Hacettepe University Graduate School of Social Sciences

Department of Economics

EVOLUTION OF ELECTRICITY MARKETS FROM THE PERSPECTIVE OF PRODUCTION AND ORGANIZED MARKETS

Mustafa Çağrı PEKER

Ph. D. Dissertation

Ankara, 2023

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ACCEPTANCE AND APPROVAL

The jury finds that Mustafa Çağrı PEKER has on the date of 14/09/2023 successfully passed the defense examination and approves his Ph. D. Dissertation titled "Evolution of Electricity Markets From The Perspective of Production and Organized Markets".

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ETİK BEYAN

Bu çalışmadaki bütün bilgi ve belgeleri akademik kurallar çerçevesinde elde ettiğimi, görsel, işitsel ve yazılı tüm bilgi ve sonuçları bilimsel ahlak kurallarına uygun olarak sunduğumu, kullandığım verilerde herhangi bir tahrifat yapmadığımı, yararlandığım kaynaklara bilimsel normlara uygun olarak atıfta bulunduğumu, tezimin kaynak gösterilen durumlar dışında özgün olduğunu, **Prof. Dr. Ayşen SİVRİKAYA** danışmanlığında tarafımdan üretildiğini ve Hacettepe Üniversitesi Sosyal Bilimler Enstitüsü Tez Yazım Yönergesine göre yazıldığını beyan ederim.

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ABSTRACT

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Electricity markets were initially established based on a vertically integrated organizational framework. The market segments underwent a process of vertical unbundling, which subsequently led to their division into four distinct categories: generation, transmission, distribution, and retail. In the first chapter of this thesis, the most common electricity market supply industry problems have been presented. Four prominent problems emerge as noteworthy, encompassing generation inadequacy, missing money, market power, and renewable intermittency. Among these problems, there exists a network of unidirectional, bidirectional, and potentially nonlinear dynamic relationships. A holistic approach is even more crucial given the complex interactions between problems. In the second chapter, the impact of renewable energy on electricity prices has been examined with panel data analysis for 25 European countries. We employed the Pesaran CD test for cross-sectional dependence, the Pesaran and Yamagata (2008) method for slope heterogeneity, and the dynamic common correlated effect estimator to explain the market clearing prices. The model results demonstrate that European countries experience the merit order effect, where the capacity of renewable energy lowers prices. This chapter presents the impact of merit order effect for generators, consumers, and policy makers. In the third chapter, the impact of solar and wind generation on market clearing prices have been examined in Turkey as an example of a developing country. We use of machine learning techniques for analysis is one of its distinguishing characteristics. According to polynomial learner results, solar and wind generation both decreased the electricity market clearing price. In addition, solar generation has a negligible effect on market clearing price volatility below a certain threshold, but reduces it above a certain demand level. However, wind generation increases volatility at both low and high demand levels.

Keywords

Wholesale Electricity Markets, Electricity Market Problems, Renewable Energy Resources, Electricity Prices

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ABBREVIATIONS AND SYMBOLS LIST

ADF	Augmented Dickey Fuller
ARDL	Autoregressive Distributed Lag
ARIMA	Autoregressive Integrated Moving Average
CD	Cross-Sectional Dependence
CfD	Contract for Difference
CIP	Cross-Sectionally Augmented Panel Unit Root Test
CR	Czechia
DCCE	Dynamic Common Correlated Effect Estimator
EM	Energy Markets
EMRA	Energy Market Regulatory Authority
ERCOT	Electric Reliability Council of Texas
EWMA	Exponential Weighted Moving Average
FIT	Feed-in-Tariff
FIP	Feed In Premium
GARCH	Generalized Autoregressive Conditional Heteroskedasticity
GI	Generation Inadequacy
GW	Gigawatt
IR	Intermittent Renewables
IRG	Inefficient Regulation and Governance
IP	Inefficient Pricing
IPP	Independent Power Producer
ISO	Indepedent System Operator
kWh	Kilowatt-Hour
LCOE	Levelized Cost of Energy

MP	Market Power
MWh	Megawatt-hour
OLS	Ordinary Least Squares
PJM	Pennsylvania-New Jersey-Maryland Interconnection System Operator
RES	Renewable Energy Sources
RESM	Renewable Energy Support Mechanism (YEKDEM)
RMSE	Root Mean Square Error
RU	Ravn-Uhlig
SMM	Supply Missing Money
TC	Transmission Congestion
TTF	Dutch Natural Gas Price Hub
UK	United Kingdom
US	United States
USA	United States of America
VECM	Vector Error Correction Model
VM	Volatility of Market
VoLL	Value of Lost Load

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INTRODUCTION

Over the last 30 years, the power market has observed a transformation in both demand and supply aspects. The growing electricity demand in recent years has created a necessity to attract new investments into the energy markets, with the primary objective of enhancing market efficiency. (Chao et al., 2005). The progress of per capita electricity consumption over the years has shown a steady increase (World Energy Outlook 2022). As technological advancements have proliferated and economies have developed, the demand for electricity has risen consistently. This trend is particularly notable in both industrialized and emerging nations. The upward trajectory of per capita electricity consumption reflects not only improved living standards but also the growing reliance on electronic devices, appliances, and various energy-intensive activities in daily life. However, it's worth noting that regional variations exist due to factors such as economic growth rates, population dynamics, energy policies, and advancements in energy efficiency technologies. In Europe, the per capita electricity consumption progress has followed a similar trend to that described earlier. Over the years, Europe has witnessed a gradual increase in per capita electricity consumption due to several factors such as urbanization, industrialization, technological advancements, and improved living standards. The region's transition to more energy-intensive activities, along with the proliferation of electronic devices and appliances, has contributed to this rise in electricity consumption.

During the initial phase of the transition in the electricity market, vertically integrated markets were separated into generation, transmission, distribution, and retail. Vertical unbundling helped create an efficient and effective electricity market structure (Jamasb and Pollitt, 2005). In the majority of OECD countries-especially European countries, nuclear, oil, and coal power plants were primarily employed for electricity generation (Melsted and Pallua, 2018). With the development of technology, natural gas power plants have come into play as cleaner energy compared to oil and coal (Rentier et al., 2019). In the ensuing process, the use of renewable energy sources for electricity generation increased, primarily through the construction of hydroelectric power plants (Zimny et al., 2013). Research and development (R&D) studies on wind and solar power plants have made contributions to increasing efficiency in this field. (Gross et al., 2003). In the 1990s, investments in solar and wind energy started to gain prominence. (Popp et al., 2011). The Paris Climate Agreement has had an accelerating effect on addressing these issues. Massive investments have been made in solar and wind power plants. Due to these various factors, diversification has been achieved in electricity generation (Zeeshan and Mohammed, 2012; Ydersbond and Korsnes, 2016).

This thesis aims to address problems faced in the electricity supply industry and examine the impact of the growing issue of renewable energy on market clearing prices. The distinctive aspect of this thesis lies not only in its holistic approach to supply-side issues but also in its empirical examination of intermittent renewables, one of the supply-side challenges, both for numerous countries (EU member states) and a single country (Turkey). To the best of our knowledge, there is no existing study that comprehensively addresses supply-side problems from a holistic perspective and empirically investigates intermittent renewables for many EU countries while also investigating a single-country case, such as Turkey.

In the first chapter of the thesis, the most common electricity market problems in the supply industry are presented. Supply industry problems are grouped under four main headings: generation inadequacy, missing money, market power, and intermittent renewables. These problems have a relationship with each other; they lead to problems in the other subsectors and market transformation. Firstly, generation inadequacy stands out as one of the oldest problems. Within the scope of electricity market dynamics, instant matching of supply with demand is the primary priority (Olsina et al., 2006). In cases where the electricity supply does not meet the demand, the problem of generation inadequacy arises (Newbery, 2002a). The second problem is the missing money. Investors are unable to realize a suitable profit level due to improper pricing and supply industry inefficiencies (Woo et al., 2019). While this situation ensures that the investor cannot meet their expectations compared to other sectors, it also reveals the problem of missing money. Thirdly, market power has become the primary problem impeding competition, brought on by problem of inadequate generation and missing money. The fact that some generators become price makers in a certain period of the market leads to a market far from efficiency and effectiveness (Borenstein et al., 2008). On the other hand, rapidly evolving electricity generation technologies have dropped energy costs, and carbon emissions have decreased as a result of the power portfolio's shift from conventional sources to renewable energy. The transformation towards renewable energy introduces intermittent renewables as the fourth problem. The intermittent generation pattern inherent to renewable energy sources is called the problem of intermittency, which yields volatile generation. The market has been impacted by the volatile generation characteristics of renewable energy facilities (Acemoglu et al., 2017; Negrete-Pincetic et al., 2017). In the first chapter, a holistic perspective is being proposed within the framework of these four problems. By doing so, we aim to present the interconnectedness of the problems and provide the solutions developed by the literature to them.

The second chapter of the thesis focuses on the analysis of intermittent renewables, which is widely recognized as the most recent problem in the supply industry. The generation volatility of renewable energy has an impact on the market clearing prices (Sirin and Yilmaz, 2021). This effect is called the merit order effect of renewable energy. In this context, we investigate the merit order effect of renewable energy by considering the wholesale electricity markets. In the second chapter of the thesis, we use a panel data from European countries in the field of renewable energy. This chapter stands out for its comprehensive analysis of the relationship between renewable energy and market clearing prices across a wide range of countries. The Pesaran CD test was employed for panel data analysis to account for cross-sectional dependence. Then, the Pesaran and Yamagata (2008) and Blomquist and Westerlund (2013) tests were conducted to address slope heterogeneity among countries. Due to the presence of slope heterogeneity and cross-sectional dependence, the dynamic common correlated effect estimator was utilized. The dependent variable in this model is the market clearing price, while the independent variables are electricity demand, generation from renewable energy, and generation from natural gas. The results reveal that electricity demand and generation from natural gas have a positive impact on the market clearing price. On the other hand, the generation of renewable energy lowers the market clearing price through the merit order effect.

In the third chapter, we investigate the merit order effect of electricity generation from solar and wind sources on the market clearing price and price volatility in Turkey. Turkey, which is an EU candidate country, leads the way in renewable investments among developing countries. The Turkish wholesale electricity market, which was established in 2015, has now exposed the connection between electricity prices and renewable energy sources.

In the third chapter, we apply machine learning techniques to investigate the effects of renewable energy on market clearing price and price volatility in Turkey. Four different machine learning methods (regression learner, tree ensemble learner, random forests, and polynomial learner) were implemented, and we found that the second-degree polynomial learner produced the best outcomes out of these. In light of obtained results, wind energy has a greater price-lowering impact than solar energy. The two sources' contribution to price volatility was also notable. Wind energy increases price volatility, while solar generation reduces it. It has been observed that the effect of renewable energy on prices differs at different demand levels.

The third chapter also provides policy recommendations for the implementation of renewable energy in Turkey. For the progression of the renewable energy sector and the attainment of sustainable and reliable electricity generation, it is imperative to establish a coherent regulatory structure-which implement competitive support mechanisms, invest in hybrid power generation and energy storage- and maintain an equilibrium between large-scale wind generation and distributed solar generation.

The three investigations mentioned above are included in Chapters 1, 2, and 3 of the dissertation. Finally, we highlight the key findings of the three studies in conclusion.

CHAPTER 1

PROBLEMS OF THE SUPPLY INDUSTRY IN WHOLESALE ELECTRICITY MARKETS

1.1. ELECTRICITY MARKETS

Since its invention in the 19th century, electricity has been used in many fields such as heating, transportation, communication, production. The increasing dependence on electricity in modern life with technological development has required a well-functioning electricity market (Streimikiene et al., 2013). However, a well-functioning electricity market relies on addressing the problems encountered on the supply side of the market, called the supply industry in the literature (Jamashb, 2002). In this chapter, we review the related literature to discuss the problems in the electricity supply industry and reveal the systematic relationships among them.

Since the 1980s, the wholesale electricity markets in the world have evolved by addressing the problems such as generation adequacy[1], market power[2] However, during its evolution[3], addressing one problem has created new problems in the supply industry due to the multifactorial nature of the problems (Woo et al., 2006). For instance, the electricity markets have been deregulated in the USA (Borenstein and Bushnell, 2000; Chao and Wilson, 2001). Deregulation in the USA has created several problems in the supply industry, such as efficiency problems and market power (Borenstein and Holland, 2003). On the other hand, countries such as Germany and the United Kingdom have launched several regulations in Europe (Newbery, 2002). However, these regulations

[1] In the literature, Kaseke and Hosking (2013); Ebhota and Tabakov (2018); Onochie et al. (2015); Cao et al. (2021); and Mukherjee and Nateghi (2018) use the terms generating, generation capacity, resource, power, and supply inadequacy term to define it as the shortage of supply to meet demand. In the study, we used the term generation inadequacy, similar to supply inadequacy, inadequate electricity supply, and power inadequacy.

[2] In the realm of electricity auction markets, market power is defined as the capacity of a buyer or seller to exert substantial and enduring influence over the prevailing market price, deviating it from the competitive price (Helman et al., 2008). We discussed market power in detail in the following sections.

[3] Electricity market evolution refers to the transition of the generation mix to renewable resources, the privatization of the supply industry and other segments, the development of a regulatory framework, and the implementation of new technologies (Liu et al., 2022; Zou et al., 2017; Sioshansi, 2013).

have also brought about inefficiency, let alone generation inadequacy and the problem of intermittent renewables[4] (Danwitz, 2006; Pollitt, 2009). Similar to the wholesale electricity markets in the USA and Europe, the ones in Latin America, Asia, and several developing countries have also faced problems of market power, (Jamashb, 2006; Kessides, 2007; Oseni and Pollitt, 2016). Therefore, even though the electricity markets in different regions have developed in different ways by overcoming specific problems, several other supply industry problems still exist.

In this chapter, we have conducted an investigation into the problems of the supply industry. The findings of this chapter suggest that the literature on electricity markets often takes a general approach, providing an overview of the subject matter without placing sufficient emphasis on specific problems related to the industry. Moreover, they generally focus on one or two problems (Rudnick et al., 2005; Roques, 2008; Newbery, 2015; Aghaie, 2016).

However, problems such as generation inadequacy, missing money[5], and market power are the main drivers of the electricity market evolution. Thus, exploring the causes and consequences of these problems is crucial to understanding this evolution. Besides, evaluating them separately might ignore the strong relationships among them (Green, 2003; Pittman, 2014). This chapter, different from the previous studies, focuses both individually and holistically[6] on problems in the supply industry. Moreover, based on the problem-oriented perspective, this chapter discusses possible solutions to these problems.

This chapter has two main contributions in terms of electricity market participants.

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[4] Intermittency defined as limited capacity to exert control over the electrical output resulting from variable and unpredictable generating power plants such as renewable resources (Initiative, 2012). We discussed intermittency of renewables in the following sections.

[5] The "missing money problem" is a phenomena that refers to the idea that energy prices set in competitive wholesale electricity markets may not fully reflect the value associated with investing in the necessary resources (Hogan, 2017). The fundamental challenge of generation adequacy lies in rectifying the absence of sufficient “financial incentives that hinder appropriate investments” (it ends up with missing Money problem) in generating capacity (Crampton and Stoft, 2006). We discussed missing money in the section 1.3.2.

[6] This chapter employs a holistic approach/view to depict the comprehensive representation of issues and their interconnectedness within a unified framework.

a. From the policy maker's point of view: if policy makers adopt the perspective of this chapter, they will formulate their partial proposals for the electricity market from a comprehensive perspective.

b. From the perspective of other market participants: when private sector actors see that the policy maker acts with a holistic view, they will be more willing to articulate solutions that make sense from the policy maker's comprehensive perspective.

The remainder of the article is structured as follows: The methodology has been described in the Section 2. In Section 3, we present the evolution of the wholesale electricity markets and supply industry. In Section 4, we mentioned the problems of wholesale electricity markets and supply industry by giving the causes, consequences, and the possible solutions of the problems. The last section concludes the chapter.

1.2. METHODOLOGY

The analysis of the problems within the electricity supply industry presented in this chapter has been compiled from literature in journals and institutions. The examples studied in this chapter have predominantly been obtained from internationally recognized journals and reputable publishers such as Springer, Wiley, Elsevier, etc. Additionally, various online websites published by official governmental and private entities, as well as research institutions, have been utilized. The journals examined and reviewed in this chapter encompassed papers deemed pertinent to problems within the electricity supply industry, including generation inadequacy, missing money, market power, and renewable intermittency.

The search terms employed within the chapter are as follows: "problems of electricity market, problems of wholesale electricity market, generation inadequacy, missing money in electricity markets, market power in electricity market, intermittent renewables in electricity markets, evolution of electricity markets, e.g." In order to gain a comprehensive overview initially, the terms "evolution of electricity markets," "problems of electricity market," and "problems of wholesale electricity market" were utilized. Through these searches, it was determined that the problems identified from the findings predominantly clustered under headings such as generation inadequacy, missing money in electricity markets, market power in the electricity market, and intermittent renewables. As a result, the study was expanded under these specific headings. Upon review of the literature, numerous papers have individually addressed supply industry problems, as exemplified by market power (Borenstein et al., 1999; Joskow and Tirole, 2000), inadequate generation (Strabac and Wolak, 2017), missing money (Hogan, 2005; Newbery, 2016), e.g..

499 articles in total were examined during the literature review. It can be seen from Appendix 1 that the publications about problems are concentrated in particular years when the distribution of these articles by year is displayed. Particularly, a rise in research activity has been noted in recent years, such as in the publications related to "Missing Money," which were prominent in 2018–2019, while "Intermittent Renewables" publications increased after 2015. In Appendix 2, the distribution of publications according to the identified problems—namely, generation inadequacy, missing money, market power, and intermittent renewables—is shown. Within the total number of publications that were investigated, the following publications were distributed among the identified problems: 21% for generation inadequacy, 23% for missing money, 26% for market power, and 30% for intermittent renewables.

Within the scope of this critical review chapter, a notable strength of the literature is its comprehensive identification of a wide array of problems. Conversely, its weaknesses lie in its segmented approach to supply industry problems and its insufficient exploration of interrelationships among these problems. Moreover, a contradiction arises from the divergence in problem naming and the tendency for solutions to be singularly problem-centric.

It has been observed that providing individual solutions to problems leads to the emergence of new challenges. This critical review chapter proposes a holistic perspective, derived from the results of a literature review, to rectify the identified problems and analytically present the subject matter. It endeavors to provide a comprehensive representation of the problems and their interconnections within a unified framework.

Alongside the holistic viewpoint, the depiction of relationships among the problems has been facilitated. This proposal of a holistic perspective aims to reveal hybrid solutions to market problems.

1.3. EVOLUTION OF WHOLESALE ELECTRICITY MARKETS

This section discusses the transformation processes of European, Asia-Pacific and Developing Countries' electricity markets with regards to ownership, generation resources, and the establishment of organized electricity markets. In this process, generation, transmission, distribution and retail divisions have been shaped. In this period, unbundling of the vertically integrated structure and privatization were used in order to liberalize the markets. The public-private transformation in the wholesale electricity markets, the change of generation resources, and the development of the organized market are the main issues during the past years. The historical evolution of supply industry of wholesale electricity market from public to private ownership is shown in Figure 1.

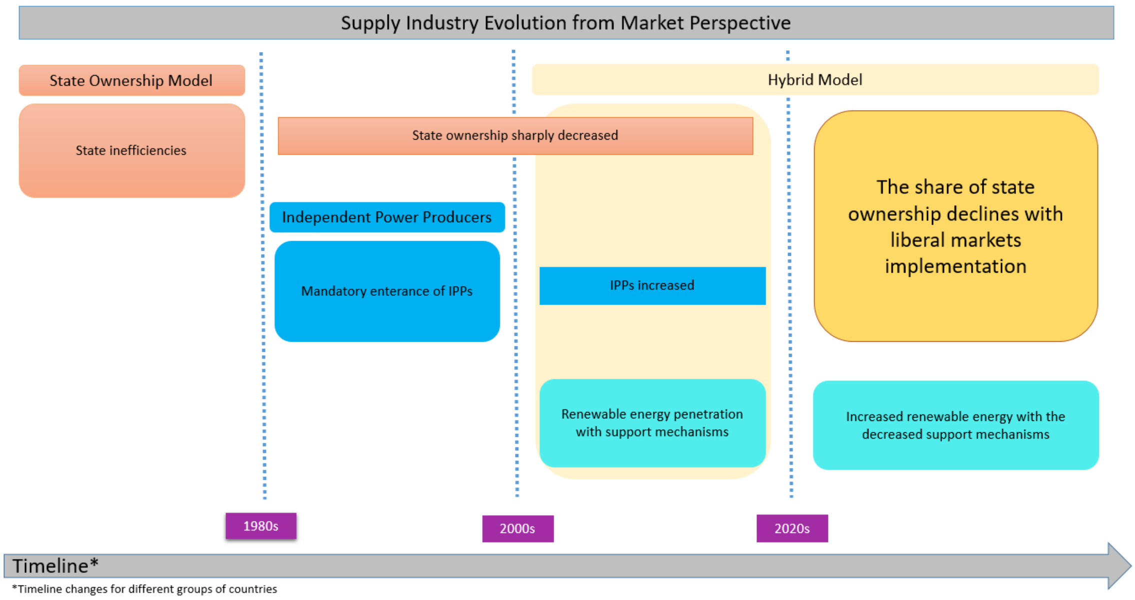

Figure 1: A Simple Representation of the Evolution of Supply Industry [7]

[7] The Figure was compiled by author via considering literature (e.g., Bacon and Besant-Jones, 2001; Kim and Kim, 2011; Streimikiene, 2013; Williams and Ghanadan, 2006; Jamashb, 2006; Krishnaswamy and Stuggins, 2003; Wilson, 2005). This public-private transformation is well known fact in the market.

As seen in Figure 1, the evolution of the supply industry determines the structure and workings of the electricity market. Until the 1980s, the government was the only owner in all segments of the electricity market due to a lack of a private sector model in most of the countries in the world. This vertical integration[8] caused low collection of bills, lack of new investment, cost-free price, poor governance, increased state budget deficits, and some exogenous poor macroeconomic factors (Danwitz, 2006; Williams and Ghanadan, 2006; Elizondo et al., 2014). These problems brought up sector reforms to decrease the cost of consumers, to utilize the profit motivation of companies, and to provide competition for sustainable efficiency.

After the 1980s, most governmentsused a variety of liberalization and privatization strategies. The order of the privatization was determined by the primary needs of the electricity industry and governments (Krishnaswamy and Stuggins, 2003; Bacon and Besant-Jones, 2001; Newbery and Pollitt, 1997; Wilson, 2005). In the privatization of the electricity market, three factors have emerged as important, beginning with the supply industry (Bacon, 1995). These factors are: the ease of financial accessibility (Bacon and Besant-Jones, 2001); the fragmented structure of generation (Gawlik & Mokrzycki, 2019); and the importance of increasing electricity generation costs in the electricity market. In the beginning, independent power producers (IPPs) were introduced in most of the countries (Ramírez-Camperos, 2013). Guarantee of purchase mechanisms, build-operate and build operate transfer models were used to initially implement IPPs. The governments design tool of with these models was the power purchase agreement. In power purchase agreements, generation investors capture the risk of fuel prices, material costs, labor costs, and unexpected plant failures. These long-run power purchase agreements reduce the risk for investors through inter-party risk sharing via closures and including force majeure conditions (Eberhard, 2014).

With the privatization of the markets, new investment flows have emerged. These investments have paved the way for research and development expenditures and technological advancements. The technological progress made during this process has not

[8] Vertical integration refers that the government holds exclusive responsibility for the generation, transmission, distribution, and retail of electricity to its customers (Mansur, 2007).

only enhanced conventional generation methods but also increased the utilization of renewable energy sources as an alternative. Renewable energy investments have become part of the electricity supply industry, which has led to a sharp decline in state generation share (Winkler, et al., 2016; Batalla-Bejerano and Trujillo-Baute, 2016). Renewable implementation has been done via auctions varying in risk allocations, bidding types, price changes, and transmission coordination. Recently, renewable penetration has continued with fewer support mechanisms and more aggressive renewable implementation policies.

Figure 2 depicts the supply industry's evolution with respect to resources. The resource composition of the supply industry affects the marginal cost of electricity and its price in the wholesale electricity markets. The share of high carbon thermal power plants that use coal and natural gas as inputs has declined in the supply industry in the last few years (Akashi and Hanaoka, 2012; Han et al., 2022; IEA, 2023). New electricity generation investments have transformed from high carbon resources to zero carbon renewables for the last fifty years. Implementing renewable energy plants using solar and wind has gained momentum with decreasing marginal costs and zero-carbon characteristics. However, renewable energy generation is instantaneously based on its resources' natural characteristics. This characteristic has caused fluctuations in wholesale electricity prices. The replacement of baseload thermal power plants with intermittent renewables has created not only price fluctuations but also new network constraints in the wholesale electricity markets. Therefore, the renewable dominance in wholesale electricity markets has not provided stable electricity generation.

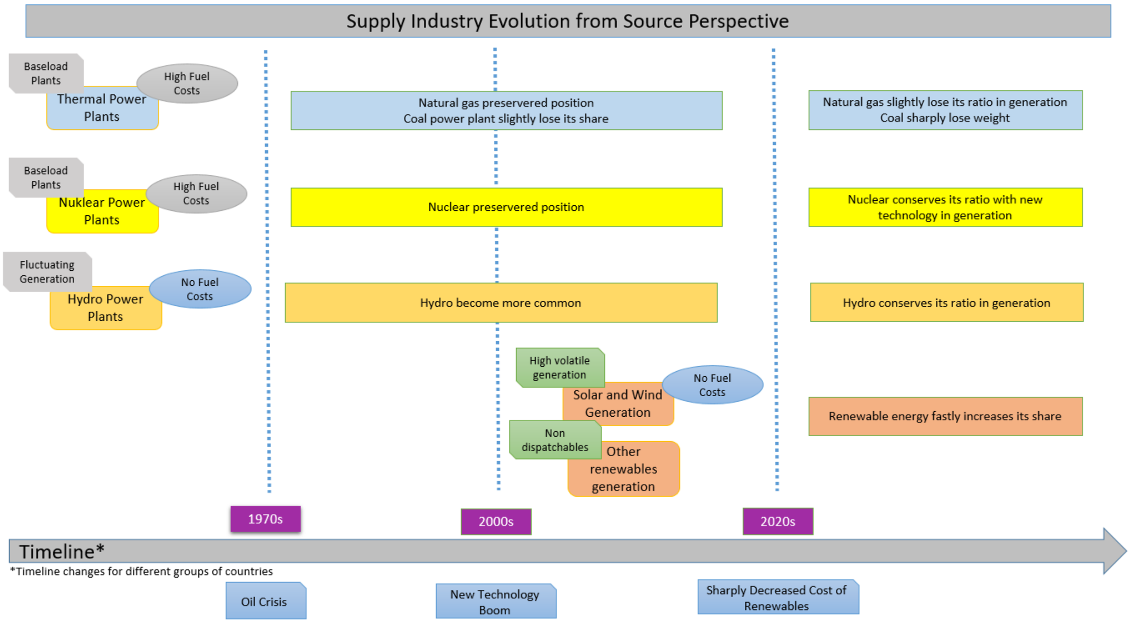

Figure 2: Supply Industry Evolution from Resource Perspective[9]

In addition to the transformation of the supply industry according to the resources it uses, the wholesale electricity market structure has also evolved. Figure 3 shows the emergence and evolution of the wholesale electricity market structure. Before 1980s generation, transmission, distribution, and retail markets were operated by governments. Some studies show this structure as the source of inefficiency as the states cross-subsidize between segments of the market (Roques, 2008a; Ibarra-Yunez, 2015; Wilson, 2005). Until 2000s, the market structure of the supply industry started to become a single buyer model in most of the world. State ownership was partly replaced by independent power producers (IPPs), while the only buyer was the government (Gratwick and Eberhard, 2008). The governments used an audit cost model to determine the marginal cost of electricity. Thus, the price of electricity was based on cost-based offers. The number of regions using independent power producers has increased. In 2000s, the wholesale electricity market's demand side is privatized. Free electricity trade was limited in wholesale electricity markets, and electricity prices were determined by bid-based offers.

[9] The Figure created by Author via using the database of International Energy Agency (IEA), https://www.iea.org/data-and-statistics.

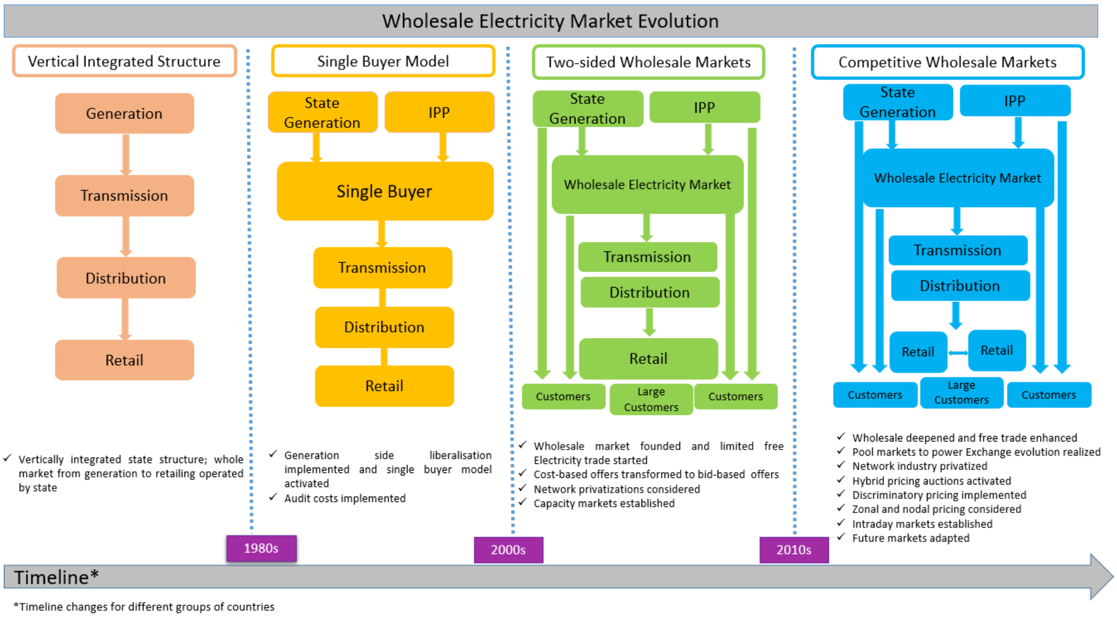

Figure 3: Wholesale Electricity Market Evolution[10] (Gratwick and Eberhard, 2008)

The wholesale electricity markets were redesigned in the 2010s in emerging economies Rudnick and Velasquez, 2018). In this period, capacity markets were implemented as a complement to energy-only markets and to support energy generation during peak demand periods. While market structures differ from one country to another, we can highlight a number of major developments (stepping stones) typical of most emerging economies. Among these, the introduction of reserve and balancing market is used to reduce inefficiencies and uncertainties in electricity markets (Wolak, 2021). Also, futures (options) markets have increasingly become an essential part of the electricity exchange as a tool to reduce risks. There have also been other new mechanisms to improve the efficiency of electricity markets, such as long-term contracts, etc. (Peng and Poudineh, 2019). The following Figure 4 provides a typical representation of wholesale electricity markets. It consists of generators, consumers, retail companies, market and system operators, and several sub-markets such as futures, day ahead, intraday, balancing, and reserve markets. The progress emerges toward a free-market structure to sustain electricity trade.

[10] Figure created by author via compiling Gratwich and Eberhard (2008).

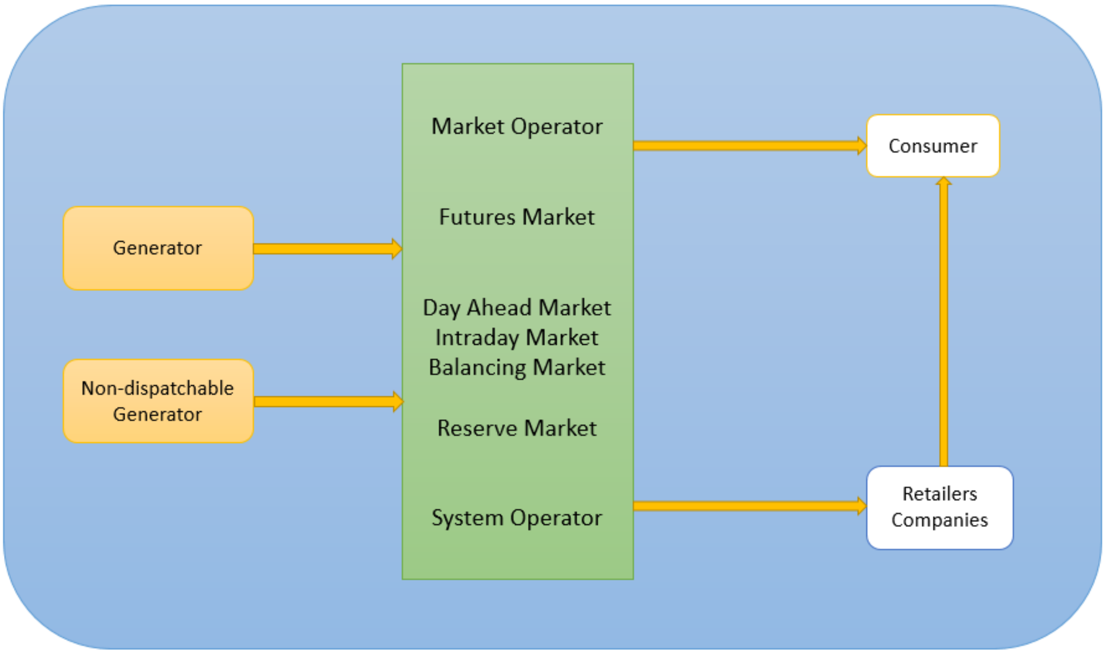

Figure 4: Final Structure of the Wholesale Electricity Market [11]

1.4. SUPPLY INDUSTRY PROBLEMS, THEIR INTERCONNECTEDNESS AND SOLUTIONS

This section discusses the basic problems of the supply industry from the perspective of wholesale electricity markets. Problems in the supply industry emerge in various segments. They have direct and indirect relationships between each other and other segments of the electricity market (Cetin and Oguz, 2007; Wolak, 2019). In the literature, electricity market problems are clustered by using many classifications. The most common one is the framework window classification (Sioshansi, 2008; Rudnick and Velasquez, 2018; Wolak, 2019). According to the Sioshansi (2008), Rudnick and Velasquez (2018), and Wolak (2019), the challenges and problems in industry which effects wholesale electricity market structure are legal framework, regulatory and institutional environment, market structure, and market rules.

The wholesale electricity market fundamentals are supply constraints, electricity grid (transmission and distribution included) congestion, and demand-side involvement. Electricity market segments excluding the supply industry are defined as governance and

[11] The figure was created by the Author compiling Hunt (2002) and Rudnick and Velasquez (2018), Kirschen and Strbac (2018).

regulation, network, and demand side. In a broad wide perspective, inefficient government and regulatory issues are followed by low financial viability and tariff problems, which distort the short-run and long run equilibrium in the wholesale electricity markets. Regulation, governance, and pricing problems are classified as inefficient regulation and governance, pricing, and the volatility of the market. In addition, network industry problems include operational inefficiency, missing money on the electricity network, and transmission congestions. Moreover, the demand-side problem is the inactive involvement of demand. These problems influence the supply industry's problems and the functioning of the wholesale electricity market. A large amount of literature provides theoretical explanations and empirical evidence for these problems, which are reviewed in this chapter.

The focus of the chapter is on problems in the supply industry that are related to other segments of the wholesale electricity markets. Supply-side problems are clustered into generation inadequacy, missing money, market power, and renewable intermittency. We categorize the wholesale electricity problems into four main branches: governance, supply, network, and demand, as shown in Figure 5.

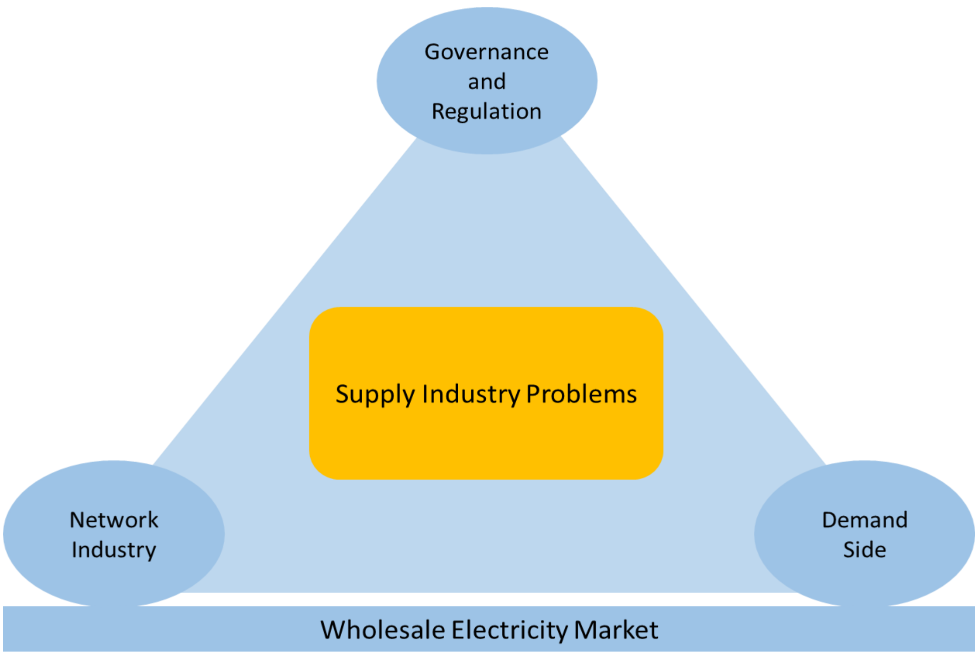

Figure 5: Supply Industry Problems in Wholesale Electricity Markets

On the one hand, governance problems are related to the market structure of electricity, which results in inefficiencies such as inefficient and volatile pricing in the wholesale electricity markets. Moreover, network problems arise from inefficient operations in the electricity grid, new grid investment problems, and capacity problems in the transmission of electricity. Another problem is the low level of consumer involvement on the demand side. To sum up, the main problems excluding the supply industry were listed as inefficient regulation and governance, inefficient pricing, volatility of the market, operational inefficiency, transmission congestions, missing money at the network, and inactive involvement of demand. Problems in the supply industry stem from the lack of new generation investment, inappropriate government planning, monitoring inadequacy in the industry, and the effects of technological evolutions. They are called generation inadequacy, missing money, market power, and intermittent renewables.

A brief summary of the relationship between supply industry problems and other segments of the wholesale electricity market is shown in Figure 6. In the following sections, we explain the problems in the supply industry with their causes, consequences, and solutions in detail.

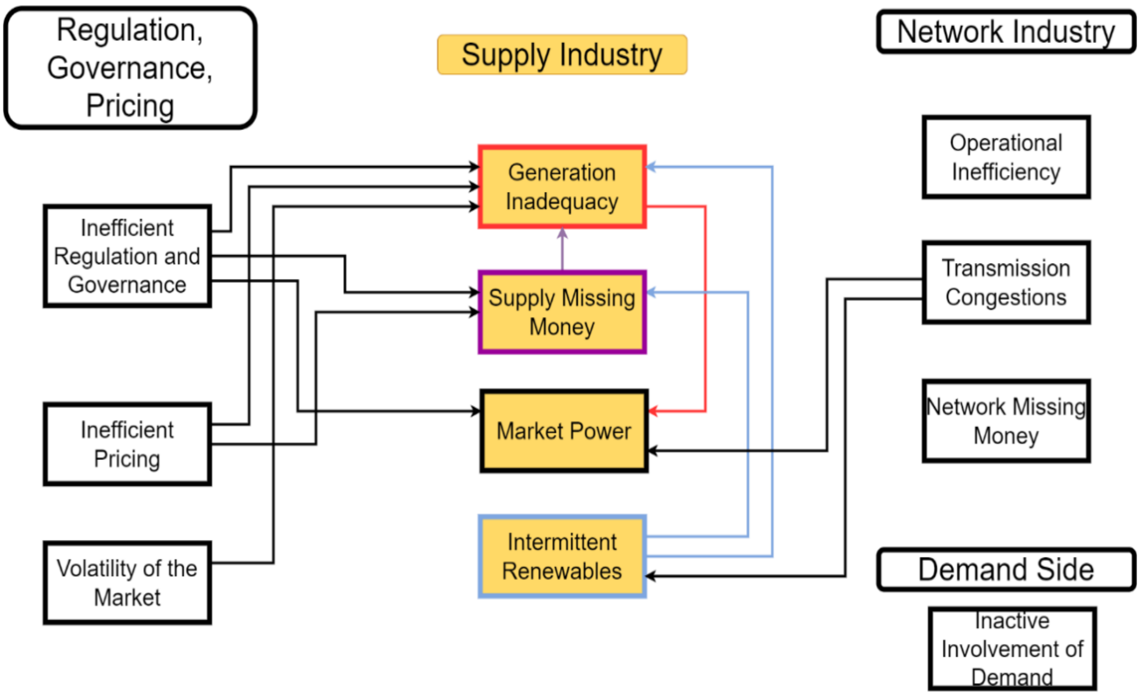

Figure 6: Summary of Causality Relations

1.3.1. Generation Inadequacy

The supply industry consists of private and public generation companies that are located on the electricity grid. Instantly, the system operator aims to achieve supply-demand equilibrium for every time slot. Therefore, the supply industry's main goal is to continuously meet electricity demand. However, it is not always the case. The situation in which electricity demand has not been met by the supply industry is called generation inadequacy in the electricity market (Bushnell, 2005). Main resource inadequacies are a lack of generation units (Bacon and Besant-Jones, 2001), a low level of generation capacity factors (Wolak, 2003), and shortages due to fluctuations in renewable energy resources (Winkler et al., 2016).

Generation inadequacy is widely accepted as a major supply side problem in the wholesale electricity market. In Figure 7, the causes (inflows) and consequences (outflows) of the generation inadequacy problem are shown as a summary of the literature. Generation inadequacy comes from inefficient regulation and governance ($B_{IRG\text{->}GI}$), inefficient pricing ($C_{IP\text{->}GI}$), volatility of the market ($D_{VM\text{->}GI}$), intermittent renewables ($L_{IR\text{->}GI}$), and supply missing money ($A_{SMM\text{->}GI}$).

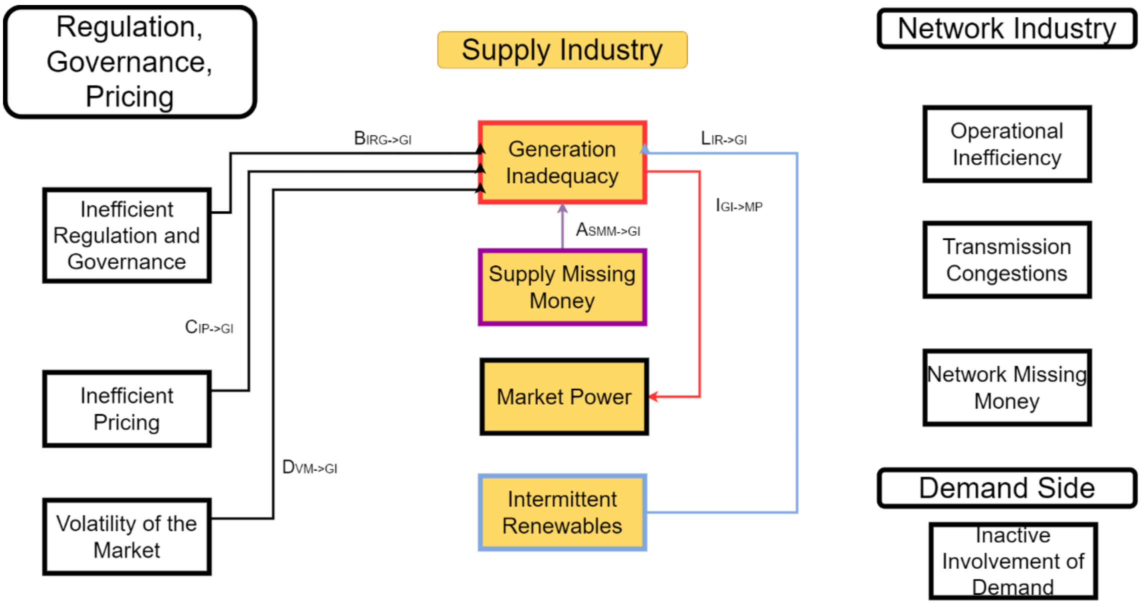

Figure 7: Problem Chart of Generation Inadequacy

Due to high initial investment costs and long payback times, generation plant investments are more difficult to realize than other investments (Joskow, 2008; Ibarra-Yunez, 2015). Roques(2008a) focuses on generation capacity, reliability of supply design, and optimization of investments. In the supply industry, investors would prefer foreseeing the possible rate of return of new power plant investments. However, false price signals and insufficient public incentive interventions create difficulties in doing so (Wolak, 2003; Kessides, 2013). On the other hand, investment security problems are experienced in wholesale electricity markets where there is excessive public intervention (Ibarra-Yunez, 2015). In addition to inefficient pricing, high price volatility in the wholesale electricity market might also result in an increase in generator (and consumer) losses both in the short term and in the long term. Due to all these problems, generation plant investments fall short of preventing generation inadequacy problems.

As shown in Figure 7 ($B_{IRG->GI}$), Borenstein (2002), Toba (2007), Sioshansi (2008), Gratwick and Eberhard (2008), Roques (2008b), Diaconu et al. (2009), Battle and Rodilla (2010), Malgas and Eberhard (2011), Ela et al. (2016), Grubb and Newbery (2018), and Rudnick and Velasquez (2018) use descriptive statistics to explore the generation adequacy problem and emphasize the importance of market design, market rules, and inefficiency. These studies reveal that the generation inadequacy problem mostly emerges from governance, market reform, state ownership, and regulation issues (e.g., Woolf and Halpern, 2001; Newbery, 2002a; Bacon and Besant-Jones, 2001; Shuttleworth, 2002; Borenstein, 2002; Rudnick and Montero, 2002; Krishnaswamy and Stuggins, 2003; Williams and Ghanadan, 2006; Joskow, 2008; Diaconu et al., 2009; Malgas and Eberhard, 2011; Ibarra-Yunez, 2015). Studies investigate the US, the UK, Europe, Latin America, and developing countries for different time periods and highlight the importance of independent regulation and good governance, while Shuttleworth (2002), Krishnaswamy and Stuggins(2003) focus on tailored (country-specific approach) market reforms to solve the generation inadequacy problem for Central Asia, Europe, Georgia, Sri Lanka, and Vietnam between 1990 and 2013. Furthermore, many studies find that state ownership in the supply industry is another reason that creates generation adequacy problems (Newbery, 2002a; Borenstein, 2002; Rudnick and Montero, 2002; Wolak, 2003; Joskow, 2008; Kessides, 2013; Ibarra-Yunez, 2015). Many studies find that strong government intervention in wholesale electricity markets ends up with generation inadequacy

(Newbery, 2002; Shuttleworth, 2002; Rudnick and Montero, 2002; Gratwick and Eberhard, 2008; Malgas and Eberhard, 2011). Wolak (2003), Joskow (2008) study finance insufficiency at the state ownership domination in the supply industry by analyzing US and Latin American countries such as Argentina, Brazil, and Chile for 1985-2005.

Furthermore, $C_{IP\text{->}GI}$ in Figure 7 shows that inefficient pricing is one of the major contributors to the generation adequacy problem. Low prices in the wholesale electricity markets harm the investment climate and hinder new investment in the supply industry (Bacon and Besant-Jones, 2001; Wolak, 2019; Krishnaswamy and Stuggins, 2003). This causes generation inadequacy challenge in the market. Volatile prices also create uncertainty in the wholesale electricity markets (Roques, 2008a; James Bushnell et al., 2017). This situation creates varying returns in the market that damage new generation plant investments. Moreover, over-regulated prices and government interventions in market clearing prices produce unreliable wholesale electricity markets. Due to this uncredible regulatory climate and therefore a low level of investment, supply adequacy emerges (Wolak, 2003; Rudnick and Velasquez, 2018; Sioshansi, 2008).

The literature also suggests that volatility in the market hinders investment and causes generation inadequacy ($D_{VM\text{->}GI}$) (Borenstein, 2002; Woo et al., 2006; Higgs and Worthington, 2008; Kalantzis and Milonas, 2013). Borenstein (2002) focuses on the California crisis to analyze its effects on the electricity market volatility by using descriptive statistics from 2000 for the US. Higgs and Worthington (2008) apply the mean-reverting and regime-switching models by using Australian data between 1999 and 2004 and find that electricity markets suffer from high prices. The study concludes that generation inadequacy emerges from volatility. Kalantzis and Milonas (2012) state that low maturity with high volatility supports generation inadequacy by considering France's and German's wholesale electricity markets in 2009 with VECM and GARCH models.

These result in missing money and investment problems. As seen in Figure 7, $A_{SMM\text{->}GI}$ missing money problem brings out generation inadequacy. Inefficient pricing also triggers missing money and investment security problems, which are experienced in wholesale electricity markets where there is excessive public intervention. In the wholesale electricity market, the government intervenes in the market with price ceilings and state-owned plants' supply bids. Joskow (2008), Battle and Rodilla(2010), Newbery(2015), Grubb and Newbery(2018) state that missing money problems result in generation inadequacy by using descriptive statistics and focusing on the UK and US.

In recent years, renewable penetration in the supply industry has changed the paradigm in wholesale electricity markets. As shown in Figure 7, renewable intermittency provokes generation inadequacy ($L_{IR\text{->}GI}$). De Sisternes et al. (2015), Batalla-Bejerano and Trujillo-Baute (2016), Winkler et al. (2016), Pollitt and Anaya (2016), Aghaie (2016), Wolak (2021) study the relationship between renewable energy and generation inadequacy and find a direct casual relationship between intermittent renewables and generation inadequacy for the last 10 years. Rudnick and Velasquez (2018) emphasize the negative effect of renewable resources on supply adequacy for developing countries.

The literature proposes capacity markets and independent power producers to overcome the generation inadequacy problem. Capacity markets are founded to fight against instantaneous demand peaks and generation shortages (Wolak, 2021). Capacity markets divide into groups according to the mechanism they use to set capacity prices and amounts. In one group of capacity markets, the regulator sets a capacity price and lets the market determine the amount of capacity. In the other group of capacity markets, the regulator sets the amount of capacity that has to be available and lets the market determine its price (Roques, 2008a). Several studies discussed how implementing capacity markets mostly solves the generation adequacy problem for the US (2007, 1972-2016), UK (1996-2001), Spain (1996-2001), and Nordpool (1996-2001) (e.g., S. Littlechild, 2000; Toba, 2007; Rudnick and Velasquez, 2018).

Most of the literature, including Borenstein (2002) for the US in the period 1999-2001; Kessides (2013) for Pakistan in the period 2004-2010, Ibarra-Yunez (2015) for Mexico, focuses on independent power producers to solve generation inadequacy problems. Independent power producers attract private investment to develop the electricity supply industry. The transformation from state-dominated generation to a more private dominated supply side solves market power and pricing problems by supporting competition in the market. Toba (2007) emphasizes the enhacement of competition using sensitivity analysis for the Phillippines between the 1990 and 2010 periods.

1.3.2. Missing Money at Supply

The supply industries in the electricity markets need to enhance their capacities to meet continuously increasing demand. However, they have several features that discourage new investments. For instance, profit margins are low and electricity prices are volatile, which makes new investments difficult. The missing money problem is the low return of investment money, which could not be matched with energy prices in the wholesale electricity market. Inefficient pricing and fluctuations in renewables increase the uncertainty in the electricity market, which brings out the missing money problem in the supply industry.

Therefore, the literature discusses the missing money problem by classifying the supply industry of the wholesale electricity market. Figure 8 shows the findings of the literature by showing the causes (inflows) and consequences (outflows) of missing money problems. On the one hand, the missing money problem stems from inefficient regulation and governance (FIRG->SMM), and inefficient pricing (EIP->SMM), intermittent renewables (GIR->SMM). On the other hand, the missing money problem results in generation inadequacy ($A_{SMM->GI}$).

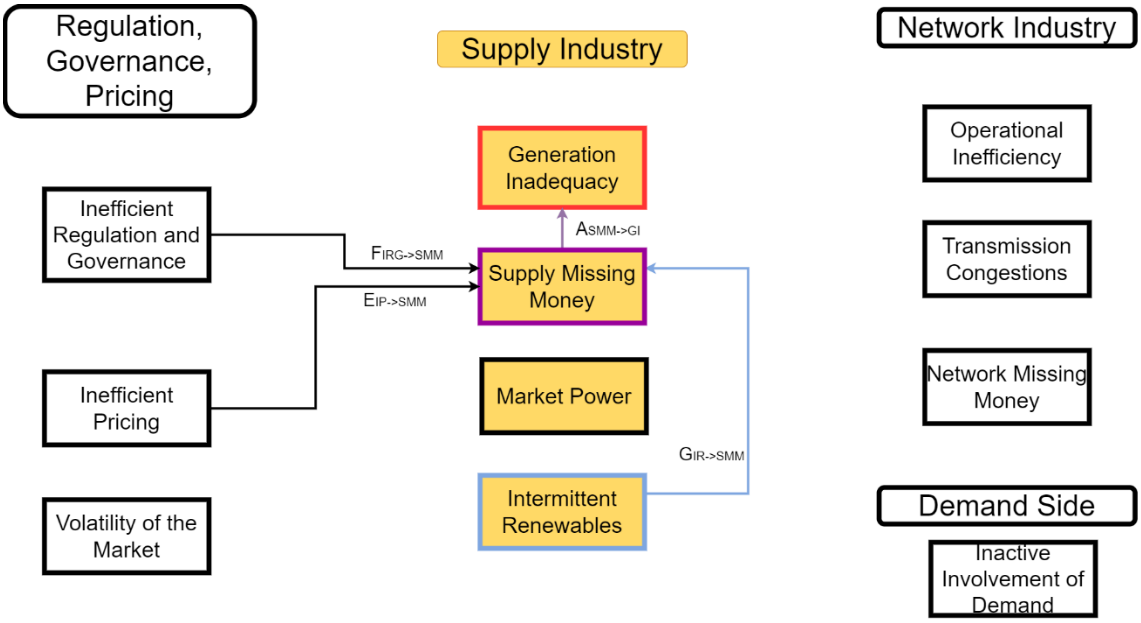

Figure 8: Problem Chart of Missing Money

In this paragraph, we will address these connections in more detail. Inefficient regulation and governance cause supply missing money problems (FIRG->SMM). Regulatory and political issues are very important to determine the short-run equilibrium of supply-demand and capacity requirements for the long-run system reliability (Newbery, 2015; Wolak, 2019). For instance, governmental interventions such as price ceilings (if price ceilings are set too low, below the Value of Lost Load, VoLL), might reveal missing money problems through a decrease in the return on investment (Pollitt, 2004). Ibarra-Yunez (2015) focuses on expected earnings as an indicator of this problem. The problem of missing money arises if the revenue is insufficient. (Joskow, 2011). Yet, there is a "missing market" problem if generation companies or their funders do not believe it to be adequate (Newbery, 1989). If ancillary services, such as flexibility and black start capability, are not sufficiently compensated, the problem of missing money can occur. (Pollitt, 2004).

Inefficient pricing is another cause of the missing money problem ($E_{IP\text{->}SMM}$). Even though Pollitt (2004) states that inefficiently low energy prices lead to a missing money problem, Newbery (2015) considers it unlikely, even when there is excess capacity. Rather, they might be above their competitive level. Inefficiently low energy prices yield generation inadequacy besides the missing money problem. To solve the generation inadequacy problem, the system operator might set energy prices above the marginal costs at a level that at least covers the generation units' fixed costs while the installed capacity of the system is fully used. This is called scarcity pricing. However, scarcity pricing, in turn, causes the missing money problem. This is because a lack of demand-side response, short-term reliability management procedures, and inefficient ancillary service procurement often undermine scarcity pricing and distort long-term investment incentives (Roques, 2008b).

Newbery(2002b), Roques(2008a), Shuttleworth (2002), and Littlechild (2000) emphasize that inefficient pricing provokes missing money at the supply and network sides ($E_{IP->SMM}$). Europe (1991-2000), the US (1999-2001), the UK (1999-2001, 1996-2001), Latin America (1990-1999, 1985-2005), and Nordpool (1996-2001) were analyzed with several methods such as descriptive statistics and non-linear optimization. These studies find that investments could sustain efficient short-run and long run equilibriums.

Intermittent renewables induce supply missing money problems via distorting stable prices ($G_{IR->SMM}$) (Newbery, 2015; Papalexopoulos et al., 2015; Hildmann et al., 2015; Winkler et al., 2016; Grubb and Newbery, 2018). Grubb and Newbery (2018) and Hildmann et al. (2015) focus on the generation volatility of renewable plants and their dominance in the supply industry with descriptive statistics. In addition, Papalexopoulos et al. (2015) and Winkler et al. (2016) propose wholesale market models for Europe and the US with intermittent renewables, and they find evidence of the missing money problems in the case of intermittent renewables by employing the non-linear simulation models.

Several studies suggest capacity markets with well-designed energy only markets to solve missing money problems (Joskow, 2008; Newbery, 2015; Papalexopoulos et al., 2015; Newbery, 2016; Grubb and Newbery, 2018; Duan et al., 2018; Woo et al., 2019). Joskow (2008), Grubb and Newbery (2018) focus on the UK via descriptive statistics and simulation models for 2007-2017 and find that self-tailored capacity markets fully remove the missing money problem. In addition, Newbery (2015), Newbery (2016), McKenna et al. (2018), and Woo et al. (2019) state the importance of implementing of capacity markets via analyzing Europe with descriptive statistics and nonlinear optimization for Europe. However, Neuhoff et al. (2013) point out that capacity auctions tend to overprocure capacity, which exacerbates the missing money problem.

Along with capacity markets, the literature offers scarcity pricing and market-oriented designs as solutions to the missing money problem. Ela et al. (2016) state that scarcity pricing in energy-only markets might help revenue be sufficient, which addresses the missing money problems. Market-oriented wholesale electricity market designs might mitigate missing money problems in supply industries (Batlle and Rodilla, 2010; Joskow, 2008; Woo et al., 2019; Winkler et al., 2016). Market-oriented solutions mean fewer governement interventions and a more deregulated structure. Therefore, the wholesale electricity market determines the equilibrium price and quantity. Battle and Rodilla (2010) and Joskow (2008) state that government intervention and over-regulated structures make the market inefficient; therefore, increasing market-oriented rules creates more sustainable and efficient wholesale electricity markets. Papalexopoulos et al. (2015), Simshauser (2019), Battle and Rodilla (2010), Grubb and Newbery (2018), Woo et al. (2019) use simulation models, central optimization for Europe, the UK, and the USA, and they find that profit and revenue optimizations in the market solve the missing money problem.

1.3.3. Market Power

Market power is the main barrier to competition by creating inefficient prices. There are three types of market power: local, temporal, and pervasive. Firstly, local market power arises from insufficient transmission lines, or, in other words, transmission congestion. Secondly, temporal market power emerges from the lack of new investments and insufficient generation. Thirdly, if a generator continuously affects prices as a pivotal supplier, this generator is said to have pervasive market power. According to Wolak (2009), a supplier who exercises all of its available unilateral market power while adhering to market rules is equivalent to a supplier who takes all legal steps to maximize its wholesale market profits. The management of the firm also has a fiduciary duty to its shareholders to take all legal steps to maximize the profits that the firm earns from participating in the wholesale market.

As indicated, market power is one of the supply-side problems that is emphasized in the wholesale electricity market literature. Figure 9 shows the causes (inflows) and consequences (outflows) of market power problems that the literature has provided so far. Market power emerges from inefficient regulation and governance ($H_{IRG\text{->}MP}$), generation inadequacy ($I_{GI\text{->}MP}$), and transmission congestion ($J_{TC\text{->}MP}$).

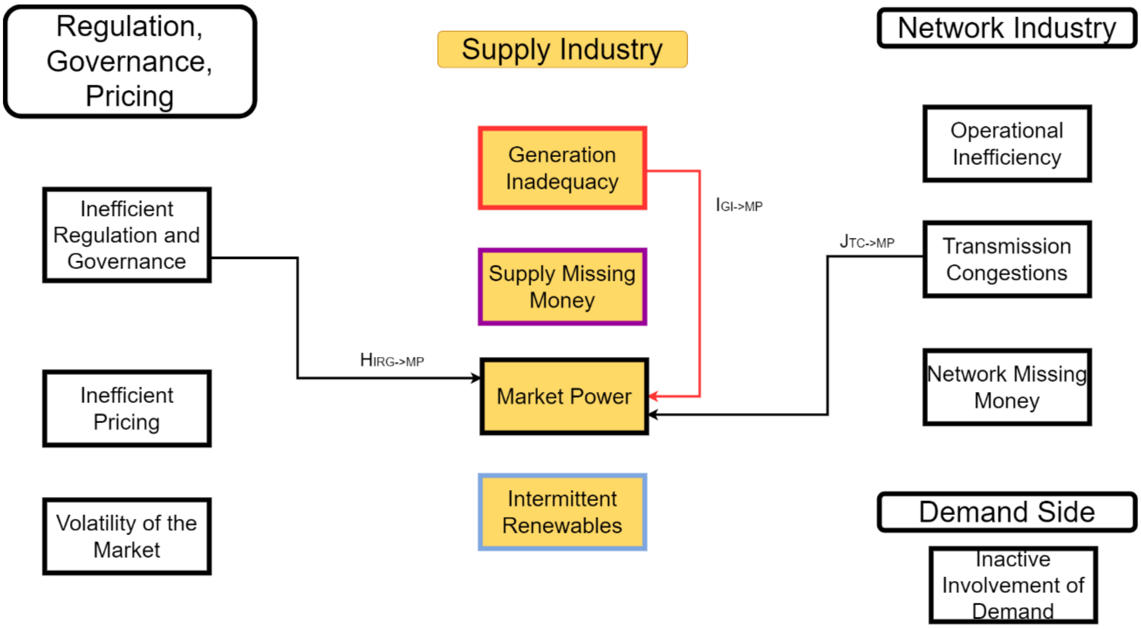

Figure 9: Problem Chart of Market Power

In this paragraph, we will address these relationships in more detail. A fully deregulated market structure (full market opening) and a deregulated structure bring out market power ($H_{IRG\text{->}MP}$). It provokes high and inefficient prices due to the profit-maximizing targets of the suppliers. Newbery(2002a) and Newbery(2002b) theoretically discuss the regulation's effect on volatility by considering the California crisis. This volatility makes the market uncertain, hinders new investment, and causes some agents to crash. Borenstein et al. (2003), Woo et al. (2006), and Wolak (2014) discuss the policy transformation of the UK, US, and Europe and state that bad governance destroys the district wholesale electricity market with several mechanisms such as auctions, bidding, and intervention. Market power occurs and binds market development.

Generation inadequacy with incompetent spot markets and inadequate long-term contract design causes market power ($I_{GI\text{->}MP}$). Newbery(1998a) studies the UK with the cournot model, Wolak (2000) focuses on the UK and US with descriptive statistics, Wilson (2005), Newbery (2002b), Newbery (2002a) analyze transmission, transaction costs, state ownership, and market crises for the US, UK, Latin America, and New Zealand, and they find that market power mostly emerges from generation inadequacy. Generation concentration, regulation dynamics, and long-term contracts are the minor determiners of market power in addition to generation inadequacy (Newbery, 2002a; Evans and Green, 2003; Wolak, 2005; Sioshansi, 2008; Diaconu et al., 2009; Wolak, 2009; Bushnell et al., 2017; Wolak, 2014; Bushnell et al., 2004; Bushnell et al., 2002).

As indicated in Figure 9, transmission congestion is a common problem in the market that provokes market power ($J_{TC\text{->}MP}$). Shuttleworth (2002), Newbery(2002a) Newbery (2002b), Wolak (2009), Ryan (2012), Bushnell and Saravia (2022) analyze the effect of transmission congestion with descriptive statistics and theoretical discussions and state that the inadequacy of the network brings out an uncompetitive structure in the wholesale electricity markets. For example, a generator that has a high network capacity to reach consumption points could easily create market power. In high-demand hours, network conditions might push limited network capacity generation units out of bounds. Therefore, the system has to sustain its electricity from the power plant, which exercises market power.

A well-functioning supply industry that has adequate generators, a competitive wholesale market, and a robust network can prevent market power issues. Several scholars such as Newbery (1998a), Chao and Wilson (2001), Wolak (2005), Diaconu et al. (2009), Ryan (2012), and Wolak (2019) propose a variety of strategies to reduce the incentive for suppliers to exercise unilateral market power. Wolak (2019) proposes five strategies for market designers, including dividing capacity owned by one firm among multiple independent suppliers, issuing fixed-price forward contracts to multiple suppliers to supply electricity to load-serving entities, involving final consumers as active participants in the wholesale market, ensuring the transmission network has adequate capacity to provide competition among suppliers, and regulating the wholesale market to incentivize all participants to meet their contractual obligations and follow market rules.

Future market implementation and well-functioning market monitoring hinder market power potential (Wolak, 2000; Bushnell et al., 2017; Wolak, 2019). Bushnell et al. (2017) state that forward commitment contracts between retail and generation increase the competitive performance of the electricity markets. Adib and Hurlbu (2008) emphasize the independence of the regulatory authorities and the monitoring of the electricity markets. Market monitoring consists of daily, long-term, and operational components. Bushnell et al. (2002) present the metrics of the electricity markets as the benchmark. Pivotal bidding analysis, oligopoly simulation, and the Herfindahl Hirschman index are the basic methods to monitor market concentration and market power indicators. In addition, investigating market power abuses is another critical issue in market design. System operators' actions, such as short-term load forecasts, ancillary services, and congestion management, are continuously monitored. Market monitoring is a critical prerequisite to mitigation (Adib and Hurlbu, 2008; Wolak, 2009).

1.3.4. Intermittent Renewables

The main renewable energy sources are hydro, wind, solar, and other sources. They cannot be used to produce energy on a continuous basis, like baseload power plants. Rather, the output of renewable power plants focuses on certain hours. The concentration varies depending on the type of source. For instance, weather conditions such as rainfall have a direct impact on the generation capacity of the hydropower plant (Wolak, 2003). The problem of discontinuous generation of renewable power plants is called intermittent renewables in the literature.

The problem of intermittent renewables is mostly classified as the supply industry of the wholesale electricity market in the literature. Figure 10 shows the causes (inflows) and consequences (outflows) of intermittent renewable energy problems that the literature has provided so far. Intermittent renewable problems emerge from transmission congestions ($K_{TC->IR}$) and intermittent renewables cause generation inadequacy ($L_{IR->GI}$), and supply missing money ($G_{IR->SMM}$).

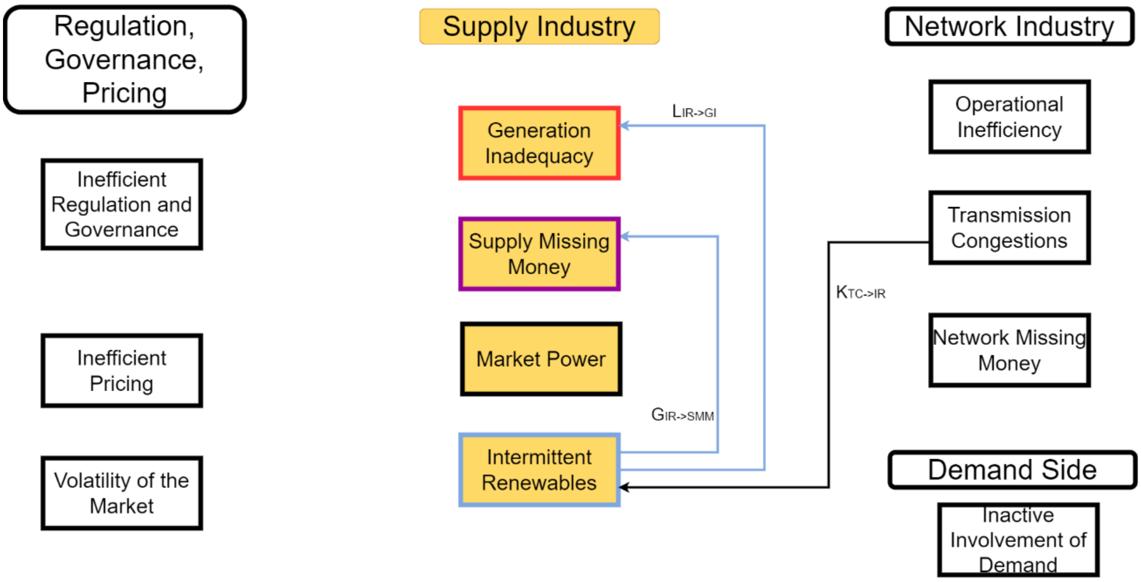

Figure 10: Problem Chart of Intermittent Renewables

In this paragraph, we provide an outline of the connections between problems that give way to intermittent renewables. In the following section, we will elaborate on these relationships. First, the output of renewable power plants is volatile. Along with it, the purchase guarantees that the states provide as an incentive create a market distortion. In addition, renewable power plants require a large amount of investment in the network, which also reduces the efficiency of renewable energy in the wholesale electricity market. Rudnick and Velasquez (2018) emphasize the generation volatility and high price effects of renewable generation plants. They also weaken new investments in wind and solar generation plants. Wolak (2019) states that renewable generation plants’ capacity factors are far below those of other baseload generation plants. Therefore, intermittent renewable generation and capacity problems occur in the electricity market.

Inadequacy of the transmission grid (transmission congestion) that cannot transmit low-cost generation to consumption locations leads to negative effects of intermittent renewables in the market ($K_{TC->IR}$). Azuela et al. (2014), Politt and Anaya (2016), Keay et al. (2016), Grubb and Newbery (2018), Leslie et al. (2020) use descriptive statistics and demonstrate transmission congestion enhancing mechanisms for renewable energy implementation in wholesale electricity markets by considering pricing methods. Varying generation characteristics of renewables merge with transmission constraints and increase the harm to the system from supply-side problems.

Renewable implementation in well-organized wholesale electricity markets and balanced network design solves intermittent renewable problems for sustainability (Elizondo et al., 2014; Perez-Arriaga and Batlle, 2012; Batalla-Bejerano and Trujillo-Baute, 2016; Politt and Anaya, 2016; Keay et al., 2016; Grubb and Newbery, 2018; Leslie et al., 2020). Azuela et al. (2014) claim that local planning in the grid decreases the volatility effect of renewables. Therefore, regional pricing and planning are mandatory in the high renewable penetration system (Politt and Anaya, 2016). Regional planning directs supply and demand investments to the correct locations. For example, if a region's price is high, then supply-side investments will increase and demand-side investments will decrease in this region. Vice versa is also correct. In this situation, the market solves its pricing, supply, and demand problems through its dynamics.

On the other hand, according to Newbery (2015), letting wind and solar power plants generate electricity on the grid provides flexibility that could make renewable generation continuous.

1.5. CONCLUSION

In this chapter, we discuss the emergence, relationships, and solutions of the supply industry problems in the wholesale electricity markets by reviewing the related literature. First, we classified supply industry problems into four problems. One of them is the missing money problem, which is the oldest problem in the electricity markets. It is defined the insufficient investments over generations due to low returns in the long run. The second problem is the generation adequacy problem, which is considered the main problem on the supply side. The supply iadequacy problem arises when electricity demand cannot be met by the supply industry. The third problem is market power, which stems from insufficient transmission lines, a lack of new investments, insufficient generations, and the existence of pivotal suppliers. The last problem is the intermittency problem of renewable energy, which occurs because of the discontinuous electricity production of renewable plants.

Then, we revealed the direction of relationships and transitions between major supply industry problems based on the literature review. By considering these relationships, this chapter focused on the functioning of the wholesale electricity market from the perspective of the supply industry. Our findings indicate the complex relationship between supply industry problems and the wholesale electricity market. We found multidimensional relationships between problems that the literature discussed. In addition, the identified findings will offer two important contributions to market participants. One of the contributions of this chapter is the policymaker's potential to establish a comprehensive and inclusive policy in the policies they will formulate in the future. Secondly, due to the comprehensive perspective of the policymaker, the market will operate more efficiently, thereby enhancing market efficiency and effectiveness for private sector actors.

Next, we presented the solutions to each supply industry problem introduced by the literature. This chapter shows that the solutions are also linked to each other. In particular, multi-factorial solutions, such as market-oriented design and effective regulations, increase market efficiency in the wholesale electricity market. Moreover, less government intervention, more private ownership, and more liberal markets are also offered in the literature to lead a sustainable and competitive market. The literature review also shows that transparency, liquidity, and predictability with future markets solve the majority of the problems in the supply industry. Furthermore, as a new generation market-oriented solution, capacity markets create more competitive pricing mechanisms. Finally, efficient network design also hinders supply industry problems.

The characterization of fundamental problems in the supply industry in wholesale electricity markets opens the door to more empirical work that would consider these problems as part of an integrated market structure. Similar to the supply industry, network industries, governance, regulation, and demand side problems can be considered. This might unveil the intricate issues in the wholesale electricity markets that have remained unexplored so far.

CHAPTER 2

THE IMPACT OF RENEWABLE ENERGY GENERATION ON MARKET CLEARING PRICE: A PANEL DATA ANALYSIS FOR EUROPEAN COUNTRIES

2.1. RENEWABLE ENERGY IN EUROPE

The progress of renewable energy has continued to escalate alongside recent developments in the past few years. The introduction of renewable energy into the energy mix through support schemes such as Feed-in-Tariff[12], Feed-in-Premium[13], and Contract for Difference[14] has made it more advantageous in terms of investment compared to conventional power plants (Kristiansen, 2004; Clo et al., 2015; Ciarreta, 2017). The use of support schemes increases costs and tariffs. The costs associated with purchase guarantees formed by the mechanisms of Feed-in-Tariff, Feed-in-Premium, and Contract for Difference are collected from consumers through tariffs. As a result, the price formation becomes detached from reflecting the actual costs.

The impact of renewable energy on market clearing prices shapes the bid strategies[15] of other electricity generators. The increase in renewable energy generation, driven by support schemes and policies, is causing a transformation in the structure of the electricity supply industry. Coal and natural gas power facilities, which have traditionally dominated the market, are modifying their bidding strategies. In this context, low-cost renewable power plants shift the supply curve in the right direction, while coal and natural gas power plants revise their offers at different times and periods based on the generation level of renewable power plants. The bid strategies of coal and natural gas power plants vary

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[12] Feed-in Tariff is a policy that guarantees generators of renewable energy sources a price above the market clearing price. (Cointe and Nadai, 2018).
[13] Feed-in Premium: the electrical energy generated from renewable energy sources is sold within the electricity spot market, with renewable energy sources generators receiving an additional premium on their electricity generation that exceeds the prevailing market clearing price (Xydis and Vlachakis, 2019).
[14] Contract for difference is a subsidy model that involves compensating the contractual partner for both positive and negative deviations from market clearing price. In this arrangement, if the actual price differs from the market clearing price, the electricity supplier receives payments to offset those deviations.
[15] Bid strategies of generators consist of quantity and price of the offer.

(Koschker et al., 2016; Ciarreta et al., 2017; Gugler et al., 2019). Coal and natural gas power plants seek to maintain their position in the merit order and continue generating electricity by lowering their offer price during peak renewable generation hours. Conversely, coal and natural gas sources increase the market clearing price during hours when renewable generation is low. Therefore, this situation leads to inefficiency in coal and natural gas power plants by causing them low level of returns. On the other hand, the fluctuations in market clearing price may lead to lack of investment in the long term.

Empirical findings on the impact of renewable energy on electricity prices do not provide a clear information as they vary depending on the period and relevant market (Mulder and Scholtens, 2013; Rintamaki, 2015; Ciarreta et al., 2017). These empirical studies are generally conducted for individual countries. Therefore, it is challenging to observe the overall movement of the market clearing price. The changing generation mix[16] accompanies the increasing use of renewable energy, and it causes fluctuation on the market clearing price in the electricity market. Therefore, a systematic approach with specific principles should be followed when integrating renewable energy into the system.

In this chapter, we investigate the European experience more closely in order to see the effects of renewables on market clearing prices in a large and well-established market. It is crucial to briefly emphasize the perspective of the European Union acquis on the issue since it encompassed European countries. The rationale behind choosing European countries for this chapter stems from the substantial growth in renewable investments observed in Europe as well as the presence of well-established and competitively organized markets within these European nations. The European Union has set ambitious goals to reduce greenhouse gas emissions by 55 percent by 2030 and achieve climate neutrality by 2050. In line with these goals, the Renewable Energy Directive[17] and the European Green Deal[18] have been enacted. Over the past decade, the energy sector in

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[16] Changing Generation mix refers to transformation of power plants from coal and natural gas to renewable energy sources.

[17] The Renewable Energy Directive serves as the official structure for promoting the growth of renewable energy in every sector of the European Union's economy. It facilitates collaboration among EU nations to foster the use of clean energy sources (https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en).

[18] In 2019, the European Commission approved the European Green Deal, which encompasses a series of policy initiatives aimed at achieving climate neutrality in the European Union by 2050 (Siddi, 2020). This

Europe, which is responsible for 75% of carbon emissions, has attracted notable attention (Dai et al., 2022). There has been an increase in electricity generation from renewable energy sources in Europe, supported by climate change targets and support schemes. The renewable energy share in electricity generation was 21.8% in 2019, and the target for 2030 is set at 42.5%.

There are numerous studies focused on European countries in the literature. They vary in terms of countries, periods, and methods used. Figueiredo and Silva (2019) investigated Spain for the period 2008-2017. Their study, which analyzed the Spanish wholesale electricity market using the GARCH model, demonstrates that renewable energy reduces the market clearing price through the merit order effect[19]. Castillo and Victoria (2015) tested the merit order effect in Spain for the year 2010. They found that the increase in renewables had a price-lowering effect and highlighted that it resulted from the Feed-in-Tariff support scheme implemented in the background. Similarly, Ballester and Furio (2015) and Ciarreta et al. (2017) researched the merit order effect in Spain for the period 2001-2013. Ciarreta et al. (2017) constructed a synthetic supply curve, while Ballester and Furio (2015) used OLS regression. Both studies found a price-lowering effect of renewable energy. Thanks to the Feed-in-Tariff support scheme, Spain's electricity production has shifted from combined cycle power plants to renewable power plants, thereby generating the merit order effect.

Hildman et al. (2015) employed a similar synthetic supply curve approach to analyze Germany and Austria for the period 2011-2013, showing that renewable energy lowers prices through the merit order effect and emphasizing the importance of the feed-in-tariff support scheme. Paraschiv et al. (2014) found similar results of the merit order effect for Germany using a dynamic fundamental model for the period 2010-2013. Clo et al. (2015) studied Italy for the period 2005-2013, using OLS regression to examine the merit order effect in Italy with the feed-in-premium support scheme. Although Italy, Spain, and

comprehensive plan involves evaluating the environmental impact of current legislation and implementing new laws concerning various areas such as the circular economy, building renovation, biodiversity, farming, and innovation.

[19] The merit order effect refers to the impact of renewable energy sources, such as wind and solar, on the overall dispatch and pricing of electricity generation. In addition, the merit order effect primarily driven by the low operating costs and often zero fuel costs associated with renewable sources.

Germany differ in terms of support scheme types, the merit order effect is identified. Mulder and Scholtens (2013) employed instrumental variables to examine the Netherlands for the period 2006-2011. While they found that prices were related to the production costs of conventional power plants, they were unable to detect the merit order effect for renewable energy. Hirth (2013) conducted an OLS regression study for European countries, including Germany, Norway, Denmark, and Sweden, for the period 2001-2012. They determined that renewable energy lowers prices through the merit order effect.

Studies related to European countries often appear to focus on individual countries at the individual level (Mulder and Scholtens, 2013; Castillo and Victoria, 2015; Clo et al., 2015). However, as previously mentioned, considering that the European Union acquis is binding for all European countries, conducting research with a panel that includes as many European countries as possible becomes important in order to observe the holistic impact of this acquis on the outcomes it generates. This chapter examines 25 European countries for the period 2016-2022. By using panel data analysis, this chapter makes it easier to combine time-series and cross-sectional dimensions, captures heterogeneity, and lets different countries be evaluated at the same time. It analyzes the merit order effect by utilizing demand, renewable energy generation, and generation from natural gas to explain the market clearing price. The main question of the chapter is: How does renewable energy generation affect market clearing prices in Europe?

In this chapter, panel data analysis is conducted. Initially, a cross-sectional dependence (CD) test (Pesaran, 2004) is employed to examine the long-term cross-dependence of 25 countries. European countries in particular can exhibit similar behavior due to shared demand and generation characteristics. Subsequently, the stationary nature of the data is assessed using the CIPS Pesaran (2007) test, which is commonly applied to panel and cross-dependent countries. To highlight the unique characteristics of each country, the Pesaran and Yamagata (2008) slope heterogeneity test is conducted. The model is estimated using the dynamic common correlated effect estimator because the stationary data have both cross-sectional dependence and slope heterogeneity.

The remaining sections are structured as follows: Section 2.2 represents the methodology and data. Section 2.3 presents the results. 2.4 includes policy implications. Section 2.5 concludes.

2.2. METHODOLOGY AND DATA

This section explains the data and empirical model. Table 1 explains the variables present in the models. We use hourly data for market clearing price, electricity demand, renewabla generation, and natural gas generation in wholesale electiricty market between 2016 and 2022. The hourly data was converted into daily data by computing the weighted average. Through this transformation, the noise in the data has been minimized.

Table 1: Types and Definitions of Variables

Symbol	Variable Type	Variable	Definition
PRICE (MCP)	Dependent Variable	Market Clearing Price	The market clearing price signifies the price formed through the equilibrium of supply and demand within the organized electricity market.
DEMAND	Independent Variable	Electricity Demand	Electricity demand represents the electricity used by consumers in the electricity market.
RENEWABLE	Independent Variable	Renewable Generation	Renewable energy generation indicates the total output of renewable energy power plants such as wind, solar, biomass, and hydropower.

NATURALGAS	Independent Variable	Natural Gas Generation	Natural gas generation represents the amount of electricity generated from power plants that utilize natural gas as their production source.

Electricity demand, renewable generation, and natural gas generation variables are seasonally adjusted by Census X-13 method. Then we take natural logarithm of the electricity demand, renewable generation, natural gas generation, and market clearing price. We used the following variables in the econometric analysis: market clearing price (LPRICE), electricity demand (LDEMAND), generation from renewable energy sources (LRENEWABLE), and generation from natural gas (LNATURALGAS). It is assessed that there exists a direct relationship between electricity electricity demand and market clearing prices (Fan and Pardalos, 2011). We used these variables as renewable energy is a substitute for natural gas in many different countries (Mohammad et al., 2021).

$$LPRICE_{it} = \alpha_i + \beta_i LDEMAND_{it} + \gamma_i LRENEWABLE_{it} + \theta_i LNATURALGAS_{it} + \varepsilon_{it} \quad (1)$$

In recent econometric analyses, the issue of cross-sectional dependence has gained attention due to the presence of spillover effects, including shocks, unnoticed components, and spatial dependency, which can propagate across individual countries. We used the cross-sectional dependence test in panel country analysis to ensure the validity of our results, as it helps detect and account for potential correlations among observations from different countries. By accounting for cross-sectional dependence, we tried to avoid biased parameter estimates and enhance the robustness of our findings, ultimately leading to more accurate and reliable economic analyses. Prior to analysing the relationship between variables, it is essential to perform tests to examine cross-sectional dependency (Khan, et al., 2020). The existence of cross-sectional dependence can present a difficulty. Consequently, without conducting a cross-sectional dependence (CD) test, the obtained results can be biased and unpredictable (Dong et al., 2019). Given the concerns raised, we prioritize testing the data for the presence of cross-sectional dependency, as suggested by Pesaran (2004). The alternative hypothesis indicates the existence of cross-sectional dependency, while the null hypothesis suggests the absence of such dependency. To check the cross-sectional dependency, we applied Pesaran (2004) CD-test. The equation for cross sectional dependence is given as:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{k=i+1}^{N}\hat{\tau}_{ik}\right) \quad (2)$$

In equation 2; N denotes the number of cross-sectional units or entities in the panel dataset, T defines the number of time periods for each cross-sectional unit in the panel dataset, i, k are the index variables representing cross-sectional units. The CD test that Pesaran (2004) proposed assumes a zero mean and constant variance. In the Equation 2, $\hat{\tau}_{ik}$ represents pairwise correlation;

$$\hat{\tau}_{ik} = \hat{\tau}_{ki} = \frac{\sum_{t=1}^{T} y_{it} y_{kt}}{(\sum_{t=1}^{T} y_{it}^2)^{\frac{1}{2}} (\sum_{t=1}^{T} y_{kt}^2)^{\frac{1}{2}}} \quad (3)$$

In equation 3; y_{it} describes the observed value of the dependent variable for cross-sectional unit i at time period t, y_{kt} denotes the matrix of observed values of independent variables for cross-sectional unit i at time period t, T is the number of time periods for each cross-sectional unit in the panel dataset, and t is index variable representing time periods.

The stationarity test holds significance to prevent spurious regression. We will carry out the second-generation panel unit root test, specifically the CIPS unit root test, to further investigate the unit root. To address heterogeneity and cross-sectional dependence among panels, we utilize the CIPS panel unit root test. The CIPS test is especially valuable as it can be applied to variables that exhibit cross-sectional dependence. Furthermore, this test yields reliable results even in the occurence of slope heterogeneity (Pesaran, 2007). The equation for the CIPS test is as follows:

$$\Delta y_{i,t} = \alpha_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + \sum_{k=0}^{p} d_{ik} \Delta \bar{y}_{t-k} + \sum_{k=1}^{p} \delta_{ik} \Delta y_{i,t-k} + e_{it} \tag{4}$$

In equation 4; y_{it} defines the observed value of the dependent variable for cross-sectional unit i at time period t, $\bar{y}_t$ denotes the cross-sectional average of y_{it}, Δ shows the first difference, p is the lag length. The cross-sectional averages in the CIPS test are denoted by y_{t-1} and Δy_{t-l}. The cross-sectional CIPS test is formulated as follows:

$$CIPS(N,T) = N^{-1} \sum_{i=1}^{N} t_i(N,T) \tag{5}$$

In equation 5; t_i is the t-statistics of b_i for ith individual country, N is the number of cross-sectional units in the panel dataset, T is the number of time periods. Furthermore, panel data models often encounter the issue of slope heterogeneity, which can distort the results. The slope heterogeneity test developed by Pesaran and Yamagata (2008) is utilized here. This test enhances the reliability of our empirical findings and takes cross-sectional dependence into consideration. In panel country analysis in econometrics, incorporating slope heterogeneity tests is crucial because they allow you to assess whether the relationships between variables differ significantly across countries. Firstly, these tests help uncover variations in the relationship between variables across different countries, providing valuable insights into the heterogeneity of economic processes. Secondly, by identifying and accounting for such heterogeneity, we create more precise and tailored econometric models, which enhance the accuracy of your policy recommendations and forecasts. Lastly, slope heterogeneity tests contribute to the robustness of our analysis by ensuring that our conclusions are not based on assumptions of uniform relationships across all countries, leading to more reliable and policy-relevant results. The test is effective in detecting slope heterogeneity without leading to biased estimates, and it is widely recognized and used in the field (Bersvendsen and Ditzen, 2021). Also, the Pesaran and Yamagata (2008) test works well when the sample size (N) is small and the time period (T) is long. The equation for the Pesaran and Yamagata (2008) test is as follows:

$$\hat{\Delta}_{SH} = N^{\frac{1}{2}} 2k^{-\frac{1}{2}} \left[\frac{1}{N}\hat{S} - 2k\right] \tag{6}$$

When conducting analysis on panel data, it is essential to assess the presence of cross-country slope homogeneity, as assuming homogeneity in slopes can potentially lead to inaccurate results. The slope homogeneity test results, developed by Pesaran and Yamagata (2008), provide valuable insights in this regard.

$$S = \sum_{i=1}^{N} (\beta_i - \beta_{WFE}) \frac{X_i' M_\tau X_i}{\sigma_i^2} (\beta_i - \beta_{WFE}) \tag{7}$$

$$\bar{\Delta} = \frac{1}{\sqrt{N}} \left[\frac{N^{-1}S - k}{\sqrt{2k}}\right] \tag{8}$$

$$\bar{\Delta}_{adj} = \sqrt{N} \left[\frac{N^{-1}S - k}{\sqrt{\frac{2k(t-k-1)}{r+1}}}\right] \tag{9}$$

In these equations, the test statistics S, $\bar{\Delta}$, and $\bar{\Delta}_{adj}$ represent the calculated values used in the testing process, with $\bar{\Delta}_{adj}$ denoting the biased-adjusted version of $\bar{\Delta}$. The coefficient of the pooled ordinary least squares is represented by β_i, γ_i, θ_i in equation 1 while the pooled estimators of the weighted fixed effect are denoted as WFE. The identity matrix is expressed by Pesaran (2008). In addition, we employed a slope homogeneity test developed by Blomquist and Westerlund (2013) to confirm the slope homogeneity between countries. This test takes into account heteroscedasticity and serial correlation. The test is relatively straightforward to implement and exhibits a limiting distribution of N(0, 1).

In the context of analyses, when cross-sectional dependence and slope heterogeneity are present in the data, the dynamic common correlated effect estimator can be applied (Dong et al., 2019).. We applied the dynamic common correlated effect (DCCE) method, which incorporates several statistical techniques. The DCCE method combines the ideas of pooled mean group (PMG) estimation, CCE estimation by Pesaran (2006), MG estimation by Pesaran and Smith (1995), and the estimation method proposed by Chudik and Pesaran (2015). It effectively addresses both homogeneous and heterogeneous coefficients and takes into account cross-sectional dependence. By assimilating cross-sectional dependence and accommodating heterogeneous slopes, the dynamic common correlated effect technique provides a comprehensive approach for our analysis. The equation for the dynamic common correlated effect model for equation 1 is as follows:

$$PRICE_{it} = \alpha_i PRICE_{it-1} + \delta_i x_{it} + \sum_{P=0}^{P_T} \gamma_{xip} \bar{X}_{t-p} + \sum_{P=0}^{P_T} \rho_{xip} \overline{PRICE}_{t-p} + \varepsilon_{it} \qquad (10)$$

In equation 10; x_{it} denotes the electicity demand, renewable generation, natural gas generation, and P_T is the maximum amount of lag included in the cross-sectional averages, $\bar{X}$ denotes the cross-sectional average of x_{it}, $\overline{PRICE}$ shows the cross-sectional average of PRICE, ε_{it} is the error term. Table shows the descriptive statistics of the natural logarithm of market clearing price, electricity demand, renewable energy generation, and natural gas generation for European Countries[20]. The average market clearing price is 3.97, with a median of 3.90. The minimum value is 2.19, and the maximum value is 5.77. As for electricity demand, the average is 7.35, with a median of 8.53. The minimum and maximum values are 6.24 and 10.73, respectively. The average renewable generation is 7.35, with a median of 7.30. The maximum value is 10.23, and the minimum value is 4.38. Regarding natural gas generation, the average is 5.91, and the median is 6.01. The minimum and maximum values are 0.49 and 9.51, respectively. In Figure 11, Combined graph of the market clearing price, electricity demand, renewable generation, and natural gas generation is presented. In the graphs, we observe similar patterns for market clearing prices due to interaction between European countries. However, electricity demand, renewable generation, and natural gas generation follow different patterns. Electricity demand is shaped by the size of the country's economy. Renewable energy and natural gas generation, on the other hand, vary according to the country's generation mix. Observations suggest that the market clearing price has a higher

[20] We used European Union countries excluding Cyprus and Poland due to their data problems such as zero generation in natural gas.

kurtosis value, indicating sharper peaks and thicker tails. On the other hand, other variables exhibit flatter peak points and thinner tails. Both the market clearing price and generation from renewable energy data are positively skewed, indicating a tail that extends towards higher values. Conversely, electricity demand and generation from renewable energy are negatively skewed, implying a tail that extends towards lower values.

Table 2: Descriptive Statistics

	LPRICE	LDEMAND	LRENEWABLE	LNATURALGAS
Mean	3.968350	8.542609	7.347132	5.911421
Median	3.899427	8.528820	7.298401	6.013376
Maximum	5.765308	10.73153	10.22759	9.505652
Minimum	2.194250	6.244194	4.379021	0.491544
Std. Dev.	0.499955	1.129618	1.271342	2.030729
Skewness	1.105039	-0.105921	0.118233	-0.379222
Kurtosis	5.167272	2.539497	2.192040	2.696264
Jarque-Bera	728.5945	19.53814	53.89193	50.75735
Probability	0.000000	0.000057	0.000000	0.000000
Sum	7242.239	15590.26	13408.52	10788.34
Sum Sq. Dev.	455.9184	2327.492	2948.148	7521.924
Observations	1825	1825	1825	1825

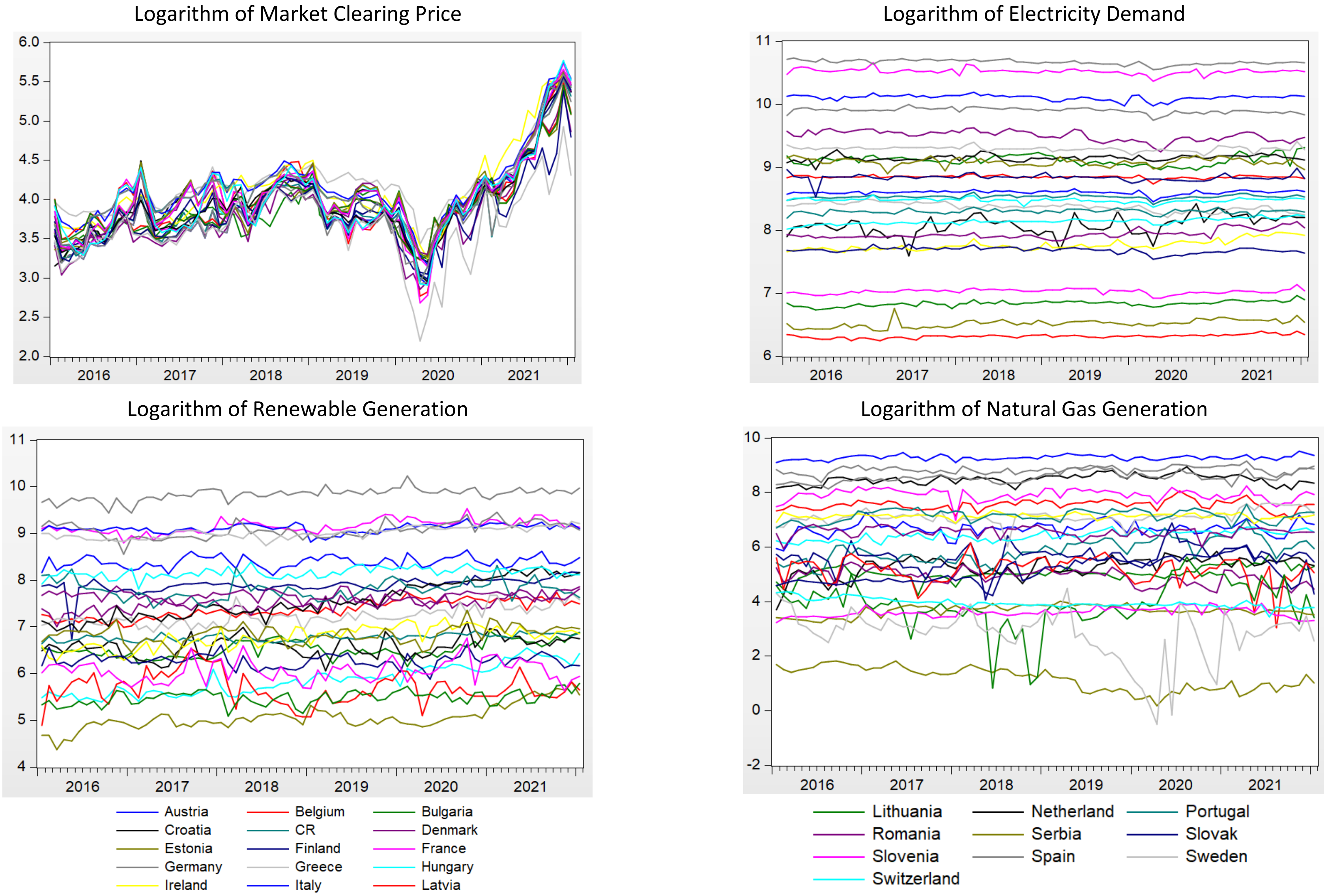

Figure 11: Market Clearing Price, Electricity Demand, Renewable Generation, and Natural Gas Generation Between 2016 and 2022

2.3 RESULTS AND DISCUSSION

We used the Pesaran (2007) CIPS test, which is a second-generation unit-root test, in our analysis. The CIPS test is particularly suitable for cases involving cross-sectional dependence and is known to produce more reliable results. We found cross sectional dependence between countries by rejecting the null hypothesis. The null hypothesis is there do not exist cross-sectional dependence (Table 3).

Table 3: Cross-sectional dependence-CD Test Results

Symbole	Variable name	CD Test	p-value
LDemand	Electricity Demand	83.7714	0.0000
LNaturalGas	Natural Gas Generation	40.2980	0.0000
LPrice	Market Clearing Price	144.8004	0.0000
LRenewable	Renewable Generation	40.1738	0.0000

Pesaran and Yamagata (2008) and Blomquist and Westerlund (2013) introduced a test called the test of slope homogeneity to examine whether the slopes of variables are homogeneous. The findings presented in Table 4 indicate that the null hypothesis of having homogeneous slope coefficients is strongly rejected at a 1% significance level for both of the tests. This suggests that there exists heterogeneity in European countries, primarily caused by energy generation composition (González & Martín-Ortega, 2020), demand patterns (Liddle & Lung, 2014; Manjunath et al., 2021), demographic (Teney et al. ,2013) and socio-economic factors (Neagu and Teodoru, 2019).

Table 4: Slope Homogeneity Test Results

	Pesaran and Yamagata (2008)		**Blomquist and Westerlund (2013)**	
	Value	P-value	Value	P-Value
$\bar{\Delta}$	28.658	0.000	11.038	0.000
Δ_{adj}	29.693	0.000	11.437	0.000

Our findings indicate that the variables Electricity Demand, Market Clearing Price, Electricity Generation from Natural Gas, and Electricity Generation from Renewable Energy exhibit stationarity at the level depicted in Table 5.

Table 5: CIPS (Unit root test) Results

Symbole	Variable name	t-stat	p-value
LDemand	Electricity Demand	-4.2048	<0.01
LNaturalGas	Natural Gas Generation	-3.3842	<0.01
LPrice	Market Clearing Price	-4.4396	<0.01
LRenewable	Renewable Generation	-3.7088	<0.01

The DCCE estimation findings indicate that electricity demand and generation from natural gas have a positive and statistically significant impact on market clearing prices at a significance level of 1%. Conversely, generation from renewable energy exhibits an inverse relationship with market clearing prices, with a significance level of 1%. We conducted two models, one with lagged market clearing prices and the other without it. This procedure has been conducted to examine both the static and dynamic states. By acknowledging that the market clearing price's historical values have an impact on its current values, this inclusion captures temporal dependencies within the data. This gave us the opportunity to add dynamic effects and the long-term persistence of trends or patterns. Both models produced similar coefficient results. In Table 6, the coefficients of generation from renewable energy in the models are -0.424 and -0.404, respectively. For electricity demand, the coefficients are 31.917 and 28.691. The coefficients for generation from natural gas are 0.252 and 0.301. According to the results of Model 1, a 1% increase in electricity demand can lead to an approximately 32% increase in the market clearing price. This is due to the significant magnitude of the electricity demand data, with a 1% change representing a substantial increase in consumption quantity. On the other hand, a 1% change in renewable energy production has been observed to decrease the market clearing price by 0.42%. Similarly, a 1% increase in natural gas production has been observed to raise the market clearing price by 0.25%. This is thought to be attributed to the higher cost of electricity generation from natural gas. In Model 2, the coefficient results are similar, with the addition of the first lag of the market clearing price. As the value of the market clearing price in t-1 increases, a tendency to decrease becomes evident in the market clearing price.

Table 6: Dynamic Common Correlated Effect Estimator Results

	Model 1		Model 2	
lprice (t-1)	-		-0.0009	(0.053)
ldemand	31.917	(0.000)	28.691	(0.000)
lrenewable	-0.424	(0.000)	-0.404	(0.008)
lnaturalgas	0.252	(0.046)	0.301	(0.105)
R^2	0.70		0.73	
Root MSE	0.43		0.42	
p-value	0.0000		0.0000	

Renewable energy not only provides benefits in terms of reducing carbon emissions and addressing climate change but also generates advantages for market participants in various aspects by lowering energy prices. Firstly, a variety of market dynamics and policy initiatives are what are driving this phenomenon, which has a noticeable cost-reducing impact on electricity generators. Hence, electricity market generators find themselves in a situation where they are compelled to reevaluate and enhance their production strategies. As market clearing prices decline, generators face the reality of lower revenue streams, making it imperative for them to reduce production costs. This financial pressure acts as a driver for innovation and process optimization, driving generators to seek ways to maximize the efficiency of their operations. Only by adopting more efficient technologies, optimizing their fuel sources, and minimizing operational waste can these power plants hope to remain economically viable. Moreover, the push for efficiency not only impacts existing power plants but also influences the choices made in future investments. In a market where lower prices persist; new power generation facilities must be designed with heightened efficiency in mind from the outset. In this evolving landscape, the electricity market undergoes a transformation towards greater sustainability and economic efficiency.

Secondly, in light of the declining costs associated with energy production, consumers are poised to reap significant benefits, particularly in the realm of reduced electricity bills. This phenomenon represents a pivotal development in the energy sector, with profound implications for households and businesses alike. As energy production becomes more cost-effective, the burden on consumers to cover the costs of their electricity consumption diminishes. This, in turn, affords individuals and enterprises greater financial flexibility, enabling them to allocate resources to other pressing needs or investments. Furthermore, the prospect of lower electricity bills not only enhances the affordability of essential services but also incentivizes the adoption of energy-efficient technologies and practices, contributing to a more sustainable and environmentally responsible energy landscape.

The third feature of this cost reduction phenomenon lies in its facilitation of government support for renewable energy initiatives through various mechanisms like feed-in tariffs, feed-in premiums, and contracts for difference. This presents an important opportunity for countries to foster the growth of sustainable energy sources. By leveraging reduced energy production costs, countries can more effectively implement these support structures, thereby incentivizing and accelerating the adoption of renewable energy technologies. This not only bolsters a country's energy security but also contributes to the global imperative of mitigating climate change. Such support mechanisms not only reduce the financial stress on consumers but also create a conducive environment for renewable energy investors and developers. Ultimately, this synergy between cost reduction and governmental support for renewable energy epitomizes a multifaceted approach towards achieving a cleaner, more sustainable energy landscape on a broader scale.

2.4 CONCLUSION

This chapter focuses on the prominent relationship between renewable energy and market clearing prices in Europe in recent years. We focus on Europe because Europe has taken a pioneering role in leading the world with its renewable energy policies and objectives (Cetkovic and Buzogany, 2016). More specifically, The Green Deal, approved the European Commission and established with the aim of achieving climate neutrality by 2050, presents a comprehensive framework.

In the econometric analysis in this section, we first conducted a cross-sectional dependence (CD) test. The result of this test indicated the presence of dependence among European countries. Subsequently, we applied the Pesaran and Yamagata (2008) and Blomquist and Westerlund (2013) slope homogeneity tests to assess the homogeneity of coefficients. The results of these tests revealed slope heterogeneity. Based on the presence of cross-sectional dependence and slope heterogeneity, we employed the dynamic common correlated effect estimator to run the models. The results of these models showed that electricity demand and electricity generation from natural gas increased the market clearing price, while generation from renewable energy decreased it. Therefore, despite having volatile generation patterns, it is concluded that renewable energy should be supported under the right conditions.

The intersection of market dynamics, policy initiatives, and technological advancements has engendered a transformative shift in the electricity generation landscape. This transformation is characterized by a pronounced cost-reduction effect on electricity generators, prompting them to adapt and optimize their production strategies in response to declining market clearing prices. Concurrently, consumers stand to benefit significantly from this evolution as reduced energy production costs translate into lower electricity bills. This economic relief not only enhances financial flexibility for individuals and businesses but also incentivizes the adoption of energy-efficient practices and technologies, contributing to a more sustainable energy future. Furthermore, the alignment of cost reduction with government support mechanisms for renewable energy underscores the pivotal role of such policies in fostering the growth of clean energy sources and advancing the global imperative of combating climate change. In summation, this multifaceted phenomenon heralds a promising era of increased efficiency, affordability, and sustainability in the energy sector.

CHAPTER 3

THE EFFECTS OF ELECTRICITY GENERATION FROM SOLAR AND WIND ENERGY ON THE DAY AHEAD MARKET-CLEARING PRICES AND PRICE VOLATILITY: THE TURKISH CASE

3.1. RENEWABLE GENERATION AND MARKET CLEARING PRICE

The issue of climate change and carbon emissions has increased the importance of solar and wind energy. Solar and wind generation sources not only possess zero carbon emission characteristics but also draw attention with their economic effects. Solar and wind energy have lower marginal costs compared to other sources such as coal and natural gas and entail zero input costs (Edenhofer et al., 2013). In addition, the cost of electricity generation from solar and wind sources is decreasing, while their efficiency is increasing with technological progress (Jahangiri et al., 2020). The increase in efficiency makes electricity generation from these natural sources feasible. In order to benefit from the advantages of electricity generation from renewable sources, solar and wind power plant investments need to be increased. However, investments in renewable energy power plants necessitate substantial financial funding due to their capital-intensive nature.

Thus, governments are actively implementing support schemes for renewables to provide financial funding (Hildman et al., 2013; Kyritsis et al., 2017). Renewable energy support schemes[21] have facilitated an increase in electricity generation from solar and wind sources. Therefore, electricity generation sources have shifted from conventional to renewable ones. The transition in the energy generation mix has effects on the wholesale

[21] Many European and Latin American countries experience different price behavior due to the various workings of wholesale energy markets and the types of renewable support schemes (Lund, 2009; Herrero, 2015; Azuela, 2014; Winkler, 2016; Bejerano, 2016). There are three major support schemes for renewables. Firstly, Ciarreta (2020) analyzed Spain between 2002 and 2017 with a structural-GARCH model and claimed that the “feed-in tariffs” support scheme makes sense to reduce the wholesale electricity price. Secondly, compared to feed-in tariffs, Market-oriented approaches such as “feed-in Premium” produced less benefit to investors while implementing renewables in the market (Winkler, 2016; Ciarreta, 2020). Thirdly, a separate support mechanism that was frequently employed is called a “contract for difference”.

electricity market. The implementation of solar and wind energy into the market raises concerns regarding market-clearing price level and volatility. Firstly, the introduction of low-cost solar and wind energy into the market has an effect on the profit margins of generators by altering the price level. Secondly, the volatile generation patterns of solar and wind power affect market-clearing price volatility. Therefore, the level and volatility of market-clearing price is evolving to a different pattern. These changes may reflect shifts in market dynamics, supply and demand factors, or regulatory developments. Analyzing the evolving nature of the market-clearing price is crucial for stakeholders, as it can impact energy generators, consumers, and policymakers alike.

In this chapter, the merit order effect of renewable energy sources on the wholesale market clearing price has been examined. The merit-order effect of renewables refers to the unique economic advantage that renewable energy sources, such as wind and solar power, often hold in the dispatch of electricity generation. It occurs because renewables typically have very low operating costs and zero fuel costs, making them some of the least expensive sources of electricity generation. Therefore, when renewable energy sources are available and able to meet the demand for electricity, they are dispatched before more expensive fossil fuel-based power plants. This leads to a reduction in the overall market-clearing price of electricity, benefiting consumers and reducing greenhouse gas emissions by displacing more carbon-intensive forms of energy generation.

In this chapter, we investigate the effects of electricity generation from solar and wind energy not only on market-clearing prices but also market-clearing price volatility in the day-ahead electricity market. We also focus on the pattern of the impact of wind and solar generation on market-clearing prices between low and high demand. This is due to the fact that in Turkey, wind generation bids are included on the supply side of the wholesale electricity market, while solar power generation is integrated on the demand side. To this end, we apply the machine learning methods using daily data from 1/1/2016 until 7/31/2022. In addition, due to the importance of renewable energy, policy recommendations have been formulated in order to enhance the efficiency of renewable energy investments in Turkey.

Governments adopt various patterns in the implementation of renewable energy despite uncertainties in market-clearing price structures. The financial funding available to advanced countries such as Germany and Spain, and their pioneering efforts in addressing climate change make them prominent in the field of renewable energy (Lagarde and Lantz, 2018). Developing countries, on the other hand, pursue different pathways in terms of renewable energy investments. While developing countries may not have made as much progress as advanced countries in this regard, Turkey stands out positively due to its high solar and wind energy investments (Simsek and Simsek, 2013; IEA, 2023). Therefore, Turkey's policies and practices regarding renewable energy support schemes provide good practice for other developing countries.

The rapid growth of renewable energy in Turkey, particularly in contrast to its status in developing countries, and the fact that Turkey is a candidate country for the European Union, collectively enhance the significance of investigating the impact of electricity generated from renewable sources on market clearing prices. The findings of this chapter will contribute to a greater understanding of how the day-ahead market clearing price and its volatility are affected by solar and wind electricity generation for generators, suppliers, and consumers.

The remainder of the chapter is structured as follows: Section 3.2 reviews the literature. Section 3.3 explains the Turkish wholesale electricity market. Section 3.4 presents the data and methodology. Section 3.5 discusses the empirical results of the models. The robustness check is implemented in Section 3.6. Section 3.7. contains the conclusion and policy recommendations.

3.2. LITERATURE REVIEW

Many studies have evaluated the impact of solar and wind generation on the market-clearing price in terms of price level and volatility from different perspectives (Würzburg et al., 2013; Huisman and Kilic, 2013; Ballester and Furio, 2015). Some studies have focused on the price level of renewables (Blazquez et al., 2018); Riesz and Milligan, 2019), while others have examined price volatility (Wozabal and Hirschmann, 2016; Paraschiv et al., 2014; Maciejowska, 2020), and some have investigated both aspects simultaneously (Ballester and Furio, 2015; Rintamaki et al., 2017). These studies vary in terms of the countries studied, time periods, and methodologies employed.

There is no consensus on the effect of renewable energy on market-clearing prices. Zeinalzadeh et al. (2018) and Mulder and Scholtens (2013) claim that renewable energy sources do not affect or adversely affect the market-clearing price in the European electricity markets. In another major work, Schöniger and Morawetz (2022) examine the European energy markets from 2015 to 2019 to consider the cost of renewable energy sources and highlight their changing effect on market-clearing price. Blazquez et al. (2018) and Riesz and Milligan (2019) highlight the ambiguity of conflicting results from different studies. They claim that increased renewable energy discourages new market investments in renewable energy due to its price-reducing impact on the wholesale electricity market.

Moreover, some studies claim that electricity generation from renewable energy sources reduces market-clearing prices (Ballester and Furio, 2015; Nieta and Contreras, 2020). Ballester and Furio (2015) and Nieta and Contreras (2020) use univariate ordinary least squares and mean reversion to investigate the price-lowering impact of renewables on Spain's Iberian energy market between 2001 and 2013 and between 2015 and 2020. They emphasize the systematic impact of renewable generation on market-clearing price. They claim that renewable energy generation entered the market's supply side with negligible marginal costs. This effect shifts the supply curve to the right so renewable energy generation reduces market-clearing prices. This phenomenon is present in the literature as the merit order effect. It refers to the situation where an increased generation of renewable energy leads to a reduction in power prices at the wholesale electricity markets (Clo et al., 2015).

The merit order effect regarding the market-clearing price for renewable energy sources is discussed. In the literature, several studies investigated the effects of merit orders on the market in different countries. Cutler et al. (2011) investigated the merit order effect of wind energy in the Australian electricity market between 2008 and 2010 using descriptive statistics. Chattopadhyay (2014) studied the Indian national electricity market in 2017 and claims that renewables' merit order price-reducing effect occurs using simulation models. Like Chattopadhyay (2014), Perez and Garcia (2021) investigate renewables' price-reducing merit order effect in the Colombian electricity market. They also model the interregional electricity transfers to fit the model to the electricity grid dynamics. Ocampo et al. (2021), Chen et al. (2019), and Brown (2012) investigate the USA and use mathematical modeling to determine the merit order effect of renewables utilizing various generating scenarios. Prol and Schill (2020) and Bushnell and Novan (2018) found the cannibalization effect of renewables by studying California between 2013 and 2017 using ordinary least squares. Woo et al. (2016) also focused on California between 2012 and 2015 in the day ahead market and the real-time market using regression analysis and found similar results to Prol and Schill (2020). Ma et al. (2022) and Maekawa et al. (2018) investigate Japan's electricity spot market to analyze the cross-regional effect of renewable penetration. They find the renewables' price-reducing merit order effect using descriptive statistics and regression models between 2010 and 2019. In order to demonstrate the merit order effect of renewables in China's electricity market, He et al. (2022) employ optimization for several scenarios. In studies on Turkey, Sirin and Yilmaz (2020) and Karatekin (2020) use quantile regression and simulation to discover the same price-decreasing effect outcome for Turkey between 2013 and 2019.

Würzburg et al. (2013), Zipp (2017), and Paraschiv et al. (2014) found the merit order effect as Ballester and Furio (2015) for Germany, Luxembourg, and Austria between 2002-2018 by using simulation, Garch, and ordinary least squares. Würzburg et al. (2013) emphasize that the effect of renewable energy on market-clearing prices varies due to regional characteristics. The feature that distinguishes the Würzburg et al. (2013) paper from the others is that it does not include hydroelectric generation while using renewable energy generation. Like Würzburg et al. (2013), Paraschiv et al. (2014) use wind and solar generation as renewable generation variables to assess renewables' merit order effect. They find the price-reducing impact of renewables. Huisman and Kilic (2013) use time series models to demonstrate the price-lowering effect of renewable energy sources and concentrate on the Nord Pool to assess the merit order effect of hydropower plants. They assert that the hydropower facilities' storage capacity boosts their merit order effect in the Nord pool wholesale market. Adom et al. (2018) estimate the impact of hydropower plants on market-clearing prices similar to Huisman and Kilic (2013). They emphasize the short- and long-run merit order effects of the ARDL model between 1970 and 2013. Janda (2018) focuses on Slovak wholesale electricity markets to quantify the solar generation impact on market clearing price between 2011 and 2016 using ordinary least squares. They discover a negligible effect of solar energy on market-clearing prices. Figueiredo and Silva (2019) and Clo et al. (2015) studied the merit order effect of renewable energy in Italy's wholesale electricity markets. They find that wind generation has a higher impact on market-clearing prices than solar generation. At increasing scales, the effect of renewable energy on prices is changing.

Some studies investigate the effect of renewable energy on market-clearing price volatility. Renewable energy shows intermittent generation characteristics that may cause volatility in the market. Rintamaki et al. (2017) examine the influence of wind and solar generation on market-clearing prices. Using ordinary least squares and the auto-regressive approach, they find opposite results for the volatility-decreasing impact of wind power in Denmark and the volatility-decreasing impact of solar generation in Germany. Ballester and Furio (2015) state that renewable energy generation raises market-clearing price volatility in Spain. Wozabal and Hirschmann (2016), Paraschiv et al. (2014), and Maciejowska (2020) focus on Germany between 2010 and 2018 and emphasize the varying volatility effect of renewables due to changing demand levels by measuring volatility with the same method as Ballester and Furio (2015).

In addition, Figueiredo and Silva (2019) used Garch to evaluate the volatility impact of renewables on market clearing prices for Portugal and Spain between 2008 and 2017. They found that, in Iberia, the residual load has a negative impact on the merit order effect while electricity demand, wind, and solar power have a positive impact. The non-dispatchable intermittent[22] nature of renewable energy source power generation is mirrored by the anticipated consistently high merit order effect volatility. Ma et al. (2022) examine electricity markets in Japan and demonstrate that renewable generation causes a volatile market-clearing price. Japan's spot market suffered increased volatility after wind

[22] Non-dispatchable refers to the fast activation (start-up) of renewable energy sources compared to conventional ones.

and solar generation. Astaneh and Chen (2013) find the merit order effect of wind generation in Denmark and Norway using ARIMA modeling between 2011 and 2012. ARIMA models reflect the volatility characteristic of wind generation. Astaneh and Chen (2013) find that wind generation increases market-clearing price volatility. According to Bushnell and Novan (2018), solar energy makes the California electricity market more volatile.

As mentioned above, the literature review conducted revealed that the analyses predominantly consisted of econometric models. On the other hand, it is also known that new analysis methods, such as machine learning, are being employed. In this context, several studies in the literature compare traditional econometrics and new-generation machine learning methods. Shobana and Umamaheswari (2021) compare econometric methods such as Time Series Model, Exponential Smoothing Model, The Random Walk Model, Arima, and Auto-Regressive Model with machine learning algorithms. They proved the superiority of machine learning methods by using root mean square error, mean absolute error, and mean mean absolute percentage error metrics. Gabriel et al. (2019), Xuerong Li et al. (2019), and Aydin and Cavdar (2015) compare econometrics and machine learning in the fields of energy prices, crude oil prices, and banking. Thus, the papers use machine learning methods to analyze the wholesale electricity market. Ahmad and Chen (2020) used machine learning methods such as neural networks to predict energy prices. They emphasize the applicability of machine learning in the energy market. Similarly, Masini et al. (2021) studied stock exchange volatility between 2000 and 2020 for the US, UK, Germany, Hong Kong, Japan by using ensemble learning, tree-based methods, and deep neural networks. They focused on nonlinear machine learning models and demonstrated that these models are effective and efficient in economic forecasting by comparing their gains. Bolhuis and Rayner (2020) and Hall (2018) analyzed macroeconomic variables such as the output gap, unemployment, and manufacturing between 1959 and 2019 to test the machine learning methods' accuracy. They find similar results to the previous literature, as machine learning outperforms time series models and creates high gains.

A few studies on the Turkish wholesale electricity markets focus on the renewable energy effect on day-ahead market-clearing prices. Some researchers try to predict market-clearing price trends using various methods. Depren et al. (2022) compare time series econometric methods (Ardl, Arma, Dols, Fmols, Markov, Ols) and machine learning methods (KNN, Mars, Rf, Svm, Xgb) for Turkey between 2019 and 2021 to find the best models to analyze market-clearing prices. They find that machine learning methods are superior to econometric ones. Their contribution focuses on the effectiveness of alternative methods. Oksuz and Ugurlu (2019) show that machine learning techniques outperform traditional approaches in the power market. Kabak and Tasdemir (2020) used artificial neural networks to find the best-fitting price forecasting model in Turkey in 2017. Upon reviewing the literature, a comprehensive body of research is encountered, wherein various aspects concerning the impact of renewable energy on market clearing prices have been monitored. Moreover, similar circumstances have been identified in studies conducted for the context of Turkey. Within the scope of the literature review conducted in the chapter, this chapter presents the initial comprehensive empirical analysis of this matter within the context of the Turkish case. In addition to empirical analysis, policy recommendations based on the implementation of renewable energy in Turkey have been presented. After the literature review, the following section outlines the wholesale electricity market in Turkey before the empirical analysis.

3.3. TURKEY ELECTRICITY MARKET

Electricity market developments have been influenced by the progress of organized wholesale markets in Turkey. Turkey established a power exchange in 2015. Parallel to these developments, the EMRA aimed to increase the volume of trades on th e day-ahead market in order to maintain the efficiency of electricity markets (Genc and Sensoy, 2019). The day-ahead market volume, 27% in 2016, increased to 39% in 2021, as seen in Figure 13. The most common trade routes in the Turkish electricity market are bilateral agreements and bidding in the day-ahead market. In a bilateral agreement, users have long-term contracts without bidding on the market. They remain outside the wholesale electricity market. These transactions do not affect wholesale market prices. In the day-ahead market, buyers enter daily bids.

As seen in Figure 12, following the electricity demand (Appendix 3), the installed capacity of Turkey has doubled in the last ten years. New hydropower, geothermal, solar, and wind plant investments increased 1.5 times in ten years. The same period's economic expansion led to an increase in residential and industrial electricity use that was 1.5 times greater than before (Yildiz and Açıkkalp, 2017; Kavaz, 2020). As seen in Figure 13, the day-ahead market share increased compared to bilateral contracts during the same period. The day-ahead market is where prices are determined by supply and demand. The equilibrium price in this market is accepted as the reference point for all transactions in the Turkish electricity market, from generation to retail.

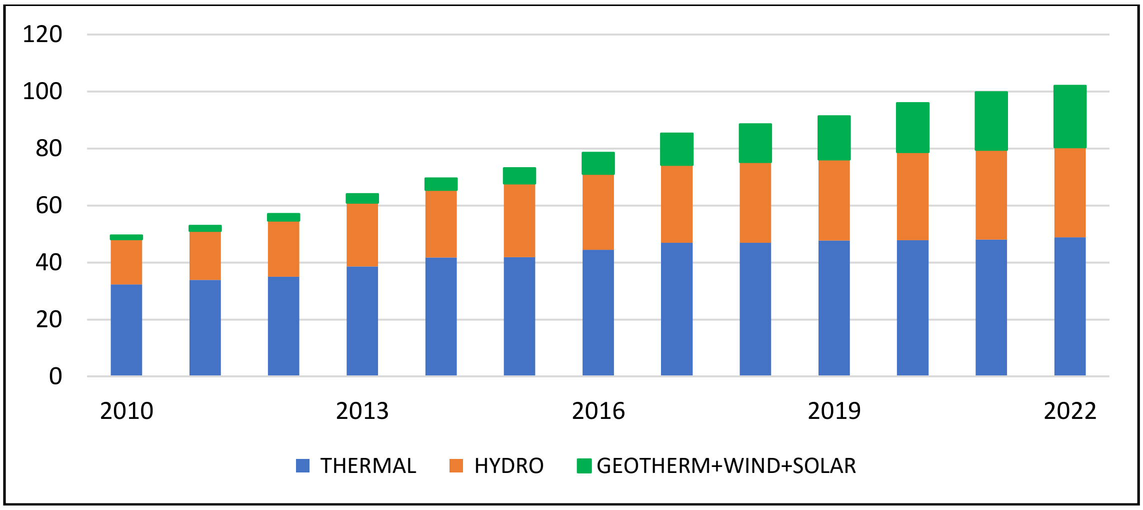

Figure 12: Installed Capacity of Turkey (GW): The Figure shows the Turkish electricity installed capacity. Turkey showed an increase in recent years that consists of wind and solar energy. Source: http://emra.gov.tr/

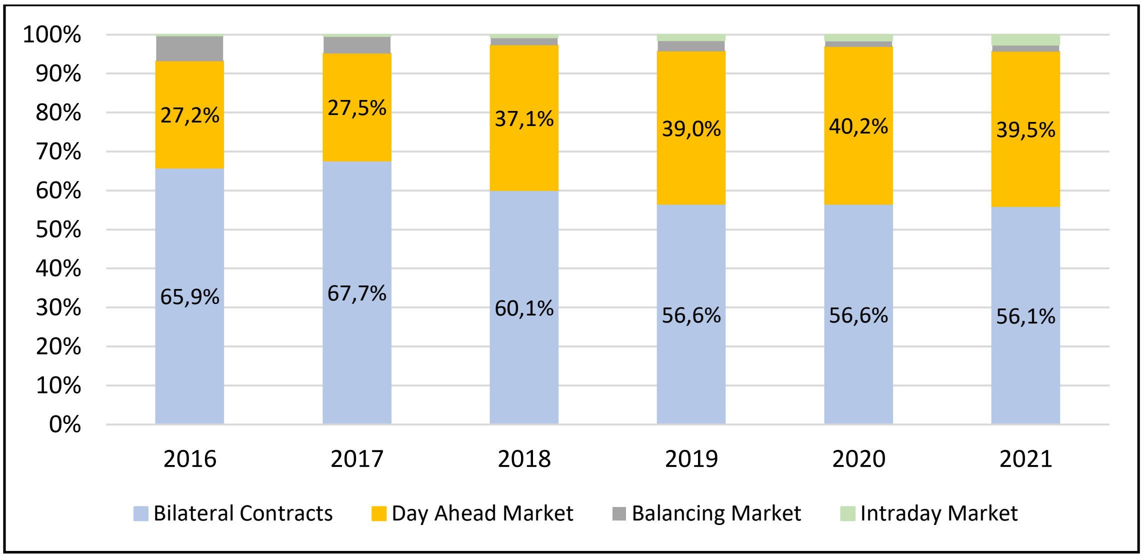

Figure 13: Share of the Trades in the Market (%): The Figure includes the share of the wholesale electricity markets. Day-ahead market share significantly increased in the last five years and reached to 39.5%. Source: https://seffaflik.epias.com.tr/transparency/

Renewable energy support mechanisms positively affect renewable investments. Through incentive mechanisms, solar and wind investments have increased rapidly. Increased solar and wind share in the organized market provides convenience in measuring the impact on the market clearing price. The RES support mechanism is crucial in understanding the relationship between solar and wind generation and market dynamics. Thus, it is beneficial to explain its evolution in detail. The following Figure 14 provides a visual representation of the history of RES subsidies in Turkey beginning in 2005.

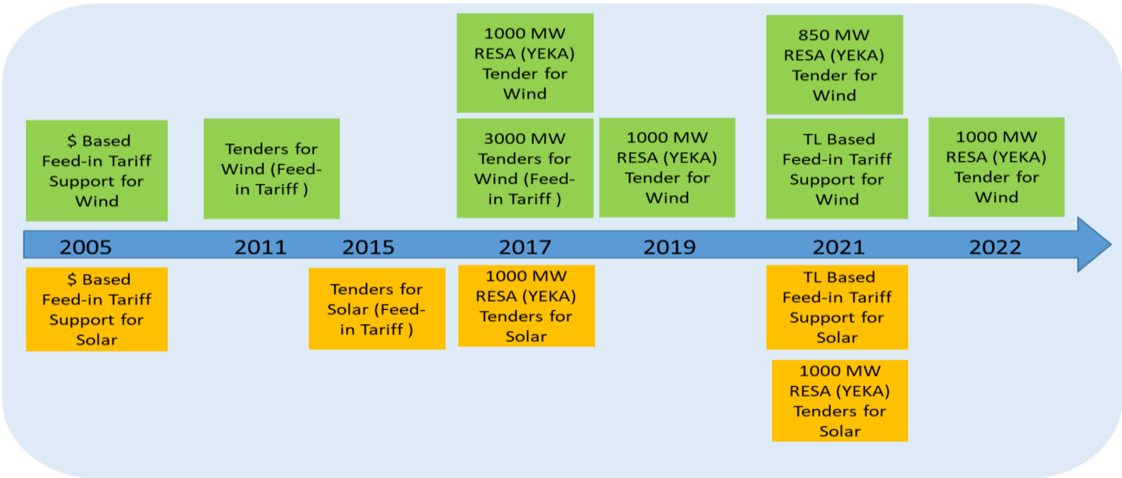

Figure 14: Renewable Energy Support Scheme in Turkey: The figure shows the renewable energy supports in Turkey. Solar and wind supports are shown from the beginning (Appendix 3).

Turkey began promoting renewable energy in 2005 with the RES (YEKDEM) mechanism, based on USD/kWh. It guarantees the feed-in tariff for ten years after the implementation of the power plant. Then, in 2011, the first wind energy tender was made. It was based on the contribution fee to be deducted from the RES (YEKDEM) Feed-in Tariffs. A 600 MW solar energy tender was held in 2015. Following solar tenders, 3000 MW-capacity wind tenders were placed in 2017. In parallel, the first tender for a 1000 MW Renewable Energy Support Zone was issued in 2017. The wind power auction was then held with 1000 MW of capacity. The second wind tender was held in 2019. The newly developed RESM (YEKDEM) mechanism was developed in TL in the middle of 2021. The first TL YEKA tender was subsequently held for 1000 MW. Additionally, a ceiling price was set for the wind auction in 2021. Finally, a 1000 MW capacity first wind TL-based YEKA tender was held in 2022.

In wholesale electricity markets, the intersection of aggregate supply and aggregate demand curves brings out market-clearing prices. The aggregate supply curve consists of the generation offers given by the generators, and the aggregate demand curve consists of the consumers' purchase offers. Generators bid on the electricity with a profit margin added to the price. Consumers enter a bid at the purchase price at which they can afford the electricity they want to buy. All generators and consumers trade at the market-clearing price formed at the intersection of aggregate supply and demand curves. The day-ahead market is where equilibrium is established and the market-clearing price is determined.

The introduction of RES changes the supply-demand curve balance in the day-ahead market. The effect of the merit order on the market-clearing price is shown in Figure 15 The figure has two graphs. In the left graph, supply-demand equilibrium occurs at the intersection of natural gas marginal cost and electricity demand. In the right graph, variable renewable energy enters the supply industry with zero marginal cost. Renewables shift the supply curve to the right, decreasing the market-clearing price.

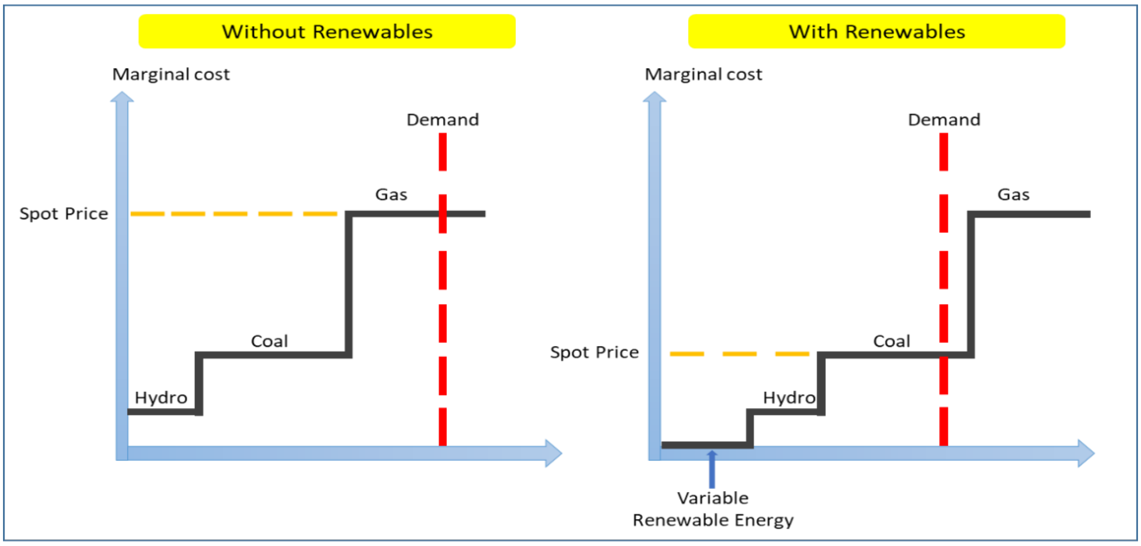

Figure 15: Merit order effect: The figure shows the shifting of the electricity supply curve due to bids coming from variable renewable energy sources such as solar and wind.

Wind and solar support mechanisms indirectly impact on the market clearing price in Turkey (Kyritsis et al., 2017). Because the support mechanism is reflected in the electricity tariffs applied to consumers and transferred to generators. In other words, in these support mechanisms, funds are not directly provided from the government budget;

rather, support is generated through the electricity bills paid by consumers (Sensfuß et al., 2008; Blumberga, 2019). As a result, the relationship between the market clearing price and electricity tariffs weakens, exerting pressure on the market clearing price. The following section starts our empirical analysis with the presentation of data and methodology.

3.4. DATA AND METHODOLOGY

The chapter examines the market-clearing price between 2016 and 2022 to test the impact of solar and wind penetration on the day-ahead market in Turkey. The effects of wind and solar generation on the price level and price volatility were investigated. Dutch Natural Gas TTF price, wind generation, solar generation, and electricity demand were used as explanatory (independent) variables. The data is obtained from the market operator of the Turkish wholesale electricity markets (Exist). We used daily market-clearing price levels ($/MWh), solar (Licensed and Unlicensed) generation (MWh), wind generation (MWh), Dutch TTF–price ($/MWh), and electricity demand (MWh) between 1/1/2016 and 07/31/2022.

Figure 16 represents the graph of the variables. First of all, when the Dutch TTF price data is analyzed, the high volatility of the data draws attention. Natural gas prices were stable until the beginning of 2021, when they started to climb with Covid-19. The pandemic has affected supply chains. Subsequently, in the period when normalization began, Russia's invasion of Ukraine led to a rise in the price of natural gas again. Although Russia is one of the largest gas suppliers, it accounts for a major part of the gas supply in Europe. These issues paved the way for a great energy crisis in the world. Turkey's electricity demand has followed a particular trend pattern since 2016. By the end of the year 2020, the increase in electricity demand will be attributable to the expansion of Turkey's burgeoning industrial sector, its expanding commercial sector, and its expanding population. When we came to the beginning of 2021, the electricity demand decreased due to the Covid-19 pandemic. The revival of the economy toward the end of the year, the operation of the production lines, and the country’s reopening by producing some solutions to the pandemic caused the demand for electricity to increase rapidly. Afterward, the electricity demand continued with a constant trend. The market clearing price reached certain levels until the pandemic, apart from the ceiling price with the intervention made in the market at the end of 2016. The deterioration of the supply-demand balance, the pandemic, and the decrease in the share of hydroelectric power plants in electricity generation led to high prices in 2021. The Russia-Ukraine war that broke out at the beginning of 2022 upset the natural gas markets and made natural gas power plants, which have a high share in Turkey's electricity generation, more effective on the price. Thus, the Dutch TTF natural gas price was used among the factors affecting the price in the analysis. When the solar and wind generation data in the graph are analyzed, a rise is observed with increasing renewable energy investments. It is proposed that renewable resource generation patterns may have an impact and, thus, have an effect on electricity prices. (Sakaguchi and Fujii, 2021). By 2023, the installed capacity of wind and solar separately exceeded 10 GW, which has increased the generation of renewable sources.

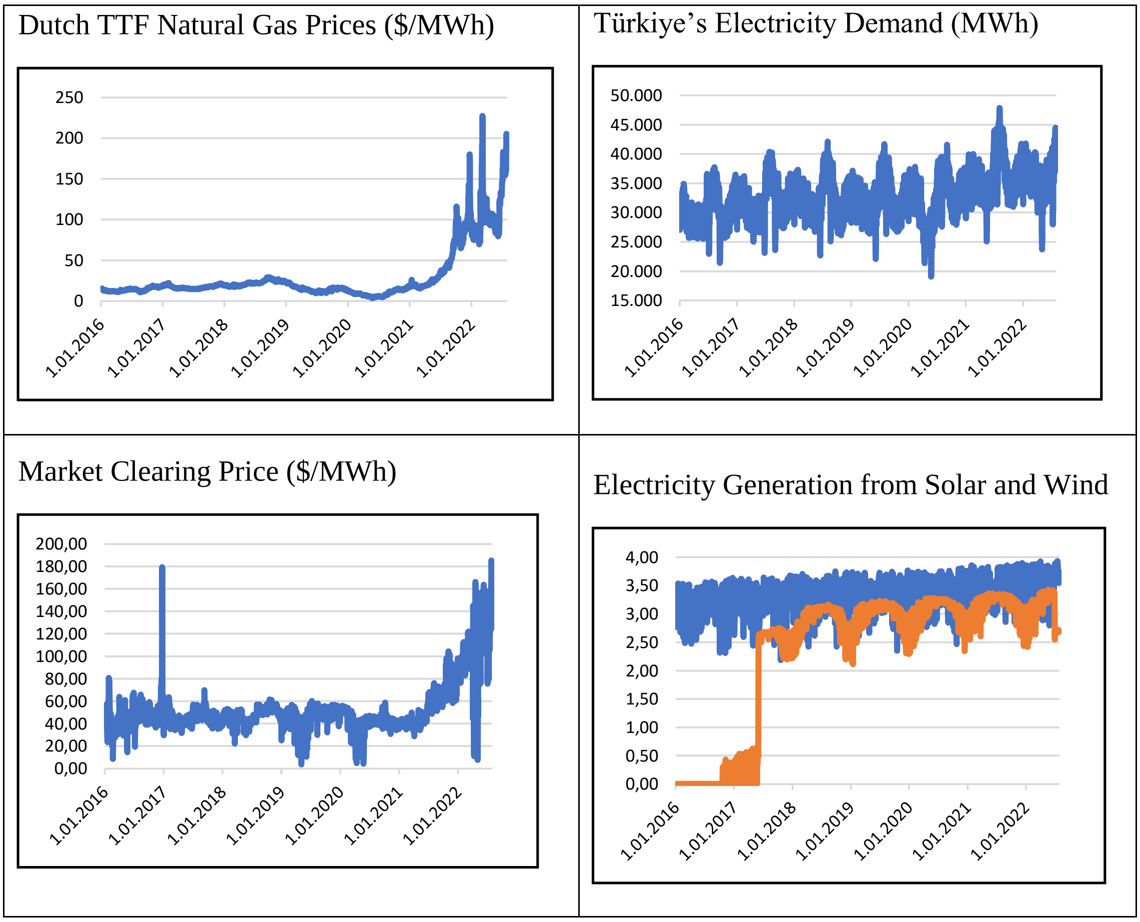

Figure 16: Dutch TTF Natural Gas Price, Turkey's Electricity Demand, Market Clearing Price, Electricity Generation from Solar and Wind Between 2016 and 2022

The last 6-year trends of the critical variables to be used in machine learning are given in the graph. When the transition mechanisms between data are examined, the effect of natural gas on the market-clearing price depends on factors such as electricity generation from natural gas in the relevant period, the use of gas in natural gas storage, and the weight of Dutch TTF in the contract where the natural gas is supplied. The expected result in the chapter is that increases in the natural gas price level and volatility will increase the market clearing price level and volatility. When we monitor the demand in Turkey in similar periods, the electricity demand, which experienced sharp declines in the first period of the pandemic, quickly recovered in the following period. Electricity demand in Turkey followed a volatile course during the analysis period.

The market clearing price, which isthe depedent variable in the model of machine learning, also showed high volatility due to similar reasons and some regulatory interventions. As seen in the literature, machine learning methods are better in estimating energy prices compared to traditional econometric methods. The fact that the data used in the analyses has high volatility, high frequencies, and dynamic relationships necessitated using machine learning instead of traditional econometric methods. We mainly aimed to measure the effect of solar and wind generation volatility on the market-clearing price through price level and price volatility. The volatility of natural gas prices has a similar effect on wind and solar production, and machine learning helps us reveal this effect more clearly. The data used in this chapter is large enough, even if it is not considered big data. While estimation with large data makes it difficult to get results using econometric methods, it creates the need for machine learning methods (Ifft et al., 2018). Since most of the data is considered to be non-normally distributed, machine learning becomes essential.

We generated market volatility measures. The first measure is the variance of the market-clearing price in a day of 24 hours, named Market-clearing Price Volatility (Volvar). The second volatility measure is the difference between the minimum and maximum hourly price in a day, named alternative market-clearing price volatility (Vold). The second volatility measure is used to check the robustness of the volatility results. We used the logarithms of the dependent and independent variables. Table 7 presents descriptive statistics for the dependent and independent variables.

Table 7: Descriptive Statistics of Variables

	Log of Dutch TTF NG Price	**Log of Electricity Demand**	**Log of Wind Generation**	**Log of Solar Generation**
Mean	1.36	4.53	3.33	2.36
Standard Error	0.02	0.00	0.01	0.02
Median	1.29	4.53	3.37	2.95
Standard Deviation	0.32	0.05	0.29	1.21
Kurtosis	0.80	0.84	-0.08	-0.17
Skewness	0.96	-0.49	-0.51	-1.28
Range	1.7	0.40	1.75	3.43
Smallest	0.63	4.28	2.18	0.00
Biggest	2.32	4.68	3.93	3.43

Count	2404	2404	2404	2404
Confidence I. (95%)	0.03	0.00	0.01	0.05

	Log of Market-clearing Price	**Market-Clearing Price Volatility$_{d}$**	**Market-Clearing Price Volatility$_{var}$**
Mean	1.70	34.62	10.64
Standard Error	0.01	0.52	0.16
Median	1.67	29.06	9.09
Standard Deviation	0.14	25.74	8.05
Kurtosis	2.47	47.19	43.79
Skewness	1.34	4.26	4.17
Range	0.93	481.95	147.51
Smallest	1.27	0.13	0.01
Biggest	2.20	482.08	147.51
Count	2404	2404	2404
Confidence I. (95%)	0.02	1.03	0.32

3.4.1. Machine Learning Methodology

We used machine learning in this chapter. "Machine learning is a field of study that gives computers the ability to learn without being explicitly programmed (Arthur Samuel, 1959)". Machine learning generates probabilistic methods. Machine learning responds to needs that econometric tool cannot meet, especially regarding large and big data. Machine learning methods are built on producing accurate predictions, where the main goal is to reach an unbiased and precise estimate. In machine learning, there are often negative degrees of freedom, and degrees of freedom are not considered. There are several machine learning methods, such as random forest learning, tree-ensemble learning, and polynomial learning. The tree ensemble learners and random forests approach, a widely used method, combines the results of multiple trees to improve prediction accuracy and reduce variance at the expense of easy interpretability. They average the results of many deep trees growing in random subsamples of observations and subsets of variables (Basu and Ferreira, 2020). Some research suggest that machine learning algorithms have more computing power compared to econometrics (Ghoddusi et al., 2019). Additionally, some studies indicate that many machine learning methods successfully explain nonlinear states, interactions, or heterogeneity (Deng et al., 2017; Deléglise et al., 2020; Gao and Sun, 2022). This chapter presents the mentioned machine learning features using the polynomial learner model due to its high explanatory power compared to other methods such as Random Forest and Tree ensemble learning. The polynomial learner model is denoted as follows:

$$P = \beta_0 + \sum_{i=1}^{m} \beta_i \times \prod_{j=1}^{n} X_j^{a_{i,j}} \quad (1)$$

In the equation 11, betas (β) are the coefficients of each variable, and a denotes the degree of the polynomial. X represents the independent variables. In machine learning, data is converted into understanding (Jordan and Mitchell, 2015). Jordan and Mitchell (2015) emphasize the importance of developing interpretable and explainable machine learning models to enhance understanding and trust in the predictions and decisions made by these models. As seen in Figure 17, in econometric methods, data and models enter, and output emerges. In machine learning, data and output enter, and the model emerges.

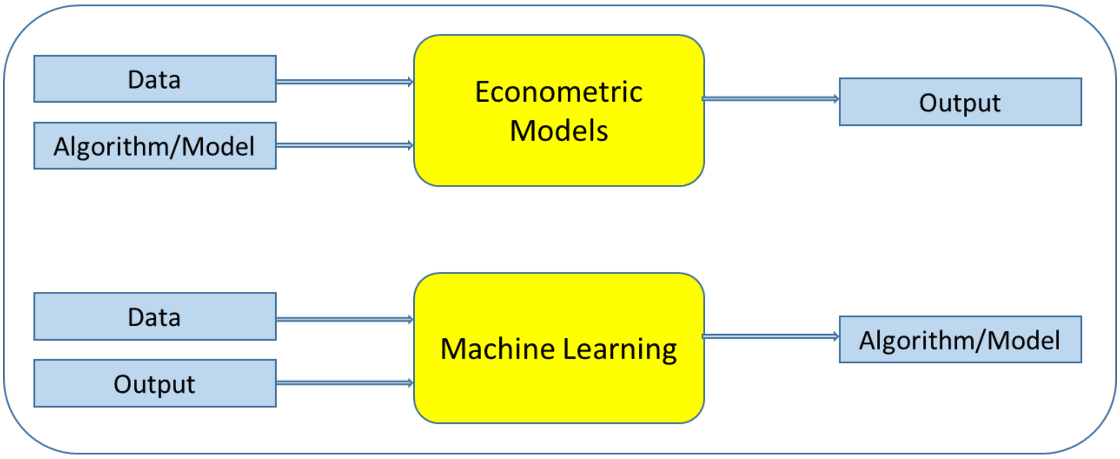

Figure 17: Comparison of Econometric Model and Machine Learning: The Algorithm/Model and Output swap are shown in detail.

3.4.1.1. Price level-Methodology

Analyzing the effect of wind and solar generation on the market clearing price is critical for the wholesale electricity market. The chapter develops comprehensive models to explain market-clearing prices. Solar and wind energy generation are independent variables in these models. In addition to these two variables, the models are set by integrating independent variables for electricity demand, and Dutch Natural Gas TTF price. These variables are explained in the Table 8.

Table 8: Types and Definitions of Variables

Symbol	Variable Type	Variable	Definition
MCP	Dependent Variable	Market Clearing Price	The market clearing price signifies the price formed through the equilibrium of supply and demand within the organized electricity market.
DEMAND	Independent Variable	Electricity Demand	Electricity demand represents the electricity used by consumers in the electricity market.
SOLAR	Independent Variable	Solar Generation	Solar generation indicates the total output of solar energy power plants.
WIND	Independent Variable	Wind Generation	Wind generation indicates the total output of wind energy power plants.
DUTCH TTF	Independent Variable	Dutch TTF Natural gas price	Dutch TTF natural gas price indicates the natural gas price of European most common natural gas hub.

We took the logarithm of variables in the models. These models are denoted as:

$$lmcp_t = \alpha_1 + \beta_1 \times lmcp_{t-1} + \beta_2 \times lDutch\,TTF_t + \beta_3 \times lwind_t + \beta_4 \times lsolar_t + \epsilon_t \qquad (2)$$

We employed different machine learning methods, including polynomial learning, to map the relationship between market-clearing price and solar or wind generation. In order to reduce the mean absolute error, root mean square error, mean squared error, and mean absolute percentage error the polynomial learner aims to increase the goodness of fit (R^2). The mean absolute error is represented by:

$$MAE = \frac{1}{n}\sum_{j=1}^{n}\left|y_j - \hat{y}_j\right| \qquad (3)$$

The root mean square error is denoted as follows:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}} \tag{4}$$

The mean squared error is represented by:

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (\hat{y}_i - y_i)^2 \tag{5}$$

The mean absolute percentage error is denoted as follows:

$$MAPE = \frac{1}{n} \sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{y_i} \tag{6}$$

where n is the number of observations, y_i represents the actual values, and $\hat{y}_i$ represents the predicted values. We studied several methods, such as polynomial learning, random forest, linear regression learning, simple regression learning, and tree ensemble learning. We compared the method results using the same variables: market clearing price, electricity demand, generation from solar and wind, and natural gas prices. We used goodness of fit, mean absolute error, and root mean square error criteria. We found a 2nd degree polynomial learner as the best fitting result. Since it is second-order polynomial learning, all models use the squares of the variables. The model is denoted as:

$$lmcp_t = \alpha_1 + \beta_1 \times lmcp_{t-1} + \beta_2 \times lDutch\,TTF_t + \beta_3 \times lwind_t + \beta_4 \times lsolar_t + \beta_5 \times {lmcp_{t-1}}^2 + \beta_6 \times {lDutch\,TTF_t}^2 + \beta_7 \times {lwind_t}^2 + \beta_8 \times {lsolar_t}^2 + \epsilon_t \tag{7}$$

In the polynomial learner models, we tried to estimate the market clearing price to assess the relationship between price and solar and wind generation. We used 90/10 learn and train ratios to estimate the model coefficients. Before applying the machine learning model, 10% of the data was separated using the random partitioning method. The Random partitioning method randomly parses a part of the data thatis not used in machine learning.

When the model coefficient results were revealed, this decomposed part was used to test the model's performance. In these models, we used only the first lag of the market-clearing price to analyse the static and dynamic states (Appendix 4). The first model is the base scenario, which includes all critical variables.

In the first model, we used the lag of market-clearing price, Dutch TTF, solar generation, wind generation, and electricity demand data as independent variables. In the second model, we excluded electricity demand to more abstractly measure the solar and wind generation effects. In the second model, we used the first lag of market-clearing price, Dutch TTF, solar generation, and wind generation as independent variables.

3.4.1.2. Price volatility-Methodology

Price volatility is a common issue in electricity markets. Volatility influences the short- and long-term choices made by power plant operators. Uncertainty grows as price volatility rises, creating a higher risk for generator failure. Assessing how RES affects volatile prices and how these two variables interact regarding investments in renewable energy is important.

We generated methods of random forest learning, tree ensemble learning, and different degrees of polynomial learning methods. We compared R^2, root mean square error, mean absolute error, mean squared error, and mean absolute percentage error values of the models. We used a 90/10 test-train ratio and found four optimal models. Variables are defined below. We used a 1^{st} degree polynomial of variables on a daily frequency. The variables are represented as follows: Volvar: Measure of daily volatility, Vold: Alternative measure of daily volatility, d: Day, t: Hour, p: Market-clearing price, Vol(t-1): 1^{st} lag of market-clearing price, Vol(t-2): 2^{nd} lag of market-clearing price, Vol(t-3): 3^{rd} lag of market-clearing price, Wind: electricity generation from wind energy, Solar: electricity generation from solar energy, TTF: natural gas price in the Dutch-TTF hub.

As we mentioned above, the volatility of the market clearing price is calculated by using a variance equation denoted as:

$$Volvar_d = \sqrt{\frac{1}{24}\sum_{t=1}^{24}(P_h - P_d)^2} \quad (8)$$

Ph is the price of an hour in a day, and Pd is the average price. In the formula, the intraday variance of the market-clearing price is calculated. In volatility models, the dependent variable is the volatility of the market-clearing price. We took the logarithm of variables in the models. These models are denoted as:

$$Volvar_t = \alpha_1 + \beta_1 \times Volvar_{t-1} + \beta_2 \times lDutchTTF_t - \beta_3 \times lwind_t + \beta_4 \times lsolar_t + \varepsilon_t \quad (9)$$

Model 1 comprises 1st lag of the volatility measure, Dutch TTF prices, wind generation, and solar generation. We added the of the volatility measure, respectively. The primary purpose here is to measure the impact of solar and wind generation on the volatility of the market-clearing price.

3.5. EMPIRICAL RESULTS

3.5.1. Price level-Empirical Results

We used Knime 4.7.0 to generate machine learning analyses. We aggregated the data to generate the analysis. We showed descriptive statistics and variable graphs. Afterward, we generated machine learning methods and compared their results.

To find the best fitting model, the market clearing price model was run using different machine learning methods, such as 1st, 2nd, 3rd, 4th, 5th degree of polynomial learning, random forest learning, linear regression learning, simple regression learning, and tree ensemble learning. In these models shown in Table 9 and Figure 18, the dependent variable is the market clearing price, and the independent variables are the first lag of the market clearing price, Dutch TTF gas hub price, electricity demand, and electricity generation from solar and wind. After machine learning was learned with 90% of the data, model estimations were made with 10% of the partitioned data.

Table 9: Results of Different Machine Learning Methods

	Polynomial Learner- 2nd degree	Polynomial Learner- 3rd degree	Polynomial Learner- 4th degree	Random Forest Learner
R^2	0.93	0.87	0.87	0.88
MAE	4.2992	4.9564	5.0016	4.2528
MSE	38.0375	71.9425	72.6625	67.3452
RMSE	6.1675	8.4819	8.5242	8.2064
MAPE	0.1068	0.1162	0.1170	0.1030

	Linear Regression Learner	Simple Regression Learner	Tree Ensemble Learner
R^2	0.87	0.80	0.88
MAE	5.0072	5.7924	4.3134
MSE	77.4386	112.2004	67.2456
RMSE	8.7999	10.5925	8.2003
MAPE	0.1135	0.1489	0.1055

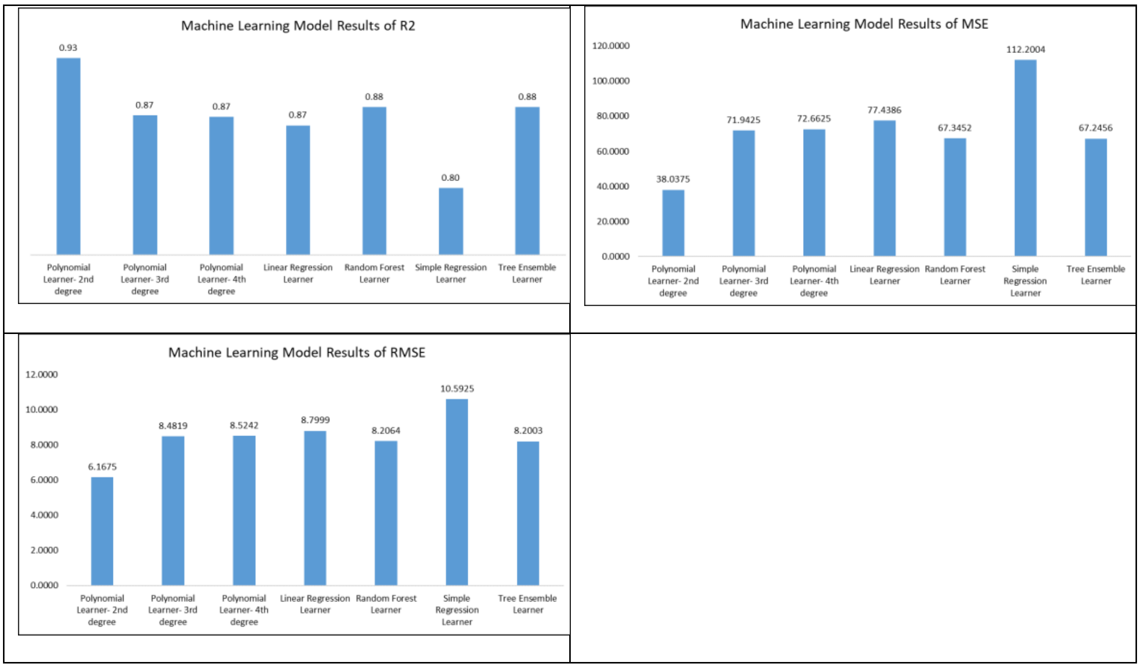

Figure 18: Results of Machine Learning Methods for Price Level

As seen in Table 9 and Figure 18, when the results of different methods are compared, 2nd order polynomial learning has the highest explanatory power (R^2). It gave the best results regarding the mean square error and root mean square Error. When a comprehensive comparison is made with other methods, it has been observed that the most successful method is 2nd-degree polynomial learning. In this context, the analysis continued with 2nd-degree polynomial learning.

Table 10 shows that market-clearing prices are positively correlated with their lags. Natural gas prices increase with market clearing prices, similar to lags in price. In Turkey, the natural gas cost reflects the market-clearing price due to the high share of natural gas in generation. Contrary to these, wind and solar generation decrease market-clearing prices with different coefficients.

Table 10: 2nd Order Polynomial Learning Model Results for Level of Market-clearing Price

MCP – LEARNING (%90)	Model 1	Model 2
lmcp(t-1)	0.44*** (0.03)	0.65*** (0.04)
lttf	0.24*** (0.02)	0.24*** (0.01)
ldemand	518.31** (155.51)	
lwind	-40.72*** (10.46)	-37.78*** (11.27)
lsolar	-1.22 (1.13)	-0.82 (0.92)
$lmcp(t-1)^2$	0.00 (0.00)	0.00 (0.00)
$lttf^2$	0.00 (0.00)	0.00 (0.00)
$ldemand^2$	50.08 (39.42)	
$lwind^2$	-7.42*** (1.61)	-6.55*** (1.73)
$lsolar^2$	-0.52* (0.27)	-5.15** (2.43)
Intercept	-1353.07* (801.66)	-42.26** (18.33)
R^2	0.90	0.93
Mean Absolute Error	4.4940	4.2992
Mean Squared Error	43.3732	38.0375
Root Mean Squared Error	6.5858	6.1675
Mean Absolute Percentage Error	0.1038	0.1068

Among six machine learning methods, 2nd degree polynomial learning methods gave the best results in R^2, mean absolute error, mean squared error, root mean squared error, and mean absolute percentage error. Therefore, after the 2nd order polynomial learning was chosen, the variables were analyzed with different configurations.

Two models utilizing 2nd-degree polynomial regression were constructed. In the first model, supply and demand are simultaneously present, allowing for the combined impact of supply and demand on market clearing price to be observed. In the second model, electricity demand was excluded, focusing solely on the supply-side effect. The second model yielded the most successful outcome, demonstrating an R^2 value of 0.93. With its higher explanatory power, the second model revealed a stronger supply-oriented effect on market clearing price. In this context, this chapter of the thesis emphasized policy recommendations concerning implementation of electricity generation from solar and wind energy.

Also, as seen in Table 10, the signs of the coefficients for the same variables in different models are the same, and the coefficients are close to each other for each independent variable. The results of the 2nd model were used when interpreting the coefficients. It is represented as;

$$volvar_t = 0.65 \times volvar_{t-1} + 0.24 \times Dutch\,TTF_t - 37.78 \times lwind_t - 6.55 \times lwind_t^2 - 5.55 \times lsolar_t^2 - 42.26 \quad (10)$$

As can be seen from the results, the market-clearing price was tied to its first lag by 0.65. With the Dutch TTF, it is seen that the increase in the Dutch TTF increases market-clearing price with a coefficient of 0.24. It has been observed that wind and solar generation reduce the market-clearing price. Wind generation has a reducing effect, with -37.78 at low demand levels and -6.55 at high demand levels. Solar generation has a price-reducing effect of -5.55 at high demand levels. Wind generation directly enters the merit order and has a price-reducing effect at low and high levels. The graphical representation of the model is shown in Figure 19.

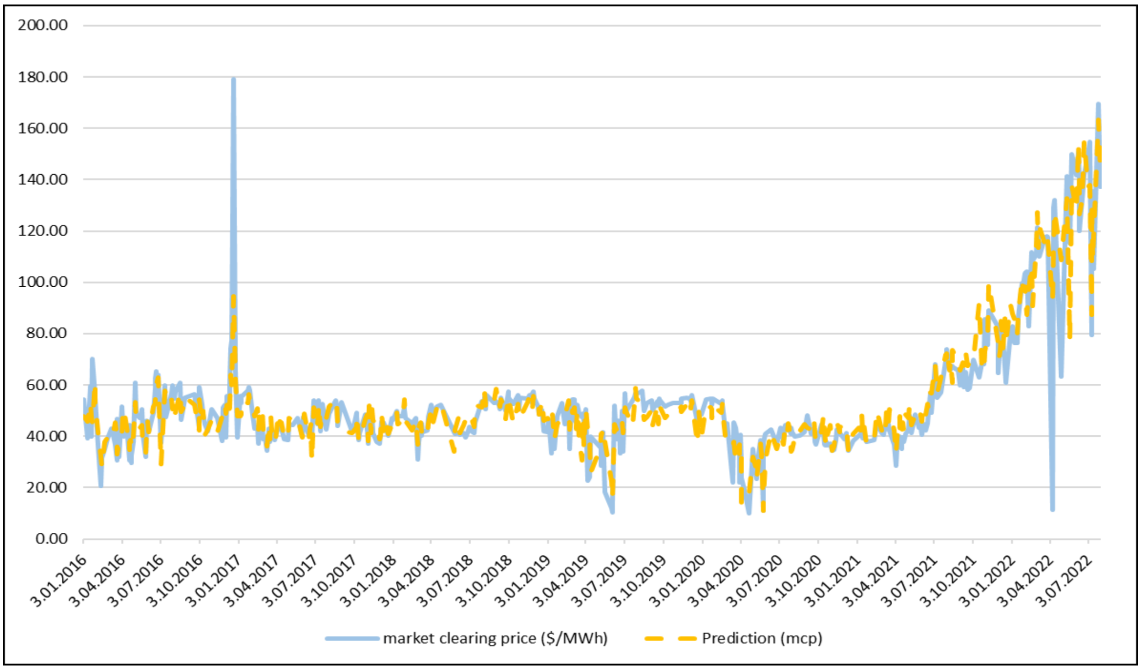

Figure 19: Polynomial Learner Forecast Results

As seen in Figure 20, the bidding types for wind and solar generation vary. While wind generation is immediately incorporated into the day-ahead market on the supply side, solar generation is integrated through the channels of retail companies.

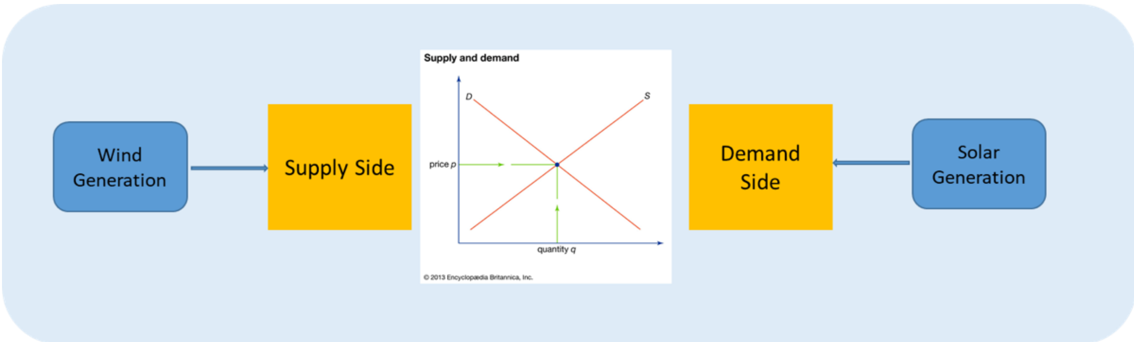

Figure 20: Wind and solar bids' entranceinto Turkey's wholesale electricity market. The Figure shows that wind energy enters the merit order from the supply side, and solar energy enters the merit order from the demand side.

The threshold demand level mentioned above is around 28.000 MWh for the low-demand period and 40.000 MWh for the high-demand period. This threshold is shown in Figure 21, and the relationship between supply and demand causes the effects of renewable resources to differ. This situation shows that the relationship between market clearing price and solar and wind generation varies across different demand levels. This aligns with the results of 2nd order polynomial learner model obtained from the analysis.

Rintamaki et al. (2017) demonstrated the volatility-reducing effect of solar energy in Germany using the SARMA model. Measuring this effect paved the way for our chapter to re-examine the impact of renewable generation on the market-clearing price. It is important to measure the same impact for Turkey and to look at the relationship between renewable energy and market-clearing price volatility in light of the distinctive features of Germany. The market-clearing price, shaped by the electricity market's demand and renewable generation conditions, reacts differently under changing demand conditions. We used a similar method to Rintamaki et al. (2017) for volatility and confirmed the results with a different method as a robustness check.

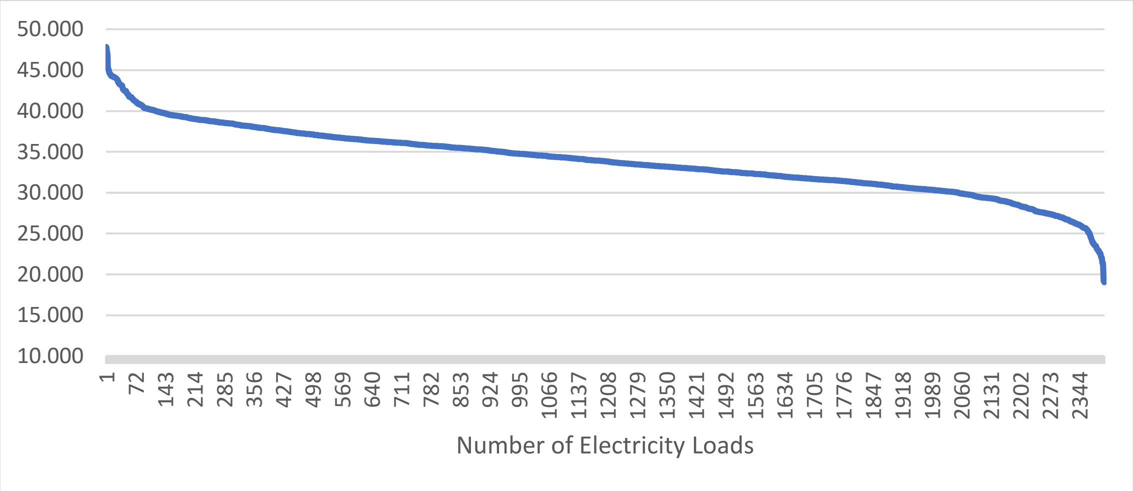

Figure 21: Electricity Load Curve in Turkey (MWh): In the graph, daily average electricity loads are classified from highest to lowest, named load curve. In this manner, we could observe the two break points in the load curve between 2016 and 2022. Source: https://seffaflik.epias.com.tr/transparency/

3.5.2. Price Volatility-Empirical Results

The results of the price volatility are represented in Tables 11 and 12. Similar to the price level analysis, we compared different machine learning methods such as polynomial learner, random forest learner, and tree ensemble learner. Table 11 and Figure 22 show the comparison of the results. 1st order polynomial learner gives the highest goodness of fit (R^2).

Table 11: Volatility Results of Different Machine Learning Methods

	1st order polynomial learner	Random Forest learner	Tree Ensemble learner
R^2	0.92	0.87	0.87
MAE	2.8950	2.8638	2.9046
MSE	23.2305	41.1295	41.0687
RMSE	4.8198	6.4132	6.4084
MAPE	5.5864	5.3894	5.5194

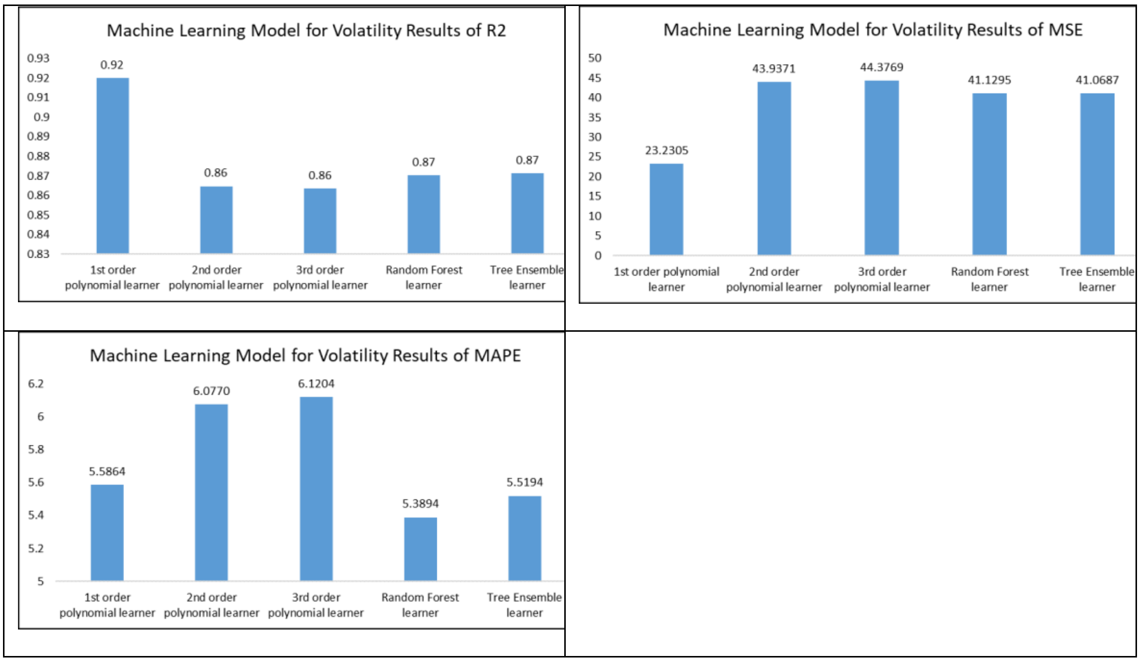

Figure 22: Volatility Results of Machine Learning Methods

Following the comparison of other machine learning methods, we focused on the 1st order polynomial learner. The best fitting model is the second one, consisting of the first lag of volatility (due to the autocorrelation 1 shown in Appendix 5), natural gas prices, solar generation, and wind generation. In Model 1 of Table 12, it is observed that volatility highly depends on its first lag. Natural gas price increases volatility. Wind generation increase volatility with uncertain generation. Solar generation decreases volatility since the solar generation pattern is predictable. Solar energy generation magnifies changes depending on the day or climate, but predicting the intraday pattern is easier as it rises in the morning hours and decreases in the afternoon until the evening. The model results differ for uncertain wind generation compared to solar generation.

Table 12: 1st Order Polynomial Learning Model Results for Volatility of Market-

clearing Price

Volatility of MCP – LEARNING (%90)	Model 1
volvar(t-1)	0.63*** (0.02)
lDutch ttf	0.04*** (0.00)
lwind	0.69** (0.13)
lsolar	-0.83*** (0.10)
Intercept	2.44* (1.39)
R^2	0.92
Mean Absolute Error	2.8950
Mean Squared Error	23.2305
Root Mean Squared Error	4.8198
Mean Absolute Percentage Error	5.5864

***** denotes significance in %1, ** denotes significance in %5, * denotes significance in %10 confidence interval.**

As seen in Table 12, The Model using volvar(t-1), Dutch TTF, wind and solar generation data yielded 0.92 R^2 with 1st degree polynomial learning. The coefficient results of the other models in the Table 10 were similar to Model 1. In Model 1, Dutch TTF and wind generation variables increased volatility with coefficients of 0.04 and 0.69; solar generation reduced volatility with a coefficient of 0.83. It has the lowest mean squared error and root mean square error. If we compare the coefficients, it is observed that wind generation increases volatility with a high coefficient.

Solar generation decreases volatility with a higher coefficient than wind generation. While the irregularity of wind generation increases market-clearing price volatility. The fact that solar generation is more predictable. It comes into play at certain hours. In these hours, the electricity supply certainly has predictable solar generation.

Contrary to its volatility, solar generation is a forecastable process. Solar generation reduces the electricity market-clearing price volatility. Model 1 is denoted as;

$$Volvar_t = 0.63 \times Volvar_{t-1} + 0.04 \times Dutch\,TTF_t - 0.69 \times \mathrm{l}wind_t - 0.83 \times \mathrm{l}solar_t\ 6.55 + 2.44 \tag{21}$$

The graphical representation of the model is shown in Figure 23.

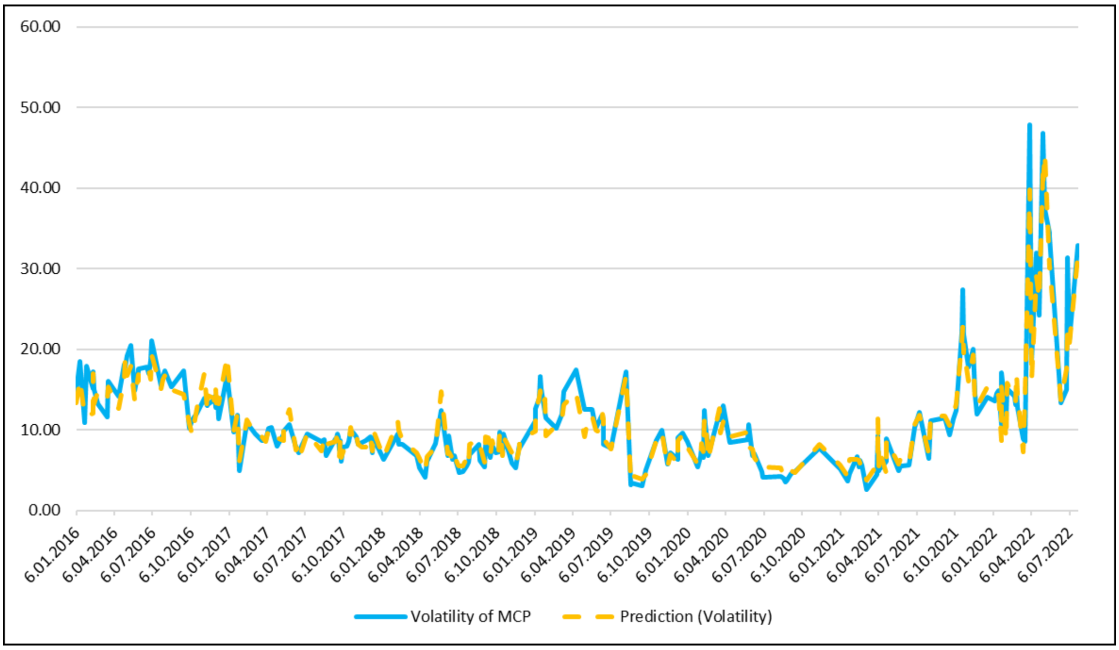

Figure 23: Volatility - Polynomial Learner Forecast Results

3.6. ROBUSTNESS

For cross-validation, the same models were re-estimated for the price level using the 2nd-degree polynomial learning method, with learning levels of 80/20% (Appendix 6) and 70/30% (Appendix 7). We examined the models' and coefficients' validity. As can be seen from the results, the signs of the coefficients are the same, and the results have high significance and model explanatory power. This confirms that the two models studied in the main table are significant. Similarly, for volatility, learning levels of 80/20 (Appendix 8) and 70/30 (Appendix 9) were re-run in the models, and consistent results were found. Dutch TTF and wind generation increase the volatility of the market-clearing price, while solar generation reduces it. As an alternative method for calculating volatility, the variable Vold is defined.

$$Vold_d = max\{P_{t+23}, \dots, P_t\} - min\{P_{t+23}, \dots, P_t\} \quad (22)$$

Similar results were obtained in the analyzes using this variable. Model 1 explanatory power is 0.90 at the 90/10 (Appendix 10) learning level in second-order polynomial learning. Cross-validation shows that the explanatory power of models differed by only 1 percent at the learning levels of 80/20 (Appendix 11) and 70/30 (Appendix 12). We saw that the solar and wind generation coefficients are at the same level with a one percentage point confidence interval. The second-order polynomial learning method is well-fitted for the variables in light of the results. Similar to explanatory power, we observed little difference across models in the mean absolute error, mean squared error, root mean squared error, and mean absolute percentage error. Table 13 provides a comparative table of explanatory power for several models. A considerable degree of similarity is present, as this table demonstrates.

Table 13: Comparison of Explanatory Powers of Price Level Models

R^2 (Explanatory Power) of the Comparison of Market Clearing Price Models			
	Main Model Results (90/10 Learning Level)	Robustness 1 (80/20 Learning Level)	Robustness 2 (70/30 Learning Level)
Model 1	0.93	0.79	0.89
Model 2	0.90	0.92	0.91

In this chapter, we did the cross-validation of volatility models by putting together the 80/20% and 70/30% learning levels of first-degree polynomial learning and a new volatility measure used in the literature. The 80/20% and 70/30% learning levels of the polynomial learning model and the new volatility measure provided similar results, showing that the main models are correct. The explanatory power of these models is displayed in Table 14.

Table 14: Explanatory Power Comparison of Volatility(variance) Models

R^2 (Explanatory Power) of the Comparison of $Volatility_{var}$ Models			
Volatility Variance Measure			
	Main Model Results (90/10 Learning Level)	Robustness 1 (80/20 Learning Level)	Robustness 2 (70/30 Learning Level)
Model 1	0.92	0.91	0.86
R^2 (Explanatory power) of the Comparison of $Volatility_d$ Models			
	Main Model Results (90/10 Learning Level)	Robustness 1 (80/20 Learning Level)	Robustness 2 (70/30 Learning Level)
Model 1	0.89	0.82	0.72

According to the results, no differences have been observed as a result of analyses conducted with different learning ratios[23]. As a result, models consistently show the

[23] Learning ratio refers to the rate that the data used to learn the model. For example: 90/10 refers to 90% of data is used to find coefficients and 10% of the data is used to test the model. 80/20 refers to 80% of data is used to find coefficients and 20% of the data is used to test the model. 70/30 refers to 70% of data is used to find coefficients and 30% of the data is used to test the model.

connection between renewable energy generation and the market-clearing price. The robustness of the models is demonstrated by the fact that their explanatory power remains constant across varying learning levels.

3.7. CONCLUSION AND POLICY RECOMMENDATIONS

The importance of solar and wind energy for climate change has increased the use of renewable resources in electricity generation. Incorporating these resources into the electricity market has far-reaching consequences. Solar and wind power plants have an impact on market-clearing price as well as the grid. The chapter investigates the impact of renewable energy generation on market clearing priceand price volatility in the Turkish electricity market. This chapter also reveals the differences of those effects between electricity generations from solar and wind.

In this chapter, we compared several artificial intelligence methods and found the polynomial learning method to be the best fitting one. Using the polynomial learning method, it is found that electricity generation from wind and solar sources reduces the market-clearing price. Electricity generation from wind reduces the market-clearing price. This results of the study also suggest that the impact of solar and wind on the market-clearing price varies depending on the demand level. Wind generation affects the price more at low electricity demand levels and less at high demand levels. Increasing solar generation at certain times of the day is effective at meeting the high demand level.

The impact of renewable energy on the price volatility of the Turkish electricity market is also examined in this chapter. The results indicate that the impacts of wind and solar generation on price volatility differ. While wind energy increases volatility, solar energy reduces volatility. This might be because their generation patterns are different (Alsaedi et al. (2020); Keeley et al., 2020). Solar energy enters the day-ahead market with a regular pattern and reduces volatility. The irregularity of wind energy might be the reason for the increase in price volatility.

Policy offers for Turkey have been provided due to the reducing impact of renewable energy on prices and its environmental benefits. Policy recommendations are listed below:

-Policy makers should provide a consistent and predictable regulatory process, so that investors do not face unceratinties about investment environment in wind and solar power. The findings of the chapter highlight the merit order effect of investments in wind and solar energy. Due to the intermittent nature of renewable energy investment programs in Turkey, which occurred in 2007, 2015, and 2022, their effects have been discontinuous as investors adjust their behavior to regulatory policy. To ensure consistent and continuous effects, the EMRA should have clear and well-defined rules about wind and solar investments to reduce uncertainties and improve efficiency in the market. This approach will have a positive impact on market-clearing prices by smoothing the effects of renewables. Increasing investments in solar and wind power is crucial for Turkey to fully utilize its high potential in renewable energy (Esmap, 2019).

-Regulation authorities should eliminate incentive mechanisms that encourage inefficient investments in the wind and solar sectors by implementing competitive support schemes. Competitive support mechanisms play a significant role in the implementation of renewable energy. Three prominent support mechanisms are feed-in tariffs, feed-in premiums, and contracts for difference. Firstly, feed-in tariffs can effectively reduce wholesale electricity prices (Ciarreta, 2020). Secondly, compared to feed-in tariffs, market-oriented approaches like feed-in premiums may provide fewer benefits to investors during the implementation of renewables in the market (Winkler, 2016). The rents created by inefficient support schemes artificially increase market prices and create welfare losses. Thirdly, a frequently employed separate support mechanism is the contract for difference. Individual long-term conracts with fixed prices also distort market efficiency. In sum, implementing the competitive support schemes, such as feed-in-premium (Purkus et al., 2015), helps create a more competitive market and mitigates the negative impact reflected in prices.

-Policymakers should increase investment in hybrid power generation and energy storage to increase the contribution of solar and wind to base-load electricity generation. Encouraging hybrid power generation eases the intermittency problem and reduces the market volatility effect of renewables. The addition of storage facilities next to solar and wind generation plants would also help intermittency problem. In this way, regulatory authorities can use storage as a complementary tool to mitigate volatility in the market. So, through the baseload power generation pattern, a competitive market-clearing price can be achieved.

-Regulatory authorities should encourage large-scale wind generation power plants as they contribute more to the market from the supply side. Support schemes for solar generation should focus on the demand side contribution of distributed solar generation. In this way, wind energy investments can be directed toward large-scale power plants, and solar can be more efficiently used as a small-scale distributed generation source. For example, during peak usage of air conditioning in the summer at noon, when solar generation is also high, the peak electricity demand remains stable. Balancing supply and demand beyond the meter reduces the burden on the market at peak times. The stability of peak demand prevents the disruption of market-clearing prices.

The implementation of these policy recommendations by decision-makers and market players would incentivize a well-functioning electricity market market.

CONCLUSION

In the past three decades, there has been a noteworthy shift in both demand and supply dynamics within the power market. It has transitioned from a vertically integrated structure to a deregulated framework where markets are segmented. Throughout this change, various challenges and the integration of renewable energy generation have emerged. This thesis examines the problems faced by the wholesale electricity market and investigates the impact of renewable energy generation on market clearing prices.

In first chapter, the major relations between the problems are revealed together with their aspects. Supply inadequacy problem is emerged from inefficient regulation and governance, inefficient pricing, volatility of market, missing money, and intermittent renewables problems. Supply inadequacy problem causes market power. This problem is one of the oldest problems of the electricity market and prevents the formation of a well-functioning electricity market. In the electricity market, the inadequacy of generation resources basically causes the problem of not being able to meet the electricity demand. Secondly, inefficient regulation and governance, inefficient pricing, and intermittent renewables problems cause the missing money problem, which draws attention in the supply industry. This problem leads to generation inadequacy. Investments in the supply industry sector should provide a return with reasonable profits, whether they are made by the state or by the private sector actors. To the extent that the investor cannot find the reasonable profit rate, the problem of missing money arises. It is remarkable that the generation of intermittent renewables reveals this problem by creating price volatility. Inefficient regulation and governance, supply inadequacy, and transmission congestion issues result in market power. It has been noted that supply inadequacy plays an important role in the formation of market power as well as poor governance. The intermittent renewable problem, which can occasionally arise due to the transmission congestion issue, has dominated recent years primarily because of the characteristics of the resource.

The first chapter proposes a holistic perspective for the problems of the wholesale electricity market. The identified findings will offer two significant contributions to market participants. One of the contributions of this chapter is the policymaker's potential to establish a comprehensive and inclusive policy in the policies they will formulate in the future. Secondly, due to the comprehensive perspective of the policymaker, the market will operate more efficiently, thereby enhancing market efficiency and effectiveness for private sector actors.

In the second chapter of the thesis, the merit order effect of renewable energy on the market clearing price is analysed by using a panel data from 25 European countries. The significance of decarbonizing energy systems has increased with the climate change and rise in carbon emissions. With the new technological development, renewable energy sources are now more prominent in the electricity market than fossil fuels like coal and natural gas, which have substantial carbon emissions. In this thesis, a cross-country analysis of 25 countries reveals the impact of intermittent renewables on the market clearing price. Since renewable energy investments around the world have accelerated in recent years, the period between 2016 and 2022 has been studied.

In the second chapter, it is highlighted that in an environment marked by carbon emissions and the deepening climate crisis, the price-reducing effect of renewable energy could indeed have long-term and even far-reaching prosperity implications. Without a doubt, in our view, this situation necessitates, even compels, a holistic perspective as proposed in the first chapter. Therefore, the perspective put forth in the first chapter serves as a comprehensive backdrop for the findings reached in the second section.

In the third chapter, we focus on the case of Turkey because Turkey is the 7th largest trade partner of Europe and holds the most significant candidate position for European Union membership. The results of the third chapter show that similar to the EU, renewable energy generation in Turkey also contributes to reducing the market clearing price through merit order effect. This chapter explains the differences arising from the entry of solar generation on the demand side and wind energy bids on the supply side. We also find that wind energy reduces market clearing prices more than solar energy. On the other hand, wind energy increases price volatility. Solar energy does, however, lessen the volatility of market clearing prices. It has been observed that the effect on price level and volatility differs at high and low electricity demand levels. These findings indicate the necessity of approaching the holistic perspective proposed in the first chapter in a dynamic and proactive manner.

Moreover, the simultaneous integration of a large number of renewable energy power plants into the electrical system will pose a threat to the system's robust operation. Therefore, the strategic planning and phased deployment of renewable energy power plants will ensure the effective operation of the system (Griffiths, 2017). In this context, integrating multi-year allocation in the determination of renewable capacity during the auction process would ensure the continuous and smooth execution of projects over time.

This thesis has some limitations. Firstly, we focus on the primary or most commonly encountered supply industry issues among the many problems in the electricity market. Secondly, due to a lack of available data, the analysis excludes some European Union countries. Thirdly, the thesis does not explore the effects of support mechanisms for renewable energy. Lastly, the analysis do not take into account the limitations caused by the electrical grid. In future work, similar to the supply industry problems, a comprehensive perspective can be adopted to examine problems in the segments of regulation and governance, demand, and networks. Other countries can be analyzed using a model similar to that applied to European countries and Turkey. Additionally, future studies can be conducted using different econometric and machine learning methods.

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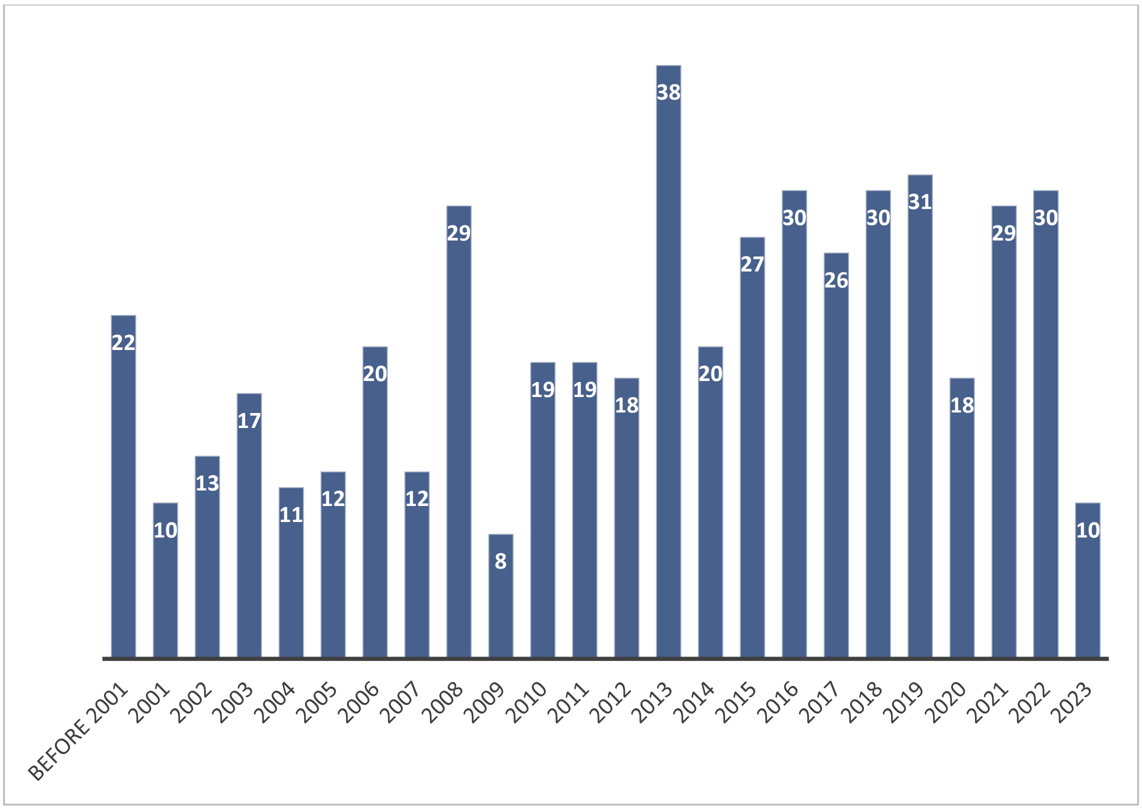
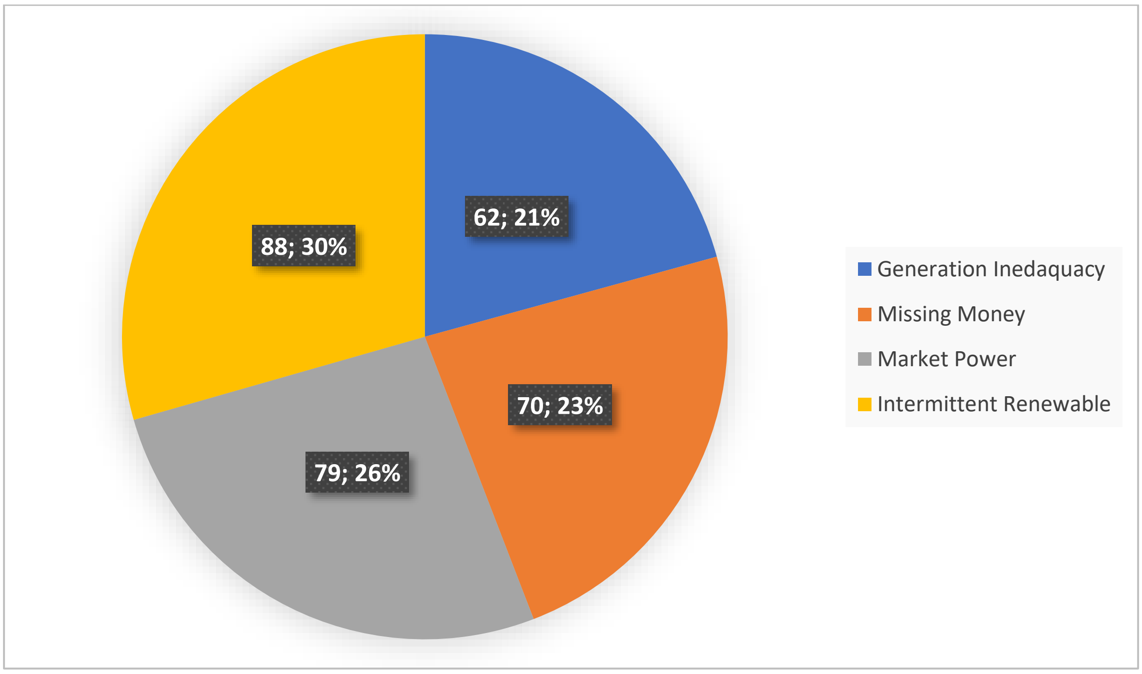
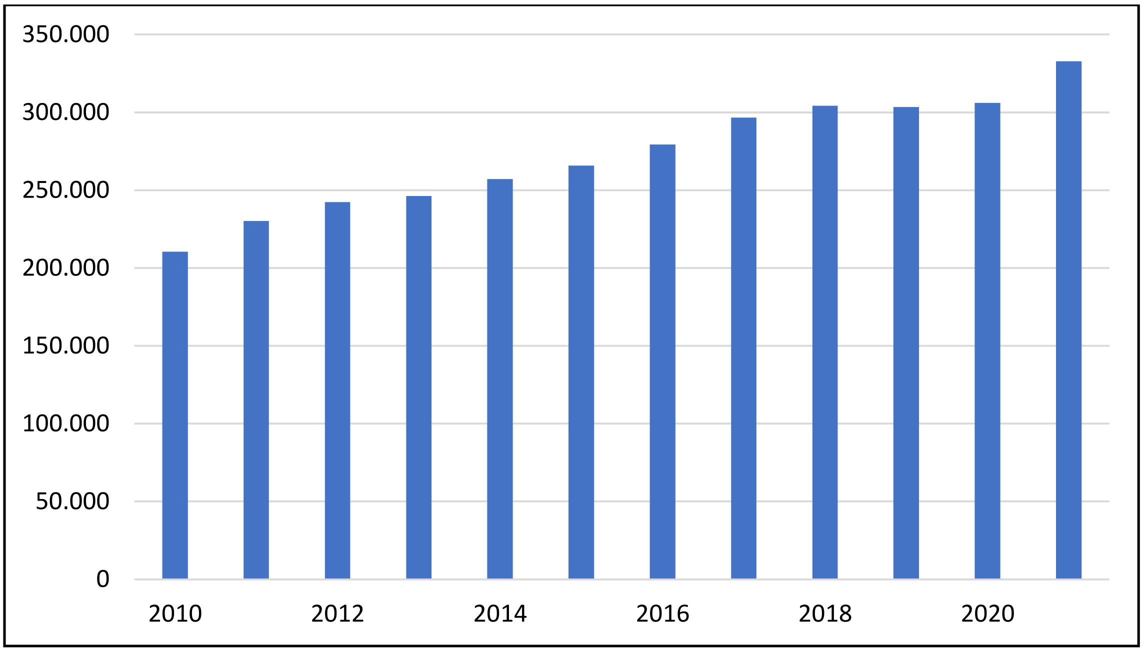
APPENDIX 1: ARTICLES BY PUBLICATION YEARS



APPENDIX 2: DISTRIBUTION OF PUBLICATIONS BY PROBLEMS



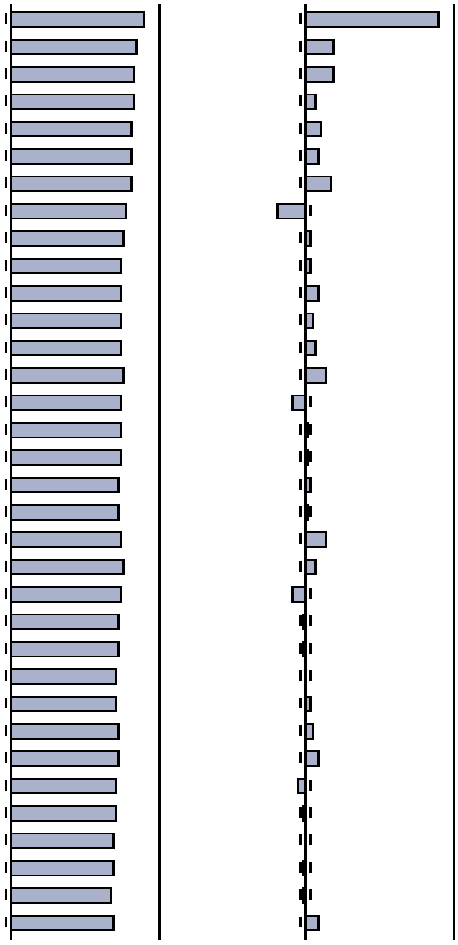
APPENDIX 3: ELECTRICITY DEMAND INCREASE IN LAST TEN YEARS (GWH)



Source: http://emra.gov.tr/

APPENDIX 4: AUTOCORRELATION AND CORRELOGRAM RESULTS OF THE MARKET CLEARING PRICE

Date: 11/20/22 Time: 14:23
Sample: 1 2404
Included observations: 2404

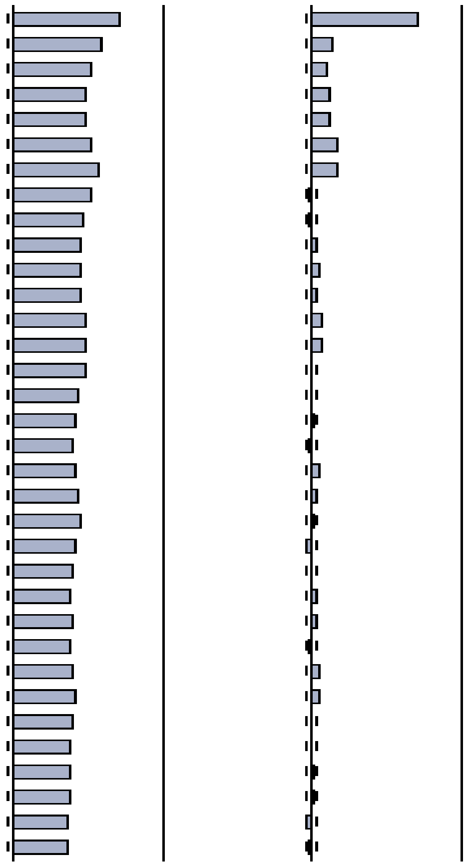


	AC	PAC	Q-Stat	Prob
1	0.931	0.931	2084.8	0.000
2	0.892	0.190	3999.1	0.000
3	0.874	0.192	5838.1	0.000
4	0.855	0.078	7601.8	0.000
5	0.844	0.104	9319.3	0.000
6	0.838	0.098	11012.	0.000
7	0.846	0.187	12738.	0.000
8	0.813	-0.203	14335.	0.000
9	0.795	0.028	15860.	0.000
10	0.786	0.027	17353.	0.000
11	0.782	0.087	18829.	0.000
12	0.779	0.048	20297.	0.000
13	0.780	0.081	21770.	0.000
14	0.795	0.139	23301.	0.000
15	0.777	-0.086	24762.	0.000
16	0.766	0.023	26184.	0.000
17	0.763	0.013	27595.	0.000
18	0.761	0.037	28998.	0.000
19	0.760	0.023	30398.	0.000
20	0.772	0.152	31845.	0.000
21	0.788	0.067	33352.	0.000
22	0.768	-0.097	34785.	0.000
23	0.755	-0.024	36170.	0.000
24	0.748	-0.014	37530.	0.000
25	0.741	-0.006	38867.	0.000
26	0.740	0.035	40199.	0.000
27	0.747	0.054	41555.	0.000
28	0.761	0.087	42966.	0.000
29	0.744	-0.065	44313.	0.000
30	0.730	-0.018	45612.	0.000
31	0.724	-0.006	46890.	0.000
32	0.717	-0.018	48145.	0.000
33	0.712	-0.012	49383.	0.000
34	0.722	0.088	50655.	0.000

APPENDIX 5: AUTOCORRELATION AND CORRELOGRAM RESULTS OF VOLATILITY OF THE MARKET CLEARING PRICE

Date: 11/20/22 Time: 14:28
Sample: 1/01/2016 7/31/2022
Included observations: 2404

Autocorrelation | Partial Correlation



	AC	PAC	Q-Stat	Prob
1	0.737	0.737	1308.0	0.000
2	0.608	0.142	2198.7	0.000
3	0.534	0.100	2885.5	0.000
4	0.508	0.127	3507.5	0.000
5	0.508	0.131	4130.2	0.000
6	0.545	0.188	4847.5	0.000
7	0.587	0.182	5678.4	0.000
8	0.545	-0.012	6396.7	0.000
9	0.491	-0.018	6978.3	0.000
10	0.464	0.035	7497.8	0.000
11	0.462	0.059	8014.0	0.000
12	0.466	0.041	8538.6	0.000
13	0.494	0.079	9128.1	0.000
14	0.516	0.067	9771.8	0.000
15	0.494	0.003	10362.	0.000
16	0.459	0.000	10872.	0.000
17	0.438	0.013	11337.	0.000
18	0.418	-0.019	11760.	0.000
19	0.436	0.063	12221.	0.000
20	0.457	0.038	12727.	0.000
21	0.463	0.011	13247.	0.000
22	0.430	-0.043	13695.	0.000
23	0.402	-0.008	14087.	0.000
24	0.399	0.039	14474.	0.000
25	0.404	0.034	14870.	0.000
26	0.401	-0.016	15261.	0.000
27	0.425	0.046	15699.	0.000
28	0.441	0.047	16173.	0.000
29	0.423	0.004	16609.	0.000
30	0.399	-0.003	16997.	0.000
31	0.390	0.011	17369.	0.000
32	0.390	0.014	17739.	0.000
33	0.376	-0.027	18084.	0.000
34	0.378	-0.008	18433.	0.000

APPENDIX 6: ROBUSTNESS CHECK 2ND ORDER POLYNOMIAL LEARNING MODEL RESULTS FOR LEVEL OF MARKET-CLEARING PRICE (%80/20 LEARNING RATIO)

MCP – LEARNING(%80)	Model 1	Model 2
mcp(t-2)		
mcp(t-1)	0.47*** 0.04)	0.80*** (0.04)
ttf	0.25*** (0.02)	0.19*** (0.02)
demand	858.43** (412.03)	
wind	-36.79*** (10.88)	-37.80*** (11.40)
solar	-1.85 (1.30)	-0.93 (0.91)
$mcp(t-2)^2$		
$mcp(t-1)^2$	0.00 (0.00)	0.00 (0.00)
ttf^2	0.00 (0.00)	0.00 (0.00)
$demand^2$	88.09* (45.66)	
$wind^2$	-6.73*** (1.68)	-6.49*** (1.75)
$solar^2$	-0.55* (0.29)	-5.34** (2.45)
Intercept	-2109.54** (929.44)	-48.02** (18.58)
R^2	0.91	0.79
Mean Absolute Error	4.3930	5.0884
Mean Squared Error	41.8719	95.1032
Root Mean Squared Error	6.4709	9.7521
Mean Absolute Percentage Error	0.1008	0.1295

*** denotes significance in %1, ** denotes significance in %5, * denotes significance in %10 confidence interval.

APPENDIX 7: ROBUSTNESS CHECK 2 - 2ND ORDER POLYNOMIAL LEARNING MODEL RESULTS FOR LEVEL OF MARKET-CLEARING PRICE (%70/30 LEARNING RATIO)

MCP – LEARNING(%70)	Model 1	Model 2
mcp(t-2)		
mcp(t-1)	0.45*** (0.04)	0.62*** (0.04)
ttf	0.26*** (0.02)	0.23*** (0.02)
demand	667.10** (212.31)	
wind	-47.31*** (12.13)	-44.83*** (12.08)
solar	-1.10 (1.22)	-0.39 1.02)
mcp(t-2)2		
mcp(t-1)2	0.00 (0.00)	0.00 (0.00)
ttf2	0.00 (0.00)	0.00 (0.0)
demand2	66.57 (45.73)	
wind2	-8.46*** (1.87)	-7.63*** (1.86)
solar2	-0.76** (0.33)	-6.02* (3.10)
Intercept	-1699.50* (929.41)	-52.71** (19.58)
R2	0.92	0.89
Mean Absolute Error	4.6573	4.9967
Mean Squared Error	55.3352	71.3842
Root Mean Squared Error	7.4388	8.4489
Mean Absolute Percentage Error	0.0946	0.1236

***** denotes significance in %1, ** denotes significance in %5, * denotes significance in %10 confidence interval.**

APPENDIX 8: ROBUSTNESS CHECK 1 - 1ST ORDER POLYNOMIAL LEARNING MODEL RESULTS FOR VOLATILITY OF MARKET-CLEARING PRICE (%80/20 LEARNING RATIO)

Volatility of MCP – LEARNING(%80)	Model 1
volvar(t-1)	0.61*** (0.02)
ttf	0.04*** (0.00)
wind	0.85* (0.45)
solar	-0.87*** (0.11)
Intercept	2.13 (1.47)
R2	0.91
Mean Absolute Error	2.8305
Mean Squared Error	22.3357
Root Mean Squared Error	4.7261
Mean Absolute Percentage Error	3.3345

***** denotes significance in %1, ** denotes significance in %5, * denotes significance in %10 confidence interval.**

APPENDIX 9: ROBUSTNESS CHECK 2 - 1ST ORDER POLYNOMIAL LEARNING MODEL RESULTS FOR VOLATILITY OF MARKET-CLEARING PRICE (%70/30 LEARNING RATIO)

Volatility of MCP – LEARNING(%70)	Model 1
volvar(t-1)	0.61*** (0.02)
ttf	0.05*** (0.00)
wind	0.72** (0.49)
solar	-0.82*** (0.12)
Intercept	2.33 (1.60)
R2	0.86
Mean Absolute Error	2.9394
Mean Squared Error	24.0759
Root Mean Squared Error	4.9067
Mean Absolute Percentage Error	2.5750

***** denotes significance in %1, ** denotes significance in %5, * denotes significance in %10 confidence interval.**

APPENDIX 10: ROBUSTNESS CHECK 3 - 1ST ORDER POLYNOMIAL LEARNING MODEL RESULTS FOR DIFFERENT VOLATILITY OF MARKET-CLEARING PRICE (%90/10 LEARNING RATIO)

Volatility of MCP – LEARNING(%90)	Model 1
vold(t-1)	0.55*** (0.02)
ttf	0.17*** (0.01)
wind	3.64** (1.45)
solar	-3.72*** (0.36)
Intercept	7.41 (4.72)
R2	0.89
Mean Absolute Error	10.0323
Mean Squared Error	215.4822
Root Mean Squared Error	14.6793
Mean Absolute Percentage Error	0.4269

***** denotes significance in %1, ** denotes significance in %5, * denotes significance in %10 confidence interval.**

APPENDIX 11: ROBUSTNESS CHECK 4 - 1ST ORDER POLYNOMIAL LEARNING MODEL RESULTS FOR DIFFERENT VOLATILITY OF MARKET-CLEARING PRICE (%80/20 LEARNING RATIO)

Volatility of MCP – LEARNING(%80)	Model 1
vold(t-1)	0.54*** (0.02)
ttf	0.18*** (0.02)
wind	4.49*** (1.50)
solar	-3.82*** (0.38
Intercept	5.09 (4.92)
R2	0.82
Mean Absolute Error	9.8376
Mean Squared Error	271.3395
Root Mean Squared Error	16.4724
Mean Absolute Percentage Error	0.5088

***** denotes significance in %1, ** denotes significance in %5, * denotes significance in %10 confidence interval.**

APPENDIX 12: ROBUSTNESS CHECK 5 - 1ST ORDER POLYNOMIAL LEARNING MODEL RESULTS FOR DIFFERENT VOLATILITY OF MARKET-CLEARING PRICE (%70/30 LEARNING RATIO)

Volatility of MCP – LEARNING(%70)	Model 1
vold(t-1)	0.55*** (0.02)
ttf	0.18*** (0.02)
wind	3.09* (1.57)
solar	-3.45*** (0.39)
Intercept	8.12 (5.10)
R2	0.72
Mean Absolute Error	10.3210
Mean Squared Error	351.2228
Root Mean Squared Error	18.7409
Mean Absolute Percentage Error	0.6026

***** denotes significance in %1, ** denotes significance in %5, * denotes significance in %10 confidence interval.**

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Date and Signature

Name Surname:	Mustafa Çağrı PEKER
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Department:	Economics
Program:	Economics - Eng
Status:	☐ MA ☒ Ph.D. ☐ Combined MA/ Ph.D.

ADVISER COMMENTS AND APPROVAL

Prof. Dr. Ayşen SİVRİKAYA

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TEZ ÇALIŞMASI ETİK KOMİSYON MUAFİYETİ FORMU

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SOSYAL BİLİMLER ENSTİTÜSÜ
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ADVISOR APPROVAL

APPROVED.

Prof. Dr. Ayşen SİVRİKAYA

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Tarih: 18/09/2023

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Tarih ve İmza

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Prof. Dr. Ayşen SİVRİKAYA