1 Introduction

1.1 Problem Definition and Objectives of this Thesis

Over the past decades, electricity markets have been liberalized and deregulated worldwide. Former monopolistic markets have been restructured into competitive systems to break down traditional relationships between suppliers and consumers. Simultaneously, both skepticism against power generation from conventional energy sources and the interest in renewable energy sources (RES) has increased. Consequently, the political and economic promotion of a transition towards a more sustainable energy supply has set in.

In Germany, major political steps were taken through the implementation of the Energy Industry Law (Energiewirtschaftsgesetz, or EnWG) in 1998 and the Renewable Energy Act (Erneuerbare-Energien-Gesetz, or EEG) in 2000. The EnWG was aimed at stimulating competition between participants of the electricity market and initiated the liberalization. During the subsequent development, several new players entered the market, and former monopolistic market structures receded. Likewise, specific targets regarding the promotion of power generation from RES were formulated in the EEG. By 2050, the EEG (in its current version from 2017) aims at 80 % of the electricity production being generated by RES.

In the German power market, the feed-in of electricity from RES into the grid is prioritized against other sources. This causes the power supply system to face new challenges, and a functioning market is required to offset demand and supply. On the supply side, electricity is (economically) non-storable, and for system stability reasons, production must meet consumption at each point in time. Electricity is required to be consumed immediately at the time of its generation. On the demand side, consumption is inelastic and is affected by seasonal behavior of consumers. This seasonal pattern corresponds to daily and weekly cycles of activities in industry, but also to the consumption behavior of individuals, which requires a flexible power plant portfolio. Therefore, electricity markets strongly differ from other (financial) markets, as they are subject to technical restrictions. The cyclical demand and the increasing share of RES are essential factors in the price formation process in electricity markets. Following the theory of supply and demand, an excess power supply leads to decreasing market prices and vice versa. Additionally, power plants with high generation costs are squeezed out of the market by RES power generation capacities. This is the so-called merit-order effect (MOE).

The technical constraints determine the price behavior in electricity markets to a great extent and can explain the well-known stylized facts of electricity prices. Power markets are highly volatile, they exhibit heteroscedasticity, non-stationary behavior, seasonally dependent price levels, mean reversion, price spikes, and negative prices. Therefore, through scientific research, it is common to include this information into models when attempting to explain the behavior of electricity prices. Furthermore, in business practice, it is in the interest of all market participants to minimize their risk by accurately forecasting prices, which requires a deep understanding of the market.

Within a future-oriented power risk and portfolio management, short term price forecasts are required, for example, to ensure the economic efficiency of power plant operations and schedules. A broad range of scientific studies have focused on price forecasts in the recent past. Time series models particularly, are a major field of study in literature. Empirical publications on time series modeling and forecasting of electricity prices vary widely regarding the conditions and findings making it difficult to generalize results. However, contradictory findings of several studies throughout the forecasting literature raise the question of what the true results are. Against this background it is surprising that there is a lack of statistics-based literature reviews on forecasting performance when comparing different models. To fill this gap, a comprehensive literature analysis is conducted in this thesis. The objective is to provide an overview on the state of the art of time series modeling and forecasting of electricity prices. However, the key issue of this study is to offer a comparison of different model types and modeling conditions regarding their forecasting performance. The findings are based on a meta-study style analysis of the forecasting performance of time series models across several markets.

A subsequent empirical analysis serves to validate the results of the literature review. The empirical analysis aims at deeper analyzing the forecasting performance of time series models compared to other studies by not only considering different model types but also varying the conditions of the study. Day-ahead forecasts are evaluated for different market phases, transformations and time windows to find the best out-of-sample performing time series model. The findings are based on the evaluation of forecasts on the German/Austrian (GER/AT) market.

By the literature analysis and the empirical study, the following key issues on the forecasting of electricity prices are addressed in this thesis:

- What is state of the art in time series modeling of wholesale electricity prices?
- Which time series models yield the best forecasting performance?

To reflect the current market situation, the evaluation of standard time series models is conducted taking into consideration the price drivers power consumption, wind power generation and solar power generation.

To achieve a deeper understanding of the price effects of these factors one should not rely on the accuracy of forecasts, but on explanatory models. Of course, the price dampening effects of power generation from RES have already been investigated in several studies, in which it is common to apply OLS (ordinary least squares) regression models. In contrast to the existing empirical literature in this area, in the present study a panel data analysis is applied. The advantage of panel data analysis against standard pooled regression is the avoidance of an omitted variables bias caused by unobserved heterogeneity (part of the error term) that is constant over time. More specifically, the so-called fixed effects model is applied according to which heterogeneity is removed by the “within transformation”.

The model for the German (and Austrian) power market comprises variables, which, by their design, capture the specific characteristics of this market. A noteworthy element of the regression model is the simulation-based design of a variable indicating the power generation technology that is price-determining at a certain point in time to model the nonlinear price behavior for a varying demand. This supports a precise calculation of the price effects of power generation from RES. Against the background of the general focus of this thesis on RES the described model with its sophisticated structure serves to answer the following third research question:

- What are the effects of RES power generation on electricity prices?

For this, besides studying the MOE, price changes due to power plant ramping as well as price changes due to forecasting errors on wind and solar power generation are quantified. Both factors may have impacts on price volatility. Ramping costs are costs which are incurred by varying operation capacities of power plants due to a lower efficiency of the power generation combined with higher operational costs. Forecasting errors on RES may occur as forecasts are frequently adjusted by the actual delivery of the electricity.

The three research questions raised above provide the superior frame to this thesis, which is modeling and forecasting of wholesale electricity in the German power market with consideration of the effects of RES.

1.2 Course of Investigation

To analyze the research issues stated above, this thesis is structured as follows. After describing the German electricity market in general, the forecasting performance of time series models is analyzed on a broad literature basis, followed by an empirical forecasting study of time series models under varying market conditions in the German (and Austrian) power market. Then, the price effects of wind and solar power generation are analyzed by means of a panel data regression.

In chapter 2, the German electricity market is described. This chapter provides a general framework regarding the market environment and serves as basic information source for the understanding of subsequent analyses of the German electricity market. Section 2.1 gives the historical development with a legal background, section 2.2 deals with the current situation on the retail market, and section 2.3 describes the functioning of the wholesale market including the market design. Finally, the structure of the power plant portfolio is characterized in section 2.4, in which focus is placed on the characteristics and cost structures of different power generation technologies. In this context, the MOE is also described, because with the increasing share of feed-ins from RES their price dampening effect is of growing importance to the power market. The understanding of the market structure and its conditions is essential, when designing adequate price models.

Chapters 3 and 4 deal with the forecasting of electricity prices with time series models, which are common models capturing the price behavior in electricity spot markets. Chapter 3 provides an extensive literature review on electricity prices forecasting, which is conducted based on 86 empirical studies from 2000 to 2015. This quantitative literature review is referred to as a quasi-meta-analysis. At first, section 3.1 provides an introduction into the topic. In section 3.2, the theory of modeling and forecasting electricity spot prices is described, which covers model types, data transformation types and the evaluation of forecasts. Section 3.3 presents a survey of the empirical literature on electricity spot price modeling and various statistics to characterize the existing literature in this area. In section 3.4, the forecasting performance of different model types is evaluated, and finally, the findings are summarized in section 3.5. Detailed lists of the related literature and definitions of the common time series models are provided in the appendix in 3.6.

Related to the findings of the literature review, in chapter 4 an empirical forecasting study is conducted. The forecasting performance of different time series models is analyzed on the German (and Austrian) day-ahead market. Section 4.1 presents an introduction into the topic. In section 4.2, hypotheses on the forecasting accuracies of different model types are formulated based on the results of other empirical studies. These hypotheses are related to the forecasting accuracy, which is subject to varying modeling conditions and the specific model selection. After a description of the study setup in sections 4.3 to 4.5, the results of the empirical study are presented and analyzed in section 4.6. A recap in section 4.7 offers a different perspective on the obtained results. And finally, the findings of the empirical forecasting study are summarized in section 4.8. Results of several model variations are provided in the appendix in 4.9. The current market conditions are reflected by applying time series models, which include explanatory variables for power consumption, and wind and solar power generation.

After the forecasting studies, in chapter 5 an empirical analysis is conducted to quantify the price effects of power generation from wind and solar on the German (and Austrian) power market from 2010 to 2016. A regression model with non-linear explanatory variables is designed to analyze the MOE, the price effects of power plant cycling and impacts of wind and solar power generation forecasting errors. The model design is more sophisticated compared to the time series models applied in chapters 3 and 4. After an introduction into fundamentals in section 5.1, section 5.2 presents a summary of the recent literature on the three facets to be analyzed. The study setup is described in section 5.3, followed by the empirical results in section 5.4. The findings of this study are summarized in 5.5. Full regression tables and robustness checks are provided in the appendix in 5.6.

Chapter 6 concludes this thesis with a summary of the results of the preceding chapters.

2 The German Electricity Market

2.1 Historical Development from a Legal Perspective

2.1.1 The Market Prior to its Liberalization

In the late 19th century, the first structures of the power supply infrastructure in Germany evolved along with the industrial revolution. The first public energy supply company of Germany (AG Städtische Elektrizitätswerke) was founded in Berlin in 1884. Later, with the foundation of further power supply companies across the country, the German electricity market was characterized by regional monopolies. These monopolies were a consequence of demarcation agreements concluded between energy supply companies to establish separate supply areas.

Within their supply areas, power supply companies were not exposed to competition. Concession agreements with municipalities enabled them to build up their power supply infrastructure in public areas. In combination with the demarcation agreements, energy supply companies were guaranteed a monopoly in their power supply area through the payment of concession fees. The power supply companies acted as vertically integrated affiliated enterprises. Their business areas included all stages of the value chain: power generation, trade, transmission, distribution, and sales.

The EnWG, which was established in 1935, codified the common practice in the power supply sector. The power supply sector – regarded as of public interest – was exempt from competition. Regional monopolies were laid down in legislation and market entry barriers were erected (§ 5 EnWG 1935). However, by law, direct governmental influence on pricing was permitted

(§ 7 EnWG 1935). In exchange for guaranteed regional monopolies, power supply companies were committed to a secure and cost-efficient power supply to the resident end consumers (preamble of EnWG 1935). For a long time, the anti-competitive restrictions were not eliminated by any legislative action. The demarcation agreements between power supply companies were even excluded from the Act against Restraints on Competition (Gesetz gegen Wettbewerbsbeschränkungen, or GWB), which was enacted in 1957. They were explicitly permitted corresponding to § 103 GWB 1957.

Consequently, by its liberalization in 1998, the electricity market in Germany was characterized by vertically integrated utilities on the supply side.

2.1.2 Amendments of EnWG and Liberalization

In 1996, the European Union (EU) parliament passed the Electricity Market Directive 96/92/EC to establish a competitive European electricity market (§ 2 96/92/EC). In Germany, the directive was transposed into the Law Updating the Legislation on Power Supply, which included replacing the EnWG 1935 with the EnWG 1998 and repealing the legal protection of regional monopolies according to § 103 GWB 1957. The value chain stages of power generation, trade, and sales were opened to a competitive market. The electricity grid infrastructure remained a natural monopoly. Power suppliers were advised to separate their businesses into units with monopoly status (infrastructure) or units with competitive orientation. This was the so-called unbundling of business units induced by the EnWG 1998, which is presented in Figure 2.1. The business units operating the (monopolistic) grid infrastructure were obliged to offer non-discriminatory conditions to competitors and affiliated companies regarding the network access.

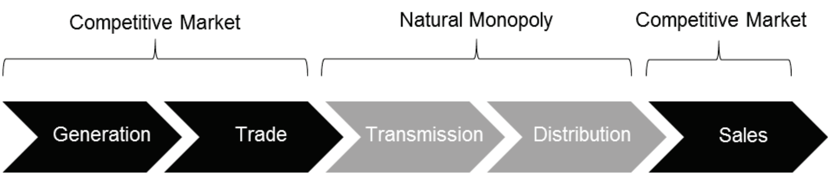

Figure 2.1: Unbundling in the power supply sector. Own illustration based on Führmann & Schlösser (2008)).

Following the Acceleration Directive 2003/54/EC of the EU, the regulatory authority Bundesnetzagentur (BNetzA) was implemented by means of the amendment law EnWG 2005. The BNetzA was given power to officially regulate tariffs for network access and monitor non-discriminatory access conditions and the unbundling of the vertically integrated power suppliers. The subsequent amendment EnWG 2011 included even stricter regulations for the unbundling process.[1]

2.1.3 The EEG and its Amendments from 2000 to 2017

The liberalization of the electricity market coincided with the transition of the energy system towards more sustainability, which was forced by several legislative actions during the past decades. In Germany, the EEG established the legal basis for the feed-in of power generated by RES into the electricity grid. Corresponding to § 3(21) EEG 2017, RES are defined as hydropower, wind power, photovoltaic (PV), biomass and geothermal energy.

The EEG had its origins in the Electricity Feed-In Act (Stromeinspeisungsgesetz, or StrEG) established in 1991, which obliged the grid operators to purchase electricity from renewable power plants at guaranteed feed-in tariffs (which were based on the retail price level). In 2000, the StrEG was replaced by the EEG, which granted a priority dispatch to power generated from RES. The feed-in tariffs to be paid by the grid operators (and passed on to the end consumers by means of the so-called EEG apportionment) were set for 20 years.

The most substantial changes of the first amendment of the EEG in 2004 included the adjustment of the tariff levels to be paid on RES feed-ins. Furthermore, reliefs from the EEG apportionment for electricity-intensive industry sectors were introduced to maintain their degree of competitiveness against foreign competitors.

As a reaction to the increasing share of RES on the total power market, from 2009 on, the compensation system for RES feed-ins was modified (amendment law EEG 2009). As an alternative to the granted feed-in tariffs, RES power plant operators were allowed to directly sell electricity to the market (§ 17 EEG 2009). The amendment law also introduced a system of

[1] The EnWG had also been amended in 2003 and 2008.

downward compensation rate adjustments for solar power feed-ins if newly installed PV capacities exceeded certain thresholds (§ 20(2a) EEG 2009).

Increasing power generation from fluctuating RES wind and PV – being independent of the demand – entailed high costs, which might threaten the electricity system's safety. The power supply infrastructure had not been designed for high shares of RES.[2] To drive the increased market integration of RES, the EEG 2012 amendment included a market premium model for power plants selling electricity to third parties at market prices (§ 33g EEG 2012). Despite reduced feed-in tariffs, the PV sector grew rapidly, which is why in the same year the PV Act came into force to further reduce tariffs at higher degression rates. Under EEG 2014, feed-in tariffs were again reduced. Furthermore, in contrast to the former system of fixed tariffs, operators of newly-installed plants with capacities larger than 500 kilowatts (kW) (from 2016 on, larger than 100 kW) were obliged to directly market their feed-in volumes.

In the EEG 2017 amendment, the most substantial adjustment was the implementation of an auction system for wind, solar, and biomass power plants. For new-installations larger than 100 kW, the former compensation system was replaced by public tenders of predetermined generation capacities, where the lowest costs bid is accepted (§ 28-39 EEG 2017).

2.1.4 European Union Emission Trading Scheme

Besides the extensive German legislative actions to push forward a sustainable power supply, in 2005, a market for the trade of greenhouse gases was launched on EU level. The so-called European Union Emission Trading Scheme (EU-ETS) was established (based on the EU emissions trading directive 2003/87/EC in follow up to the climate agreement of Kyoto from 1997, and in an effort to reduce greenhouse gas emissions. By means of the emission rights, the impacts of environmental pollution are economized. Consequently, the EU-ETS serves to internalize the external effects of carbon dioxide (CO_2) emissions. Given a sufficient system of controls, the trading scheme ensures reductions of emissions at the lowest macroeconomic

[2] See Deutscher Bundestag Drucksache 17/6071.