for electricity is low, is about 0.55. After that, serial correlation is increasing from 0.61 at hour 7 to 0.71 at hour 12. On average first lag serial correlation for morning hours is given by 0.62. For the second lag of forecasted necessary conventional load time series serial correlation is increasing from 0.27 at hour 1 to 0.58 at hour 12. On average second lag serial correlation for morning hours is given by 0.41. For the third lag of forecasted necessary conventional load time series serial correlation is increasing from 0.19 at hour 1 to 0.53 at hour 12. On average third lag serial correlation for morning hours is given by 0.35.

For the first lag of the realized necessary conventional load time series serial correlation for hours one to six, is about 0.65. After that, serial correlation is increasing up to 0.70 at hour 12. On average first lag serial correlation for morning hours is given by 0.66. For the second lag of realized necessary conventional load time series serial correlation is increasing from 0.42 at hour 1 to 0.59 at hour 12. On average second lag serial correlation for morning hours is given by 0.49. For the third lag of realized necessary conventional load time series serial correlation is increasing from -0.06(!) at hour 1 to 0.52 at hour 12. On average third lag serial correlation for morning hours is given by 0.38.

For the first lag of the forecasted necessary conventional load time series serial correlation for hours thirteen to nineteen is about 0.70 and rather stable. For hours 20 to 24, where demand is smaller than at noon, serial correlation is decreased to about 0.60. On average first lag serial correlation for midday and evening is given by 0.66. For the second lag of the forecasted necessary conventional load time series serial correlation for hours thirteen to nineteen is about 0.57 and rather stable. For hours 20 to 24, when demand is smaller than at noon, serial correlation is decreased to about 0.35. On average second lag serial correlation for midday and evening is given by 0.48. For the third lag of the forecasted necessary conventional load time series serial correlation for hours thirteen to

Trading Block	Forecasted Load			Realized Load		
	Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3
1	0.53	0.27	0.19	0.64	0.42	-0.06
2	0.54	0.28	0.20	0.63	0.43	0.32
3	0.55	0.30	0.21	0.63	0.43	0.33
4	0.55	0.30	0.21	0.62	0.42	0.33
5	0.55	0.30	0.22	0.62	0.42	0.33
6	0.56	0.31	0.24	0.65	0.44	0.35
7	0.61	0.38	0.32	0.68	0.49	0.41
8	0.67	0.48	0.43	0.70	0.53	0.48
9	0.71	0.55	0.53	0.70	0.55	0.52
10	0.73	0.59	0.56	0.70	0.58	0.54
11	0.72	0.58	0.56	0.69	0.59	0.54
12	0.71	0.58	0.53	0.70	0.59	0.52
Mean	0.62	0.41	0.35	0.66	0.49	0.38

Table 2.10: Serial Correlation of Demand for Conventional Load on Weekdays (0-12 hrs)

Trading Block	Forecasted Load			Realized Load		
	Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3
13	0.72	0.57	0.54	0.71	0.58	0.54
14	0.71	0.57	0.54	0.69	0.58	0.53
15	0.72	0.57	0.55	0.71	0.59	0.55
16	0.70	0.57	0.53	0.71	0.60	0.55
17	0.69	0.56	0.52	0.70	0.60	0.55
18	0.71	0.58	0.54	0.72	0.60	0.57
19	0.68	0.53	0.47	0.70	0.57	0.52
20	0.62	0.42	0.36	0.65	0.48	0.42
21	0.58	0.34	0.26	0.62	0.42	0.36
22	0.57	0.34	0.26	0.63	0.43	0.34
23	0.59	0.36	0.31	0.68	0.49	0.41
24	0.60	0.38	0.33	0.70	0.53	0.44
Mean	0.66	0.48	0.43	0.68	0.54	0.48

Table 2.11: Serial Correlation of Demand for Conventional Load on Weekdays (13-24 hrs)

nineteen is about 0.55 and rather stable. For hours 20 to 24, when demand is smaller than at noon, serial correlation is decreased to about 0.30. On average third lag serial correlation for midday and evening is given by 0.43.

For the first lag of the realized necessary conventional load time series serial correlation for hours thirteen to nineteen is about 0.70 and rather stable. For hours 20 to 24 serial correlation is decreased to about 0.65. On average first lag serial correlation for midday and evening is given by 0.68. For the second lag of the realized necessary conventional load time series serial correlation for hours thirteen to nineteen is about 0.60 and rather stable. For hours 20 to 24, when demand is smaller than at noon, second lag serial correlation is decreased to about 0.35. On average second lag serial correlation for midday and evening is given by 0.54. For the third lag of the forecasted necessary conventional load time series serial correlation for hours thirteen to nineteen is about 0.55 and rather stable. For hours 20 to 24, when demand is smaller than at noon, serial correlation is decreased to about 0.37. On average third lag serial correlation for midday and evening is given by 0.48.

Table 2.12 shows serial correlation for the time series of forecasted and realized necessary conventional load for morning hours on weekend days (Saturday and Sunday) as well as the mean of all correlations of the morning, whereas table 2.13 shows serial correlation for the time series of forecasted and realized necessary conventional load for weekend evening hours.

For the time series of forecasted necessary conventional load the first lag serial correlation is about 0.30 for hours 1 to 5. It decreases to 0.17 for hour 8 and then increases to 0.50 for hour 12. The mean first lag serial correlation for hours 1 to 12 is given by 0.30. The second lag serial correlation is larger, since for trading hours 1 to 7 second lag serial correlation is about 0.45 and then increases to about 0.63 for hours 9 to 12 and mean second lag serial correlation is given by 0.51. At first glance this seems to be rather strange. At second glance this result becomes clear, since weekend time series consists of Saturday and Sundays, with different patterns of demand for electricity. A serial correlation being higher for the second lag compared to the first lag just means that the daily component is larger than the weekly component of demand for electricity. The third lag serial correlation is rather small for most trading hours, which means that e.g. forecasted

Trading Block	Forecasted Load			Realized Load		
	Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3
1	0.30	0.46	0.12	0.39	0.46	0.11
2	0.31	0.44	0.10	0.37	0.44	0.07
3	0.31	0.43	0.09	0.38	0.44	0.06
4	0.29	0.43	0.09	0.37	0.47	0.06
5	0.28	0.40	0.10	0.36	0.47	0.05
6	0.25	0.40	0.09	0.36	0.49	0.08
7	0.17	0.46	0.03	0.25	0.54	0.01
8	0.17	0.57	0.07	0.25	0.61	0.06
9	0.23	0.64	0.14	0.31	0.67	0.19
10	0.32	0.65	0.22	0.40	0.68	0.30
11	0.40	0.64	0.28	0.45	0.67	0.33
12	0.50	0.62	0.36	0.50	0.64	0.37
Mean	0.30	0.51	0.14	0.37	0.55	0.14

Table 2.12: Serial Correlation of Demand for Conventional Load on Weekends (0-12 hrs)

Trading Block	Forecasted Load			Realized Load		
	Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3
13	0.55	0.61	0.41	0.53	0.65	0.40
14	0.54	0.59	0.40	0.52	0.65	0.42
15	0.53	0.58	0.39	0.52	0.66	0.42
16	0.51	0.60	0.40	0.53	0.68	0.44
17	0.51	0.61	0.43	0.54	0.72	0.47
18	0.53	0.64	0.45	0.55	0.74	0.51
19	0.51	0.59	0.39	0.53	0.69	0.49
20	0.44	0.44	0.26	0.45	0.58	0.39
21	0.44	0.32	0.18	0.45	0.48	0.31
22	0.46	0.30	0.18	0.49	0.47	0.33
23	0.51	0.37	0.27	0.52	0.06	0.39
24	0.51	0.38	0.30	0.56	0.53	0.45
Mean	0.50	0.50	0.34	0.51	0.57	0.42

Table 2.13: Serial Correlation of Demand for Conventional Load on Weekends (13-24 hrs)

demand for conventional electricity on Saturday of week 1 is almost uncorrelated with forecasted demand for conventional electricity in week 2 .

For the time series of realized necessary conventional load a similar pattern of serial correlation can be seen. The first lag serial correlation for realized necessary conventional load is about 0.37 for hours 1 to 5. After a decrease to 0.25 at hour 8 serial correlation increases to 0.50 at hour 12. On average serial correlation is given by 0.37. Again, the second lag serial correlation is larger than first lag serial correlation, since it is about 0.45 for hours 1 to 5 and about 0.65 for hours 8 to 12 and on average second serial correlation is about 0.55. The third lag serial correlation is rather small, which again means that necessary conventional load on morning hours is almost unrelated for a Saturday and Sunday not belonging to the same weekend.

Serial correlation of necessary conventional load for weekend evening hours shows a slightly different pattern. The first lag serial correlation of forecasted necessary conventional load is about 0.52 for hour 13 to 19. After a decrease to 0.44 for hour 21 serial correlation increases to 0.51 at hour 24 again. The average first lag serial correlation is 0.50. The second lag serial correlation is about 0.60 for hour 13 to 19 and decreases to 0.38 at hour 24. The average serial correlation is given by 0.50. The third lag serial correlation is about 0.40 for hours 13 to 19. It decreases to 0.18 for hour 22 and increases to 0.30 for hour 24. The average third lag serial correlation is given by 0.34.

The first lag serial correlation of realized necessary conventional load is about 0.53 for hour 13 to 19. After a decrease to 0.45 for hour 21 serial correlation increases to 0.56 at hour 24 again. The average first lag serial correlation is 0.51. The second lag serial correlation is about 0.68 for hour 13 to 19 and decreases to 0.53 at hour 24. For hour 23 it is 0.06, which means there is no correlation. The average second lag serial correlation is given by 0.57. The third lag serial correlation is about 0.45 for hours 13 to 19. It decreases to 0.31 for hour 21 and increases to 0.45 for hour 24. The average third lag serial correlation is given by 0.42.

In general serial correlation seems to be higher for times of strong demand for electricity. The serial correlation of weekday time series is decreasing with a higher lag. For the weekend time series the second lag is very important, since serial correlation is rather strong. This is due to different demand patterns on Saturdays and Sundays, which espe-

cially for morning hours seem to be stronger than the weekly pattern. Another interesting point is that serial correlation of forecasted necessary conventional load is usually below serial correlation of realized necessary conventional load. Both time series show up a clear mean reversion, since even the highest calculated values of serial correlation do not exceed 0.75. Thus, the time series of demand for conventional electricity can be computed by statistical standard methods and procedures such as cointegration have not to be applied. The serial correlation is decreasing rather fast. This means fluctuations can be seen as rather transitory instead of persistent.

2.3.3 Conventional Load and Day-Ahead Spot Prices

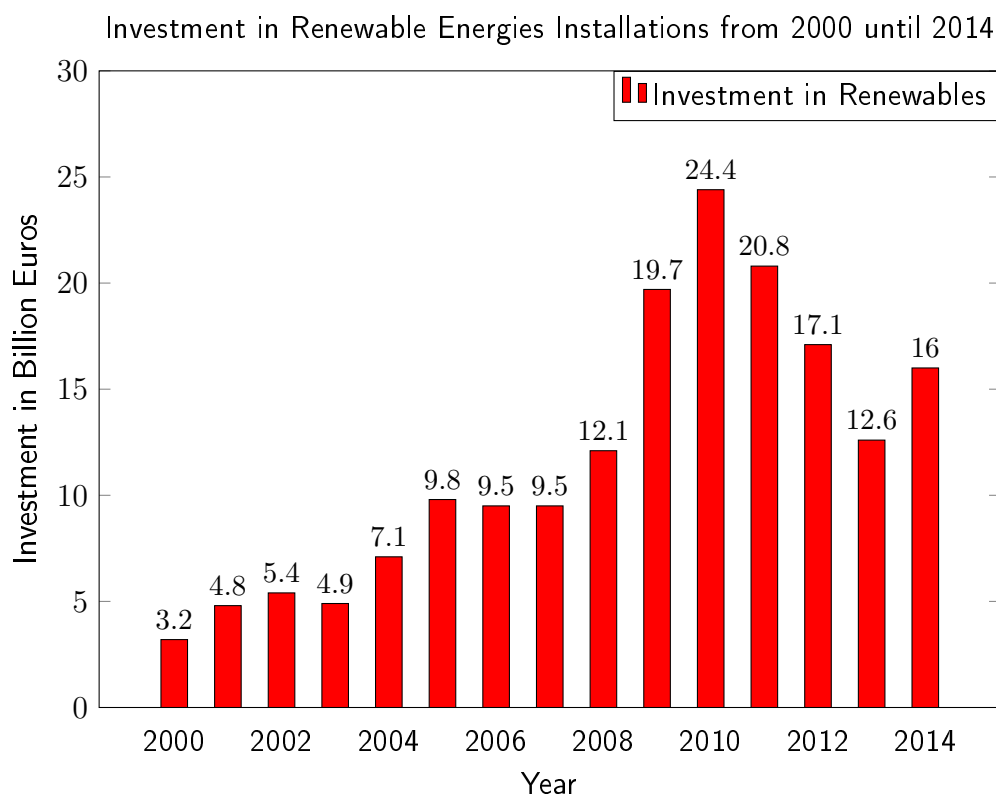


Figure 2.48: Forecasted Necessary Conventional Load and EPEX SPOT Day-Ahead Spot Price

In order to analyze the relationship between necessary conventional load and EPEX SPOT day-ahead spot prices a scatter plot is used. More precisely speaking, a scatter plot for forecasted necessary conventional load and the corresponding EPEX SPOT day-ahead spot price as well as a scatter plot for realized necessary conventional load and the corresponding EPEX SPOT day-ahead spot price is drawn.

Figure 2.48 shows the relationship between forecasted necessary conventional load and the EPEX SPOT day-ahead spot price. In general a linear relationship between forecasted necessary load and the EPEX SPOT day-ahead spot price can be found. However, the range of possible combinations is rather wide. For values of the forecasted necessary conventional load below 30 GW there appear outliers from this linear relationship. This can be seen by a minimal day-ahead price of -100.03 €/MWh that appears together with a forecasted necessary conventional load of 19.08 GW. In contrast the minimal forecasted necessary conventional load of 17.43 GW appears together with a day-ahead spot price of 9.77 €/MWh.

A slightly larger forecasted necessary conventional load of 17.89 GW has led to a price of 20.19 €/MWh and a forecasted necessary conventional load of 18.24 GW has led to a price of 29.41 €/MWh. Especially for forecasts of the necessary conventional load below 20 GW, a simple (e.g. linear) relationship between day-ahead spot price and necessary conventional load cannot be found. For a forecasted necessary conventional load between 30 GW and 45 GW the linear relationship does not show any real outliers. For forecasts of necessary conventional load above 50 GW again several outliers occur. For example, in 2013 the maximal price was 130.27 €/MWh. This price was realized for a forecasted necessary conventional load of only 50.19 GW. In contrast the maximally forecasted necessary conventional load was more than 20 GW above (71.61 GW) but has led to a lower day-ahead price of 87.94 €/MWh. Outliers for large forecasts of necessary conventional load deviate rather positively. This means that the EPEX SPOT day-ahead spot price, compared to the value a linear relationship would suggest for the corresponding forecasted necessary conventional load, is higher. On average forecasted necessary conventional load in 2013 was 44.48 GW and on average EPEX SPOT day-ahead spot price was 37.78 €/MWh.

For any forecasted necessary conventional load between 30 GW and 45 GW the linear relationship does not show any real outliers. For forecasts of necessary conventional load above 50 GW again several outliers occur. For example, in 2013 the maximal price was 130.27 €/MWh. This price was realized for a forecasted necessary conventional load of only 50.19 GW. In contrast the maximally forecasted necessary conventional load was more than 20 GW above (71.61 GW), but has led to a lower day-ahead price of

87.94 €/MWh. Outliers for large forecasts of necessary conventional load deviate rather positively. This means that the EPEX SPOT day-ahead spot price, compared to the value a linear relationship would suggest for the corresponding forecasted necessary conventional load, lies above.

Realized Necessary Conventional Load and EPEX SPOT Day-Ahead Spot Price

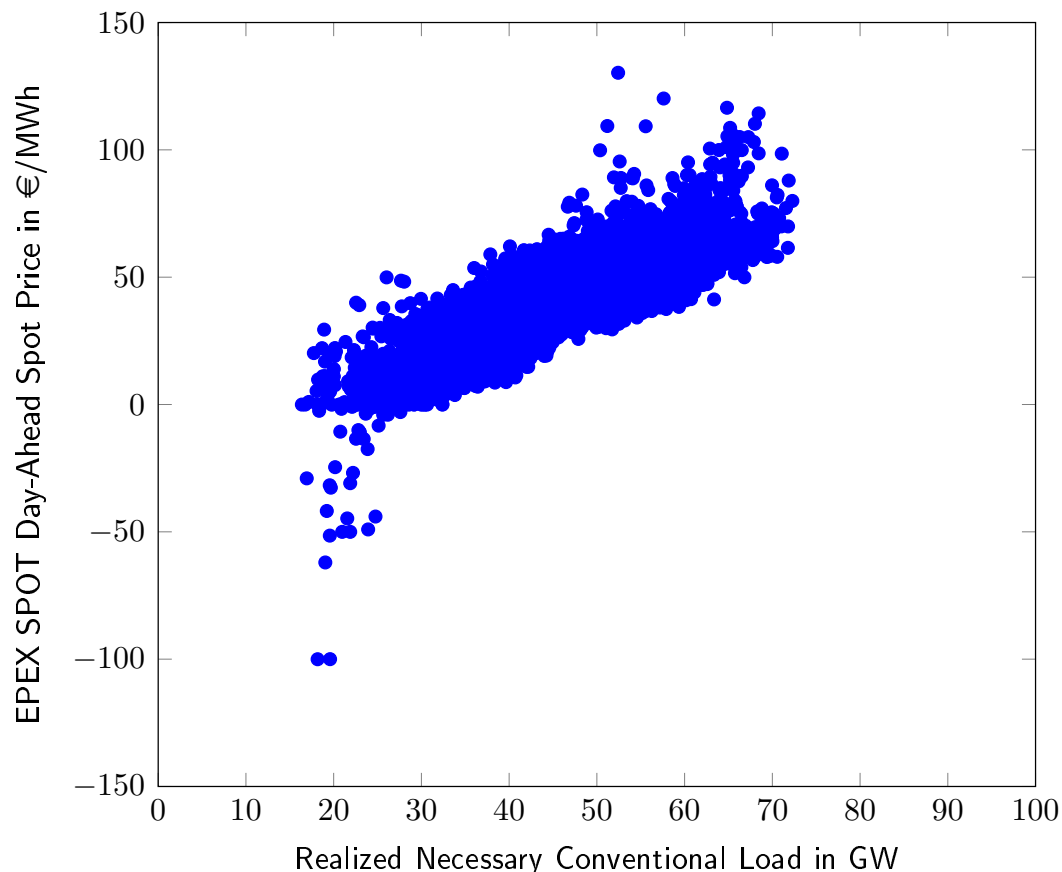


Figure 2.49: Realized Necessary Conventional Load and EPEX SPOT Day-Ahead Spot Price

Figure 2.49 shows the relationship between realized necessary conventional load and the EPEX SPOT day-ahead spot price. For a necessary conventional load between 30 GW and 50 GW a linear relationship describes the relationship between realized necessary load and the EPEX SPOT day-ahead spot price very well. This relationship does not fundamentally differ from the relationship between the EPEX SPOT day-ahead spot price and forecasted necessary conventional load, since e.g. the range of possible combinations is rather wide and especially for values of realized necessary conventional load below 25 GW outliers from this linear relationship appear.

For the maximal EPEX SPOT day-ahead spot price in 2013 of 130.27 €/MWh a necessary conventional load of 52.42 GW was realized. However, for the maximally realized necessary conventional load of 72.28 GW EPEX SPOT day-ahead spot price was "only" 79.94 €/MWh. For the minimal EPEX SPOT day-ahead spot price of -100.03 €/MWh a necessary conventional load of 18.17 GW was realized. However, for the minimally realized necessary conventional load of 16.37 GW EPEX SPOT day-ahead spot price was -0.03 €/MWh. These examples show again that especially for realized necessary conventional load below 25 GW and above 50 GW outliers occur.

The analysis of the influence of necessary conventional load can be summarized as follows: Firstly, in general a linear relationship of necessary conventional load and the EPEX SPOT day-ahead spot price exists. Secondly, this relationship applies to forecasted necessary conventional load as well as for realized necessary conventional load. Thirdly, outliers, which cannot be easily described by this linear relationship, mainly occur for small values of necessary conventional load below 25 GW or for large values of necessary conventional load above 50 GW.

Chapter 3

Forward Trading and Competitive Pressure

3.1 Introduction

As shown above, for the German electricity market the following market characteristics seem to be central: Few competitors due to high entry costs, a large market share that is sold either on the futures market or on over-the-counter markets and a large volatility on the demand as well as on the supply side. Stochastic influences play a central role in the German power market and are one of the main reasons for forward trading. Thus, a volatile market context is added to the existing economic literature (Liski and Montero, 2006) in order to gain a deeper insight into forward trading and collusion of firms. Of course, there are important other reasons than collusive behavior for forward trading in these markets, e.g. risk sharing. However, the common effect of large forward-traded amounts, volatility and (tacit) collusion of firms deserves a closer look.

The intuition behind the effect of forward trading on collusion is as follows: Firms fix a certain quantity at a certain price via forward trading. This induces two effects: On the one hand it decreases the demand available for a deviating firm. Here, the consequence of forward trading is pro-collusive. On the other hand, forward trading decreases the demand available for collusive price-setting. Here, the consequence of forward trading is contra-collusive. Liski and Montero (2006) and Green and Coq (2010) in a deterministic model show that especially short-term forward contracts are suitable to stabilize collusive agreements. As will be shown in the upcoming model, trading short-term forward contracts strictly promotes collusion in volatile markets, too. However, as will be pointed

out, trading more forward contracts than the respective monopoly quantity decreases the profits of colluding firms. This is a problem for colluding firms in a volatile market, especially when demand and cost parameters are continuously distributed, since firms cannot avoid having involuntarily contracted more than the corresponding monopoly quantity. This "over-contracting" leads to a decrease of the spot and forward market price and of the expected collusive profit.

The rest of this theoretical contribution is organized as follows:

Section 3.2 presents existing economic literature, that is suitable to describe strategic behavior on the German electricity market. The focus of this literature overview is on competition and collusive behavior as well as on economic consequences of forward trading. In section 3.3.1 the main assumptions of the model and some general remarks are presented. Then in section 3.3.3 the effects of forward trading on a collusive agreement are modeled for a volatile market structure. In section 3.3.4 each firm's expected profit is derived for any probability density function. Then an exponential distribution is used to show the profit decreasing effect of forward trading. Section 3.3.5 incorporates the possibility for firms to trade forward contracts while setting a price below the monopoly price. The properties of such a semi-collusive strategy are modeled for a two state distribution of cost and demand parameters. Section 3.3.6 analyzes the stability of a collusive agreement, when firms take a long position on the forward market. This means that firms are committed by forward contracts to buy their own production. Section 3.4 concludes.

3.2 Literature on Forward Trading and Competitive Pressure

The Economic Analysis of Anti-Competitive Pricing

There exist several approaches to analyze the competitiveness of a certain industry. One famous approach models the incentive to agree on a price above equilibrium price (tacitly). The main idea of such an agreement, which is referred to as collusion in economic literature, is a trade-off for repeatedly competing firms: On the one hand, a large incentive to set a price below the actual market price exists, since this can lead to additional demand and profit. On the other hand, this is followed by a price decrease of all competitors, since

they want to regain market shares and retaliate for deviation from the former market price. An exceptional survey of theoretical and empirical literature about collusion is provided by Feuerstein (2005).

The starting point for the discussion about collusive behavior of firms was the publication "A non-cooperative Equilibrium for Supergames" of Friedman (1971). In his pioneering work Friedman (1971) introduced the concept of a supergame, which was firstly able to describe strategic behavior in an endless sequence of "ordinary" games. Whenever a firm is undercutting a collusive price exceeding the competitive outcome, its opponent chooses a price to match this competitive outcome (forever). This strategy is called grim trigger strategy, since no return to the collusive outcome is possible. This basic concept of non-cooperative firms that compete over and over again and therefore incorporate future competitive pressure into the actual pricing decision, seems to describe the basic situation on the German electricity market. As has been shown above, on the German electricity market the demand for (conventional) electricity is fluctuating and shows a stochastic component. Thus, using the supergame concept according to Friedman (1971) as a starting point, seems promising, but has in any case to be augmented by demand fluctuations.

Green and Porter (1984) were the first to allow for changing market conditions in a supergame setting. These changing market conditions are modeled by identically distributed independent demand shocks. Each (tacitly) colluding competitor has information about its own price and market share. However, to what extent the actual market share depends on a boom or on a recession that affects all competitors a firm does not know. Firms cannot distinguish between a decrease in sales, which is triggered by a recession, or by a competitor that is undercutting a certain market price. Grim trigger strategy cannot be implemented and firms will have to decrease their common market price for a certain period of time, whenever sales have decreased. This is necessary to ensure price matching behavior, since otherwise undercutting any collusive market price would be too profitable. Thus, each recession induces a price war for a certain period of time.

Rotemberg and Saloner (1986) contributed to the economic literature by incorporating stochastic market conditions, too. The main difference to the work of Green and Porter (1984) comes from their assumption about observability, since Rotemberg and Saloner (1986) assume full observability of prices, marginal costs and the general economic

situation. This eliminates the requirement of price wars after a recession. In a boom temptation to undercut the market price is increased, since this would lead to a disproportionate increase in current profits. Long-term profitability of collusion is not altered, since according to Rotemberg and Saloner (1986) demand shocks are (again) independent and identically distributed. In contrast to Green and Porter (1984) price wars are induced by booms. The different outcomes of both contributions led to a broad discussion, since for both theories empirical evidence could be found. Aiginger (1991) provided a profound survey about empirical literature on the question whether price wars occur in booms or recessions. For most industries longer-lasting periods of boom or recession can be observed. Thus, one crucial assumption of Rotemberg and Saloner (1986) as well as Green and Porter (1984) was that demand shocks are independent and identically distributed. A first attempt of introducing business cycles instead of business fluctuations was made by Haltiwanger and Harrington (1991). They allow "the level of current demand and firms expectations on future demand to change over time" (Haltiwanger and Harrington, 1991, p.89) and identify two effects: "First, the gain to deviation from the established pricing rule varies over the cycle and is highest when demand is strongest. Second, the discounted loss from such a deviation is also found to vary over the cycle and is lowest during a recession as demand is anticipated to be falling in the immediate future" (Haltiwanger and Harrington, 1991, p.102). At first glance these deterministic fluctuations seem to fit perfectly demand fluctuations on the German electricity market and one might conclude that collusion is hardest to sustain after the peak during noon, since profit on deviation is high and foregoing profits for the next hours are comparatively low. However, as described above, electricity is mainly traded on the day-ahead spot market. On the day-ahead spot market until 12 (noon) bids for all hours of the next day have to be submitted. Thus, each firm has to submit a vector of prices and quantities and the strong daily demand pattern becomes strategically less important. Kandori (1991) introduced serial correlated shocks and confirms the theory of Rotemberg and Saloner (1986), since the equilibrium exhibits "the same counter-cyclical movement as in the i.i.d. case, if the discount factor and the number of firms satisfy certain relationship". In contrast Bagwell and Staiger (1997) introduced longer periods of recession with small or negative growth rates and of booms with high growth rate using a markov process. Additionally they allow for transitory (in the

sense of uncorrelated) shocks and show that Rotemberg and Saloner (1986) can be seen as a special case of Bagwell and Staiger (1997), if only such transitory demand shocks occur. Bagwell and Staiger (1997) show that for positive correlated demand shocks prices are weakly procyclical and that c.p. shorter boom phases and longer recession phases increase the amplitude of the collusive pricing cycle.

Fabra and Toro (2005) raised the question of competitiveness on the Spanish electricity market. They present a theoretical framework to analyze pricing behavior and empirically test for hypotheses of individual profit maximization and collusive prices. Evidence for (tacitly) collusive behavior is found, since "the performance of the Spanish electricity market during 1998 is not consistent with the predictions of models of individual profit maximizing behavior" (Fabra and Toro, 2005, p.179).

For an analysis of the German electricity market these models about collusive pricing and competitive pressure exhibit some similarities to the German electricity market. However, one very important tool, which could be used strategically, is missing above all: Forward Trading!

The Economic Analysis of Strategic Forward Trading

As the analysis of the German electricity market has shown, more than 70% of the total market volume are traded forward. This is not only a special feature of the German electricity market, but also holds true for other commodity markets, such as gas, steel, oil and precious metals. These commodity markets are characterized by a substantial amount traded in forward and futures contracts as well as only few oligopolistic firms are able to serve demand. However, there exists hardly any literature about the strategic aspects of forward trading. To be successful on an oligopolistic market each firm has to incorporate all actions and reactions of its competitors. Thus, strategic behavior becomes important and the methods typically used in industrial organization are suitable to analyze firms' behavior on commodity markets and to predict market results.

Economic literature about financial markets often assumes atomistic small traders, sellers and buyers, not being able to have any influence on market prices. Thus, strategic aspects are normally not modeled and firms' motives of forward trading is risk hedging.

This strong focus on risk hedging motives for forward trading seems misleading for commodity markets. Moraga-González and van Eijkel (2010) fundamentally questions risk hedging motives as the main reason for forward trading in a working paper about the Dutch natural gas wholesale market. In this contribution the question whether forward contracts are mainly used for strategic or risk-hedging motives is discussed theoretically as well as empirically. They "find evidence that strategic reasons play an important role at explaining the observed firms' hedge ratios" (Moraga-González and van Eijkel, 2010, p.34). In contrast they see little support for the risk hedging story, since "the data do not support the idea that risk-hedging motives are an important aspect behind the observed firms' hedge ratios" (Moraga-González and van Eijkel, 2010, p.34). Thus, relying solely on risk-hedging motives to explain large forward-traded amounts on commodity market, would be a bit naive.

Ronald W. Anderson was one of the first to bridge this gap in discussing the two-way effects of market imperfections and futures trading. On his initiative a conference called "The industrial organization of future markets: structure and conduct" was organized in 1982 to discuss the effects of imperfect competition and futures markets. All papers of this conference were collected and published by Anderson (1984) by the title "The Industrial Organization of Futures Markets". Most of the papers focused on the possibility of market manipulations with forward contracts (e.g. Newbery (1998) and Kyle (1984)) or disadvantageous self-regulation (Saloner, 1984). However, one contribution, made by Anderson and Sundaresan (1984), directly addresses the problem of imperfect competition and market power on futures markets.

At the same time Greenstone (1981) described in detail how coffee-exporting countries formed "pancafe and the bogota group" to collude on a higher world market coffee price. One popular tool, which was used for their coordination, were forward contracts. However, it took more than twenty years, until Liski and Montero (2006) analyzed the effects of forward trading on colluding firms within a theoretical framework. They model an infinitely repeated oligopoly game, in which firms are allowed to act on the spot as well as on the forward market. They show under a deterministic demand and supply structure that forward trading has a stabilizing effect on a collusive agreement. In addition Liski and Montero (2006) show that the amount of forward contracts being sold does not influence

the profit of colluding firms, as long as it does not exceed the monopoly quantity. Thus, in a deterministic market structure forward contracts can be used to stabilize a collusive agreement without any disadvantage for the involved firms. This analysis of collusive incentives for firms that compete in prices as well as in quantities is based on one-period forward contracts. Then, Green and Coq (2010) analyzed in a similar setting the collusive effects of forwards with varying contract lengths.

Effects of forward trading on (imperfectly) competing firms, were modeled by Allaz and Villa (1993) for quantity-setting firms and a homogenous product and by Mahenc and Salanié (2004) for price-setting firms with a heterogeneous good. The welfare effects of both models contradict each other, since for price competition and heterogeneous products (Mahenc and Salanié, 2004) forward trading leads to weaker competition, whereas for homogenous products and quantity competition (Allaz and Villa, 1993) forward trading leads to fiercer competition.

If one assumes for the German electricity market that firms compete in quantity competition for a single period, forward trading leads to welfare gains. For commodities that can be stored Thille (2003, p.652) shows in an "infinite horizon, discrete time dynamic game of forward trading with storage" that the welfare enhancing effects found by Allaz and Villa (1993) are still present. However, if forward contracts are used to stabilize a collusive agreement under repeated competition (Liski and Montero, 2006), welfare losses result from forward trading.

For an analysis of the German electricity market kind of few literature about strategic aspects of forward trading exhibits similarities and the most important market characteristic is always missing: Stochastic and fluctuating business cycles!

Modeling Forward Trading and Competitive Pressure

As shown above, for the analysis of the German electricity market theoretical models have to be directly tailored, since central aspects are missing in the existing literature. The next pages are dedicated to show how central aspects, that have been derived in the empirical analysis of the German electricity market, are incorporated into the upcoming micro-economic analysis.

	German Electricity Market	Micro-Economic Model
1	Strategic Competition between 4 Asymmetric Firms	Strategic Competition between 2 Symmetric Firms
2	Forward Contracts with Different Maturities	Standardized One-Period Forward Contracts
3	Day-Ahead Spot Market	Day-Ahead Spot Market
4	Intraday Spot Market	Only (Day-Ahead) Spot Market
5	Large Number of Electricity Traders	No Strategic Influence of Traders
6	Heterogeneity of Consumers (Industry and Households)	One Linear Demand Function for All Consumers
7	Electricity Tariffs are Offered	"One Price Fits All"
8	Convex Marginal Costs	Constant Marginal Costs
9	Stochastic Fluctuations of Demand and Supply	Supply and Demand only Known in Expectation

Table 3.1: Comparison of German Electricity Market and the Micro-Economic Model

Table 3.1 shows central aspects of the German electricity market and the way they are incorporated into the micro-economic model.

First, on the German electricity market the four largest electricity suppliers (E.ON, RWE, ENBW, Vattenfall) have the most significant market shares, whereas market shares of other electricity suppliers are hardly worth mentioning. For conventionally generated electricity this effect is even stronger, since smaller electricity suppliers have mainly invested in renewable energies. Feed-in of renewable energies are remunerated by a fixed compensation and renewable energies are fed into the German grid independently of market conditions. Thus, for an analysis of the electricity wholesale market conventional load matters and strategic linkages between competitors are likely to occur. Strategic interaction is incorporated by assuming only two symmetric firms. This can be done without loss of generality, since directions of strategic effects are not changed.

Second, about 70 % of the total electricity is traded forward on the German electricity market. The rest is mainly traded on the day-ahead spot market. A rather small amount is traded on the intraday spot market. This market structure is reflected in the presented model, by allowing firms to trade on a forward market as well as on a spot market. Firms are only able to trade forward contracts with maturity of exactly one period in the model. This seems to be justified, since to a great extent forward contracts with a maturity of one-year are traded on the German electricity market. There is no such thing as an intraday spot market in the micro-economic model. This negligence can be justified by the fact, that market volumes on the intraday spot market are rather low in Germany.

Third, there is a large number of electricity traders on the German wholesale electricity market. It is not likely that these electricity traders have a significant influence on market outcomes or exercise market power. In the presented model this is reflected by a forward price that equals the expected spot market price. This results from rational expectations of electricity traders and their insignificant influence on the spot market price.

Fourth, electricity demand in Germany comes from round about 40 million households and a vast number of commercial consumers. Thus, electricity demand comes from very heterogeneous private and commercial consumers. As a consequence electricity tariffs are offered to private and commercial consumers. Large (commercial) consumers can directly negotiate their electricity contract with a utility company. In order to keep the micro-

economic analysis tractable all this sorts of heterogeneity are neglected and consumers are assumed to be price takers.

Fifth, electricity demand and supply are very volatile. Fluctuations between 20 GW and 70 GW could be found for conventionally generated electricity in 2013. This market characteristic is reflected by allowing for fluctuations of demand and supply in the model. However, one important characteristic of electricity markets is missing: Increasing marginal costs and the merit order curve! In order to keep the model analytically tractable constant marginal costs are assumed and the question to what extent convex marginal costs influence forward trading and the market outcome is left for further research.

Having this set of important characteristics of the German electricity market in mind, adding volatile market conditions to the model of Liski and Montero (2006) seems to be appropriate for the analysis of forward trading on competitive pressure. The literature about collusion and business cycles proposes three ways of introducing these fluctuations:

Firstly, Haltiwanger and Harrington (1991) are modeling business cycles of known length. This would be the best way to incorporate the daily rather deterministic pattern of electricity demand. On the German day-ahead spot market electricity is traded one day in advance for all trading blocks. Thus, fluctuations coming from the daily pattern are of minor strategic importance for electricity trading firms, since they do not change this daily total traded amount and the strategic pricing decision for firms differs from the one Haltiwanger and Harrington (1991) propose.

Secondly, Bagwell and Staiger (1997) allow for serial correlation in the business cycles by using a Markov process. They allow for transitory identically independent distributed shocks additionally. Stochastic fluctuations coming from different weather conditions significantly influence demand for conventional electricity. From a strategic perspective this stochastic fluctuations are of great importance for pricing behavior of firms, since they cannot be anticipated in advance. Tables 2.10, 2.11, 2.12 and 2.13 illustrate serial correlation of demand for conventionally generated electricity and show that demand for electricity is serially correlated. However, this serial correlation declines rapidly.

Thirdly, Rotemberg and Saloner (1986) assume identically independent distributed

shocks, which cannot be directly supported by the evaluation of serial correlation. However, the model of Rotemberg and Saloner (1986) is used as a starting point for the upcoming analysis. Allowing for serial correlation would lead to a significant increase in complexity of the model without the generation of a significantly better understanding of the German electricity market. The empirical analysis of serial correlation of necessary conventional load has shown that fluctuations are rather transitory. Combined with the findings of Bagwell and Staiger (1997) that for transitory shocks their results are equivalent to Rotemberg and Saloner (1986), this approach seems to be justified. Therefore the model of Rotemberg and Saloner (1986) is taken as a starting point.

The model, that is presented on the next pages, has been published in the series University of Tübingen Working Papers in Economics and Finance (Aichele, 2014a). Results were additionally presented on the "Jahrestagung 2012 des Vereins für Socialpolitik in Göttingen" as well as on the GEABA conference 2012 in Graz. Results about aspects of semi-collusive strategies were presented on the "Jahrestagung 2013 des Vereins für Socialpolitik in Düsseldorf" as well as on the annual meeting 2013 of the European Association of Research in Industrial Economics (Aichele, 2013)

3.3 The model

3.3.1 Assumptions and General Remarks

Collusive behavior of firms can occur, if and only if, there is no incentive for any firm to deviate from the collusive agreement unilaterally. If the net present value of profits gained by collusion is greater or equal than the net present value of profits gained by ending collusion, no incentive for any firm to break the collusive agreement unilaterally exists. The highest profit that can be earned in each period is the monopoly profit, which is shared equally by both (symmetric) firms.

It is assumed that firms face a linear demand function ($D = a - p$) and bear constant marginal costs c . The exact outcome of prices, quantities and profits is stochastic and depends on the difference between the reservation price a and marginal costs c . I do not distinguish between demand and supply shocks. The difference between the reservation price and marginal costs ($\gamma = a - c$) will be denoted "spread" in the analysis. The first

two moments of this “spread” are given by $E[\gamma]$ and $V[\gamma]$. In order to give comparative static results, the König-Huygens theorem is used later in this paper to decompose the expectation of the squared “spread” into its variance and its squared expectation ($E[\gamma^2] = V[\gamma] + E[\gamma]^2$).

Whenever I use monopoly prices, quantities and profits for the argumentation, I refer to monopoly prices, quantities and profits for a given realization of the stochastic difference between reservation price and marginal costs. As shown by Liski and Montero (2006, p. 226) assuming a linear demand function is possible without loss of generality. I denote the price, quantity and profit associated with the one-period monopoly solution by $p^M = \frac{a+c}{2}$, $q^M = \frac{a-c}{2}$ and $\Pi^M = (p^M - c)q^M = \frac{(a-c)^2}{4}$.

The spot and the forward market are connected as follows: During the first period, both firms simultaneously choose the amount of forward contracts they want to trade (forward market period). During the second period, contracts are settled and firms choose the amount they additionally want to sell on the spot market (spot market period). The forward market opens in the even periods ($t = 0, 2, \dots$) and the spot market in the odd periods ($t = 1, 3, \dots$). To maintain comparability with pure-spot market games the per period discount factor is given by $\sqrt{\delta}$. Alternatively the spot market opens for a marginal unit of time right after the forward market and the discount factor is given by δ . The important fact is that discounting only takes place between two spot markets, two forward markets or the forward market in t and the spot market in $t + 1$. Hence, no discounting takes place between consecutive forward and spot markets. The structure of trading initially on the forward market and settling contracts afterwards as well as meeting residual demand on the spot market is infinitely repeated. One can think of firms deciding around Christmas each year about forward contracts to be delivered in the following year.

Firms compete in prices and sell a homogenous product, which seems a valid assumption especially for electricity markets. Whenever firm i sets a price lower than its competitor j firm i meets the whole spot market demand. However, this spot market demand is decreased by the total amount of forward contracts that have been sold before by firm i and by firm j ($\tilde{F} = \tilde{f}_i + \tilde{f}_j$). Thus, the demand to serve and the spot market profit can be

stated as:

$$\begin{aligned} D_i^{SM} &= (a - \tilde{F} - p_i) \\ \Pi_i^{SM} &= (p_i - c) (a - \tilde{F} - p_i) \end{aligned} \quad (3.1)$$

When prices are equal, firms split the market equally. Consider the following trigger strategy to ensure collusive behavior: In the first forward market round (period 0), firm i sells an amount of contracts that are settled right in the next period, $\tilde{f}_i^{0,1}$, and sells no contracts that are settled in subsequent periods, $\tilde{f}_i^{0,l} = 0$ for all $l > 1$, where l denotes the period of delivery. Hence firms only sell forward contracts that will be settled in the following spot market, since no forward contracts with delivery in $t > 1$ are sold ($\tilde{f}_i^{0,l} = 0 \quad \forall \quad l > 1$). In this following spot market period firm i sets the monopoly price ($p_i^t = p^M$) if and only if in every period preceding period t both firms have set monopoly prices in the spot market and have contracted the collusive amount $\tilde{f}_i^{0,1} = \tilde{f}_j^{0,1} = \tilde{f}$ in the forward market one period ahead. Whenever firm j deviates from this agreement, firm i sets a price equal to marginal costs in the spot market and sells any arbitrary amount of forward contracts forever. This can be seen as the grim trigger strategy for games, where firms are allowed to trade on a spot as well as on a forward market. It corresponds to the grim trigger strategy analyzed by Friedman (1971), when firms were solely allowed to trade on a spot market.

Liski and Montero (2006) do not allow forward contracts exceeding monopoly quantity in their model of forward trading and collusion in a deterministic market structure. However, in a volatile market, firms do not know in any forward market period the demand and cost structure they will face in the following spot market period. Hence, firms might have traded forward more than the quantity they can sell with monopoly prices on spot market. This may happen e.g. for a relatively small realization of the difference of reservation price and marginal costs. Therefore the critical discount factor will be derived for the forward traded amount being less than monopoly quantity as well as for the forward traded amount being larger than monopoly quantity.

3.3.2 Profits for a Deviating Firm and for a Colluding Firm

In general, two possibilities of deviation exist: Firstly, setting a price lower than the collusive price in the spot market. Secondly, increasing the forward sales in the forward market. The latter is never profitable, as speculators, which take the counterpart, immediately realize any deviation from collusion in the forward market and are not willing to pay any price higher than the next period's spot market price, which is given by marginal costs. Hence, profitable deviation is restricted to the spot market and a firm trying to deviate knows the actual state of the economy.

The demand that can be achieved on the spot market for a deviating firm is restricted by future contracts already sold. Each firm has a secured supply of \tilde{f}_i . The secured supply of both firms is given by $\tilde{F} = \tilde{f}_i + \tilde{f}_j$. Total traded amount decreases accessible demand ($a - \tilde{F}$ instead of a). This results in the (residual) demand function on the spot market:

$$D_i^R = \begin{cases} (a - \tilde{F} - p_i) & \text{if } p_i < p_j, \\ \frac{1}{2}(a - \tilde{F} - p_i) & \text{if } p_i = p_j, \\ 0 & \text{if } p_i > p_j \end{cases} \quad (3.2)$$

A firm deviating from collusion maximizes its profit over its (deviation) price. This leads to the following optimal deviation price (p^d) and quantity (q^d) and profit (Π^d):

$$\begin{aligned} \max_p \quad \Pi_i &= (p_i - c) (a - \tilde{F} - p_i) \\ p^d &= \frac{1}{2} [a + c - \tilde{F}], q^d = \frac{1}{2} (a - \tilde{F} - c), \Pi^d = \frac{1}{4} [a - c - \tilde{F}]^2 \end{aligned} \quad (3.3)$$

Deviation price, quantity and profit are quite similar to price, quantity and profit in a deviation from collusion without forward trading. However, the amount already contracted decreases the demand that is reachable on the spot market ($\frac{\partial D_i^d}{\partial \tilde{F}} < 0$). Hence, deviation price, quantity and profit become smaller. When the total contracted amount exceeds or equals the Bertrand quantity (q^B), which is given by twice monopoly quantity ($\tilde{F} \geq q^B = 2q^M = a - c$), no positive deviation profit can be earned, since any deviation would require a price that is lower than the Bertrand price on the spot market, which is given by marginal costs.

As described in section 3.3.1 a deviation yields to zero profits in all following forward and spot market periods. Consequently, the net present value of deviation is given solely

by the deterministic deviation profit of this single period:

$$E_{NPV}[Deviation] = \begin{cases} \frac{1}{4} [a - c - \tilde{F}]^2 & \text{if } \tilde{F} < 2q^M \\ 0 & \text{if } \tilde{F} \geq 2q^M, \end{cases} \quad (3.4)$$

The demand that can be reached by collusive behavior in this period is also restricted by forward contracts already sold and each firm's collusive profit on the spot market can be stated as:

$$\begin{aligned} \Pi^C &= \frac{1}{2} D^R \pi^C = \frac{1}{2} (a - \tilde{F} - p^M) (p^M - c) \\ &= \frac{1}{8} \gamma^2 - \frac{1}{4} \gamma \tilde{F} = \frac{1}{2} \left[\frac{1}{4} (\gamma^2 - 2\gamma \tilde{F} + \tilde{F}^2) - \frac{1}{4} \tilde{F}^2 \right] \\ &= \frac{1}{2} \left[\frac{1}{4} (a - c - \tilde{F})^2 - \frac{1}{4} \tilde{F}^2 \right] = \frac{1}{2} \Pi^d - \frac{1}{8} \tilde{F}^2 \end{aligned} \quad (3.5)$$

Colluding firms set monopoly prices behaving as if no forward trading had occurred ($p^M = \frac{a-c}{2}$ instead of $p^M = \frac{a-\tilde{F}-c}{2}$). If they would not do so, they would not be able to sell collusive forward contracts at expected (monopoly) prices as speculators would anticipate the (expected) price discount on the spot market. When firms set this collusive price, they split residual demand given by $D^R = a - \tilde{F} - p^M$ and earn a per-unit-profit of $\pi^C = p^M - c$.

Whenever the total forward-traded amount does not exceed or equal monopoly quantity ($\tilde{F} < q^M$), collusive behavior leads to collusive profits in this period. Additionally collusive profits given by half of the expected monopoly profit are expected in all upcoming periods.

Whenever the total forward-traded amount exceeds or equals monopoly quantity ($\tilde{F} \geq q^M$) no collusive profits can be earned in this period, since the total demand for the monopoly price has already been satisfied. However, not deviating from collusion promises half of the expected monopoly profit in all upcoming periods. This defines the net present value of collusion as a piecewise function:

$$E_{NPV}[Collusion] = \begin{cases} \frac{1}{2} \Pi^d - \frac{1}{8} \tilde{F}^2 + \frac{1}{2} \frac{\delta}{1-\delta} E[\Pi^M] & \text{if } \tilde{F} < q^M \\ \frac{1}{2} \frac{\delta}{1-\delta} E[\Pi^M] & \text{if } q^M \leq \tilde{F} < 2q^M \end{cases} \quad (3.6)$$

The different collusive profits in the period of (possible) deviation lead to two different scenarios. In the first scenario (*I*), the total forward-traded amount is less than the

monopoly quantity ($\tilde{F} < q^M$). In the second scenario (II), the total forward-traded amount exceeds monopoly quantity $q^M < \tilde{F}$. In the third case, the total traded amount exceeds Bertrand quantity ($q^B = 2q^M < \tilde{F}$). However, the third case is not analyzed more deeply since neither collusive nor deviation profits can be earned in the corresponding period and a firm is not facing the trade-off between collusion or deviation in the corresponding period. Hence, both firms will stick to the collusive agreement, since it is the only way that promises future (collusive or deviation) profits.

3.3.3 Forward Trading and Stability of a Collusive Agreement

A firm that is involved in an (explicit or tacit) collusive agreement with its competitor has two alternative strategies. Firstly, it can collude and gain a profit in the corresponding period and in future periods. Secondly, it can deviate and gain an additional profit in the corresponding period, but forgo all collusive profits in future periods. A firm chooses the strategy yielding the highest expected net present value of profits. Comparing the net present values leads to an inequality, which represents the trade-off between collusion and deviation. This inequality is called the no deviation constraint and will be used to find the critical discount factor. The concept of the critical discount factor is applied in supergames to measure the stability of non-cooperative collusive behavior. The two scenarios mentioned above will now be discussed in detail.

Scenario I: The monopoly quantity exceeds total forward-traded amount ($\tilde{F} < q^M$)

For a stable collusive agreement, the net present value of collusion must be larger than the net present value of deviation. Hence, for the forward-traded amount to be lower than the monopoly quantity, the following no deviation constraint has to be fulfilled for a stable collusive agreement. See equation A.1 in the appendix for a more detailed derivation:

$$\begin{aligned}
 E_{NPV}[Deviation] &\leq E_{NPV}[Collusion] \\
 \Pi^d &\leq \frac{1}{2}\Pi^d - \frac{1}{8}\tilde{F}^2 + \frac{1}{2}\frac{\delta}{1-\delta}E[\Pi^M] \\
 \Pi^d &\leq \frac{1}{2}\Pi^d - \frac{1}{8}\tilde{F}^2 + \frac{1}{2}\frac{\delta}{1-\delta}E\left[\frac{1}{4}\gamma^2\right] \\
 \frac{1}{4}\gamma^2 + \frac{1}{2}\tilde{F}^2 - \frac{1}{2}\tilde{F}\gamma &\leq \frac{\delta}{1-\delta}\frac{1}{4}[E[\gamma]^2 + Var[\gamma]]
 \end{aligned} \tag{3.7}$$

Rearranging leads to the following discount factor for collusive behavior:

$$\delta \geq \delta^* = 1 - \frac{E[\gamma]^2 + Var[\gamma]}{E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2} \quad (3.8)$$

Scenario II: Total forward-traded amount exceeds the monopoly quantity

($q^M < \tilde{F}$)

For a stable collusive agreement, the net present value of collusion must be larger than the net present value of deviation. No collusive profits are earned on the spot market, since the total forward-traded amount exceeds monopoly quantity ($q^M < \tilde{F}$). Hence, the net present value of collusion is restricted to half of the future expected monopoly profits. For the forward-traded amount exceeding monopoly quantity this results in the following no deviation constraint for a stable collusion. See equation A.2 in the appendix for a more detailed derivation:

$$\begin{aligned} E_{NPV}[Deviation] &\leq E_{NPV}[Collusion] \\ \Pi^d &\leq \frac{1}{2} \frac{\delta}{1-\delta} E[\Pi^M] \\ \Pi^d &\leq \frac{1}{2} \frac{\delta}{1-\delta} E\left[\frac{1}{4}\gamma^2\right] \\ \frac{1}{2}\gamma^2 - \tilde{F}\gamma + \frac{1}{2}\tilde{F}^2 &\leq \frac{\delta}{1-\delta} \frac{1}{4} [E[\gamma]^2 + Var[\gamma]] \end{aligned} \quad (3.9)$$

Rearranging again yields the critical discount factor for collusive behavior:

$$\delta \geq \delta^* = 1 - \frac{E[\gamma]^2 + Var[\gamma]}{E[\gamma]^2 + Var[\gamma] + 2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2} \quad (3.10)$$

Thus, the critical discount factor for any forward-traded amount under full-collusion is given by:

$$\delta^* = \begin{cases} 1 - \frac{E[\gamma]^2 + Var[\gamma]}{E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2} & \text{if } \tilde{F} < q^M \\ 1 - \frac{E[\gamma]^2 + Var[\gamma]}{E[\gamma]^2 + Var[\gamma] + 2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2} & \text{if } q^M \leq \tilde{F} < 2q^M \end{cases} \quad (3.11)$$

In the following I will analyze how the critical discount factor is influenced by the realization of the random difference between reservation price and marginal costs (γ), the amount of forward contracts (\tilde{F}), the expected difference between reservation price and marginal cost ($E[\gamma]$) and the variance of the difference between reservation price and marginal cost ($Var[\gamma]$).

The partial derivative of the critical discount factor with respect to the difference between reservation price and marginal costs is given by:

$$\frac{\partial \delta^*}{\partial \gamma} = \begin{cases} 2 \frac{[\gamma - \tilde{F}][E[\gamma] + Var[\gamma]]}{[E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2]^2} & \geq 0 \quad \text{if } \tilde{F} < q^M \\ 4 \frac{[\gamma - \tilde{F}][E[\gamma]^2 + Var[\gamma]]}{[E[\gamma]^2 + Var[\gamma] + 2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2]^2} & \geq 0 \quad \text{if } q^M \leq \tilde{F} < 2q^M \end{cases} \quad (3.12)$$

A higher difference between reservation price and marginal costs leads to a higher profit and is leading to a higher critical discount factor, because deviation becomes more attractive.

The partial derivative of the critical discount factor due to the amount of contracts is given by:

$$\frac{\partial \delta^*}{\partial \tilde{F}} = \begin{cases} -2 \frac{[\gamma - 2\tilde{F}][E[\gamma]^2 + Var[\gamma]]}{[E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2]^2} & \leq 0 \quad \text{if } \tilde{F} < q^M \\ -4 \frac{[\gamma - \tilde{F}][E[\gamma]^2 + Var[\gamma]]}{[E[\gamma]^2 + Var[\gamma] + 2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2]^2} & \leq 0 \quad \text{if } q^M \leq \tilde{F} < 2q^M \end{cases} \quad (3.13)$$

A higher forward-contracted amount strictly reduces the critical discount factor, since for forward-traded amounts less than the monopoly quantity ($0 \leq \tilde{F} < q^M = \frac{1}{2}\gamma$) the deviation profit is cut more sharply than the collusive profit in the corresponding period. This is derived analytically in the appendix (equations A.5 - A.8). If the forward-traded amount is larger than the monopoly quantity ($\frac{1}{2}\gamma = q^M \leq \tilde{F} < q^M = \gamma$), no collusive profit can be earned in the corresponding period. Thus, only the deviation profit is reduced and forward contracts strictly promote collusion.

The partial derivative of the critical discount factor with respect to the expected difference

between reservation price and marginal costs is given by:

$$\frac{\partial \delta^*}{\partial E[\gamma]} = \begin{cases} -2 \frac{[\gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2]E[\gamma]}{[E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2]^2} & \leq 0 \quad \text{if } \tilde{F} < q^M \\ -2 \frac{[2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2]E[\gamma]}{[E[\gamma]^2 + Var[\gamma] + 2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2]^2} & \leq 0 \quad \text{if } q^M \leq \tilde{F} < 2q^M \end{cases} \quad (3.14)$$

A higher expected difference of reservation price and marginal costs decreases the critical discount factor. Deviation from collusion becomes less attractive. A higher expected difference increases future collusive profits, which cannot be earned after a deviation. Hence, the additional profits earned by deviation become smaller in relative terms.

The partial derivative of the critical discount factor with respect to the variance of the difference between reservation price and marginal costs is given by:

$$\frac{\partial \delta^*}{\partial Var[\gamma]} = \begin{cases} - \frac{\gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2}{[E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2]^2} & \leq 0 \quad \text{if } \tilde{F} < q^M \\ - \frac{2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2}{[E[\gamma]^2 + Var[\gamma] + 2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2]^2} & \leq 0 \quad \text{if } q^M \leq \tilde{F} < 2q^M \end{cases} \quad (3.15)$$

A higher variance of the difference of reservation price and marginal costs decreases the critical discount factor. At a first glance this seems to be counter-intuitive, since fluctuations are said to threaten collusions. One should keep in mind the relationship between variance squared, expectation and expectation squared used above ($E[\gamma^2] = E[\gamma]^2 + Var[\gamma]$). As can be seen, expected profit given by $\frac{1}{4}E[\gamma^2]$ *ceteris paribus* increases by an increasing variance. As presented above, a higher expected profit increases the stability of collusion. Thus, it is not variance itself that decreases the stability of an collusive agreement, but more precisely the appearance of a high realization of the random difference between reservation price and marginal costs. For a higher variance, this high realization of the random variable is more likely to be drawn. However, for a given realization of the random variable, a higher variance decreases the critical discount factor. Table 3.2 summarizes the partial effects on the critical discount factor. The expected difference between reservation price and marginal costs and its variance have *ceteris paribus* a stabilizing effect on a collusive agreement, as well as the total forward-traded amount. High realizations of the difference between reservation price and marginal costs have a destabilizing effect on a collusive agreement.

Variable	Partial Effect	I Monopoly quantity exceeding contracts	II Contracts exceeding monopoly quantity
Expected spread	$\frac{\partial \delta^*}{\partial E[\gamma]}$	↓	↓
Variance of spread	$\frac{\partial \delta^*}{\partial Var[\gamma]}$	↓	↓

Table 3.2: Total Effects on the Critical Discount Factor

Figure 3.1 shows the evolution of the critical discount factor due to forward contracts and due to the ratio of boom and expected profits. The discount factor is plotted for positive ratios of contracted amount and monopoly quantity. Neither collusive nor deviation profits can be earned for a higher amount of contracts than the Bertrand quantity, and the critical discount factor becomes zero. Hence, the graph starts at a ratio of the forward traded amount and monopoly quantity of zero and stops at a ratio of two. It is known through Rotemberg and Saloner (1986) that deviation from collusion is more profitable in booms. The graph in figure 3.1 starts at a ratio of profit over the expected profit of 1, since in booms per definition profits are higher than the expected ones. In this dimension it ends at a profit that is ten times the expected one.

The horizontal front-line of figure 3.1 shows the evolution of the discount factor for expected profit equal to actual profit $\left(\frac{\gamma^2}{E[\gamma^2]+Var[\gamma]} = 1\right)$. This represents the case of certainty described by Liski and Montero (2006), since without any forward contracts and without any volatility the critical discount factor is one half, and when total monopoly quantity is traded forward, the discount factor is one third. For forward contracts between these two extreme cases $(0 \leq \frac{F}{q^M} < 1)$, the critical discount factor strictly decreases in forward contracts. When firms have contracted more than the monopoly quantity of the corresponding state (scenario *II*), the critical discount factor still decreases in forward contracts. In scenario *II* the critical discount factor decreases more rapidly than in scenario *I*, since in scenario *II* forward trading solely cuts the deviation profit. In contrast to this in scenario *I* it cuts the deviation profit as well as the collusive profit.

Introducing a volatile market creates an incentive to deviate from collusion during booms. Without forward contracts ($F = 0$) the critical discount factor strictly increases and is converging to one for boom profits increasing to infinity. The functional form of the

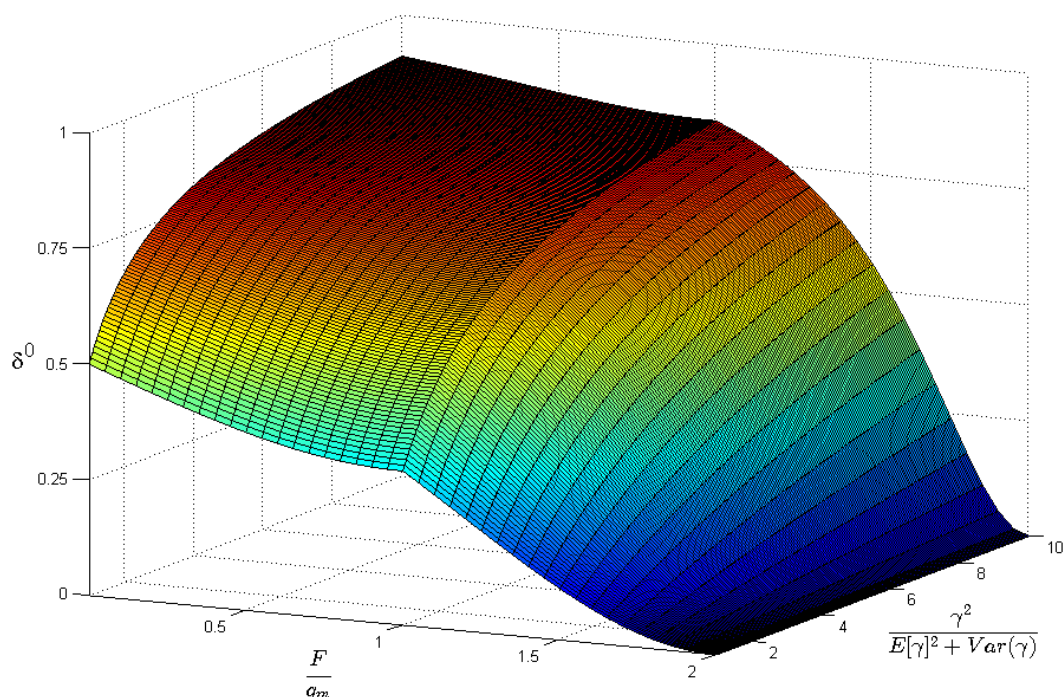


Figure 3.1: Effects of Forward Trading and Ratio of Boom and Expected Profit on Discount Factor

critical discount factor depends on the ratio of boom and expected profit and is given by $\frac{\gamma^2}{E[\gamma^2] + \text{Var}[\gamma] + \gamma^2} = \delta^0 \leq \delta$, which is equivalent to the findings of Rotemberg and Saloner (1986). When contracts are traded forward and at the same time boom profits are larger than expected profits, the evolution of the critical discount factor described above does not change fundamentally. Other things being equal, a higher amount of contracts decreases the critical discount factor, whereas boom profits exceeding expected profit increase the critical discount factor. This is shown graphically in figure 3.1 by the evolution of the plane between the front-lines described above. When firms contract a sufficiently high quantity, stable collusion becomes possible for any discount factor.

3.3.4 Forward Trading and Profitability of a Collusive Agreement

Scenario I: The monopoly quantity exceeds the forward-traded amount ($\tilde{F} < q^M$)

The profit of colluding firms that trade a certain amount forward has two sources: Firstly,

the profit coming from selling production on the spot market. Secondly, the profit coming from selling production on the forward market. As long as the forward-traded amount does not exceed the collusive quantity, the spot market profit for colluding firms is given by equation 3.5. Inserting an arbitrarily collusive price leads to a collusive spot market profit of:

$$\Pi_i^{SM} = \frac{1}{2} (a - p^{SM}) (p^{SM} - c) - \frac{1}{2} \tilde{F} (p^{SM} - c) \quad \forall \tilde{F} < (a - p) \quad (3.16)$$

The profit on the forward market is given by each firm's forward-traded amount multiplied by the difference of the forward price and marginal costs. As mentioned before, the forward market price is given by the anticipated spot market price, since speculators build rational expectations. Thus, the expected profit on the forward market is given by the expected difference of the spot market price and marginal costs times each firm's forward-traded amount

$$\Pi_i^{FM} = \frac{1}{2} \tilde{F} (p^{SM} - c) = \frac{1}{2} \tilde{F} (p^{SM} - c) \quad \forall \tilde{F} \leq (a - p) \quad \square \quad (3.17)$$

The total (semi-)collusive profit for a firm is given by the spot and the forward market profit:

$$\begin{aligned} \Pi_i^{SC} &= \frac{1}{2} (a - p^{SM}) (p^{SM} - c) - \frac{1}{2} \tilde{F} (p^{SM} - c) + \frac{1}{2} \tilde{F} (p^{SM} - c) \\ &= \frac{1}{2} (a - p^{SM}) (p^{SM} - c) \quad \forall \tilde{F} < (a - p) \quad \square \end{aligned} \quad (3.18)$$

Thus, the increase of the expected forward market profit, which comes from forward trading, is totally offset by a decrease of the expected spot market profit. Therefore, as long as the forward-traded amount does not exceed the spot market quantity, any firm's profit is not changed by forward trading.

Scenario II: The forward-traded amount exceeds monopoly quantity ($\tilde{F} > q^M$)

When firms set a price, for which the amount already forward traded exceeds the spot market quantity that is associated with this price, firms cannot sell any unit on the spot market. Speculators always supply the total forward traded amount to the market, since by assumption they cannot store the commodity. Hence, the price on the spot market is given

by $p^{sm} = a - \tilde{F}$, which is below the monopoly price ($p^{SM} = a - \tilde{F} < p^M = \frac{1}{2}(a - c)$) and colluding firms do not earn any profit on the spot market. However, both firms earn a profit, that is coming from the amount that they have traded forward. Thus, when firms have traded forward an amount above the amount that is associated with their price on the spot market, the profit is solely given by the profit, that is coming of forward trading:

$$\begin{aligned}\Pi_i^{SC} &= \frac{1}{2}\tilde{F}(p^{SM} - \tilde{F}) = \frac{1}{2}\tilde{F}(a - \tilde{F} - c) \\ &= \frac{1}{2}(2q^M\tilde{F} - \tilde{F}^2) \quad \forall \quad \tilde{F} \leq (a - p)\end{aligned}\quad (3.19)$$

The total collusive profit for each firm is given by the profit, when the total forward traded amount does not exceed the quantity sold by firms on the spot market as well as the profit, when firms set a price, for which the amount already forward traded exceeds the spot market quantity. Combining profits derived in equation 3.18 and profits derived in equation 3.19 leads to each firm's expected total collusive profit for any distribution function:

$$E[\Pi_i^{SC}] = \frac{1}{2} \left[E \left[2q^M\tilde{F} - \tilde{F}^2 \mid \tilde{F} > (a - p) \right] + E \left[(a - p)(p - c) \mid \tilde{F} \leq (a - p) \right] \right] \quad (3.20)$$

Scenario I:

Firms set the monopoly price and the monopoly quantity exceeds the forward traded amount ($\tilde{F} < q^M$)

The expected profit on the forward market is given by each firm's forward traded amount multiplied by the difference of the forward price and the marginal costs. As mentioned before, the forward market price is given by the expected spot market price, since speculators build rational expectations. Thus, the expected profit on the forward market is given by the expected difference of the spot market price and marginal costs times each firm's forward traded amount ($E[\Pi_i^{fm}] = \frac{1}{2}\tilde{F}(p^{fm} - c) = \frac{1}{2}\tilde{F}E[p - c]$).

The expected profit on the spot market is found by calculating the expected value of the collusive profit (equation 3.5). The spread is distributed according to a continuous distribution function $\hat{F}(\gamma)$ with a density of $\hat{f}(\gamma)$. The realization of the spread can be

any real number ($-\infty < \gamma < \infty$). This states the expected profit in scenario *I* as:

$$\begin{aligned}
E \left[\Pi_i \mid 2\tilde{F} < \gamma < \infty \right] &= E \left[\Pi_i^{sm} \mid 2\tilde{F} < \gamma < \infty \right] + E \left[\Pi_i^{fm} \mid 2\tilde{F} < \gamma < \infty \right] \\
&= E \left[\frac{1}{8}\gamma^2 - \frac{1}{4}\gamma\tilde{F} + \frac{1}{2}\tilde{F}(p^M - c) \mid 2\tilde{F} < \gamma < \infty \right] \quad (3.21) \\
&= \int_{2\tilde{F}}^{\infty} \frac{1}{8}\gamma^2 \hat{f}(\gamma) d\gamma
\end{aligned}$$

The increase of the expected forward market profit, which is coming from forward trading, is totally offset by a decrease of the expected spot market profit. As long as firms are able to collude at the monopoly price and the forward traded amount does not exceed the monopoly quantity (condition for scenario *I*), the expected collusive profit equals half of the expected monopoly profit. Thus, in scenario *I* the expected profit is not influenced by the forward traded amount.

Scenario II:

Firms set a collusive price for which the forward traded amount exceeds the collusive quantity

The price on the spot market is solely determined by speculators' behavior, since colluding firms sell no additional quantities on the spot market. Speculators will bring the total forward traded amount to the market, since by assumption they cannot store the commodity. Hence, the price on the spot market is given by $p^{sm} = a - \tilde{F}$, which is below the monopoly price and above the residual monopoly price ($p^{rm} = \frac{1}{2}(a - c - \tilde{F}) + c < p^{sm} = a - \tilde{F} < p^M = \frac{1}{2}(a - c)$). Colluding firms do not earn any profits on the spot market. However, they earn a profit, that is coming from their forward-traded amount. Thus, the expected profit in scenario *II* is solely given by the profit, which is coming from forward trading:

$$\begin{aligned}
E \left[\Pi_i \mid -\infty < \gamma < 2\tilde{F} \right] &= E \left[\Pi_i^{sm} \mid -\infty < \gamma < 2\tilde{F} \right] + E \left[\Pi_i^{fm} \mid -\infty < \gamma < 2\tilde{F} \right] \\
&= 0 + \frac{1}{2}\tilde{F} \int_{-\infty}^{2\tilde{F}} (\gamma - \tilde{F}) \hat{f}(\gamma) d\gamma \quad (3.22)
\end{aligned}$$

The total expected collusive profit can easily be found by summing up the expected for-

ward and spot market profits of scenario *I* and scenario *II*.

$$\begin{aligned}
E[\Pi_i] &= E[\Pi_i | -\infty < \gamma < 2\tilde{F}] + E[\Pi_i | 2\tilde{F} < \gamma < \infty] \\
&= \frac{1}{2}\tilde{F} \int_{-\infty}^{2\tilde{F}} (\gamma - \tilde{F}) \hat{f}(\gamma) d\gamma + \int_{2\tilde{F}}^{\infty} \frac{1}{8} \gamma^2 \hat{f}(\gamma) d\gamma \\
&= -\frac{1}{2}\tilde{F}^2 \hat{F}(2\tilde{F}) + \frac{1}{2}\tilde{F} \int_{-\infty}^{2\tilde{F}} \gamma \hat{f}(\gamma) d\gamma + \frac{1}{8} \int_{2\tilde{F}}^{\infty} \gamma^2 \hat{f}(\gamma) d\gamma
\end{aligned} \tag{3.23}$$

On the following pages this total expected collusive profit is specified using an exponential distribution as well as a two point distribution. These both distributions are chosen, since both distributions can illustrate two different scenarios. Firstly, realizations of an exponential distribution can take any value between zero and infinity. Thus, an exponential distribution is suitable to model a market, on which demand can be close to zero in heavy recessions as well as very large in booms. A good example is the demand for conventional electricity in Germany. On the one hand demand can be close to zero (or theoretically even below), if a small demand occurs together with a high feed-in of electricity coming from renewable energies. On the other hand demand can be very large, if a large demand occurs together with a small supply coming from renewable energies. Secondly, there are exactly two realizations of a two-point distribution. Thus, there exists a recessive scenario as well as a boom scenario, that is clearly defined. A stylized example of this situation is given by the total demand for electricity in Germany, since a clear lower bound of demand is given, since even if demand is very small it exceeds a certain threshold. The upcoming analysis will show, that the existence of a lower threshold is very important from a strategic perspective.

The total expected collusive profit for an exponential distribution

At this point, the exponential distribution is used to specify the total expected profit. See equations A.9 to A.13 in the appendix for the detailed derivation of the expected collusive profit for an exponentially distributed spread.

$$E[\Pi_i] = \frac{1}{2} \frac{\tilde{F}}{\lambda} - \frac{1}{2} \tilde{F}^2 + \frac{1}{4} \frac{1}{\lambda^2} e^{-2\lambda\tilde{F}} \tag{3.24}$$

The effect of forward trading on the expected collusive profit can easily be found by taking the first and second order derivatives with respect to the forward traded amount:

$$\begin{aligned}\frac{\partial E[\Pi_i]}{\partial \tilde{F}} &= \frac{1}{2} \frac{1}{\lambda} \left[1 - e^{-2\lambda\tilde{F}} \right] - \tilde{F} < 0 \quad \forall \tilde{F} > 0 \\ \frac{\partial^2 E[\Pi_i]}{\partial \tilde{F}^2} &= -1 + e^{-2\lambda\tilde{F}} < 0 \quad \forall \tilde{F} > 0\end{aligned}\quad (3.25)$$

Thus, the total expected profit for colluding firms is concavely decreasing in the contracted amount. Suppose the colluding firms trade the total expected monopoly quantity forward ($F = \frac{1}{2\lambda}$). This leads to a profit of only about 87% of the profit compared to a situation where firms do not trade any forward contracts, since :

$$\frac{E\left[\Pi_i \mid \tilde{F} = \frac{1}{2\lambda}\right]}{E\left[\Pi_i \mid \tilde{F} = 0\right]} = \frac{1}{2} + e^{-1} \approx 0.8679 \quad (3.26)$$

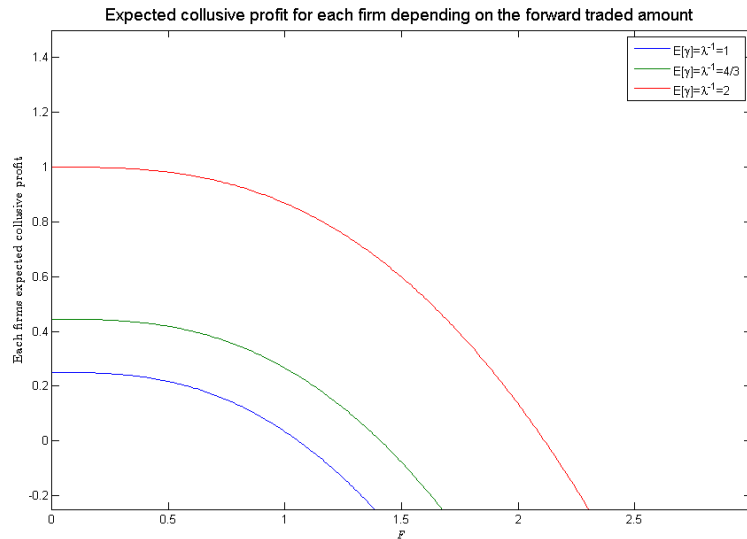


Figure 3.2: Effect of the Forward-Traded Amount on the Collusive Profit for $\delta \rightarrow 1$

Figure 3.2 shows the collusive profit for firms depending on the forward traded amount, when they could sustain a full collusion at any price ($\delta \rightarrow 1$). For an exponentially distributed spread the expected monopoly quantity is given by $E[q^M] = \frac{1}{2\lambda}$. Thus, in Figure 3.2 the expected collusive per period profit is drawn for an expected monopoly quantity of $E[q^M] = \frac{1}{2}$, $E[q^M] = \frac{2}{3}$ and $E[q^M] = 1$.

For moderate amounts traded forward the profit-decreasing effect of forward trading is

rather small mainly due to two reasons. Firstly, when firms only trade a moderate amount forward, the probability that the forward traded amount exceeds the collusive monopoly quantity is rather small. Secondly, even if the forward traded amount exceeds the collusive monopoly quantity, only rather small monopoly profits on the spot market are crowded out by forward trading. Higher realizations of the random difference between the reservation price and marginal costs, which contribute much more to the expected profit, are not affected. The opposite is true for excessive amounts traded forward. Then, it becomes rather likely that the forward traded amount exceeds the monopoly quantity and even relatively large realizations of the spread are affected. This strengthens the fundamental finding that is in contrast to the deterministic market conditions modeled by Liski and Montero (2006): Stabilizing a collusive agreement using forward contracts is costly in volatile markets.

The total expected collusive profit for a two point distribution

At this point, a two-point distribution is used to specify the expected collusive profit. A recession that is associated with a rather low profit of Π_R occurs with probability $\tilde{\mu}$. A boom that is associated with a rather high profit of Π_B occurs with probability $1 - \tilde{\mu}$. Each firm's expected collusive profit is given exactly by half of the expected monopoly profit ($E[\Pi_i] = \frac{1}{2} [\tilde{\mu}\Pi_R^M + (1 - \tilde{\mu})\Pi_B^M]$) as long as firms discount factor is above the threshold discount factor of:

$$\delta > \delta^* = 1 - \frac{\Pi_B^M (1 - \tilde{\mu}) + \tilde{\mu}\Pi_R^M}{\Pi_B^M (2 - \tilde{\mu}) + \tilde{\mu}\Pi_R^M - q_R^M q_B^M + \frac{1}{2}q_R^{M^2}} \quad (3.27)$$

See equation A.3 appendix for a detailed derivation.

For a two-state distribution the recessive amount is exactly known. A forward traded amount less or equal the recession monopoly quantity stabilizes collusion, but is not altering the profit. Thus, for a discrete distribution colluding firms can trade up to this recessive monopoly quantity forward, without altering the expected profit. Equation 3.27 gives the smallest discount factor, that can lead to a "full-collusion" associated with monopoly profits in a boom as well as in a recession. This is in contrast to the findings for an exponential distribution, where the recessive monopoly amount can be any positive real number and firms are always in danger of "over-contracting".

3.3.5 Forward Trading and Semi-Collusion

The next pages are used to derive the best semi-collusive strategy of firms. Unfortunately, even for the rather simple two-point distribution no closed form solution can be found. The solution for an exponential is likely to be even much more complex and therefore is not conducted in this thesis.

When colluding firms trade forward an amount that is above the monopoly quantity in recession, the expected collusive profit for a two-state distribution is given by:

$$\begin{aligned} E[\Pi_i^{SC}] &= \frac{1}{2} \left[E \left[2q^M \tilde{F} - \tilde{F}^2 \mid \tilde{F} > (a-p) \right] + E \left[(a-p)(p-c) \mid \tilde{F} \leq (a-p) \right] \right] \\ &= \frac{\tilde{\mu} \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1-\tilde{\mu}) (a^B - p) (p - c^B)}{2} < \frac{1}{2} E[\Pi^M] \quad \forall \tilde{F} > q_R^M \end{aligned} \quad (3.28)$$

Equation 3.28 follows straightforward from equation 3.20, since for a two-state distribution with probability $\tilde{\mu}$ a recession and with probability $1 - \tilde{\mu}$ a boom occurs. Thus, the expected recession profit is given by $\tilde{\mu} \left(2q_R^M \tilde{F} - \tilde{F}^2 \right)$, since firms have traded forward a higher amount than the corresponding monopoly quantity. However, the expected boom profit remains unaffected and is given by $(1 - \tilde{\mu}) (a^B - p) (p - c^B)$.

When firms cannot collude by contracting the total recessive quantity forward, firms adopt their price in boom as well as sell more than the recessive monopoly quantity forward. Then the optimal boom price (p_B^{sc}) and forward traded amount (\tilde{F}^{sc}) is found by using the first order derivatives of equation 3.28:

Maximizing the expected collusive profit due to the forward traded amount leads to:

$$\begin{aligned} \frac{\partial E[\Pi]}{\partial \tilde{F}} &= \tilde{\mu} \left(2q_R^M - 2\tilde{F} \right) + (1-\tilde{\mu}) \left((a+c) \frac{\partial p}{\partial \tilde{F}} - 2p \frac{\partial p}{\partial \tilde{F}} \right) \stackrel{!}{=} 0 \\ \tilde{F}^{sc} &= q_R^M + \frac{1-\tilde{\mu}}{2\tilde{\mu}} (a-2p+c) \frac{\partial p}{\partial \tilde{F}} > q_R^M \quad \forall p < p_B^M \end{aligned} \quad (3.29)$$

Maximizing the expected collusive profit due to the boom price leads to:

$$\begin{aligned} \frac{\partial E[\Pi]}{\partial p} &= \tilde{\mu} \left(2q_R^M \frac{\partial \tilde{F}}{\partial p} - 2\tilde{F} \frac{\partial \tilde{F}}{\partial p} \right) + (1-\tilde{\mu}) (a-2p+c) \stackrel{!}{=} 0 \\ p_B^{sc} &= p_B^M - \frac{\tilde{\mu}}{1-\tilde{\mu}} \left(\tilde{F} - q_R^M \right) \frac{\partial \tilde{F}}{\partial p} < p_B^M \quad \forall \tilde{F} > q_R^M \end{aligned} \quad (3.30)$$

Firms will choose the forward traded amount \tilde{F} and the boom price p , in the way that they maximize the expected collusive profit. Unfortunately, optimization of the expected collusive profit such that the no deviation constraint holds, cannot be solved analytically. As a consequence the total differential is used to show the structure of optimal collusive design.

When firms cannot fully collude, firms choose price and forward traded quantity exactly to match the no deviation constraint ($C \stackrel{!}{=} 0$). The partial effect of the semi-collusive price on the forward traded amount is:

$$\begin{aligned}\frac{\partial p}{\partial \tilde{F}} &= \frac{(a - \tilde{F} - p)(1 - \delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F})}{(1 - \delta)\tilde{F} - (1 - \delta\tilde{\mu})(a - 2p + c)} > 0 \\ \frac{\partial \tilde{F}}{\partial p} &= \frac{(1 - \delta)\tilde{F} - (1 - \delta\tilde{\mu})(a - 2p + c)}{(a - \tilde{F} - p)(1 - \delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F})} > 0\end{aligned}\quad (3.31)$$

For derivation see equation A.21 to A.28 in the appendix. For the upcoming analysis, the most important partial effects are:

$$\frac{\partial p}{\partial \tilde{F}} > 0, \quad \frac{\partial \tilde{F}}{\partial p} > 0, \quad \frac{\partial \frac{\partial \tilde{F}}{\partial p}}{\partial \tilde{\mu}} > 0, \quad \frac{\partial \frac{\partial p}{\partial \tilde{F}}}{\partial \tilde{\mu}} < 0 \quad (3.32)$$

As long as semi-colluding firms set a price below the monopoly boom price, they choose an forward traded amount above recessive monopoly quantity and vice versa ($p_{sc} < p_B^M \Leftrightarrow \tilde{F} > q_R^M$). Therefore, in recession as well as in booms the optimal strategy departs from the monopoly outcome.

The effect of the recession probability $\tilde{\mu}$ on the semi-collusive outcome is given by the derivatives of the optimal semi-collusive price and forward traded amount with respect to the recession probability $\tilde{\mu}$

$$\begin{aligned}\frac{\partial \tilde{F}^{sc}}{\partial \tilde{\mu}} &= (a - 2p + c) \left[-\frac{1}{(1 - \tilde{\mu})^2} \frac{\partial p}{\partial \tilde{F}} + \frac{1 - \tilde{\mu}}{\tilde{\mu}} \frac{\partial \frac{\partial p}{\partial \tilde{F}}}{\partial \tilde{\mu}} \right] < 0 \\ \frac{\partial p_B^{sc}}{\partial \tilde{\mu}} &= - \left[\tilde{F} - q_R^M \right] \left[\frac{1}{(1 - \tilde{\mu})^2} \frac{\partial \tilde{F}}{\partial p} + \frac{\tilde{\mu}}{1 - \tilde{\mu}} \frac{\partial \frac{\partial \tilde{F}}{\partial p}}{\partial \tilde{\mu}} \right] < 0\end{aligned}\quad (3.33)$$

For a given discount factor, which forces firms to semi-collude, firms can either trade forward more than the corresponding recession monopoly quantity or set a boom price below the monopoly one. Ceteris paribus a higher recession probability $\tilde{\mu}$ leads to a lower forward traded amount as well as to a lower collusive boom price. This means

firms stabilize their collusive agreement rather by adopting boom prices than by trading forward. Quite the opposite is true, when the probability for a boom $1 - \tilde{\mu}$ is increased. Then firms trade a rather large amount forward, but are reluctant to adopt boom prices.

The economic intuition of this result is straightforward: Semi-colluding firms have to choose whether they sacrifice a larger amount of boom or of recession profit. When the expected recession profit increases, they prefer sacrificing more of the boom profit. When in contrast the expected boom profit increases, firms prefer sacrificing more of the recession profit.

Another important question is, which discount factor of firms is necessary for such a semi-collusive agreement. As shown above the semi-collusive strategy consists of a forward traded amount above the recessive monopoly quantity as well as a boom price below the monopoly outcome. As shown by Green and Coq (2010, p.23) for a semi-collusive price below the monopoly outcome two different deviation prices exist. Firstly, the residual monopoly price ($p^d = \frac{1}{2}(a - f + c)$) whenever the semi-collusive price is close to the monopoly one. Secondly, a price that is slightly below the semi-collusive price ($p_2^d = p^{sc} - \epsilon$) whenever the semi-collusive price is close to marginal costs. Comparing the profit of deviation and of collusion for both deviation prices leads to following lower bound of the critical discount factor for a sustainable semi-collusion.

If it is optimal for a deviating firm to undercut the collusive price infinitesimally ($p^d = p_2^d = p^{sc} - \epsilon$) the trade-off between deviation and collusion leads to following critical discount factor:

$$\delta_*^2 = 1 - \frac{\mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu) (a - p^{sc}) (p^{sc} - c)}{\left(a - \tilde{F} - p^{sc} \right) (p^{sc} - c) + \mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu) (a - p^{sc}) (p^{sc} - c)} \quad (3.34)$$

See equation A.15 and equation A.17 in the appendix for a detailed derivation.

If it is optimal for a deviating firm to set the residual monopoly price ($p^d = p_1^d = \frac{1}{2}(a - \tilde{F} - p^{sc})$) the trade-off between deviation and collusion leads to following critical discount factor:

$$\delta_*^1 = 1 - \frac{\mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu) (a - p^{sc}) (p^{sc} - c)}{\mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu) (a - p^{sc}) (p^{sc} - c) + \frac{1}{2} \left(a - \tilde{F} - c \right)^2 - \left(a - \tilde{F} - p^{sc} \right) (p^{sc} - c)} \quad (3.35)$$

See equation A.18 in the appendix for a detailed derivation.

Thus, the smallest critical discount factor for a semi-collusive can be stated as:

$$\delta_* = \begin{cases} 1 - \frac{\mu(2q_R^M F - F^2) + (1-\mu)(a-p^{sc})(p^{sc}-c)}{\mu(2q_R^M F - F^2) + (1-\mu)(a-p^{sc})(p^{sc}-c) + \frac{1}{2}(a-F-c)^2 - (a-F-p^{sc})(p^{sc}-c)} & \text{for } p^d \\ 1 - \frac{\mu(2q_R^M F - F^2) + (1-\mu)(a-p^{sc})(p^{sc}-c)}{\mu(2q_R^M F - F^2) + (1-\mu)(a-p^{sc})(p^{sc}-c) + (a-F-p^{sc})(p^{sc}-c)} & \text{for } p_2^d \end{cases} \quad (3.36)$$

If firms set a price very close to marginal costs ($p^{sc} \rightarrow c$), they can decrease the critical discount factor even to zero. However, the profitability of such a semi-collusive price critically depends upon the constellation of parameters, since negative expected collusive profits could occur, too.

See equation A.20 in the appendix for a more detailed derivation.

Figure 3.3 illustrates the three different collusive strategies that depend on the critical discount factor of each firm. Whenever the critical discount factor of both firms exceeds δ^* (see equation 3.27) each firm can earn half of the the expected monopoly profit by colluding. Whenever each firms critical discount factor is below δ^* but above δ_* (see equation 3.36) firms can semi-collude and earn an expected positive collusive profit. Whenever each firms critical discount factor is below δ_* firms cannot collude at all. From a theoretical perspective firms can decrease δ_* to zero. However, it critically depends on the constellation of parameters, whether firms earn a positive collusive profit by doing so.

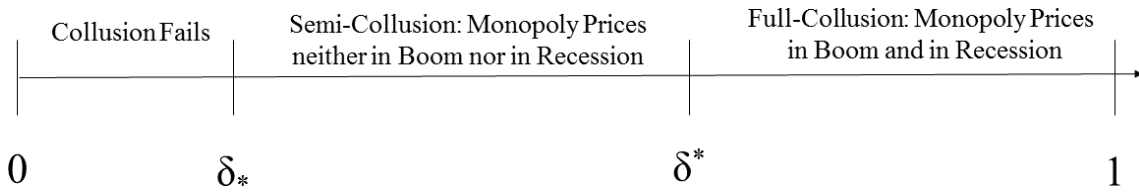


Figure 3.3: Relationship between the Critical Discount Factor and Collusive Behavior

3.3.6 Forward Trading and Taking a Long Position

In the analysis of collusive incentives above firms always had a short position on the forward market, which means that firms are committed by forward contracts to sell a certain amount of their output to speculators. In the upcoming pages collusive incentives for firms having a short position on the forward market are analyzed. If physical delivery

is mandatory and firms have a short position on the forward market, they are obliged to buy output from speculators. In other words: Firms are obliged to buy back parts of their own output, since speculators do not have any capacities to produce the corresponding commodity.

Suppose each firm has a long position on the forward market given by \underline{f} . This long position in the forward market is equivalent to a negative short position in the forward market ($-\tilde{f} = \underline{f}$). This variable is introduced to avoid notational confusion associated with a negative short position.

Deviation Profit

In order to close their short positions, speculators seek the exact quantity that is traded in both firms' long positions ($D_{Spec} = 2\underline{f}$). Speculators buy the product from the firm that charges the lowest price and sell it to both firms to close all positions. When firms are long on the forward market, "firm i's optimal deviation is to charge $p^M - \epsilon$ as in the pure-spot case" (Liski and Montero, 2006, p.220). The same holds true for any (profitable) collusive price below monopoly price $p^M > p^c > c$. A deviating firm attracts total demand induced by speculators. This leads to a profit of $D_{Spec}(p^c - c) = 2\underline{f}(p^c - c)$. However, to close its forward market obligation, the deviating firm has to pay $\Omega = \underline{f}p^c$ to speculators. Additionally it gets back \underline{f} units of the corresponding product. Thus, a deviating firm earns a profit by the interaction with speculators of:

$$\begin{aligned}\tilde{\Pi}^D &= \Omega + D_{Spec}(p^c - c) = -\underline{f}p^c + 2\underline{f}(p^c - c) \\ &= \underline{f}(p^c - c) - \underline{f}c\end{aligned}\tag{3.37}$$

After all positions have been closed, the deviating firm earns a profit by interaction with speculators of $\tilde{\Pi}^D$. Additionally, the deviating firm owns \underline{f} units of the product, since it had to buy back these units from speculators.

When a deviation occurs, the "duped" firm cannot sell any output to the speculators. However, the duped firm has to meet its forward obligation. Therefore, the duped firm has to buy \underline{f} units of the product from speculators, which were originally produced by the deviating firm. This effect increases the demand that can be met by a deviating firm.

All consumers buy from the deviating firm. As was mentioned above, the deviating

firm has to buy back \underline{f} units coming from its forward obligation. These units are sold immediately to consumers at the deviation price, which undercuts the monopoly price infinitesimally. After these units have been sold, there is remaining demand coming from consumers, which is denoted by $D^R = (a - \underline{f} - p^M)$.

The total profit of a deviating firm can be separated into three different profits: Firstly, the profit coming from interaction with speculators ($\tilde{\Pi}^D$). Secondly, the profit coming from firms' produced amount that is sold on the market ($\underline{f}p^c$). And finally, the profit coming from serving remaining demand ($D^R(p^c - c)$). This states the total profit of a deviating firm as follows:

$$\begin{aligned}\Pi^D &= \tilde{\Pi}^D - \underline{f}p^c + D^R(p^c - c) \\ &= \underline{f}(p^c - c) - \underline{f}c + \underline{f}p^c + (a - \underline{f} - p^c)(p^c - c) \\ &= (a - p^c)(p^c - c) + \underline{f}(p^c - c)\end{aligned}\quad (3.38)$$

Collusive Profit

For both firms setting the same price ($p_i = p_j = p^c$), half of the demand induced by speculators is met by each firm. Each firm has a forward market obligation to pay $\Omega = \underline{f}p^c$ and to take \underline{f} units of the product. Since both transactions are done at the collusive price, firms and speculators close their positions and neither earn nor lose money. However, each firm bears production costs of $\underline{f}c$ and owns \underline{f} units of the product. This leads to a "profit" from interaction with speculators of:

$$\begin{aligned}\tilde{\Pi}^C &= \frac{1}{2}D_{Spec}(p^c - c) + \Omega = \underline{f}(p^c - c) - \underline{f}p^c \\ &= -\underline{f}c\end{aligned}\quad (3.39)$$

Both firms own \underline{f} units of the product, since they had to settle their forward market obligation. These units are sold to consumers by both firms immediately. Thus, the demand function of remaining demand coming from consumers is given by $D^R = (a - 2\underline{f} - p^c)$.

The profit of colluding firms can be separated into three different profits: Firstly, the profit coming from interaction with speculators ($\tilde{\Pi}^c$). Secondly, the profit coming from firms' already produced amount sold to consumers ($\underline{f}p^c$). And finally, the profit coming from serving remaining demand ($\frac{1}{2}D^R(p^c - c)$). The total profit function for each

colluding firm is given by:

$$\begin{aligned}\Pi^C &= \tilde{\Pi}^C + \tilde{f}p^c + \frac{1}{2}D^R(p^c - c) \\ &= -\tilde{f}c + \tilde{f}p^c + \frac{1}{2}\left(a - 2\tilde{f} - p^c\right)(p^c - c) = \frac{1}{2}\Pi^c\end{aligned}\quad (3.40)$$

In the end, the collusive profit equals half of the monopoly profit, since "forward positions do not imply additional output being effectively supplied to the market" (Liski and Montero, 2006, p.221).

The Critical Discount Factor for a Long Position

When a firm has to decide between collusion and deviation it chooses the strategy that promises the highest net present value. Collusion is stable whenever:

$$\begin{aligned}NPV(Collusion) &\geq NBV(Deviation) \\ \frac{1}{2}\Pi^c + \frac{1}{2}\frac{\delta}{1-\delta}E[\Pi^C] &\geq \Pi^c + \tilde{f}(p^c - c) \\ \frac{\delta}{1-\delta}E[\Pi^C] &\geq \Pi^c + 2\tilde{f}(p^c - c) \\ \delta &\geq \frac{\Pi^c + 2\tilde{f}(p^c - c)}{\Pi^c + 2\tilde{f}(p^c - c) + E[\Pi^C]} = 1 - \frac{E[\Pi^c]}{\Pi^c + 2\tilde{f}(p^c - c) + E[\Pi^C]}\end{aligned}\quad (3.41)$$

It is obvious that the critical discount factor derived in equation 3.41 exceeds for any arbitrary long position of firms ($\tilde{f} > 0$ or $\tilde{f} < 0$) the discount factor without forward trading. Thus, taking a long position on the forward market destabilizes a collusive agreement and colluding firms have no incentive to take any long position on the forward market. If colluding firms decide to trade forward contracts, they will choose a short position, which means that firms commit to deliver a certain amount to speculators and speculators sell this amount to consumers.

3.4 Conclusion

Uncertainty, volatility and fluctuations are the most frequent reasons given for forward trading. The contribution of the presented model has been the simultaneous analysis of fluctuations and forward contracts on collusive agreements. The incorporation of stochastic market conditions led to a more precise understanding of the effects of forward trading

and collusion. In terms of the economic literature, the gap between Rotemberg and Saloner (1986) and Liski and Montero (2006) has been closed.

The first part answered the question, whether forward trading can be used in volatile markets to stabilize a collusive agreement. Therefore, the critical discount factor was determined and the partial derivatives of the critical discount factor were analyzed. The main findings were: High realizations of the random difference between reservation price and marginal costs (“spread”) have a destabilizing effect, whereas a higher expectation of the “spread” has a stabilizing effect on collusive agreements. The results are totally in line with the analysis of Rotemberg and Saloner (1986). However, decomposition of the expectation of the squared “spread” into its squared expectation and variance led to an interesting insight: For a given positive fluctuation (boom), a higher variance increases the stability of collusion, since a higher variance makes a boom more common. Hence, it is not the variance itself that decreases the stability of a collusive agreement in volatile markets, but rather the appearance of high realizations of the “spread” that destabilizes collusive agreements. However, extraordinary booms only occur if the distribution of the spread is characterized by a sufficient degree of dispersion. As a further insight I found that short-term forward contracts can be used by firms to strictly stabilize collusion. This is in line with the analysis of Liski and Montero (2006) and Green and Coq (2010).

The second part answered the question, how the expected collusive profit is influenced by forward trading. For deterministic market conditions the profit that is earned by colluding firms, is not at all influenced by the forward traded amount (Liski and Montero, 2006). As shown in the presented model for continuous distributed cost and demand parameters, the expected profit earned by colluding firms strictly decreased concerning the forward-traded amount. When firms trade forward on a volatile market, they do not know in advance the demand and cost structure they will face at the date of delivery. For colluding firms this always leads to the problem of involuntarily having contracted more or less than the optimal collusive amount. When firms have contracted less than the optimal collusive amount, colluding firms can sell an additional amount on the spot market, which gives them the possibility to share the monopoly profit. However, for rather small contract volumes (in relation to the total accessible demand) a deviation could become profitable for “impatient firms”. When firms have contracted more than the optimal collu-

sive amount, solely the speculators decide about the price on the spot market, which leads to a lower price. This lowers the forward price, since the forward price is determined on a basis of rational expectations. As a consequence, the expected profit by trading forward a certain amount is beneath the expected profit by selling the same amount on the spot market. Therefore, the total expected value of the profit for each colluding firm is decreased by forward trading. The more forward contracts are sold the more severe is the reduction of collusive profit by (additional) forward contracts.

The third part described the optimal semi-collusive strategy for a two-state distribution of cost and demand parameters. Semi-colluding firms choose a forward-traded amount above recession monopoly quantity and a boom price below the monopoly price. Thus, neither during a recession nor in a boom the monopoly outcome is generated.

The four main results of the presented model can be stated as follows: Firstly, forward contracts can be used in deterministic as well as in volatile markets to stabilize collusive agreements. Secondly, in volatile markets forward trading decreases the expected total profit of colluding firms, when they "involuntarily" trade forward an amount above the recession quantity. For a discrete distribution, the lowest recession quantity is known. Therefore, this is not a severe problem for colluding firms. When in contrast to this for a continuous distribution the lowest recession monopoly quantity is not known, a firm's expected profit is strictly decreasing in forward contracts. Thirdly, semi-colluding firms will generate neither in times of a boom nor in times of a recession the monopoly outcome. Fourthly, feeding the theoretical model with data for the German wholesale electricity market leads to the insight that very strong incentives to collude exist.

3.5 Appendix

No Deviation Constraint and the Critical Discount Factor

To find the critical discount factor, the no deviation constraint (equation 3.7), which represents the trade-off between collusion and deviation, is solved for the discount factor δ .

When firms trade less than the monopoly quantity forward, the critical discount factor is:

$$\begin{aligned}
NPV(\text{Collusion}) &\geq NPV(\text{Deviation}) \\
\Pi^d &\leq \frac{1}{2}\Pi^d - \frac{1}{8}\tilde{F}^2 + \frac{1}{2}\frac{\delta}{1-\delta}E[\Pi^m] \\
4\Pi^d + \tilde{F}^2 &\leq \frac{\delta}{1-\delta}E[\gamma^2] \\
\gamma^2 - 2\gamma\tilde{F} + 2\tilde{F}^2 &\leq \frac{\delta}{1-\delta}[E[\gamma]^2 + Var[\gamma]] \\
\delta &\geq \frac{\gamma^2 - 2\gamma\tilde{F} + 2\tilde{F}^2}{E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\gamma\tilde{F} + 2\tilde{F}^2} = 1 - \frac{E[\gamma]^2 + Var[\gamma]}{E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\gamma\tilde{F} + 2\tilde{F}^2}
\end{aligned} \tag{A.1}$$

When firms trade more than the monopoly quantity forward, the no deviation constraint in equation 3.9 has to hold and the critical discount factor is given by:

$$\begin{aligned}
NPV(\text{Deviation}) &\leq NPV(\text{Collusion}) \\
\frac{1}{4}(a - \tilde{F} - c)^2 &\leq \frac{1}{2}\frac{\delta}{1-\delta}E[\Pi^m] \\
2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2 &\leq \frac{\delta}{1-\delta}[E[\gamma]^2 + Var[\gamma]] \\
\delta &\geq \frac{2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2}{E[\gamma]^2 + Var[\gamma] + 2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2} = 1 - \frac{E[\gamma]^2 + Var[\gamma]}{E[\gamma]^2 + Var[\gamma] + 2\gamma^2 - 4\tilde{F}\gamma + 2\tilde{F}^2}
\end{aligned} \tag{A.2}$$

Inserting the two state distribution function into the no deviation constraint when forward contracted amount not exceeding the monopoly quantity (equation A.1):

$$\begin{aligned}
\frac{1}{4}\gamma^2 - \frac{1}{2}\gamma\tilde{F} + \frac{1}{2}\tilde{F}^2 &\leq \frac{\delta}{1-\delta}E[\Pi^M] \\
\Pi_B^M - q_B^M\tilde{F} + \frac{1}{2}\tilde{F}^2 &\leq \frac{\delta}{1-\delta}[\tilde{\mu}\Pi_R^M + (1-\tilde{\mu})\Pi_B^M] \\
\delta &\geq \frac{\Pi_B^M - \tilde{F}q_B^M + \frac{1}{2}\tilde{F}^2}{\tilde{\mu}\Pi_R^M + (1-\tilde{\mu})\Pi_B^M + \Pi_B^M - \tilde{F}q_B^M + \frac{1}{2}\tilde{F}^2} \\
\delta &\geq 1 - \frac{\tilde{\mu}\Pi_R^M + (1-\tilde{\mu})\Pi_B^M}{\tilde{\mu}\Pi_R^M + (2-\tilde{\mu})\Pi_B^M - q_R^M q_B^M + \frac{1}{2}q_R^M} \quad \square
\end{aligned} \tag{A.3}$$

The last line comes from the fact that the highest forward traded amount without a loss in (recession) profit is given by recession monopoly quantity ($\tilde{F} = q_R^M$).

The critical discount factor for full-collusion without forward trading (δ^0) (Rotemberg and Saloner (1986) in a two state representation according to Tirole (1988)) is above the

critical discount factor with forward trading, since

$$\begin{aligned} \delta^0 &= 1 - \frac{\Pi_B^M (1 - \tilde{\mu}) + \tilde{\mu}\Pi_R^M}{\tilde{\mu}\Pi_R^M + (2 - \tilde{\mu})\Pi_B^M} > 1 - \frac{\Pi_B^M (1 - \tilde{\mu}) + \tilde{\mu}\Pi_R^M}{\Pi_B^M (2 - \tilde{\mu}) + \tilde{\mu}\Pi_R^M - q_R^M q_B^M + \frac{1}{2}q_R^{M^2}} = \delta^* \\ &< \frac{\Pi_B^M (1 - \tilde{\mu}) + \tilde{\mu}\Pi_R^M}{\Pi_B^M (2 - \tilde{\mu}) + \tilde{\mu}\Pi_R^M - q_R^M q_B^M + \frac{1}{2}q_R^{M^2}} \\ & \quad q_B^M > \frac{1}{2}q_R^M \quad \square \end{aligned} \tag{A.4}$$

Why Does Forward Trading Stabilize Collusive Agreement?

Deviation profit (equation 3.3) can be rearranged to

$$\begin{aligned} \Pi^d &= \frac{1}{4} [a - c - \tilde{F}]^2 \\ &= \frac{1}{4} [(a - c)^2 - 2\tilde{F}(a - c) + \tilde{F}^2] \\ &= \Pi^m \left[1 - \frac{\tilde{F}}{\frac{1}{2}(a - c)} + \frac{1}{4} \frac{\tilde{F}^2}{\frac{1}{4}(a - c)^2} \right] \\ &= \Pi^m \left[1 - \frac{1}{2} \frac{\tilde{F}}{q^M} \right]^2 \end{aligned} \tag{A.5}$$

Collusive profit in a spot market period (equation 3.5) can be brought to:

Remember: Collusive profits in a spot market period can be earned if and only if $\tilde{F} < q_m$

$$\begin{aligned} \Pi^C &= \frac{1}{2} \left[\frac{1}{4} (a - c)^2 - \frac{1}{2} \tilde{F}(a - c) \right] \\ &= \frac{1}{2} \left[\Pi^m - \frac{2}{4} (a - c)^2 \frac{\tilde{F}}{a - c} \right] \\ &= \frac{1}{2} \Pi^m \left[1 - \frac{\tilde{F}}{q^M} \right] \end{aligned} \tag{A.6}$$

As easily can be seen, deviation profit as well as collusive profit in a spot market period is decreased by forward contracts. However, as long as the total amount of forward contracts is less than the monopoly quantity, the decreasing effect is stronger on deviation profit.

This is due to the fact that forward trading influences deviation profit squared ($\Pi^D = \Pi^m \left[1 - \frac{1}{2} \frac{\tilde{F}}{q^M} \right]^2$) whereas collusive profit is influenced linearly ($\Pi^C = \frac{1}{2} \Pi^m \left[1 - \frac{\tilde{F}}{q^M} \right]$).

Proof:

Partial derivatives of collusion and deviation profit in a spot market period are given by:

$$\begin{aligned}\frac{\partial \Pi^C}{\partial \tilde{F}} &= -\frac{1}{2} \frac{\Pi^m}{q^M} \\ \frac{\partial \Pi^D}{\partial \tilde{F}} &= -\frac{\Pi^m}{q^M} \left[1 - \frac{1}{2} \frac{\tilde{F}}{q^M} \right]\end{aligned}\quad (\text{A.7})$$

Comparing both partial derivatives leads to

$$\begin{aligned}-\frac{1}{2} \frac{\Pi^m}{q^M} &\geq -\frac{\Pi^m}{q^M} \left[1 - \frac{1}{2} \frac{\tilde{F}}{q^M} \right] \\ \frac{1}{2} &\geq \frac{1}{2} \frac{\tilde{F}}{q^M} \\ q^M &\geq \tilde{F}\end{aligned}\quad (\text{A.8})$$

If the forward traded amount is less than the respecting monopoly quantity ($\tilde{F} < q^m$), additional forward contracts decrease deviation profit more sharply than collusive profit. If the forward traded amount is greater than the respective monopoly quantity ($\tilde{F} > q^M$), no collusive profits in the corresponding period can be earned. Additional forward contracts decrease deviation profit. Hence, the effect of additional forward contracts on the critical discount factor increases.

Exponential Distribution and the Total Expected Collusive Profit

For derivation of the total expected profit for an exponentially distributed spread it is separated into part A, part B and part C

$$E[\Pi_i] = \underbrace{\frac{1}{2} \tilde{F} \int_0^{2\tilde{F}} \gamma \hat{f}(\gamma) d\gamma}_A + \underbrace{-\frac{1}{2} \tilde{F}^2 \hat{F} (2\tilde{F})}_B + \underbrace{\frac{1}{8} \int_{2\tilde{F}}^{\infty} \gamma^2 \hat{f}(\gamma) d\gamma}_C \quad (\text{A.9})$$

The first part (A) can be brought to:

$$\begin{aligned}A &= \frac{1}{2} \tilde{F} \lambda \int_0^{2\tilde{F}} \gamma e^{-\lambda \gamma} d\gamma = \frac{1}{2} \tilde{F} \lambda \left[-2\tilde{F} \frac{1}{\lambda} e^{-2\tilde{F}\lambda} + 0 + \frac{1}{\lambda} \int_0^{2\tilde{F}} e^{-\lambda \gamma} d\gamma \right] \\ &= -\tilde{F}^2 e^{-2\tilde{F}\lambda} + \frac{1}{2} \frac{\tilde{F}}{\lambda} \left[1 - e^{-2\tilde{F}\lambda} \right]\end{aligned}\quad (\text{A.10})$$

The second part (B) can be brought to:

$$B = -\frac{1}{2} \tilde{F}^2 \left[1 - e^{-2\tilde{F}\lambda} \right] \quad (\text{A.11})$$

The third part (C) can be brought to:

$$\begin{aligned}
C &= \frac{1}{8}\lambda \int_{2\tilde{F}}^{\infty} \gamma^2 e^{-2\tilde{F}\lambda} d\gamma = \frac{1}{8}\lambda \left[\frac{1}{\lambda} 4\tilde{F}^2 e^{-2\tilde{F}\lambda} + 2\frac{1}{\lambda} \int_{2\tilde{F}}^{\infty} e^{-\lambda\gamma} d\gamma \right] \\
&= \frac{1}{2}\tilde{F}^2 e^{-2\tilde{F}\lambda} + \frac{1}{4} \left[\frac{1}{\lambda} e^{-2\tilde{F}\lambda} 2\tilde{F} + \frac{1}{\lambda} \int_{2\tilde{F}}^{\infty} e^{-\lambda\gamma} d\gamma \right] \\
&= \frac{1}{2}\tilde{F}^2 e^{-2\tilde{F}\lambda} + \frac{1}{2} \frac{\tilde{F}}{\lambda} e^{-2\tilde{F}\lambda} + \frac{1}{4} \frac{1}{\lambda^2} e^{-2\tilde{F}\lambda}
\end{aligned} \tag{A.12}$$

Summing up the first (A), the second (B) and the third part (C) yields:

$$\begin{aligned}
E[\Pi_i] &= -\tilde{F}^2 e^{-2\tilde{F}\lambda} + \frac{1}{2} \frac{\tilde{F}}{\lambda} [1 - e^{-2\tilde{F}\lambda}] - \frac{1}{2} \tilde{F}^2 [1 - e^{-2\tilde{F}\lambda}] + \frac{1}{2} \tilde{F}^2 e^{-2\tilde{F}\lambda} + \frac{1}{2} \frac{\tilde{F}}{\lambda} e^{-2\tilde{F}\lambda} \\
&\quad + \frac{1}{4} \frac{1}{\lambda^2} e^{-2\tilde{F}\lambda} \\
&= \frac{1}{2} \frac{\tilde{F}}{\lambda} - \frac{1}{2} \tilde{F}^2 + \frac{1}{4} \frac{1}{\lambda^2} e^{-2\tilde{F}\lambda}
\end{aligned} \tag{A.13}$$

Representation of the critical discount factor used for plotting in figure 3.1:

$$\begin{aligned}
\delta^* &= 1 - \frac{E[\gamma]^2 + Var[\gamma]}{E[\gamma]^2 + Var[\gamma] + \gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2} \\
&= 1 - \frac{2}{2 + \frac{\gamma^2}{E[\gamma]^2 + Var[\gamma]} \left[2 - 2\frac{\tilde{F}}{2}\gamma + \frac{\tilde{F}^2}{4}\gamma^2 \right]} = 1 - \frac{2}{2 + \frac{\gamma^2}{E[\gamma]^2 + Var[\gamma]} \left[2 - 2\frac{\tilde{F}}{q^M} + \frac{\tilde{F}^2}{q^{M^2}} \right]}
\end{aligned} \tag{A.14}$$

Derivation of the Necessary Discount Factor for Semi-Collusion

Derivation of the necessary discount factor for semi-collusion in equation 3.36. A firm that is deviating from a semi-collusive agreement chooses following deviation price:

$$p^d = \min \left\{ p_1^d = \frac{1}{2} (a - \tilde{F} + c), p_2^d = p^{sc} - \epsilon \right\} \tag{A.15}$$

If it is optimal for a deviating firm to set the residual monopoly price ($p^d = p_1^d = \frac{1}{2}(a - \tilde{F} - p^{sc})$) the trade-off between deviation and collusion can be stated as follows:

$$\begin{aligned}
NPV(\text{Deviation}) &\leq NPV(\text{Collusion}) \\
\frac{1}{4}(a - \tilde{F} - c)^2 &\leq \frac{1}{2}(a - \tilde{F} - p^{sc})(p^{sc} - c) + \frac{1}{2} \frac{\delta}{1 - \delta} E[\Pi^{sc}] \\
\frac{1}{4}(a - \tilde{F} - c)^2 &\leq \frac{1}{2}(a - \tilde{F} - p^{sc})(p^{sc} - c) \\
&\quad + \frac{1}{2} \frac{\delta}{1 - \delta} \left(\mu(2q_R^M \tilde{F} - \tilde{F}^2) + (1 - \mu)(a - p^{sc})(p^{sc} - c) \right) \quad (\text{A.16})
\end{aligned}$$

$$\begin{aligned}
(1 - \delta) \left(\frac{1}{2}(a - \tilde{F} - c)^2 - (a - \tilde{F} - p^{sc})(p^{sc} - c) \right) &\leq \\
\delta \left(\mu(2q_R^M \tilde{F} - \tilde{F}^2) + (1 - \mu)(a - p^{sc})(p^{sc} - c) \right) & \\
\delta \geq \frac{\frac{1}{2}(a - \tilde{F} - c)^2 - (a - \tilde{F} - p^{sc})(p^{sc} - c)}{\frac{1}{2}(a - \tilde{F} - c)^2 - (a - \tilde{F} - p^{sc})(p^{sc} - c) + \mu(2q_R^M \tilde{F} - \tilde{F}^2) + (1 - \mu)(a - p^{sc})(p^{sc} - c)} & \\
\delta_*^1 = 1 - \frac{\mu(2q_R^M \tilde{F} - \tilde{F}^2) + (1 - \mu)(a - p^{sc})(p^{sc} - c)}{\mu(2q_R^M \tilde{F} - \tilde{F}^2) + (1 - \mu)(a - p^{sc})(p^{sc} - c) + \frac{1}{2}(a - \tilde{F} - c)^2 - (a - \tilde{F} - p^{sc})(p^{sc} - c)} & \quad (\text{A.17})
\end{aligned}$$

If it is optimal for a deviating firm to undercut the collusive price infinitesimally ($p^d = p_2^d = p^{sc} - \epsilon$) the trade-off between deviation and collusion can be stated as follows:

$NPV (Deviation) \leq NPV (Collusion)$

$$\begin{aligned}
(a - \tilde{F} - p^{sc})(p^{sc} - c) &\leq \frac{1}{2}(a - \tilde{F} - p^{sc}) + \\
&\quad + \frac{1}{2} \frac{\delta}{1 - \delta} \left(\mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu)(a - p^{sc})(p^{sc} - c) \right) \\
(1 - \delta)(a - \tilde{F} - p^{sc})(p^{sc} - c) &\leq \delta \left(\mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu)(a - p^{sc})(p^{sc} - c) \right) \\
\delta &\geq \frac{(a - \tilde{F} - p^{sc})(p^{sc} - c)}{(a - \tilde{F} - p^{sc})(p^{sc} - c) + \mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu)(a - p^{sc})(p^{sc} - c)} \\
\delta_*^2 &= 1 - \frac{\mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu)(a - p^{sc})(p^{sc} - c)}{(a - \tilde{F} - p^{sc})(p^{sc} - c) + \mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu)(a - p^{sc})(p^{sc} - c)}
\end{aligned} \tag{A.18}$$

The critical discount factor, that makes a semi-collusion to fail, is higher, when the optimal deviation price is given by the residual monopoly price of $p_1^d = \frac{1}{2}(a - \tilde{F} - p^{sc})$, than the critical discount factor, when it is optimal to undercut the semi-collusive price infinitesimally. This easily can be seen by comparing equation A.17 and A.18. They only differ in one term in the denominator. A higher value in the denominator leads to a smaller value of the fraction. A smaller value of the corresponding fraction leads to a higher value of the discount factor, since a smaller value is deducted from 1. For δ_*^1 the term $\frac{1}{2}(a - \tilde{F} - c)^2 - (a - \tilde{F} - p^{sc})(p^{sc} - c)$ stands in the denominator and exceeds the corresponding value in the denominator of δ_*^2 of $(a - \tilde{F} - p^{sc})(p^{sc} - c)$, since

$$\begin{aligned}
\frac{1}{2}(a - \tilde{F} - c)^2 - (a - \tilde{F} - p^{sc})(p^{sc} - c) &\geq (a - \tilde{F} - p^{sc})(p^{sc} - c) \\
\frac{1}{4}(a - \tilde{F} - c)^2 &\geq (a - \tilde{F} - p^{sc})(p^{sc} - c) \\
\Pi^d \left(p_1^d = \frac{1}{2}(a - \tilde{F} + c) \right) &\geq \Pi^d (p_2^d = p^{sc} - \epsilon)
\end{aligned} \tag{A.19}$$

This means, that when firms set a very small semi-collusive price the critical discount factor becomes minimal. For a semi-collusive price close to marginal costs, this enables firms to reduce the critical discount to zero, since:

$$\begin{aligned} \lim_{p^{sc} \rightarrow c} \delta_*^2 &= \lim_{p^{sc} \rightarrow c} 1 - \frac{\mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu) (a - p^{sc}) (p^{sc} - c)}{\left(a - \tilde{F} - p^{sc} \right) (p^{sc} - c) + \mu \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \mu) (a - p^{sc}) (p^{sc} - c)} \\ &= 0 \end{aligned} \tag{A.20}$$

Derivation of the Optimal Semi-Collusive Strategy

When firms trade more than the recessive monopoly quantity forward, the no deviation constraint looks as follows:

$$\begin{aligned} \frac{1}{4} \left(a - \tilde{F} - c \right)^2 &\leq \frac{1}{2} (a - \tilde{F} - p) (p - c) + \frac{1}{2} \frac{\delta}{1 - \delta} \left[\tilde{\mu} (2q_R^M \tilde{F} - \tilde{F}^2) + (1 - \tilde{\mu}) (a - p) (p - c) \right] \\ 0 &\leq -\frac{1}{2} \left(a - \tilde{F} - c \right)^2 + (a - \tilde{F} - p) (p - c) + \frac{\delta}{1 - \delta} \left[\tilde{\mu} \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) + (1 - \tilde{\mu}) (a - p) (p - c) \right] \\ C &:= -\frac{1}{2} \left(a - \tilde{F} - c \right)^2 + (a - p) (p - c) \frac{1 - \delta \tilde{\mu}}{1 - \delta} - \tilde{F} (p - c) + \frac{\delta \tilde{\mu}}{1 - \delta} \left(2q_R^M \tilde{F} - \tilde{F}^2 \right) \stackrel{!}{=} 0 \end{aligned} \tag{A.21}$$

Firms that collude and need to adopt forward traded amount above the recessive monopoly quantity and/or set a price during booms below monopoly price, choose the contracted amount and the price exactly to match no deviation constraint.

Lowering the boom price stabilizes a collusive agreement, if, and only if, the partial derivative according to the price is negative ($\frac{\partial C}{\partial p} < 0$):

$$\begin{aligned} \frac{\partial C}{\partial p} &= (a - 2p + c) \frac{1 - \delta \tilde{\mu}}{1 - \delta} - \tilde{F} < 0 \\ p &> \frac{1}{2} (a + c) - \tilde{F} \frac{1 - \delta}{1 - \delta \tilde{\mu}} \end{aligned} \tag{A.22}$$

The partial derivative of the constraint according to the price is negative for all prices above the residual monopoly price ($\frac{\partial C}{\partial p} \leq 0 \quad \forall p \geq \frac{1}{2} (a - \tilde{F} - c)$), as long as:

$$\frac{1 - \delta}{1 - \delta \tilde{\mu}} > \frac{1}{2} \Leftrightarrow \delta < \frac{1}{2 - \tilde{\mu}} \tag{A.23}$$

This condition is fulfilled for any discount factor that forces firms to semi-collude (see equation A.4 for the condition of semi-collusion without forward trading), since:

$$\begin{aligned} \frac{1}{2 - \tilde{\mu}} > \delta^0 &= \frac{\Pi_B^M}{\tilde{\mu}\Pi_R^M + (2 - \tilde{\mu})\Pi_B^M} \\ \frac{\tilde{\mu}}{2 - \tilde{\mu}}\Pi_R^M + \Pi_B^M > \Pi_B^M &\Rightarrow \frac{\tilde{\mu}}{2 - \tilde{\mu}}\Pi_R^M > 0 \quad \square \end{aligned} \quad (\text{A.24})$$

Selling a higher amount than the recessive monopoly quantity forward, stabilizes a collusive agreement, if, and only if, the partial derivative according to forward contracts is positive ($\frac{\partial C}{\partial \tilde{F}} > 0$):

$$\begin{aligned} \frac{\partial C}{\partial \tilde{F}} &= (a - \tilde{F} - c) - (p - c) + \frac{\delta\tilde{\mu}}{1 - \delta} (2q_R^M - 2\tilde{F}) > 0 \\ \frac{(1 - \delta)(a - p)}{1 - \delta(1 - 2\tilde{\mu})} + \frac{2\delta\tilde{\mu}}{1 - \delta(1 - 2\tilde{\mu})}q_R^M &> \tilde{F} \end{aligned} \quad (\text{A.25})$$

The first part of the condition is given by a factor depending on the discount factor and the recession probability multiplied with the boom quantity ($\frac{(1-\delta)(a-p)}{1-\delta(1-2\tilde{\mu})}$). The second part is given by a factor depending on the discount factor and the recession probability multiplied with the recession quantity ($\frac{2\delta\tilde{\mu}}{1-\delta(1-2\tilde{\mu})}q_R^M$). This condition is fulfilled for forward-traded quantities that do not "exceed too much" the recessive collusive quantity. If the condition was negative, firms exactly would choose $\tilde{F} = \frac{(1-\delta)(a-p)}{1-\delta(1-2\tilde{\mu})} + \frac{2\delta\tilde{\mu}}{1-\delta(1-2\tilde{\mu})}q_R^M$, since a higher amount would decrease the stability of a collusive agreement and decrease the profit.

To identify the partial effect of the forward-traded amount and the boom price the total differential of the no deviation constraint is used.

$$\begin{aligned} \frac{\partial \tilde{F}}{\partial p} &= -\frac{\frac{\partial C}{\partial p}}{\frac{\partial C}{\partial \tilde{F}}} = \frac{(1 - \delta)\tilde{F} - (1 - \delta\tilde{\mu})(a - 2p + c)}{(a - \tilde{F} - p)(1 - \delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F})} > 0 \\ \frac{\partial p}{\partial \tilde{F}} &= -\frac{\frac{\partial C}{\partial \tilde{F}}}{\frac{\partial C}{\partial p}} = \frac{(a - \tilde{F} - p)(1 - \delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F})}{(1 - \delta)\tilde{F} - (1 - \delta\tilde{\mu})(a - 2p + c)} > 0 \end{aligned} \quad (\text{A.26})$$

This leads to the following optimal forward-traded amount and boom price:

$$\begin{aligned} \tilde{F}_{sc} &= q_R^M + \frac{1}{2} \frac{1 - \tilde{\mu}}{\tilde{\mu}} (a - 2p + c) \frac{(a - \tilde{F} - p)(1 - \delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F})}{(1 - \delta)\tilde{F} - (1 - \delta\tilde{\mu})(a - 2p + c)} > q_R^M \\ p_{sc} &= p_B^M - \frac{\tilde{\mu}}{1 - \tilde{\mu}} (\tilde{F} - q_R^M) \frac{(1 - \delta)\tilde{F} - (1 - \delta\tilde{\mu})(a - 2p + c)}{(a - \tilde{F} - p)(1 - \delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F})} < p_B^M \end{aligned} \quad (\text{A.27})$$

The partial derivatives of the relationship between forward traded amount and semi-collusive boom price with respect to recession probability μ are:

$$\begin{aligned}\frac{\partial p}{\partial \tilde{\mu}} &= \frac{2\delta (q_R^M - \tilde{F}) \left((1-\delta)\tilde{F} - (1-\delta\tilde{\mu})(a-2p+c) \right) - \delta(a-2p+c) \left((a-\tilde{F}-p)(1-\delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F}) \right)}{\left((1-\delta)\tilde{F} - (1-\delta\tilde{\mu})(a-2p+c) \right)^2} < 0 \\ \frac{\partial \tilde{F}}{\partial p} &= \frac{\delta(a-2p+c) \left((a-\tilde{F}-p)(1-\delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F}) \right) - 2\delta [q_R^M - \tilde{F}] \left((1-\delta)\tilde{F} - (1-\delta\tilde{\mu})(a-2p+c) \right)}{\left((a-\tilde{F}-p)(1-\delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F}) \right)^2} > 0\end{aligned}\tag{A.28}$$

Here the signs can easily be deduced from the fact that the forward traded amount exceeds recessive monopoly quantity $\tilde{F} > q_R^M$, that $(1-\delta)\tilde{F} - (1-\delta\tilde{\mu})(a-2p+c) > 0$ (see equation A.22) and $(a-\tilde{F}-p)(1-\delta) + 2\delta\tilde{\mu}(q_R^M - \tilde{F}) > 0$ (see equation A.25)

Negligible uncertainty as a special case

Under certainty, firms never trade more than the monopoly quantity in a full collusive agreement, since trading forward more than (a priori known) monopoly quantity would decrease profits. The total traded amount is given by summing up the single (symmetrically) traded amount where x gives the proportion of monopoly quantity that is traded forward ($\tilde{F} = \tilde{f}_i + \tilde{f}_j = 2\tilde{f} = q^M x = \frac{1}{2}\gamma x$). Under certainty, the “spread” equals its expectation and the variance of the “spread” is equal to zero. Then the critical discount factor (equation 3.8) can be brought to:

$$\begin{aligned}\delta \geq \delta^* &= 1 - \frac{E[\gamma]^2 + V[\gamma]}{E[\gamma]^2 + V[\gamma] + \gamma^2 - 2\tilde{F}\gamma + 2\tilde{F}^2} \\ &= 1 - \frac{\gamma^2}{2\gamma^2 - x\gamma^2 + \frac{1}{2}x^2\gamma^2} \\ &= 1 - \frac{2}{(2-x)^2 + 2x}\end{aligned}\tag{A.29}$$

The partial derivative of the critical discount factor due to proportion of monopoly quantity traded forward is given by:

$$\frac{\partial \delta^*}{\partial x} = \frac{-4[1-x]}{(2-x)^2 + 2x} \leq 0\tag{A.30}$$

The partial derivative of the critical discount factor due to proportion of monopoly quantity traded forward is strictly negative. Hence, in a deterministic market structure, trading forward helps to stabilize collusive agreements, too.

Chapter 4

Forward Trading and Strategic Investment

4.1 Introduction

Especially on electricity markets investment decisions play a crucial role for strategic competition. There are very long-lasting investments like building up a plant or introducing a cost-reducing new technology for electricity generation. Other investments like developing capacities in an existing plant, distributing electricity or marketing campaigns have a much shorter time horizon. The presented model contributes to the economic literature in modeling simultaneously two, especially for commodity markets, important strategic decisions: The decisions on investment and on forward trading.

The importance of investment decisions can be illustrated by the German power market and the investment costs for the ongoing turnaround towards a sustainable energy supply. The German Institute for Economic Research (DIW Berlin) (Blazejczak, Diekmann, Edler, Kemfert, Neuhoff, and Schill, 2013) estimated these investment costs up to 38 billion euros for the years between 2014 and 2020. From this total amount of 38 billion euros approximately 26 billion euros are needed for investments in power and heating supply and 7 billion euros for investments in the electricity network.

The German Federal Ministry for Economic Affairs and Energy collected investment data for renewable energies installations from the years 2000 until 2014 (BMWi, 2014a, p.37). This data, which is presented in figure 4.1, shows the increasing importance of investments in renewable energies. Total investments in renewable energies were rather

moderate in the year 2000 (3.2 billion euros). Investments were even five times higher in 2014 (16 billion euros). This clearly illustrates the importance of investment decisions on the German electricity market.

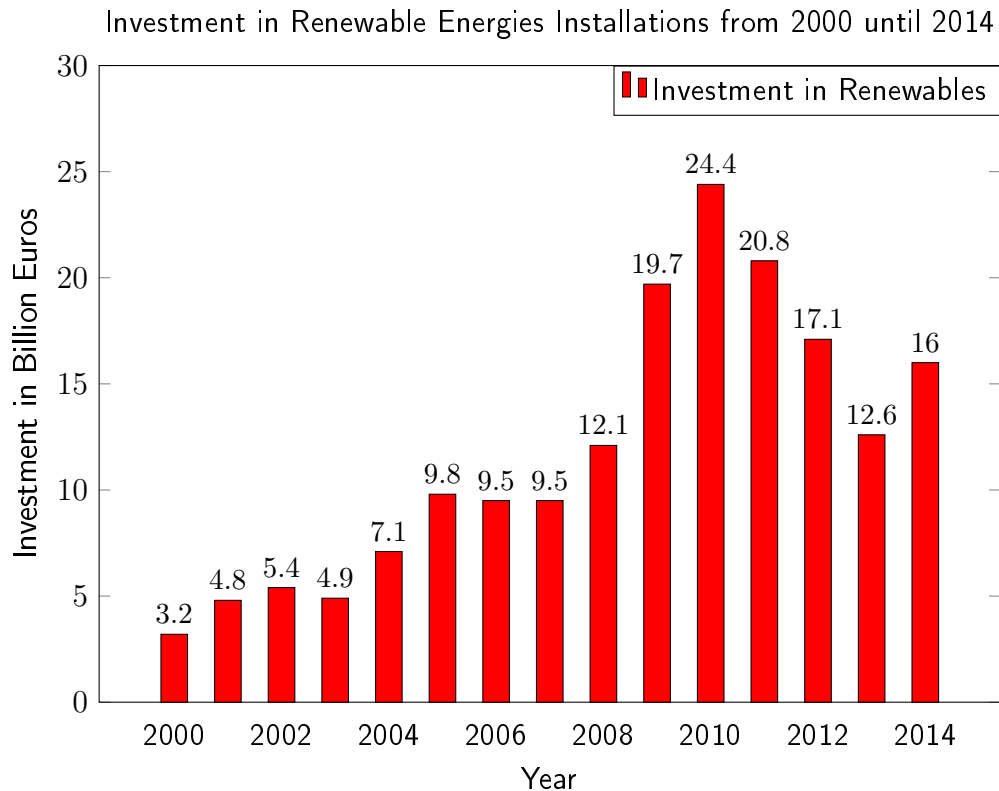


Figure 4.1: Investment in Renewable Energies Installations from 2000 until 2014

To what extent imperfectly competing firms invest depends mainly on whether the decision variables such as quantity, price and investment are seen as strategic complements or substitutes (see the influential contributions of Fudenberg and Tirole (1984) and Bulow, Geanakoplos, and Klemperer (1985)). As will be shown in the presented model, the market performance significantly depends on the time horizon of firms' investment decision. For a long-lasting investment decision that takes place before firms trade forward and compete in quantities competition is rather weak and rather a low social welfare is achieved. In contrast to this, for shorter investment decisions, which take place after firms have traded forward, but before firms compete in quantities, competition becomes fierce and social welfare becomes rather high.

The next pages are organized as follows: In section 4.3.1 the main assumptions and the structure of the model are presented. In section 4.3.2 a long term strategic investment

is modeled. Therefore in a first stage firms choose their investments before in a second stage, firms engage in forward contracts and, in a third stage, they compete in quantities. In section 4.3.3 a mid-term strategic investment is modeled. Therefore in the first stage firms engage in forward contracts before they decide about an investment in the second stage and then compete in quantities in the third stage.

In section 4.3.4 the results of both decision structures are compared to one another. They are also compared to the results of a two-stage game consisting of a forward trading stage followed by quantity competition as well as to a two stage game consisting of an investment decision followed by quantity competition. The results of both two-stage games are derived in a simple and concise form in the appendix. Section 4.4 concludes.

The model, that is presented on the next pages, has been published in the series University of Tübingen Working Papers in Economics and Finance (Aichele, 2014b).

4.2 Literature on Strategic Forward Trading and Investment

The Economic Analysis of Investment Incentives

In the very beginning of industrial organization authors like Flaherty (1980), Spence (1977) and Dixit (1980) already worked out the strategic dimension of investment decisions for oligopolistic firms. These first contributions mainly focused on the possibility of a certain level of investment to deter market entry of competitors. Then Brander and Spencer (1983) analyzed strategic dimensions of investment decisions for two firms that already serve a certain market. Therefore they use a two-stage decision structure for two competing firms: In a first step, firms have to decide about their R&D expenditure that decreases marginal costs of production. In a second step, firms can choose for a given cost structure that has been determined by R&D expenditure, about quantities supplied to consumers. They compare this two-stage strategic decision setting to a simultaneous and therefore non strategic decision setting and conclude: "In the strategic setting firms use more R&D, they do not minimize the cost of producing output, and there is a tendency for the total output of each firm to be larger" (Brander and Spencer, 1983, p.232). This leads to lower firm profits. However, "net welfare, as measured by the sum of consumer surplus

and profit, is likely to rise" (Brander and Spencer, 1983, p.232). Thus, the strategic effect of commitment by R&D expenditures is socially beneficial.

The influential contributions of Fudenberg and Tirole (1984) and Bulow, Geanakoplos, and Klemperer (1985) followed. They break down the question to what extent imperfectly competing firms invest on the question whether the type of decision variables such as quantity and price are seen as strategic complements or substitutes and whether an investment makes competitors "tough" or "soft". Whether a strategic variable is said to be a strategic complement or a strategic substitute depends on the slope of its reaction function. A reaction function shows the best action of a firm for each given action of its competitor. For a positive slope of the reaction function a firm chooses c.p. a higher realization of its own variable, whenever a competitor chooses a higher realization of its variable. For a positive slope of the reaction function variables are strategic complements. For a negative slope of the reaction function a firm chooses c.p. a lower realization of its own variable whenever a competitor chooses a higher realization of its variable. For a negative slope of the reaction function variables are strategic substitutes. In industrial organization a classical example of strategic substitutes and complements are prices and capacities. "Prices are often strategic complements and capacities are often strategic substitutes" (Tirole, 1988, p.208). An investment makes a competitor "tough", if this investment decreases competitors profit. An investment makes a competitor "soft", if this investment increases competitors profit.

Combining the concept of strategic complements and substitutes with the idea of investment that makes firms "tough" or "soft" leads to the famous taxonomy of strategic competition. Four different strategies for competing firms, in which "the strategy names are related to the incentive for the strategic firm to overinvest or underinvest in equilibrium, relative to a nonstrategic firm playing the same game" (Church and Ware, 2000, p.534) can be distinguished. Firstly, there is the top dog strategy, which describes aggressive overinvestment. This strategy is optimal if an investment makes competitors tough and if there are strategic substitutes. The rationale of this strategy is to (heavily) overinvest in order to discourage a competitor and to decrease its market share. As an example for this setting cost cutting investments for firms that compete in quantities can be given. Secondly, there is the puppy dog strategy, which describes a peaceful underinvestment.

This strategy is optimal if an investment makes competitors tough and if there are strategic complements. The rationale of this strategy is to invest reluctantly in order to avoid aggressive reaction of a competitor thus may leading to low profits, for example due to a price war. As an example for this product differentiation for firms that compete in prices can be given. Thirdly, there is the lean and hungry strategy, which describes aggressive underinvestment. This strategy is optimal if an investment makes competitors soft and there are strategic substitutes. The rationale of this strategy is to (heavily) underinvest in order to make the market environment less attractive for a competitor, which leads to a decreased market share of the competitor. As an example for this advertising (with advertising spillovers) for firms that compete in quantities can be given. Fourthly, there is the fat cat strategy, which describes a peaceful overinvestment. This strategy is optimal if an investment makes competitors soft and there are strategic complements. The rationale of this strategy is to overinvest (heavily) in order to induce a less aggressive behavior of the competitor. As an example for this advertising for firms that produce a heterogenous product and compete in prices can be given.

Publications about investment incentives in complex market structures of network industries have recently been presented. Especially three contributions should be mentioned here. Choi and Kim (2010) focus on the interaction between net neutrality and investment incentives for internet service providers and conclude "that the relationship between the net neutrality regulation and investment incentives is subtle" (Choi and Kim, 2010, p.34). Valletti and Cambini (2005) model the interaction between investments and network competition for telecommunication operators and find tendencies for strategic underinvestment in network quality. Fabra, von der Fehr, and de Frutos (2011) study the interaction between market design and investment incentives for electricity markets. Therefore, they model the investment incentives for a discriminatory and for a uniform-price auction. Even though their contribution leads to important insights about investment decisions on electricity markets, the important strategic interaction of forward contracts and investment cannot be analyzed.

For an analysis of the German electricity market all these models about strategic investment in certain respects show similarities to the German electricity market. However, one very important instrument that could interact strategically with investment decisions,

is missing: Forward Trading!

My theoretical model about the interaction of forward trading and investment incentives is based on the market characteristics presented in table 3.1, too. However, three important different assumptions are made. Firstly, investment is incorporated by the possibility to reduce marginal costs by paying a certain amount of money in an earlier stage. Secondly, in contrast to the model presented above firms compete in quantities. This assumption is made to show, that even when firms do not collude on the German electricity market, forward trading leads to important strategic consequences. Thirdly, firms compete in quantities. As Kreps and Scheinkman (1983) showed, there exists a strong relationship between quantity competition and capacity building. Thus, quantity competition gives the possibility to reflect another important feature on electricity markets: Capacity building!

4.3 The Model

4.3.1 Assumptions and General Remarks

The model that is presented adds an additional third stage of investment decision to the two-stage model of Allaz and Villa (1993). Concerning the contribution of Allaz and Villa (1993), in a first stage firms can engage in contracts (forward market stage) and in a second stage firms serve these contracts and sell an additional quantity to the customers (spot market stage). In order to compare the results of the presented model with the results of Allaz and Villa (1993) all underlying assumptions are chosen very closely to the assumptions made by Allaz and Villa (1993).

Firms compete in quantities and face a linear (inverse) demand function $p = a - x_i - x_j$, where the production that is sold by firm i either via forward contracts or directly on the spot market is denoted by x_i , x_j respectively. There is perfect foresight of all market participants and in equilibrium the forward market has to be efficient, which means "the forward price as a function of the forward positions must be equal to the price that will result from cournot competition on the spot market given these positions" (Allaz and Villa, 1993, p.3). The total production x_i of each firm i can either be sold via a binding and observable forward contract denoted by \tilde{f}_i or directly on the spot market. Thus, the amount that is sold on the spot market by firm i is given by the difference of the total

production and the amount already traded forward before ($x_i^{sm} = x_i - \tilde{f}_i$).

To focus on the strategic aspects of investment decisions, forward trading and quantity competition on the spot market, the presented model works with deterministic market conditions. Alternatively the results could be interpreted as the results of a model with risk-neutral agents competing under uncertainty.

In the presented model firms decide about an investment I_i , that increases their contribution margin linearly by exactly I_i but produces quadratic costs of I_i^2 . This investment I_i can either be interpreted as a level of technology that decreases marginal costs ($c - I_i$) or as an advertising campaign that increases the prohibitive price ($a + I_i$).

In section 4.3.2 the market results from competition of a long term strategic investment are derived. Therefore the following three-stage game is solved by backward induction:

Structure of decision making for a long-term strategic investment

Stage 1. (Cost reducing) Investment:

Firms decide about an (cost reducing) investment. They anticipate the effect on the quantities being delivered on the forward market as well as on the spot market.

Stage 2. Forward market:

Firms decide about the quantity they contract forward. They take the investment of both firms as given and anticipate all effects on the quantity competition on the spot market.

Stage 3. Quantity competition:

Firms take the investment as well as the forward contracts of both firms as given and decide about the (additional) quantity they want to supply on the spot market.

In section 4.3.3 the market results from competition of a mid term strategic investment is derived. Again the, following three-stage game is solved by backward induction:

Structure of decision making for a mid term strategic investment

Stage 1. Forward market:

Firms decide about the quantity they contract forward. They anticipate the effects on the investment decisions as well as on the quantities delivered on the spot market.

Stage 2. (Demand increasing) Investment:

Firms decide about their investment. They take as given the forward contracted amount in the first stage and anticipate all effects on the quantity competition on the spot market.

Stage 3. Quantity competition:

Firms take the forward contracts as well as the investment of both firms as given and decide about the (additional) quantity they want to supply on the spot market.

4.3.2 Long-Term Strategic Investment Like Cost Cutting

Quantity competition, in which firms take costs and forward contracts as given

In the third stage, each firm's investment as well as the forward contracted amount is given. Thus, the profit of each firm can be stated as:

$$\Pi_i = (a - x_i - x_j) (x_i - \tilde{f}_i) - (c - I_i) x_i \quad (4.1)$$

In the third stage, each firm i decides about the quantity it supplies on the spot market ($x_i^{sm} = x_i - \tilde{f}_i$), where the forward traded amount \tilde{f}_i is given from the decision made in the first stage. The costs for each unit sold (either to consumers or to speculators) are given by the marginal cost less the level of technology $c - I_i$. The marginal costs, which have been reduced by the level of technology $c - I_i$, incur to the total output x_i . Maximizing the spot market profit of each firm, given by equation 4.1, in respect to the total quantity x_i , yields the best quantity response of a firm. This reaction function of firm i depends on the prohibitive price a , the marginal costs c the amount traded forward by each firm \tilde{f}_i, \tilde{f}_j , its own investment I_i and the quantity set by the rival firm x_j . For the reaction function of firm j the same holds true except that i has to be changed in j and

vice versa.

$$\begin{aligned} \frac{\partial \Pi_i}{\partial x_i} &= a - 2x_i - x_j + f_i - c + I_i \stackrel{!}{=} 0 \\ \implies x_i &= \frac{1}{2} \left(a + \tilde{f}_i - c + I_i - x_j \right) \end{aligned} \quad (4.2)$$

Both firms perfectly take into account the quantity set by the rival. The Nash-equilibrium (x_*), in which neither firm has an incentive to set another quantity, is found in the intersection point of both reaction functions.

$$\begin{aligned} x_i &= \frac{1}{2} \left(a + \tilde{f}_i - c + I_i - x_j \right), & x_j &= \frac{1}{2} \left(a + \tilde{f}_j - c + I_j - x_i \right) \\ x_{*i} &= \frac{1}{2} \left(a + \tilde{f}_i - c + I_i \right) - \frac{1}{2} \frac{1}{2} \left(a + \tilde{f}_j - c + I_j - x_{*i} \right) \\ &= \frac{1}{3} \left(a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c \right) \end{aligned} \quad (4.3)$$

The quantity set in equilibrium by firm i depends positively on the prohibitive price a , the own forward contracted amount \tilde{f}_i and its own investment I_i . The quantity depends negatively on the competitor's forward traded amount \tilde{f}_j , the competitor's investment I_j and marginal cost c . The same functional form holds true for the quantity set by firm j . With these optimal quantities in the third stage the (reduced form) spot-market equilibrium price p_{sm}^* can easily be determined as:

$$\begin{aligned} p_{*}^{sm} &= a - x_{*i} - x_{*j} \\ &= \frac{1}{3} \left(a + 2c - \tilde{f}_i - \tilde{f}_j - I_i - I_j \right) \end{aligned} \quad (4.4)$$

The (reduced form) spot-market equilibrium price p_{sm}^* depends positively on the prohibitive price a as well as on marginal costs c . It depends negatively on each firm's forward traded amount \tilde{f}_i, \tilde{f}_j and each firm's investment I_i, I_j .

Decision on forward contracts, in which firms take cost structure as given

In the second stage, firms anticipate the spot market quantities that are additionally supplied to the forward contracted amount ($x_i^{sm} = x_* - \tilde{f}_i, x_j^{sm} = x_* - \tilde{f}_j$). This reduces the problem of profit maximization to the optimal choice of one's own forward traded amount \tilde{f}_i , for a given own investment I_i , for a given investment of the competitor I_j as well as for a given competitor's forward traded amount \tilde{f}_j . In the second stage firms take the investment decision as given, since it was made in the first stage.

The price for each firm's forward traded amount is given by the anticipated spot market price, since speculators, taking the counterpart on the forward market, have perfect foresight and build rational expectations. Thus, no additional arbitrage profit or loss is made by a firm when it is trading forward. Therefore, all forward sales are perfectly offset by the same amount that cannot be delivered on the spot market and both firms' profit functions in the second stage look as follows:

$$\begin{aligned}
\Pi_i &= (p_{sm}^* - c + I_i)(x_i^* - \tilde{f}_i) + \tilde{f}_i(p_{sm}^* - c + I_i) \\
&= \left(\frac{1}{3}(a + 2c - \tilde{f}_i - \tilde{f}_j - I_i - I_j) - c + I_i\right) \frac{1}{3}(a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c) \\
&= \frac{1}{9}(a - c - \tilde{f}_i - \tilde{f}_j + 2I_i - I_j)(a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c)
\end{aligned} \tag{4.5}$$

In the second stage the firms decide about their contracted amount. Thus, the optimal forward traded amount is found by maximizing both firms' (reduced) profit function with respect to the forward contracted amount:

$$\begin{aligned}
\frac{\partial \Pi_i}{\partial \tilde{f}_i} &= \frac{1}{9} \left(- (a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c) + 2(a - c - \tilde{f}_i - \tilde{f}_j + 2I_i - I_j) \right) \stackrel{!}{=} 0 \\
\implies \tilde{f}_i &= \frac{1}{4}(a - c - \tilde{f}_j + 2I_i - I_j)
\end{aligned} \tag{4.6}$$

The optimal forward traded amount of each firm in the second stage depends positively on the prohibition price a but negatively on the marginal costs c , the competitor's forward traded amount \tilde{f}_j and the investments made by each firm in the first stage I_i, I_j . The equilibrium forward positions are found in the intersection of both firms' best response functions.

$$\begin{aligned}
\tilde{f}_i &= \frac{1}{4}(a - c - \tilde{f}_j + 2I_i - I_j), \quad \tilde{f}_j = \frac{1}{4}(a - c - \tilde{f}_i + 2I_j - I_i) \\
\tilde{f}_i &= \frac{1}{4}(a - c + 2I_i - I_j) - \frac{1}{4} \frac{1}{4}(a - c - \tilde{f}_i + 2I_j - I_i) \\
\tilde{f}_i &= \frac{1}{5}(a - c + 3I_i - 2I_j)
\end{aligned} \tag{4.7}$$

Using the equilibrium forward contracts the quantities that emerge from the forward and the spot market game can be determined as:

$$\begin{aligned}
 x_i &= \frac{1}{3} \left(a - c + 2I_i - I_j + 2\tilde{f}_i - \tilde{f}_j \right) \\
 &= \frac{1}{3} \left(a - c + 2I_i - I_j + \frac{1}{5}(a - c) + \frac{8}{5}I_i - \frac{7}{5}I_j \right) \\
 &= \frac{1}{5} (2(a - c) + 6I_i - 4I_j)
 \end{aligned} \tag{4.8}$$

The equilibrium price in the second stage is easily determined either by setting these quantities into the inverse linear demand function or by setting the second stage forward traded amount into the equilibrium spot market price (equation 4.4):

$$\begin{aligned}
 p^{fm} &= a - x_i - x_j \\
 &= a - \frac{1}{5} (2(a - c) + 6I_i - 4I_j) - \frac{1}{5} (2(a - c) + 6I_j - 4I_i) \\
 &= \frac{1}{5} (a + 4c - 2I_i - 2I_j)
 \end{aligned} \tag{4.9}$$

When firms are trading forward and subsequently compete in quantities, a classical prisoners' dilemma forces firms to sell forward contracts, even though in equilibrium this makes both firms worse off (Allaz and Villa, 1993, p.5). This is not changed, when firms have to decide on an earlier stage about the level of technology they choose.

Decision on the level of technology, under anticipation of the forward and the spot market amount

In the first stage firms perfectly anticipate the forward and spot market decisions made by both firms. The first stage profit for each firm is found by putting the quantity resulting from the forward and spot market competition into the first stage profit function. The first stage reduced form profit function looks as follows:

$$\begin{aligned}
 \Pi_i &= (p^{fm} - c + I_i) * x_i - I_i^2 \\
 &= \left(\frac{1}{5} (a + 4c - 2I_i - 2I_j) - c + I_i \right) \frac{1}{5} (2(a - c) + 6I_i - 4I_j) - I_i^2 \\
 &= \frac{1}{25} (a - c + 3I_i - 2I_j) (2(a - c) + 6I_i - 4I_j) - I_i^2
 \end{aligned} \tag{4.10}$$

In the first stage the firms decide about their investments. Thus, the optimal investment of each firm is found by maximizing both firms' (reduced) profit function with respect to

their investment:

$$\begin{aligned}
\frac{\partial \Pi_i}{\partial I_i} &= \frac{1}{25} [3(2(a-c) + 6I_i - 4I_j) + 6(a-c + 3I_i - 2I_j)] - 2I_i \stackrel{!}{=} 0 \\
\implies &\frac{1}{25} [12(a-c) + 36I_i - 24I_j] = 2I_i \\
\implies &I_i = \frac{1}{7} (6(a-c) - 12I_j)
\end{aligned} \tag{4.11}$$

The optimal investment of each firm in the second stage depends positively on the prohibition price a but negatively on the marginal costs c and the investments made by a competitor I_j . This leads to following investment of each firm in the first stage:

$$\begin{aligned}
I_i &= \frac{1}{7} (6(a-c) - 12I_j), \quad I_j = \frac{1}{7} (6(a-c) - 12I_i) \\
I_i &= \frac{1}{7} (6(a-c)) - \frac{12}{7} (6(a-c) - 12I_i) \\
I_i &= \frac{6}{19} (a-c) \approx 0.3159 (a-c)
\end{aligned} \tag{4.12}$$

Remark: To avoid negative marginal costs after the decision on the level of technology ($c - I_i = c - \frac{6}{19}(a-c) > 0$) it has to be assumed that $c > \frac{6}{25}a$. For the interpretation of the investment as an advertising campaign this assumption is not needed.

The subgame-perfect quantity is found by inserting the subgame-perfect investment in stage one (4.12) into the subgame-perfect quantity in stage two (equation 4.8):

$$\begin{aligned}
x_i &= \frac{1}{5} (2(a-c) + 6I_i - 4I_j) \\
&= \frac{1}{5} \left(2(a-c) + 2 * \frac{6}{19} (a-c) \right) \\
&= \frac{10}{19} (a-c) \approx 0.5263 (a-c)
\end{aligned} \tag{4.13}$$

Forward traded amount is found by inserting subgame-perfect investment in stage one into the subgame-perfect forward traded amount in stage two (equation 4.7):

$$\begin{aligned}
f_i &= \frac{1}{5} (a-c + 3I_i - 2I_j) \\
&= \frac{1}{5} \left(a-c + \frac{6}{19} (a-c) \right) \\
&= \frac{5}{19} (a-c) \approx 0.2632 (a-c)
\end{aligned} \tag{4.14}$$

Inserting the optimal investment into the subgame-perfect price function in stage two

(equation 4.9) leads to:

$$\begin{aligned}
 p^* &= \frac{1}{5} (a + 4c - 2I_i - 2I_j) \\
 &= \frac{1}{5} \left(a + 4c - 4 \frac{6}{19} (a - c) \right) \\
 &= -\frac{1}{19} (a - c) + c \approx -0.0523 (a - c) + c
 \end{aligned} \tag{4.15}$$

Each firms' profit is found by inserting the subgame-perfect price (equation 4.15), investment (equation 4.12) and quantity (equation 4.13) in stage one into the profit function (equation 4.10):

$$\begin{aligned}
 \Pi_i &= (p^* - c + I_i) x_i - I_i^2 \\
 &= \left(-\frac{1}{19} (a - c) + c - c + \frac{6}{19} (a - c) \right) \frac{10}{19} (a - c) - \left(\frac{6}{19} (a - c) \right)^2 \\
 &= \frac{50}{361} (a - c)^2 - \left(\frac{6}{19} (a - c) \right)^2 \\
 &= \frac{14}{361} (a - c)^2 \approx 0.0388 (a - c)^2
 \end{aligned} \tag{4.16}$$

Consumer surplus can be determined using optimal price (equation 4.15) and quantity (equation 4.13):

$$\begin{aligned}
 \sigma &= \frac{1}{2} (a - p^*) (x_i + x_j) \\
 &= \frac{1}{2} \left(a + \frac{1}{19} (a - c) - c \right) \left(\frac{10}{19} (a - c) + \frac{10}{19} (a - c) \right) \\
 &= \frac{200}{361} (a - c)^2 \approx 0.5540 (a - c)^2
 \end{aligned} \tag{4.17}$$

Welfare is found by adding each firms' profit to the consumer surplus:

$$\begin{aligned}
 \omega &= \Pi_i + \Pi_j + \sigma \\
 &= \frac{14}{361} (a - c)^2 + \frac{14}{361} (a - c)^2 + \frac{200}{361} (a - c)^2 \\
 &= \frac{12}{19} (a - c)^2 \approx 0.6316 (a - c)^2
 \end{aligned} \tag{4.18}$$

For each subgame-perfect outcome of the decision structure investment, forward trading and quantity competition the letters I,F,Q are added. This will be helpful to compare the market results with the results for other structures of decision. For example $p_{I,F,Q}$ means the price that emerges, when (as described in this section) first the investment,

then forward trading, and afterwards quantity competition takes place.

$$\begin{aligned}
 x_{I,\tilde{F},Q} &= \frac{10}{19}(a-c), & p_{I,\tilde{F},Q} &= -\frac{1}{19}(a-c) + c & f_{I,\tilde{F},Q} &= \frac{5}{19}(a-c) \\
 I_{I,\tilde{F},Q} &= \frac{6}{19}(a-c) & \Pi_{I,\tilde{F},Q} &= \frac{14}{361}(a-c)^2, & \sigma_{I,\tilde{F},Q} &= \frac{200}{361}(a-c)^2 \\
 \omega_{I,\tilde{F},Q} &= \frac{26}{45}(a-c)^2
 \end{aligned} \tag{4.19}$$

4.3.3 Mid-Term Strategic Investment Like Advertising

Quantity competition, in which firms take demand and forward contracts as given

In the third stage, each firm's prohibitive price and forward contracted amount is given. Thus, the profit of each firm can be stated as:

$$\Pi_i = (a - x_i - x_j)(x_i - \tilde{f}_i) - (c - I_i)x_i \tag{4.20}$$

Remark: In the context of advertising, the profit function should rather look like $\Pi_i = (a + I_i - x_i - x_j)(x_i - \tilde{f}_i) - cx_i$. To ensure comparability with the long-term investment decision, the profit function used above is taken. This can be done without loss of generality, since both profit functions are equivalent.

The best quantity response of a firm due to the quantity set by the competitor is found by maximizing the profit function with respect to the quantity x_i .

$$\begin{aligned}
 \frac{\partial \Pi_i}{\partial x_i} &= a - 2x_i - x_j + \tilde{f}_i - c + I_i \stackrel{!}{=} 0 \\
 \implies x_i &= \frac{1}{2}(a + \tilde{f}_i - c + I_i - x_j)
 \end{aligned} \tag{4.21}$$

The quantities set by each firm in Nash-equilibrium is given by $x_{i,j}^*$. The quantities depend on both firms' forward contracted amount and both firms' investment.

$$\begin{aligned}
 x_i &= \frac{1}{2}(a + \tilde{f}_i - c + I_i - x_j), & x_j &= \frac{1}{2}(a + \tilde{f}_j - c + I_j - x_i) \\
 x_i &= \frac{1}{2}(a + \tilde{f}_i - c + I_i) - \frac{1}{2} \frac{1}{2}(a + \tilde{f}_j - c + I_j - x_i) \\
 x_i^* &= \frac{1}{3}(a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c)
 \end{aligned} \tag{4.22}$$

With the equilibrium quantities x_i^* , x_j^* the spot market price p_{sm}^* in the third stage can be determined as:

$$\begin{aligned} p_{sm}^* &= a - \frac{1}{3} \left(a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c \right) - \frac{1}{3} \left(a + 2\tilde{f}_j - \tilde{f}_i + 2I_j - I_i - c \right) \\ &= \frac{1}{3} \left(a + 2c - \tilde{f}_i - \tilde{f}_j - I_i - I_j \right) \end{aligned} \quad (4.23)$$

Investment decision, in which firms take forward contracts as given

In the second stage firms decide about their investments, knowing each firm's forward contracted amount and anticipating the quantity decision each firm makes in the third stage. Thus, the profit functions can be reduced to a relationship of forward contracts, amount of investment, marginal costs and the prohibitive price and look as follows:

$$\begin{aligned} \Pi_i &= (p_{sm}^* - c + I_i) x_i^* - I_i^2 \\ &= \left(\frac{1}{3} \left(a + 2c - \tilde{f}_i - \tilde{f}_j - I_i - I_j \right) - c + I_i \right) \frac{1}{3} \left(a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c \right) - I_i^2 \\ &= \frac{1}{9} \left(a - c - \tilde{f}_i - \tilde{f}_j + 2I_i - I_j \right) \left(a - c + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j \right) - I_i^2 \end{aligned} \quad (4.24)$$

The best investment response of each firm in the second stage due to the investment of the competitor is given by:

$$\begin{aligned} \frac{\partial \Pi_i}{\partial I_i} &= \frac{1}{9} \left[2 \left(a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c \right) + 2 \left(a - c - \tilde{f}_i - \tilde{f}_j + 2I_i - I_j \right) \right] - 2I_i \stackrel{!}{=} 0 \\ &\quad \frac{1}{9} [4(a - c) + 2\tilde{f}_i - 4\tilde{f}_j - 4I_j] = 2I_i - \frac{8}{9}I_i \\ I_i &= \frac{1}{5} \left(2a - 2c + \tilde{f}_i - 2\tilde{f}_j - 2I_j \right) \end{aligned} \quad (4.25)$$

Each firm's investment depends positively on the prohibitive price a and on its own forward traded amount \tilde{f}_i . Each firm's investment depends negatively on the competitor's forward traded amount \tilde{f}_j , the competitor's investment I_j and on marginal costs c .

Remark: Again, for the cost-cutting interpretation positive marginal costs after the investment have to be ensured. When interpreting the investment decision in the second stage as advertising, this is not necessary. Therefore and to ensure comparability with the results of section 4.3.2, this is not explicitly modeled in the presented model.

The investment chosen by each firm in Nash-equilibrium is given by I_i^*, I_j^* and found in the intersection of the best investment reaction functions.

$$\begin{aligned}
I_i &= \frac{1}{5} (2a - 2c + \tilde{f}_i - 2\tilde{f}_j - 2I_j), & I_j &= \frac{1}{5} (2a - 2c + \tilde{f}_j - 2\tilde{f}_i - 2I_i) \\
I_i^* &= \frac{1}{5} (2a - 2c + \tilde{f}_i - 2\tilde{f}_j) - \frac{2}{5} \frac{1}{5} (2a - 2c + \tilde{f}_j - 2\tilde{f}_i - 2I_i^*) \\
\frac{21}{25} I_i^* &= \frac{1}{25} (6(a - c) + 9f_i - 12f_j) \\
I_i^* &= \frac{1}{7} (2a - 2c + 3\tilde{f}_i - 4\tilde{f}_j)
\end{aligned} \tag{4.26}$$

Each firm's investment depends positively on the prohibitive price a and its own forward traded amount \tilde{f}_i . It depends negatively on the competitor's forward traded amount \tilde{f}_j .

With the equilibrium of investments the quantities of each firms can easily be determined as:

$$\begin{aligned}
x_i &= \frac{1}{3} (a + 2\tilde{f}_i - \tilde{f}_j + 2I_i - I_j - c) \\
&= \frac{1}{3} \left(a - c + 2\tilde{f}_i - \tilde{f}_j + \frac{2}{7} (2(a - c) + 3f_i - 4I_j) - \frac{1}{7} (2(a - c) + 3I_j - 4I_i) \right) \\
&= \frac{1}{21} (9(a - c) + 24f_i - 18f_j) \\
&= \frac{1}{7} (3a - 3c + 8\tilde{f}_i - 6\tilde{f}_j)
\end{aligned} \tag{4.27}$$

Each firm's quantity x_i depends positively on the prohibitive price a and positively on its own forward traded amount \tilde{f}_i . It depends negatively on the competitor's forward traded amount \tilde{f}_j and marginal costs c .

The equilibrium price in the second stage is easily determined either by inserting these quantities into the inverse linear demand function or by inserting the second-stage forward traded amount into the equilibrium spot market price (equation 4.23).

$$\begin{aligned}
p^* &= a - x_i^* - x_j^* \\
&= a - \frac{1}{7} (3a - 3c + 8\tilde{f}_i - 6\tilde{f}_j) - \frac{1}{7} (3a - 3c + 8\tilde{f}_j - 6\tilde{f}_i) \\
&= \frac{1}{7} (a - c - 2\tilde{f}_i - 2\tilde{f}_j) + c
\end{aligned} \tag{4.28}$$

The price in the second stage depends positively on the prohibitive price a and the marginal costs c . It depends negatively on each firm's forward traded amount \tilde{f}_i, \tilde{f}_j .

Decision on forward contracts, under anticipation of investment and spot market competition

In the first stage firms decide about the amount of forward contracts they supply on the market. In doing so they perfectly anticipate the consequences on both firms' investments as well as on the quantity supplied on the spot market. Thus, the profit can be reduced to a function solely dependent on each firm's amount contracted forward as well as the fundamental market conditions, which are given by marginal costs and the prohibitive price. The profit function is given by the contribution surplus multiplied by the amount sold to the market less the investment costs resulting from both firms' positions on the forward market.

$$\begin{aligned}
 \Pi_i &= (p_I^* - c + I_i) x_i - I_i^2 \\
 &= \left(\frac{1}{7}(a - c - 2\tilde{f}_i - 2\tilde{f}_j) + c - c + \frac{1}{7}(2a - 2c + 3\tilde{f}_i - 4\tilde{f}_j) \right) \frac{1}{7} (3a - 3c + 8\tilde{f}_i - 6\tilde{f}_j) \\
 &\quad - \left(\frac{1}{7}(2a - 2c + 3\tilde{f}_i - 4\tilde{f}_j) \right)^2 \\
 &= \frac{1}{49} (3a - 3c + \tilde{f}_i - 6\tilde{f}_j) (3a - 3c + 8\tilde{f}_i - 6\tilde{f}_j) - \frac{1}{49} (2a - 2c + 3\tilde{f}_i - 4\tilde{f}_j)^2
 \end{aligned} \tag{4.29}$$

The optimal amount of forward contracts of each firm in the second stage due to the forward contracted amount of the rival is given by:

$$\begin{aligned}
 \frac{\partial \Pi_i}{\partial f_i} &= \frac{1}{49} \left[1 (3a - 3c + 8\tilde{f}_i - 6\tilde{f}_j) + 8 (3a - 3c + \tilde{f}_i - 6\tilde{f}_j) \right] \\
 &\quad - \frac{2}{49} (2a - 2c + 3\tilde{f}_i - 4\tilde{f}_j) * 3 \stackrel{!}{=} 0 \\
 \implies &\quad (27(a - c) + 16\tilde{f}_i - 54\tilde{f}_j) - 6(2(a - c) + 3\tilde{f}_i - 4\tilde{f}_j) \stackrel{!}{=} 0 \\
 \implies &\quad \tilde{f}_i = \frac{1}{2} (15a - 15c - 30\tilde{f}_j)
 \end{aligned} \tag{4.30}$$

The Nash-equilibrium forward traded amount is found in the intersection of both firms' forward contract best response function.

$$\begin{aligned}
 \tilde{f}_i &= \frac{1}{2} (15a - 15c - 30\tilde{f}_j), \quad \tilde{f}_j = \frac{1}{2} (15a - 15c - 30\tilde{f}_i) \\
 \tilde{f}_i^* &= \frac{1}{2} (15a - 15c) - \frac{30}{2} \frac{1}{2} \tilde{f}_j (15a - 15c - 30\tilde{f}_i) \\
 \tilde{f}_i^* &= \frac{15}{32} (a - c)
 \end{aligned} \tag{4.31}$$

The subgame-perfect quantity is found by inserting the subgame-perfect forward traded amount \tilde{f}_i^* (equation 4.31) into the subgame-perfect quantity on the 2 stage (equation 4.27):

$$\begin{aligned} x_i &= \frac{1}{7}(3a - 3c + 8\tilde{f}_i - 6\tilde{f}_j) \\ &= \frac{1}{7} \left(3a - 3c + 8\frac{15}{32}(a - c) - 6\frac{15}{32}(a - c) \right) \\ &= \frac{9}{16}(a - c) \end{aligned} \quad (4.32)$$

The subgame-perfect investment is found by inserting the subgame-perfect forward traded amount \tilde{f}_i^* (equation 4.31) into the subgame-perfect investment on stage 2 (equation 4.26):

$$\begin{aligned} I_i^* &= \frac{1}{7}(2a - 2c + 3\tilde{f}_i - 4\tilde{f}_j) \\ &= \frac{1}{7}(2a - 2c + 3\frac{15}{32}(a - c) - 4\frac{15}{32}(a - c)) \\ &= \frac{7}{32}(a - c) \end{aligned} \quad (4.33)$$

The subgame-perfect price is found by inserting the subgame-perfect forward traded amount \tilde{f}_i^* (equation 4.31) into the inverse demand function:

$$\begin{aligned} p^* &= a - x_i - x_j \\ &= a - \frac{9}{16}(a - c) - \frac{9}{16}(a - c) \\ &= -\frac{1}{8}(a - c) + c \end{aligned} \quad (4.34)$$

The subgame-perfect profit is found by inserting the subgame-perfect price (equation 4.34), investment (equation 4.33) and quantity (equation 4.32) into the profit function (equation 4.29):

$$\begin{aligned} \Pi_i &= (p - c + I_i^*)x_i - I_i^{*2} \\ &= \left(-\frac{1}{8}(a - c) + c - c + \frac{7}{32}(a - c) \right) \frac{9}{16}(a - c) - \left(\frac{7}{32}(a - c) \right)^2 \\ &= \frac{27}{512}(a - c)^2 - \frac{49}{32^2}(a - c)^2 \\ &= \frac{5}{1024}(a - c)^2 \end{aligned} \quad (4.35)$$

The consumer surplus σ can be easily determined using the subgame-perfect price (equation 4.34) each firms' quantity (equation 4.32):

$$\begin{aligned}\sigma &= \frac{1}{2} (a - p^*) (x_i + x_j) \\ &= \frac{1}{2} a - \left(-\frac{1}{8} + c\right) \left(\frac{9}{16} (a - c) + \frac{9}{16} (a - c)\right) \\ &= \frac{81}{128} (a - c)^2\end{aligned}\quad (4.36)$$

The social welfare ω can be determined by summing up the consumer surplus and each firms profit:

$$\begin{aligned}\omega &= \sigma + \Pi_i + \Pi_j \\ &= \frac{81}{128} (a - c)^2 + \frac{5}{1024} (a - c)^2 + \frac{5}{1024} (a - c)^2 \\ &= \frac{329}{512} (a - c)^2\end{aligned}\quad (4.37)$$

Note: For each subgame-perfect outcome of the decision structure forward trading, investment and quantity competition the letters \tilde{F}, I, Q are added. This will be helpful to compare the market results with the results for other structures of decision. For example, $p_{\tilde{F}, I, Q}$ means the price that emerges, when (as described in this section) first forward trading, then the investment, and afterwards quantity competition takes place.

$$\begin{aligned}x_{\tilde{F}, I, Q} &= \frac{18}{32} (a - c), & p_{\tilde{F}, I, Q} &= -\frac{1}{8} (a - c) + c, & f_{\tilde{F}, I, Q} &= \frac{15}{32} (a - c) \\ I_{\tilde{F}, I, Q} &= \frac{7}{32} (a - c), & \Pi_{\tilde{F}, I, Q} &= \frac{5}{1024} (a - c)^2, & \sigma_{\tilde{F}, I, Q} &= \frac{81}{128} (a - c)^2 \\ \omega_{\tilde{F}, I, Q} &= \frac{329}{512} (a - c)^2\end{aligned}\quad (4.38)$$

4.3.4 Comparison of Results

Table 4.1 gives as a benchmark the market outcome for the decision structure, first investment and then quantity competition, as well as for the decision structure first forward trading and then quantity competition (Allaz and Villa, 1993). The derivation of all results for the case of investment and then quantity competition is shown by equation B.1 to equation B.7 in the appendix. The derivation of all results for the case of forward trading and then quantity competition is shown by equation B.8 to equation B.14 in the appendix.

Table 4.2 gives the market outcome for the decision structure, first forward trading,

	Investment, Competition	Forwards, Competition
Price	$p_{I,Q} = 0.1429(a - c) + c$	$p_{\bar{F},Q} = 0.2(a - c) + c$
Quantity	$x_{I,Q} = 0.4286(a - c)$	$x_{\bar{F},Q} = 0.4(a - c)$
Forwards	$f_{I,Q} = 0$	$f_{\bar{F},Q} = 0.2(a - c)$
Investment	$I_{I,Q} = 0.2857(a - c)$	$I_{\bar{F},Q} = 0$
Cons. surplus	$\sigma_{I,Q} = 0.3673(a - c)^2$	$\sigma_{\bar{F},Q} = 0.32(a - c)^2$
Profit	$\Pi_{I,Q} = 0.1020(a - c)^2$	$\Pi_{\bar{F},Q} = 0.08(a - c)^2$
Welfare	$\omega_{I,Q} = 0.5714(a - c)^2$	$\omega_{\bar{F},Q} = 0.48(a - c)^2$

Table 4.1: Benchmark Prices, Quantities etc.

then investment, and then quantity competition as well as for the decision structure, first investment, then forward trading, and then quantity competition. The results for the decision structure forward trading, then investment and subsequently quantity competition have been derived in section 4.3.2 and can be found in a concentrated form in equation 4.19.

The results for the decision structure, investment, forward trading and then quantity competition have been derived in section 4.3.3 and can be found in a concentrated form in equation 4.38. For the sake of comparability all results in table 4.1 and 4.2 are shown in decimal numeration.

	Forwards, Investment, Competition	Investment, Forwards, Competition
Price	$p_{F,I,Q} = -0.125(a - c) + c$	$p_{I,F,Q} = -0.0526(a - c) + c$
Quantity	$x_{F,I,Q} = 0.5625(a - c)$	$x_{I,F,Q} = 0.5263(a - c)$
Forwards	$f_{F,I,Q} = 0.4686(a - c)$	$f_{I,F,Q} = 0.2632(a - c)$
Investment	$I_{F,I,Q} = 0.2188(a - c)$	$I_{I,F,Q} = 0.3158(a - c)$
Cons. surplus	$\sigma_{F,I,Q} = 0.6328(a - c)^2$	$\sigma_{I,F,Q} = 0.4986(a - c)^2$
Profit	$\Pi_{F,I,Q} = 0.0049(a - c)^2$	$\Pi_{I,F,Q} = 0.0388(a - c)^2$
Welfare	$\omega_{F,I,Q} = 0.6425(a - c)^2$	$\omega_{I,F,Q} = 0.6316(a - c)^2$

Table 4.2: New results: Forward Trading, Investment and Quantity

The price chosen by each firm, when firms are able to trade forward and compete in

quantities $p_{\tilde{F},Q} = \frac{1}{5}(a - c) + c$ is above the price when they invest and compete in quantities: $p_{I,Q} = \frac{1}{7}(a - c)$. This price is above the price resulting from competition with an investment decision before forward trading and quantity competition ($p_{I,F,Q} = -\frac{1}{19}(a - c)$). The lowest price results from forward trading, decision on investment and quantity competition of $p_{I,\tilde{F},Q} = -\frac{1}{8}(a - c) + c$.

Thus, the resulting prices can be ordered as:

$$p_{\tilde{F},I,Q} < p_{I,\tilde{F},Q} < p_{I,Q} < p_{\tilde{F},Q} \quad (4.39)$$

For the quantities supplied by both firms the order is the other way round. The quantity, when both firms decide about forward contracts and then compete in quantities ($x_{\tilde{F},Q} = \frac{2}{5}(a - c)$) is below the quantity chosen by firms, when both firms decide about their investments and compete in quantities ($x_{I,Q} = \frac{3}{7}(a - c)$). Larger quantities are chosen, when firms decide about their investments, choose their forward contracts, and compete in quantities ($x_{I,\tilde{F},Q} = \frac{10}{19}(a - c)$). The highest quantity results from forward trading, decision on investment and quantity competition ($x_{\tilde{F},I,Q} = \frac{18}{32}(a - c)$).

Thus, the resulting quantities can be ordered as:

$$x_{F,Q} < x_{I,Q} < x_{I,\tilde{F},Q} < x_{\tilde{F},I,Q} \quad (4.40)$$

When firms solely decide about their investment and compete in quantities, by definition the amount traded forward is zero ($f_{I,Q} = 0$). Then the smallest (positive) amount is traded forward when firms solely decide about forward contracts and compete in quantities ($f_{F,Q} = \frac{2}{5}(a - c)$). A larger amount is traded forward when firms decide about their investment, trade forward and compete in quantities ($f_{I,\tilde{F},Q} = \frac{5}{19}(a - c)$). When firms first decide about the amount traded forward, then decide about their investments, and subsequently compete in quantities, the largest amount is traded forward ($f_{\tilde{F},I,Q} = \frac{15}{32}(a - c)$).

Thus, the forward-traded amount can be ordered as:

$$f_{I,Q} < f_{F,Q} < f_{I,\tilde{F},Q} < f_{\tilde{F},I,Q} \quad (4.41)$$

For strategic reasons firms choose a relatively low forward traded-amount, when the investment decision takes place in the first round, whereas firms choose a relatively high

amount traded forward, when the decision on the forward-traded amount takes place in the first round. Following the strategic taxonomy of Fudenberg and Tirole (1984) one can state: Firms under-invest in the strategic variable (forward-traded amount), when the investment decision takes place in the first round. Firms over-invest in the strategic variable (forward-traded amount), when the decision on the forward traded amount takes place in the first round.

When firms solely decide about their forward traded amount and compete in quantities, by definition the investment is zero ($I_{\bar{F},Q} = 0$). Then the smallest (positive) amount is invested when firms first decide about the amount traded forward, then decide about their investments, and subsequently compete in quantities ($I_{\bar{F},I,Q} = \frac{7}{32}(a - c)$). A larger investment is done when firms solely decide about their investment and compete in quantities ($I_{I,Q} = \frac{2}{7}(a - c)$). The highest investment is done when firms decide about their investment, trade forward and compete in quantities ($I_{I,\bar{F},Q} = \frac{6}{19}(a - c)$).

Thus, the resulting investment can be ordered as:

$$I_{\bar{F},Q} < I_{\bar{F},I,Q} < I_{I,Q} < I_{I,\bar{F},Q} \quad (4.42)$$

For strategic reasons firms choose a relatively low investment, when the decision on the forward traded amount takes place in the first round, whereas firms choose a relatively high investment, when the investment decision takes place in the first round. Due to the strategic taxonomy of Fudenberg and Tirole (1984) one can state in turn: Firms under-invest in the strategic variable (investment), when the decision on forwards takes place in the first round. Firms over-invest in the strategic variable (investment), when the decision on the investment takes place in the first round.

Thus, firms choose a high amount of forwards and a rather low investment, when the investment decision takes place in the first round. In contrast firms choose a high amount of investment and a rather low forward traded amount, when the investment decision takes place in the first round. The different strategic behavior of the competitors can mainly be explained by the cost of their investment and the anticipation of (fierce) competition.

The smallest consumer surplus results when firms solely trade forward and compete in quantities ($\sigma_{F,Q} = \frac{8}{25}(a - c)^2$). A larger consumer surplus results, when firms solely decide about their investment and compete in quantities ($\sigma_{I,Q} = \frac{18}{49}(a - c)^2$). A larger

consumer surplus occurs when firms decide about their investment, trade forward and then compete in quantities ($\sigma_{I,\tilde{F},Q} = \frac{200}{361}(a-c)^2$). The highest consumer surplus results when firms trade forward, then decide about their investments, and subsequently compete in quantities ($\sigma_{\tilde{F},I,Q} = \frac{81}{128}(a-c)^2$). Thus, the resulting consumer surplus can be ranked as:

$$\sigma_{F,Q} < \sigma_{I,Q} < \sigma_{I,\tilde{F},Q} < \sigma_{\tilde{F},I,Q} \quad (4.43)$$

The lowest profit is realized by firms when they trade forward, decide about their investment and subsequently compete in quantities ($\Pi_{\tilde{F},I,Q} = \frac{5}{1024}(a-c)^2$). A higher profit is realized by firms when firms invest, then trade forward and subsequently compete in quantities ($\Pi_{I,\tilde{F},Q} = \frac{14}{361}(a-c)^2$). When they trade forward and compete in quantities ($\Pi_{\tilde{F},Q} = \frac{2}{25}(a-c)^2$) they earn a higher profit. The highest profit is earned by each firm, when firms invest and subsequently compete in quantities ($\Pi_{I,Q} = \frac{5}{49}(a-c)$). Thus, the resulting profits can be ordered as:

$$\Pi_{\tilde{F},I,Q} < \Pi_{I,\tilde{F},Q} < \Pi_{\tilde{F},Q} < \Pi_{I,Q} \quad (4.44)$$

The lowest welfare results when firms first decide about forward contracts and then compete in quantities ($\omega_{\tilde{F},Q} = \frac{12}{25}(a-c)^2$). A higher welfare is realized, when firms decide about their investments and then compete in quantities ($\omega_{I,Q} = \frac{4}{7}(a-c)^2$). When firms invest, then trade forward and subsequently compete in quantities, the welfare is slightly higher ($\omega_{I,\tilde{F},Q} = \frac{12}{19}(a-c)^2$). The highest welfare is realized, when firms first decide about their forward contracts, then decide about their investments and subsequently compete in quantities ($\omega_{\tilde{F},I,Q} = \frac{329}{512}(a-c)$). Thus, the resulting welfare can be ordered as:

$$\omega_{\tilde{F},Q} < \omega_{I,Q} < \omega_{I,\tilde{F},Q} < \omega_{\tilde{F},I,Q} \quad (4.45)$$

4.4 Conclusion

The aim of this model is to identify the strategic interaction between competing firms and its influence on their investment decisions, on their forward-traded amount and on spot market competition. Therefore, in section 4.3.2 a long-term strategic investment decision that takes place before firms engage in forward contracts and compete in quantities on the spot market has been modeled. For this kind of long-term investment decision, firms

choose a combination of small forward traded amount and high investment.

In section 4.3.3 a mid-term strategic investment decision that takes place after firms have chosen their forward contracts, but before firms compete in quantities on the spot market, has been modeled. For this kind of mid-term investment decision, firms choose a combination of large forward traded amount and small investment.

Section 4.3.4 compared the results found in section 4.3.2 and section 4.3.3 with each other as well as with the results of a two-stage game, where in the first stage firms either decide about investment or on the amount traded forward and in a second stage firms compete in quantities.

For a long-term investment decision a rather small forward-traded amount but larger investment led to a smaller amount supplied to the market, a higher price, higher profits of firms, a lower consumer surplus and smaller social welfare. Therefore, when firms' investments can mainly be viewed as long-term, introduction of a forward market has a smaller welfare increasing effect.

For a mid-term investment decision a large forward traded amount but smaller investment led to a higher amount supplied to the market, a relatively low price, relatively low profits of firms, a higher consumer surplus and a relatively large social welfare. Therefore, when firms' investments can mainly be viewed as mid-term, introduction of a forward market has a large welfare-enhancing effect.

Looking at strategic aspects, forward trading and competition one can conclude: The social desirability of a forward market, where firms additionally to the spot market supply their commodities, depends on the typical time horizon of the investments made by firms: For investment decisions, which mainly have a mid-term time horizon, the introduction of a forward market is socially most favorable. However, for investment decisions, which mainly have a long-term time horizon, the introduction of a forward market only leads to a smaller increase in social welfare.

For the policymakers of the German energy turnaround there is the following general insight: The overall effect of a pro-competitive instrument critically depends on its influence on other strategic decisions and their time horizons.

4.5 Appendix

Investment Decision and Quantity Competition

When firms have to decide in the first stage on an investment decision, and in the second stage on the quantity they supply to the market, the market results can be found by backward induction again.

Stage 1. Cost reducing investment:

Firms decide about a cost reducing investment. They anticipate the effect on the quantities being delivered on the spot market.

Stage 2. Quantity competition:

Firms take the cost structure of both firms as given and decide about the quantity they want to supply on the spot market

Stage 1. profit function:

$$\Pi_i = (a - x_i - x_j - c + I_i) x_i - I_i^2 \quad (\text{B.1})$$

Stage 2. profit function:

$$\Pi_i = (a - x_i - x_j - c + I_i) x_i \quad (\text{B.2})$$

Stage 2. reaction function:

$$x_i = \frac{1}{2} (a - x_j - c + I_i) \quad (\text{B.3})$$

Stage 2. Nash-Equilibrium

$$\begin{aligned} x_i^* &= \frac{1}{3} (a - c + 2I_i - I_j) \\ p^* &= \frac{1}{3} (a - c - I_i - I_j) + c \end{aligned} \quad (\text{B.4})$$

Stage 1. reduced profit function

$$\Pi_i = \frac{1}{9} (a - c + 2I_i - I_j)^2 - I_i^2 \quad (\text{B.5})$$

Stage 1. reaction function:

$$I_i = \frac{2}{5} (a - c - I_i) \quad (\text{B.6})$$

Stage 1. Nash-Equilibrium

$$\begin{aligned} I_i^* = I_j^* &= \frac{2}{7} (a - c) & p^* &= \frac{1}{7} (a - c) + c, & x_i = x_j &= \frac{3}{7} (a - c) \\ \Pi_i = \Pi_j &= \frac{5}{49} (a - c)^2, & \sigma &= \frac{18}{49} (a - c)^2, & \omega &= \frac{4}{7} (a - c)^2 \end{aligned} \quad (\text{B.7})$$

Forward Trading and Quantity Competition

Stage 1. Forward trading:

Firms decide about the amount they want to trade on the forward market. They anticipate the effect on the quantities being delivered on the spot market.

Stage 2. Quantity competition:

Firms take the forward traded amount as given and decide about the quantity they want to supply on the spot market

Stage 1. profit function:

$$\Pi_i = (a - x_i - x_j - c) x_i \quad (\text{B.8})$$

Stage 2. profit function:

$$\Pi_i = (a - x_i - x_j - c) (x_i - \tilde{f}_i) - cx_i \quad (\text{B.9})$$

Stage 2. reaction functions

$$x_i = \frac{1}{2} (a - c + \tilde{f}_i - x_j) \quad (\text{B.10})$$

Stage 2. Nash-Equilibrium

$$\begin{aligned} x_i^* &= \frac{1}{3} (a - c + 2\tilde{f}_i - \tilde{f}_j) \\ p^* &= \frac{1}{3} (a - c - \tilde{f}_i - \tilde{f}_j) + c \end{aligned} \quad (\text{B.11})$$

Stage 1. reduced profit function

$$\Pi_i = \frac{1}{9} (a - c - \tilde{f}_i - \tilde{f}_j) (a - c + 2\tilde{f}_i - \tilde{f}_j) \quad (\text{B.12})$$

Stage 1. reaction function:

$$\tilde{f}_i = \frac{1}{4} (a - c - \tilde{f}_j) \quad (\text{B.13})$$

Stage 1. Nash-Equilibrium

$$\begin{aligned} f_{\bar{F},Q}^* &= \frac{1}{5} (a - c) & p_{\bar{F},Q} &= \frac{1}{5} (a - c) + c, & x_{\bar{F},Q} &= \frac{2}{5} (a - c) \\ \Pi_{\bar{F},Q} &= \frac{2}{25} (a - c)^2, & \sigma_{\bar{F},Q} &= \frac{8}{25} (a - c)^2, & \omega_{\bar{F},Q} &= \frac{12}{25} (a - c)^2 \end{aligned} \quad (\text{B.14})$$

In stage 2 and in stage 3 the costs of investments do not influence any result, since the level of technology I_i is taken as given. In stage 1 firms decide about their investments in technology. The profit function looks as follows:

Chapter 5

Summary and Discussion

The purpose of this thesis has been to take a closer look at strategic effects of forward trading on the German electricity market. It contributes to the economic literature by analyzing the market structure of the German electricity market empirically and by presenting two distinct micro-economic models: The first model focuses on effects of forward trading on competitive pressures. The second model focuses on effects of forward trading on investment incentives.

Chapter 2 described the competitive setting of the German electricity market, evaluated fluctuations, due to stochastic feed-in of renewable energy sources and figured out fluctuations coming from consumer behavior. **Chapter 3** added to the micro-economic literature about forward trading and competitive pressure by allowing for volatile market conditions. **Chapter 4** contributed to the existing economic literature by simultaneously modeling forward trading and investment incentives.

This final chapter summarizes the most noteworthy results and presents an outlook on possible future research.

Analysis of the German Electricity Market

In a first step the vertical structure of the German electricity market was described. Starting with electricity generation up to electricity consumption three distinct markets could be identified. Firstly, there is the market for electricity generation, which is dominated by four electricity generators (E.ON, RWE, Vattenfall, EnBW and Vattenfall), and can be seen as an oligopolistic market with strategic interaction. Secondly, there is the transmis-

sion of electricity from plants to regional suppliers being organized as regulated regional monopolies. These regulated regional monopolies are operated by the following four Transmission System Operators: Tennet, 50 Hertz, Amprion and TransnetBW. Thirdly, the market for electricity supplied to households and industrial consumers, which is characterized by the interaction of many electricity sellers and buyers and quite effective competition. Indeed strategic interaction of firms is an important factor on the market for electricity generation, since oligopolistic firms can easily monitor behavior of all competitors. Thus, especially the electricity wholesale market has been studied for further analysis of strategic behavior.

On the electricity wholesale market electricity can either be traded on an electricity exchange or by bilateral contracts. Trading electricity on bilateral contracts, which is often called over-the-counter-trading (OTC), is not based on standardized rules, whereas when trading electricity on an exchange clear rules have to be applied.

Referring to data collected by the Bundesnetzagentur and the Bundeskartellamt (2014) it was shown that electricity sales are highly concentrated, since about 50% of the sales volume is traded by only 5 firms. Electricity purchases are concentrated, too. However, purchases are slightly less concentrated, since 40% of the purchased volume comes from 5 firms.

An overview of the most important contracts traded on the European Energy Exchange (EEX) as well as the most important contracts traded over-the-counter bilaterally was given. The three most important markets are the day-ahead spot market, the futures market and the intraday spot market. Taking the market volume as a signal for the importance of a corresponding market, markets could be ranked as follows: The futures market seems to be most important for electricity trading by far, since 72% of the total market volume was traded on the futures market in 2013. The day-ahead spot market followed with a clear distance, since it accounts for about 26% of market volume. The intraday spot market had a minor importance, since it only accounts for about 2% of the market volume.

Futures contracts with different maturities can be traded on the European Energy Exchange. Most popular was the futures contract with maturity in 2014, since 54% of futures contracts traded in 2013 had a maturity of one year. Futures contracts that expired in 2013 or 2015 followed with clear distance, since they had a market share of 17% and 18% of all

futures contracts. Futures contracts with a maturity of three years and more had a market share of only 11%. Over-the-counter trading was most popular for futures contracts that expired in 2014, too. This clearly shows the importance of 1-year-futures contracts for electricity trading. Evaluation of prices paid for electricity traded in futures contracts or on the day-ahead spot market led to an first interesting insight. Price of PHELIX futures contracts are rather stable over time, whereas day-ahead- spot prices as well as intraday spot prices are approximately normally distributed. This can be easily explained by the fact that a futures contract obliges to deliver/purchase electricity for all time blocks of all days until maturity. Thus, price fluctuations that result from differences in time, from seasonal factors or from changing weather conditions are smoothed. In contrast the day-ahead spot market price tends to fluctuate due to different times of delivery and stochastic weather conditions.

The energy mix used for electricity generation in Germany consists mainly of the following five different energy sources: Soft coal, hard coal, nuclear energy, natural gas and renewable energies. The composition of this electricity generating mix was shown for all years between 1990 and 2013 and explanations for fundamental changes of the energy mix were given.

Of particular note was the significant increase of electricity production from renewable energies. This increase followed from a significant increase of electricity production from wind power, from solar power and from biomass. It led to an increase of volatility in electricity supply, since wind power and solar power depend on stochastic weather conditions and cannot easily be dispatched. Electricity generated by renewable energy sources is subsidized by feed-in tariffs, which lead to a compensation for the suppliers. This compensation is calculated in the way that a constant amount of money is earned by a supplier. Thus, electricity generated by solar power and wind power feeds power into the German grid independently of market conditions. Renewable energies feed-in data, which is collected by the four German Transmission Operators and provided by the European Energy Exchange, was used to quantify feed-in fluctuations of solar power and wind power as well as fluctuations coming from simultaneous feed-in of wind and solar power.

In general feed-in fluctuations of renewable energies feed-in can be decomposed in a

time-dependent component and a purely stochastic component. For feed-in of electricity generated by solar power the time-dependent component was very dominant, since sunshine very much depends on time intervals. This resulted in no feed-in of solar energy during the night, a small feed-in during morning hours, a peak of feed-in during noon, declining feed-in during afternoon and no feed-in from late evening until next morning. However, this time-dependent component goes along with an additional strong stochastic component. In contrast, feed-in from wind energy did not show any time dependent component. Thus, its feed-in solely is depended on stochastic wind conditions.

An evaluation of simultaneous feed-in of wind and solar energy led to the following three insights. Firstly, on an average wind energy fed round about 5 GW into the German grid without any time pattern. Additionally, solar energy fed into the German grid according to its clear time pattern between 0 GW during night up to 10 GW at noon. Thus, the average feed-in of renewable energies is fluctuating according to its time pattern between 5 GW an 15 GW. Looking at the 5% highest feed-in from renewable energies the same time pattern could be found. However, extremal values for feed-in of solar and wind were negatively correlated, since wind and sunshine rarely show up together. Thus, the 5% highest feed-in of renewable energy sources consequently was below the sum of the 5% highest feed-in of each energy source. Looking at the 5% lowest feed-in from renewable energy drew a different picture, since lack of wind and sunshine more often occur. This led to the 5% lowest feed-in from renewable energy sources fluctuating between 0.5 GW during nights and 4 GW at noon. Thus, conventional capacity is still needed as a back-up.

Correlation coefficients for renewable energies feed-in and net-exports of electricity of Germany were computed. Pearson's as well as Spearman's correlation showed a positive relationship between feed-in from renewable energies and electricity exports. However, feed-in of renewable energy was mainly consumed in Germany, since in 2013 the amount of correlation according to Pearson (0.39) as well as Spearman (0.36) can be seen as rather moderate.

Demand for electricity showed high fluctuations, too. Data provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) has been evaluated to analyze demand fluctuations. Demand for electricity showed a strong pattern, since during nights and morning hours demand for electricity is rather small. Demand for

electricity increased until noon. After a decrease during the afternoon an increase occurs in the early evening hours. Then demand for electricity decreased until next morning. This pattern was generally the same for all week days, even though on business days total demand is larger than on Saturdays or on Sundays. However, differences between working days, Saturdays and Sundays mainly shifted this pattern, but do not led to fundamental changes of the corresponding pattern.

In order to estimate the amount of electricity that had to be generated by conventional power plants, demand data set provided by ENTSO-E has been combined with renewable energy supply data set provided by the European Energy Exchange. More precisely renewable energy supply was deducted from demand for electricity to find necessary conventional generated load for Germany in 2013. This necessary conventional load can be seen as total amount of electricity that has to be supplied by all electricity providers. Again a clear daily pattern emerged, since during night and in the early morning hours demand was rather low. However, the former demand peak at noon has been compensated normally by an increasing solar feed-in. Thus, necessary conventional load had a peak in the afternoon, since during the afternoon supply of solar energy was decreasing much faster than demand for electricity.

Data provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) contains day-ahead forecasts of demand for electricity as well as indeed realized demand for electricity. In combination with day-ahead forecasts of renewable energies feed-in this allowed to calculate day-ahead forecast errors of necessary conventional load. Histograms were used to visualize day-ahead forecast error. Forecast error approximately followed a normal distribution that is located around 0 GW. In general day-ahead forecasts of necessary conventional load matched realizations of necessary conventional load on the next day quite well. However, for few trading blocks very high over- or underestimations of about 10 GW could be found.

Another important question about necessary conventional load was, whether its stochastic component followed a daily, weekly or seasonal trend. This question has been answered by calculating serial correlation of the time series of necessary conventional load. More precisely, serial correlation for first, second and third lag has been calculated. This had been done for each of the 24 trading blocks separately, since otherwise computation of

serial correlation would have been distorted by the daily pattern of necessary conventional load. Serial correlation of necessary conventional load seemed to be moderate, since the average first lag serial correlation of all trading blocks was about 0.65, the average second lag serial correlation was about 0.5 and the average third lag serial correlation was about 0.4. Of course, these values of serial correlation reflected a certain persistency, but decreased clearly over time. Thus, it could be concluded that there was some trend in the time series of necessary conventional load to expire over time.

In order to show the effect of necessary conventional load on day-ahead spot prices scatter plots were illustrated. For most combinations of day-ahead spot prices and necessary conventional load a clear linear relationship emerged. This linear relationship held for realized necessary conventional load as well as for day-ahead forecast of necessary conventional load. However, for extreme low or high realizations of the necessary conventional load this linear relationship broke down. For very low realizations of necessary conventional load the day-ahead spot price seemed to be rather incidental, since for comparable values of necessary conventional load positive prices of about 40 EUR/MWh as well as negative prices of about -100 EUR/MWh were realized. This unclear price pattern may reflect missing experience of electricity market stakeholders with low demand for conventionally generated electricity.

The analysis of the German electricity market was helpful to explain behavior of many stakeholders as well as market outcomes. However, it leads to at least three further questions:

Firstly, within the German debate about subsidies for renewable energies it is often claimed, that highly subsidized electricity is exported to other countries, whenever weather conditions are positive and feed-in of electricity from renewable energy sources is high. It is claimed additionally that electricity generated by ecologically unfavorable energy sources, such as nuclear energy and brown coal, is imported from other countries, whenever weather conditions are negative and feed-in of electricity from renewable energy sources is low. Correlation between feed-in of electricity generated by renewable energies and exports did not support this hypothesis, since positive correlation of feed-in and exports was rather moderate. Thus, renewable energies were largely used in the German grid. However, to give a precise answer to this question a more detailed analysis incor-

porating feed-in and demand data of other countries could be presented. However, such a detailed analysis of this specific question seemed beyond the scope of the presented analysis of the German electricity market.

Secondly, feed-in of electricity generated by renewable energy sources will keep increasing in the next years and periods, in which only a little or no electricity generated by conventional energy sources is needed, will more often occur. It has been shown that whenever demand for conventionally generated electricity is low, no clear pattern of electricity prices could be identified. Comparable values of demand for conventional electricity can lead either to quite normal (positive) spot prices or to strongly negative spot prices. Thus, additional parameters of the electricity market could be used to explain this price differences. Gaining a deeper understanding of economic consequences coming from very low demand for conventionally generated electricity, is left for further research, since more and more data of this phenomenon can be expected in the next years.

Thirdly, control energy is used to compensate for short term positive and negative differences of demand and supply for electricity. Control energy is managed by each Transmission Operator for its regional area. Whenever a Transmission System Operator notices differences of demand and supply it has to order additional electricity or to force suppliers not to feed into the grid respectively. For both interventions Transmission System Operator have to pay a compensation. Depending on the profitability of such an intervention for electricity suppliers there might be an incentive to stimulate such differences strategically. Thus, an evaluation of profitability of control energy in Germany would be of specific interest, since it may help to explain forecast errors of necessary conventional load as well as decisions of power plant owners. However, an evaluation of profitability of control energy seems to be a very extensive research question, since contracts, costs and technical aspects of control energy have to be considered. Thus, this evaluation is left for further research.

Forward Trading and Competitive Pressure

Based on the previous findings about the German electricity market a theoretical model was presented. This model investigated the relationship between forward contracts, volatile market conditions and competitive pressure simultaneously.

The trade-off between current profits as well as future expected profits was shown for firms that are engaged in forward contracts. Using the "critical discount factor" as a concept it was shown that forward contracts lead to a decreased incentive to undercut the price set by a competitor. This result, which was firstly shown by Liski and Montero (2006) under deterministic market conditions, holds under stochastic market conditions, too.

However, under volatile market conditions firms that rely on stabilizing a collusive agreement by forward trading face another problem. They never know the profit maximizing quantity in advance and always have a threat of involuntarily having traded forward more than the optimal quantity. Thus, profitability of a collusive agreement is reduced by (excessive) forward trading.

Firms can trade a certain amount forward to stabilize a collusive agreement. As long as the forward-traded amount does not exceed monopoly quantity, this does not reduce collusive profit. Another way to stabilize a collusive agreement is to set a lower collusive price, since this reduces the profit of a firm, which is undercutting this price more sharply than collusive profit. In contrast to forward contracts this directly leads to decreasing profits. If firms cannot stabilize a collusive agreement by trading less than monopoly quantity forward, they have two ways to stabilize their collusive agreement, either by trading forward more than respective monopoly quantity or by setting a price below the monopoly price. The optimal semi-collusive strategy of collusive firms was derived for a stylized world, in which either a boom or a recession occurs. This optimal semi-collusive strategy is given by a combination of trading forward more than recessive monopoly outcome and in booms setting a price below the monopoly price. It mainly depends on the probability of a recession or boom to what extent additional forward contracts, which reduce profits in a recession or lower spot market prices, are used to stabilize a collusive agreement. *Ceteris paribus* a higher boom probability leads to more forward contracts, which reduces recession profit, whereas *ceteris paribus* a higher recession probability leads to less forward contracts and a stronger adaption of the collusive boom price.

From a theoretical point of view there is another interesting question. What happens if firms decide to take a long position on the forward market? This means firms oblige to partly buy their own production (back) from speculators. A destabilizing effect of long

positions on a collusive agreement was shown, which does not make any long positions interesting for colluding firms.

The micro-economic model presented above provides interesting insights into the interdependence of forward trading and competitive pressure. However, some more assumptions could be relaxed to give a more detailed description of the German electricity market:

The model assumes linear marginal costs that do not vary between competitors. This clearly gives the possibility to adapt this model in two ways: Firstly, the cost structure for an electricity supplier has a convex shape, since for a while electricity can be generated by power plants with low marginal cost. If additional electricity is needed, electricity is generated by power plants with higher marginal costs. Competitors have different power plants, which are generating electricity from different energy sources. Thus, allowing for convex cost patterns, which differ between competitors, could lead to further insights about competitive effects of forward trading.

Another assumption of the presented model taken into consideration is perfect observability of forward and spot market positions. Economic research (Green and Porter, 1984) has shown that imperfect observability of spot and forward market positions leads to different behavior of colluding firms, since they never know whether their competitor has decreased its price or unfortunately a recession has occurred. After each recession a price war happens that will last for some periods. This price war is necessary to avoid hidden price reduction. It could be very interesting to find out how forward contracts could be used in such a setting to decrease competitive incentives.

In the empirical analysis necessary conventional load is found to be serially correlated. The presented theoretical model is stochastic, but does not allow for serial correlation. For the analysis of competitive pressure on the German electricity market this does not seem to be necessary, since serial correlation seemed to decline fast. However, for markets that show a large serial correlation, which is not declining immediately, this extension could be more important.

Forward Trading and Strategic Investment

On the electricity market investment decisions play a crucial role in strategic competition. There are very long-lasting investments like those for building up a plant or introducing a cost-reducing new technology. Other investments like those for building up capacities in an existing plant, distributing or advertising the product have a shorter time horizon.

Depending on the time horizon of an investment incentive, the theoretical model presented above showed very different strategic effects of forward trading on investment incentives: For a long-term investment decision a rather small forward traded amount and moderate investments led to a smaller amount supplied to the market, higher prices, higher profits of firms, lower consumer surplus, and smaller social welfare. Thus, if firms's investments mainly can be viewed as long-term, introduction of a forward market has only a slightly welfare-enhancing effect. For a mid-term investment decision a rather large forward traded amount, moderate investments, a relatively high amount supplied to the market, a relatively low price, relatively low profits of firms, a higher consumer surplus and a relatively large social welfare, was chosen by firms in equilibrium. Thus, if firms's investments can be mainly viewed as mid-term, introduction of a forward market has a stronger welfare-enhancing effect.

Thus, for strategic aspects of forward-trading on investment decisions one could conclude: The social desirability of a forward market critically depends on the typical time horizon of the investments made by firms:

For investment decisions that mainly have a mid-term time horizon the introduction of a forward market is socially most favorable. However, for investment decisions that mainly have a long-term time horizon, the introduction of a forward market only leads to a small increase in social welfare!

This is bad news for the policymakers of the German energy turnaround, since most investment decision on the German electricity market have a long-lasting time horizon.

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