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Risks and Risk Management in the Renewable Energy Transition

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ABSTRACT:

Vihreän siirtymän kriittisyys on kerännyt kasvavaa huomiota viime vuosikymmenten aikana, minkä takia myös uusiutuvan energian tuotantotavat ovat keränneet kasvavaa huomiota. Uusiutuva energia on kasvattanut markkinaosuuttaan merkittävästi viime vuosikymmenten aikana, mikä on myös kasvattanut sen kiinnostavuutta tutkimuskohteena. Uusiutuvan energian ominaisuudet poikkeavat kuitenkin merkittävästi perinteisistä fossiilisista energialaitoksista, minkä integrointi nykyiseen markkinainfrastruktuuriin voi olla fundamentaalisesti haastava prosessi. Tämä integrointi epäoptimoituun markkinainfrastruktuuriin voi aiheuttaa huomattavia riskejä uusiutuvan energian hankkeille, joille fossiiliset tuotantolaitokset eivät altistu. Tämän tutkielman tarkoitus on tunnistaa nämä riskit talousteorian mallien ja akateemisen kirjallisuuden pohjalta ja tutkia, mikäli nämä riskit voidaan observoida jo nykyisessä Euroopan sähkömarkkinassa. Lisäksi tämä tutkielma pyrkii tutkimaan rahoitusjohdannaisia ja julkisia kannustimia, joilla uusiutuvan energian hankkeet voivat minimoida näiden riskien vaikutuksen hankkeen kannattavuuteen.

KEYWORDS: Renewable energy, Energy Transition, Electricity markets, Price volatility, Systematic risk, Negative prices

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1 Introduction

1.1 Purpose of the study

Historically, after the Industrial Revolution at the end of the 18th century, the global economy depended on fossil fuels to power rapid economic growth. Moving from coal, wood, and crop waste to oil and gas at the turn of the 20th century further accelerated the development of the global economy. However, the negative side of fossil fuels, creating substantial amounts of greenhouse gases, has caused a relatively new phenomenon known as global warming.

The urgency of the green transition is undeniable, and great strides towards it have already been taken. Environmental concerns and thus increasing regulatory actions in the energy market are the driving forces for change (Conlon et al., 2024, p. 1). As of 2020, the most significant single factor of greenhouse gases was energy production, of which three-quarters were met with fossil fuels. However, increasing environmental concerns have driven research for more sustainable energy production practices (Ritchie & Rosado, 2024).

Most common renewable energy production methods in Europe, as of 2019, including hydro, solar, and wind power, all harvest energy directly from nature and, as such, their production is affected by changes in environmental conditions (European Commission, 2021). This, among other characteristics, creates a unique set of variables when they operate in a market system initially designed for traditional power plants.

The integration of weather-based production methods into the existing market infrastructure is a relatively new phenomenon and thus has been the subject of a wide range of studies. The theoretical framework of the subject suggests that renewable projects may face substantial competitive disadvantages compared to traditional power plants, thereby creating risks that conventional power plants do not face. The key point of this study is to identify the risks suggested by the macroeconomic theoretical framework during the transition period and to investigate whether those risks have been realized in practice. To limit the scope, this thesis focuses mainly on two key characteristics of renewable energy. The focus points in this thesis are production variability and production predictability in the European energy market system and the corresponding risks created by these characteristics.

1.2 Structure of the Study

This thesis focuses to investigate the integration process of renewable energy characteristics into the current European electricity infrastructure and the key market risks that an unoptimized electricity market can create to renewable projects. Furthermore, after outlining these risks, the thesis strives to evaluate the adequacy of governmental support schemes and whether if these risks can be mitigated with financial tools available in the market.

To reform this into research questions: How does the integration of renewable characteristics contribute to the risk of increased price volatility in the electricity market, and what are the implications of this risk for renewable energy projects? Furthermore, to what extent can such volatility be mitigated through financial instruments or governmental support schemes for renewable energy projects to minimise the effect of these risks?

The first hypothesis of this thesis can be formulated as follows. Given the changing market system and the inelastic nature of electricity, there is a risk that price volatility will temporarily increase during the transition, affecting renewable projects more than traditional power plants due to their production variability. Historically, the grid infrastructure has not needed to store large amounts of electricity, as conventional power plants can be adjusted more easily to meet demand. However, as new production methods enter the market in large quantities that lack this feature, they must compete in an unoptimized market system, which can be expected to create challenges until the market system and grid infrastructure have time to adapt.

Renewable projects, especially wind and solar, are highly weather-dependent and require suitable conditions to produce electricity efficiently; thus, they are typically at peak efficiency during periods of high supply. According to supply and demand theory, when renewable projects can efficiently produce electricity, the electricity price is keen to fall as the supply increases. Thus, the renewable energy sources are more likely to be negatively affected by the price fluctuations than traditional power plants.

The second hypothesis in this thesis focuses on the risks created by the difficulty of accurately predicting the production of renewable projects. Historically, the predictability of renewable energy sources has been more challenging to forecast than that of traditional power plants. The adaptation of this trait to the current market system can also disadvantage renewable energy sources, leading to higher imbalance fees. As the current market system is structured to match future supply and demand through progressively more accurate marketplaces as the delivery time approaches, forecasting errors in the day-ahead market can lead to substantial imbalance fees in the balancing markets.

Regarding the third and final hypothesis, given that the electricity market is one of the largest commodity markets, these risks should already be addressed to some extent. Even though such risks are systematic and cannot be eliminated through diversification, the market scale suggests that appropriate financial instruments should be available to mitigate these risks. Furthermore, as the energy transition is also in the interest of governmental institutions, corresponding policies should be implemented to further reduce the impact of these risks and promote the energy transition as a macroeconomic trend.

2 Theoretical Framework

2.1 Status of energy transition

The global shift from carbon-based energy production has accelerated over the past two decades (Bains et al., 2023, p. 36). The need for an energy transition is scientifically indisputable, as its achievement is directly tied to environmental well-being. Global warming's impact can be extensive, even leading to the extinction of many animal and plant species and disrupting entire ecosystems.

According to IPCC, the Intergovernmental Panel on Climate Change, even a 1,5% increase in global temperature can cause extreme weather phenomena and the corruption of current ecosystems. In more recent studies, these thresholds were observed to be lower than previously assumed (O’Neal et al., 2022, p. 2501). Furthermore, the IPCC estimates that about 9-14% of current species are expected to face a very high risk of extinction if global temperatures increase by 1,5%. This number will increase to 12-48 % if the average temperature increases by 3% (O’Neal et al., 2022, p.259). These environmental damages will directly affect human well-being.

Moreover, according to the United Nations, as of 2022, over 68% of global greenhouse gas emissions and 90% of all carbon dioxide emissions were caused by fossil fuels. These figures included emissions caused by burning oil, coal, and gas across all sectors. The United Nations has listed the most significant sectors as power generation, manufacturing, deforestation, transportation, food production, residential buildings, and overconsumption. (United Nations, n.d.)

The World Resources Institute has also published a sectoral breakdown of greenhouse emissions in 2021. The largest sector by far is the energy sector, accounting for 75,7% of all emissions, which matches the United Nations figures. Following this, the next-largest is agriculture at 11,7%. Following up with industrial processes, 6,5%, Waste management, 3,4% and Land use changes and forestry, with 2,7 %.

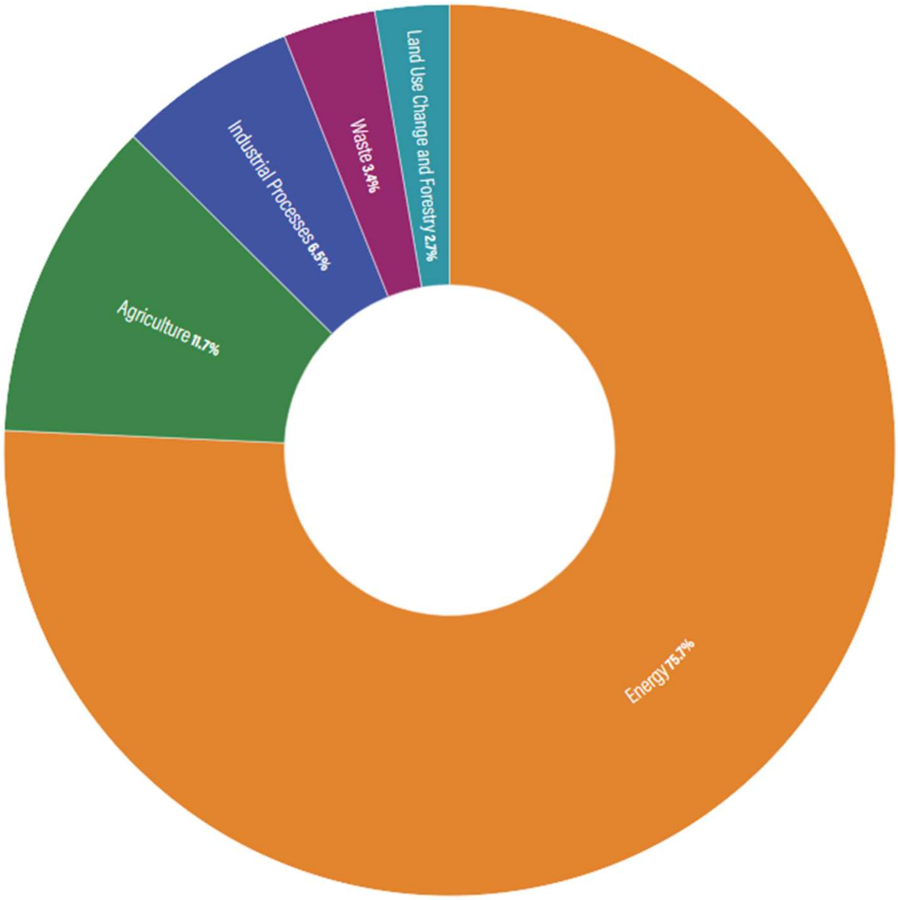

Figure 1. Global greenhouse gas emissions by sector and end use (Ge et al., 2024)

To further break down the 75,7% of emissions caused by energy production, it can be observed that electricity and heat are responsible for 29,7% of the energy sector's emissions. Followed by transportation 13,7%, manufacturing and construction 12,7%, buildings 6,6%, Fugitive emissions 6,6%, Other fuel combustion 4,4% and international bunker 2% (Ge et al., 2024).

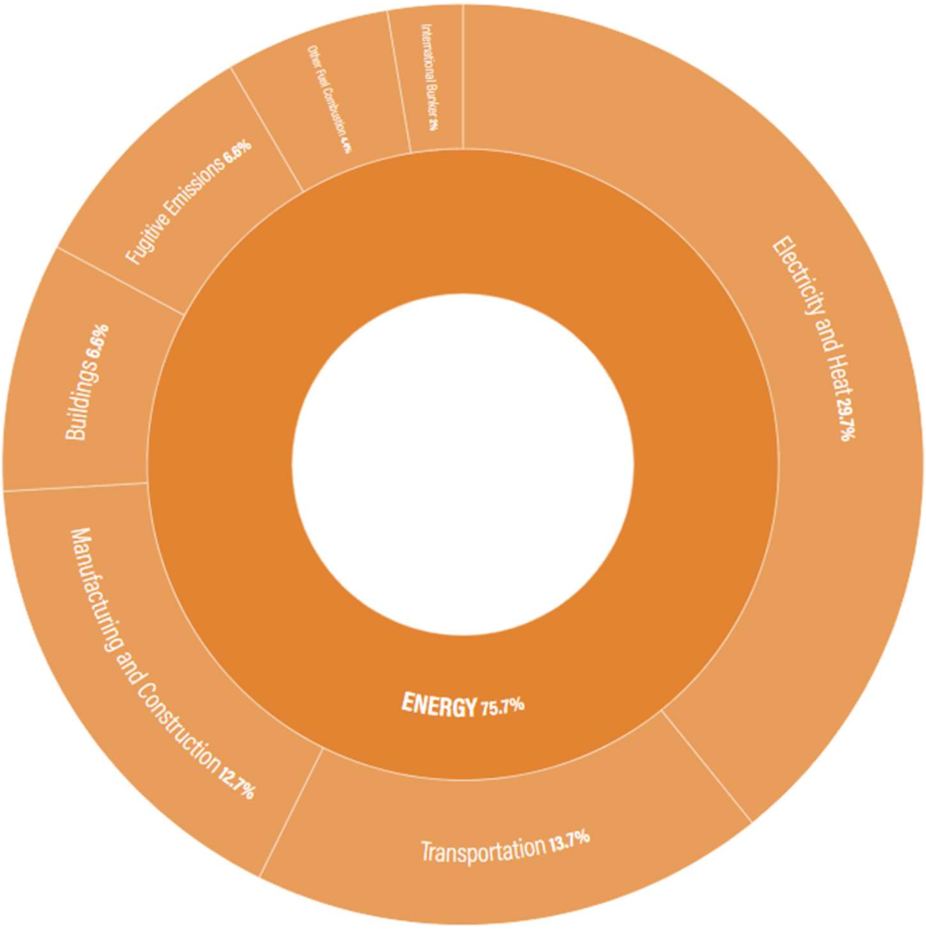

Figure 2. Global greenhouse gas emissions by sector and end use (Ge at al., 2024)

These figures align with United Nations figures with different breakdown methods, as seen in diagram 2, electricity and heat production account for 22.5% of all global emissions. Intuitively, this is a clear point of focus when tackling global warming. As briefly mentioned in the introduction to this thesis, this sector has experienced rapid development over the last few decades.

To accurately illustrate the changing fundamentals of electricity markets, it is essential to analyse the trends of each energy production method and assess their trajectories. According to the International Energy Agency, electricity demand in 2024 increased by 4,3%. This was almost twice the corresponding figure in 2023, at 2,7%. However, this is somewhat intuitive, as the global population is growing at an exponential rate. From this

4,3 %, renewable sources have powered 81,1 %, and only 18,9 % have been powered by fossil fuels. Based on these figures, the trend in global electricity production is clear. Fossil fuels are gradually losing market share, while renewable energy sources are accelerating. However, it is essential to note that despite the growth of renewables, overall emissions are not yet declining as the absolute use of fossil fuels continues to rise. As of 2024, nearly 60% of global electricity demand was still met by fossil fuels.

There are significant regional differences in this trend. According to the IEA, India and Southeast Asia are still heavily dependent on fossil fuels and thus key areas of focus when tackling global warming. In India, nearly 77% of total energy needs are met by fossil fuels. The corresponding figure in Southeast Asia was 74,2 %. The European Union is the forerunner in this comparison, with the corresponding figure of 27,8% (IEA, 2025, p. 27).

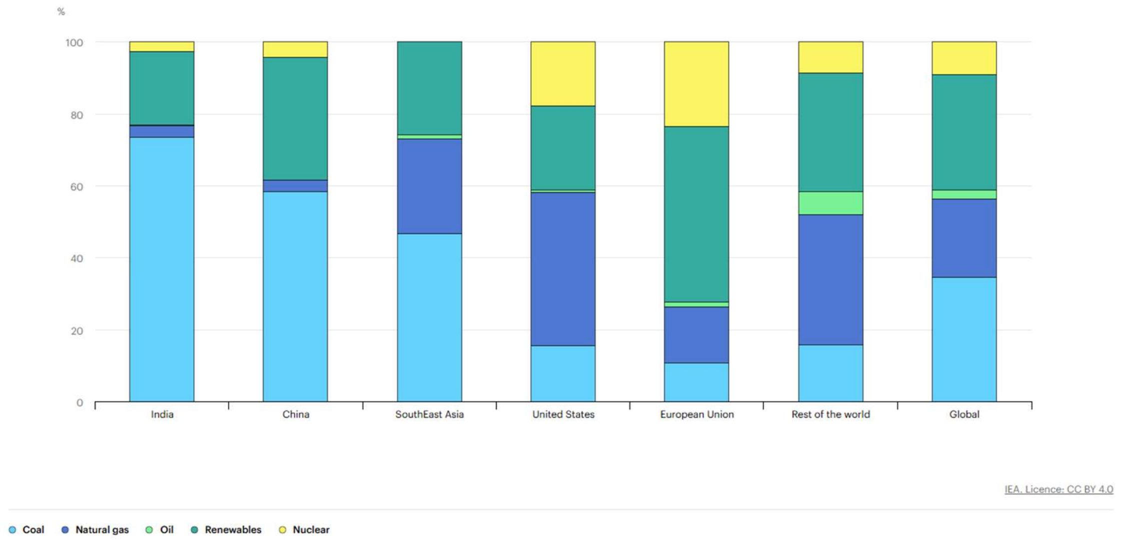

Figure 3. Electricity generation mix for selected regions (IEA, 2025)

Based on this data the need for transition is not only inevitable but already widely recognised. Furthermore, the trend in the data suggests that the share of renewable production is increasing, highlighting not only the growing investments in renewable energy but also the long-term shaping of energy structure. As the share of renewable energy production increases, so do also the risks created by renewable characteristics, such as risks related to production variability and unpredictability.

2.2 Market balance and market infrastructure

To illustrate how these risks translate into electricity markets, it is vital to understand the basics of electricity market systems and how electricity is actually traded. It is vital to note that the energy and electricity markets are distinct in this context. In this thesis, when referring to electricity markets, the term refers to markets where actual electricity is traded between supplier-distribution parties.

The electricity markets can be divided into four market systems that are all responsible for balancing demand and supply: the capacity market, the day-ahead market, the Intraday market, and the balancing market. This multiple-market system exists because forecasting the equilibrium between demand and supply can be difficult within a single marketplace. To establish rough estimates of the equilibrium, the future supply and demand need to be estimated first. This is primarily done in capacity markets and in the day-ahead market. As delivery time approaches, intraday markets and the last-hand-balancing markets are designed to balance the disequilibrium created in the capacity and day-ahead markets. (ACER, n.d.)

In principle, capacity markets differ from other electricity markets in that they do not involve the immediate trade of electricity, but rather the commitment to have generation capacity available if needed. Consequently, within the electricity delivery timeline, the capacity market operates first. The capacity market mechanism ensures that power producers remain available during periods of tight supply. In exchange for this availability, the producers receive capacity payments that supplement their revenues from actual energy production. Capacity markets are designed to ensure sufficient generation capacity is always available, supporting long-term grid stability and supply security. (European Commission, n.d.)

Initially, the capacity markets were introduced to offer financial incentives for traditional power plants to remain available to adjust production to meet electricity demand (Erbach, 2017, p. 1). Even as renewable energy sources are dependent on weather conditions, they are still able participate in modern European capacity markets under certain conditions. Ensuring access to renewables is essential to maintaining fair competition in the market and avoiding conventional power plants to receive an unfair advantage through additional compensation. (Kozlova & Overland, 2021, p.9-10)

The day-ahead market is the primary wholesale market for trading electricity and occurs once daily. As the name suggests, the electricity traded refers to production and delivery scheduled for the following day, divided into 15-minute or hourly intervals in most market systems. Bidding for the next day's electricity closes at 12:00 CET, after which a centralized algorithm executes the auction. If the supply and demand offers match, the results become legally binding. In principle, the day-ahead market is a blind auction between electricity producers and buyers, in which market participants submit their bids independently. (Epexspot, n.d.)

Intraday shares many of the same characteristics as the day-ahead market, with the main difference that bidding, production, and delivery all occur within the same day. The Intraday market balances the supply-and-demand imbalance left over from the day-ahead market. In the intraday market, the trade interval is typically shorter than in the day-ahead market, enabling electricity suppliers and buyers to make last-minute adjustments with more precise forecasts. (Epexspot, n.d.)

After the Intraday market, several frequency control markets are designed to make the final adjustments to grid balance. These are essential to maintaining the power system's stability and reliability in real time. This ties back to the earlier-mentioned capacity markets, which aim to ensure long-term adequacy of electricity supply. In cases of imbalances in intraday or frequency markets, the earlier-purchased capacity can be exercised to balance the supply shortfall. (ENTSO-E, n.d.)

Europe's most common frequency control mechanisms are the automatic Frequency Restoration Reserve and the manual Frequency Restoration Reserve. These are part of the broader European balancing market framework, coordinated by ENTSO-E, the European Network of Transmission System Operators for Electricity. (ENTSO-E, n.d.)

2.3 Macroeconomic theories during the transition

In game theory, Nash's equilibrium describes a situation in which no player can improve their outcome by changing their strategy, thereby creating equilibrium in the game. This equilibrium cannot change in game theory without communication between parties or third-party involvement. It is researched that this equilibrium can also be observed in electricity markets. (Dahlin & Jain, 2022, p. 831)

This raises the question of whether complete electricity market restructuring, as the green transition demands, can occur solely through competitive bidding or whether it requires third-party involvement.

As outlined in the introduction of the thesis, the fundamental reason for energy transition is increasing environmental concerns. However, as global market systems operate under a highly capitalised model, environmental factors are not automatically incorporated into macroeconomic analysis.

Some studies have concluded that the current market system energy transition cannot be expected to happen spontaneously. Instead, energy transition can be judged as a highly socialised process with several factors influencing it, with varying influence. Yu Yang, Siyou Xia, Ping Huang, and Junxi Qian identify interrelated factors as the most crucial driving forces of the energy transition. They believe optimising technology innovation, market mechanisms, policy design, and sociocultural conditions are key to a greener future. The same article states that technical innovation is one of the most critical factors for a successful energy transition. (Yang et al., 2024, p. 5-6) Technological advancements are already reflected in the average price per MW of wind farm capacity.

The Wind Technologies Market Report 2016, issued by the U.S. Department of Energy, shows that the price per kW averaged around $ 1,590 in the United States in 2016. (Wiser & Bolinger, 2016, p.49) Comparing this figure to data from another similar report issued by Berkeley Lab under the sponsorship of the U.S. Department of Energy, the corresponding value for onshore turbines is roughly 1,000 $ per kW in 2023. (Wiser et al., 2024, p. 41)

IRENA also supports this downward trend. A press release by Global Energy states that, according to IRENA, the average cost per kW of capacity has decreased from $2,272 in 2010 to $1,160 in 2023. (Global energy, 2024)

However, stating that technological improvements are the main driving force of the energy transition can, at some level, be counterintuitive. If new technology is likely to replace the previous technology in a relatively short time, this might make investing in the market unattractive altogether. The declining attractiveness is expected to slow technological improvements at some point; eventually, the industry reaches equilibrium. (Jovanovic & MacDonald, 1994, p. 322-345)

Furthermore, the industry concludes that the extent to which technological improvement is the main driving force of the energy transition is disputed. Jorge Blazquez, Ronaldo Fuentes, and Baltasar Manzano argue in the article “On some economic principles of the energy transition” that, rather than technology, policies hold the key role of driving the energy transition. (Blazquez et al., 2020, p. 8)

On a larger scale, it can be argued that in a market-driven society, the government’s role is to correct market inefficiencies. As the current energy production is not sustainable, it should be recognized as inefficient in the market. It can also be argued that there is a

Nash equilibrium in the energy market without governmental intervention. Without governmental intervention, there is no incentive for fossil-fuelled power methods to reduce production, and there is no initiative for sustainable practices to compete in the market system or in the infrastructure created for fossil-powered production methods. (Shen et al., 2024, p. 36)

From the companies' standpoint, they can only continue to take advantage of fossil fuels as a capitalist market assumption, which is unlikely to change without governmental intervention. Thus, governments must initiate policies to promote the energy transition in this context, including measures to mitigate the risks that renewable projects may face.

Moreover, even if efficient governmental policies continue, several technical bottlenecks are coming with the energy transition, most of which are related to the nature of electricity as a commodity. As electricity cannot yet be stored in large quantities, the demand and supply must be continuously met. As electricity demand has been met by fossil fuels for the last 200 years, the entire market and technical infrastructure have been built on the assumption that production can be adjusted to fluctuations in demand. However, this cannot be done with the same accuracy as the most common renewable sources are largely weather-dependent.

Fundamentally, in an efficient market, if supply cannot adjust, the price should rise until demand falls to the equilibrium level. Considering that electricity is primarily an inelastic good, this, in theory, may cause severe price fluctuations.

Following this theory creates a need for new infrastructure to store large amounts of electricity, which in turn creates another bottleneck: a material shortage. Large-scale battery storage systems require an unseen number of rare elements such as lithium, copper, cobalt, and nickel. According to the IEA, this scale of infrastructure change would require the establishment of new supply chains, which can take a long time and involve complex processes. (Bains et al., 2023, p. 23)

3 Literature Review

While macroeconomic theories indicate that, without governmental support, renewable projects are likely to face competitive disadvantages, the scientific literature and empirical findings further support this view. While there is a broad consensus on the risks renewable projects face during the transition period, the extent of these risks is under debate in the research.

3.1 Zero margin prices push the energy prices down

It is essential to recognize that factors that can contribute to long-term advantages for renewable projects may also function as disadvantages during the transition period. One key factor is the theoretical zero marginal cost of production. Producing electricity directly from renewable sources such as solar or wind does not need additional feedstock and thus, there are no marginal costs for producing power after the initial setup costs and maintenance costs (Taylor, 2024, p. 5).

This characteristic creates a rather interesting conflict according to the law of supply and demand. According to this theory once supply exceeds the demand the prices should start to fall closer to the level or marginal cost. To illustrate this, during a windy period, the electricity demand can be exceeded only by production from wind farms. Assuming electricity markets are efficient, the electricity price should start dropping to the level of the marginal cost until the demand meets the production. Since all wind farms have a marginal cost of zero, energy prices should drop to zero as well.

According to this theory, when renewable energy sources can efficiently produce electricity, the equilibrium price established by the market drops substantially. Thus, during periods of low renewable output, the remaining conventional power plants can charge higher prices, as the inelastic demand for electricity exceeds the available supply.

This hypothesis is however highlighted by economic principles that assumes the market to be always efficient and rational. However, these assumptions do not necessarily translate into practice. To determine whether this risk translates to real world applications, it is essential to examine empirical evidence of this phenomenon.

To observe this theory, there should be a positive correlation between residual load in power production and prices in the day-ahead markets. Residual load refers to the directly controllable load, such as production from oil or coal power plants. The following charts issued by Synertics show this phenomenon in practice.

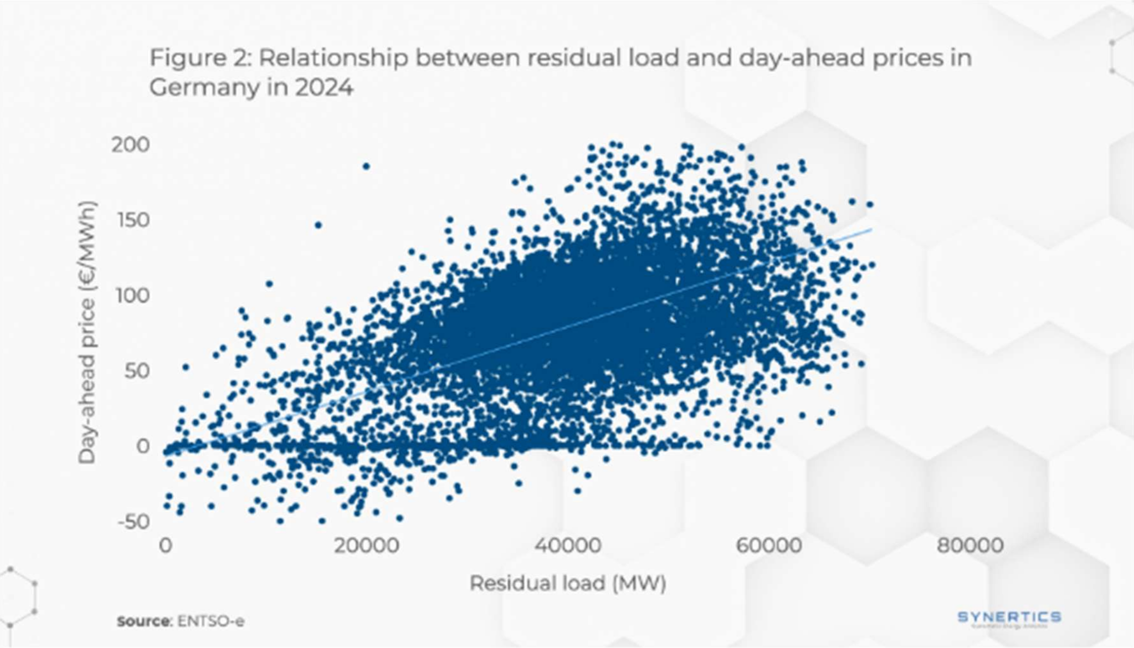

Figure 4. Relationship between residual load and day-ahead prices in Germany in 2024 (Castro, 2025)

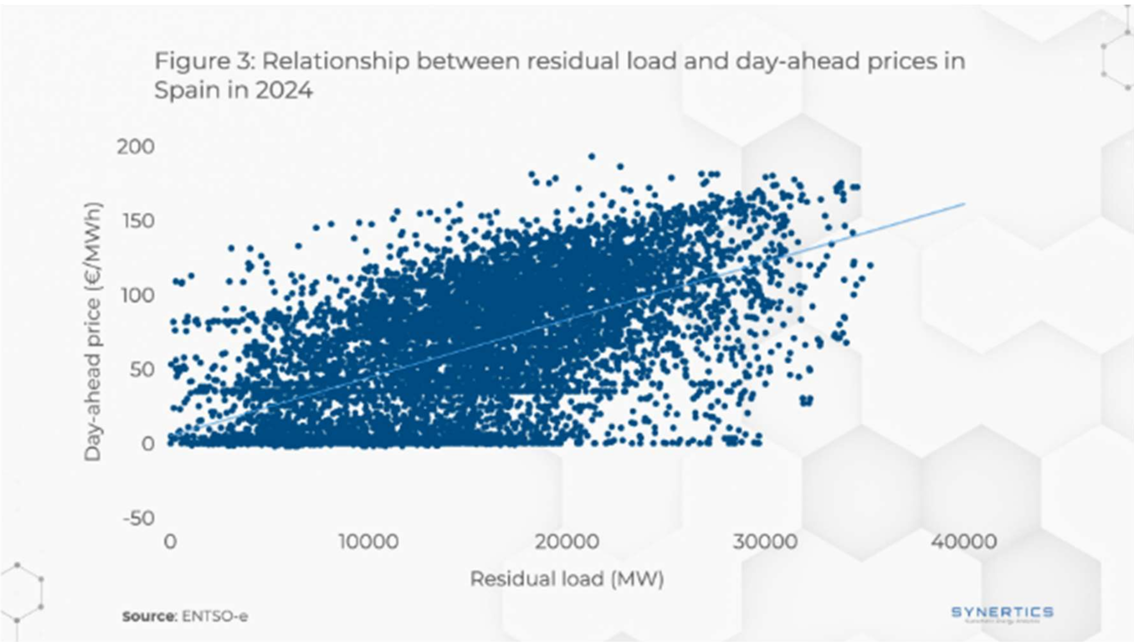

Figure 5. Relationship between residual load and day-ahead prices in Spain in 2024 (Castro, 2025)

In both cases, data from Germany and Spain reflect a clear trend line that indicates lower residual load leads to lower day-ahead prices. More intriguingly, the data suggest that Spain has a policy preventing energy prices from falling below zero, as the market price is not freely determined. Focusing on the correlation in German day-ahead prices, the lower the residual load, the more rapidly the frequency of negative electricity prices increases. In these cases, the power suppliers are even willing to pay to feed the grid.

Based on this data, it can be assumed that the greater the share of global electricity demand met by renewable sources, the greater the price fluctuations and the more frequent the occurrence of negative prices under the current infrastructure.

This phenomenon is also supported in scientific literature. In the article “The impact of renewables on the incidents of negative prices in the energy spot,” Oleksandra Prokhorov and Dina Dreisbach have investigated negative prices in the German and Luxembourg day-ahead markets. The simulation that Prokhorov and Dreisbach concluded was based on real-world wholesale demand and supply curves. The results of this research suggested that if strong support for renewables, auction design, and marginal-cost bidding remain unchanged, it would lead to more negative energy prices in the coming years. (Prokhorov & Dreisbach, 2022, p. 11)

The same correlation was also observed 3 years later by Marek Pavlik, Frantisek Kurimsky, and Kamil Sevc in the article “Renewable Energy and Price Stability: An Analysis of Volatility and Market Shifts in the European Electricity Sector”. The correlation between increasing volatility and the integration of wind and solar power was found to be significant (Pavlik et al., 2025, p.31).

As this correlation is supported by supply-and-demand theory, observed data, and academic simulations, it can be concluded that there is consensus on the relationship between green energy integration and price volatility. However, the research is somewhat inconsistent in how much of the price fluctuations and negative price occurrences can be explained by the correlation alone. Research suggests that external macroeconomic risks, along with other factors, can also cause high volatility and negative prices during the same period.

With the increasing share of renewable energy, the energy market has also been affected by geopolitical shocks, which can heighten the electricity market's vulnerability to macroeconomic factors (Cevik & Zhao, 2025, p. 15).

The research in "Renewable Energy and Price Stability: An Analysis of Volatility and Market Shifts in the European Electricity Sector (2015–2025)” also found that in Germany, when combined electricity production exceeded 195,000 MW, the occurrence of negative energy prices approached 100%. As this trend was observed to be nonlinear, this phenomenon would indicate that the system capacity had been reached. Thus, some of the negative price occurrences are more the result of insufficient grid capacity, and, in theory, the price would not increase even if demand increased.

This article also found that system flexibility can significantly affect price fluctuations. It was observed that greater flexibility was associated with lower price volatility (Pavlik et al., 2025, p. 15).

Both observations indicates that technical improvements to the grid configuration would have a positive effect reducing price fluctuations driven by the nonlinear development of negative prices. However, it is not clear whether improving the grid configuration would directly eliminate negative prices, as in theory the demand would likely still fall short of supply.

3.2 Inaccuracy issue in the current market system

Another key risk rising during the transition period is the limited ability to forecast accurately renewable energy output. As briefly illustrated in the theoretical framework, the structure of electricity markets along with market pricing implies that inaccurate production estimates in the day-ahead market can result in significant balancing fees in later markets. The theoretical framework suggests that integrating this characteristic into the existing market system can create a substantial risk that traditional power plants do not face. While academic research acknowledges the risk, the extent of this risk is somewhat inconsistent in the academic research.

In an article “Quantifying the predictability of renewable energy data for improving power systems decision-making,” published in 2023 Sahand Karimi-Arpanahi, S. and other researchers concluded that solar farms can lose up to 10% of their revenue due to inaccurate production estimates. This directly affects the investors' profits on such projects. Predictability and the risks associate with it are vital to consider also when implementing support policies for renewable energy sources (Karimi-Arpanhiet al., 2023, p.7). A similar correlation can also be observed with wind farms. The accuracy and precision of the production estimate can even dictate the profitability of the wind farm project. (Lee & Fields, 2021, p.321)

The underlying reason why misestimating the production can cause such a significant loss of revenue is that not only does the power producer lose the revenue of the electricity that it was not able to produce, but furthermore, the power producer must buy the promised electricity back from either the Intraday market or, lastly, from the frequency markets. As these marketplaces are designed to be last-minute resorts for balancing the demand and supply, the buyback price is often higher than what the power producer would have received from the day-ahead market (Kuppelwieser & Wozabal, 2022, p.58).

However, theoretical frameworks and empirical research suggest that inaccurate forecasting can also lead to unpredictable revenue if production is forecasted against the dominant market. To illustrate, if a wind farm has underestimated its output while the dominant market has overestimated, it puts the wind farm in a position to sell the excess production in balancing markets when the expected price is likely to exceed the price in the day-ahead market (Klyve et al., 2023, p.5).

The risk of imbalanced prices affecting renewable projects is widely recognised, but the extent of this risk depends heavily on each project's trading strategy. The most successful trading strategy is heavily reliant on market conditions at the time and thus scientific research has not identified a single correct approach. Theoretically, with an effective trading strategy not only can the project eliminate the risk but also take advantage of it.

Market imbalances not only affect producers’ forecasts and trading strategies but also the dominant market forecasts, which in turn affects the imbalance prices. Thus, the relationship is not reciprocal as each variable influences the other (Miettinen & Holttinen, 2018, p.232). As the positive correlation between the share of renewable energy in the grid and the imbalance prices is supported by both academic literature and empirical evidence, it can be stated that this risk affects renewable energy more than traditional power plants.

To highlight the significance of accurate forecasting, it is vital to recognise the magnitude of the difference between imbalance prices and the wholesale price, as even a minor forecasting issue can cause substantial financial losses. In the graph published by the Finnish TSO operator Fingrid, it can be observed that there were two occasions in 2025 when the price per MVh in the balance markets exceeded 10,000 €/MVh. (Fingrid, 2025)

Period: 1.1.2025 - 31.12.2025

Voit tarkastella arvoja tarkemmin rullaamalla hiirtä kuvaajan päällä

Figure 6. Fingrid**:** Imbalance price from 1.1.2025

In perspective, the Finnish energy authorities concluded that the average energy price in the day-ahead market in Q2 was 28,07 € (Energiavirasto, 2025). So, one MVh miss-estimation at a crucial time can wipe out revenue for a combined 356 MVh of production. One way to address this issue is to treat it as a newsvendor problem, where the optimal bid is constrained to avoid high imbalance prices (Bruninx et al., 2025, p.1).

The dynamics of this relationship lead to competition for the most accurate forecasting models that are most commonly provided by the balance responsible parties, referred to as BRP. BRPs are most often external parties that offer electricity trading services for a wide range of projects (Herre et al., 2019, p. 697).

As in theory, there can be only one most accurate forecasting model, and as dominant BRPs provide services for a wide range of projects, when that underlying forecasting model fails, it can affect the market substantially. In practice, dominant BRPs rely on very similar statistical algorithms; the most common are time-series algorithms such as SARIMAX or ARIMAX models. Without further examination of these complex mathematical models, SARIMAX is an extended version of the ARIMAX model that includes a seasonal component. ARIMAX, in turn, is an extended format of the ARIMA model that contains an exogenous variable that can influence the target series but not the past series (Basmadjian et al., 2021, p. 2). This thesis will not examine in detail how these models work, beyond noting that they are interconnected.

This interconnection between the models could theoretically explain how the forecasting inaccuracy translates to market imbalance prices. When the basic model underlying fails, in theory, it should push a considerable number of renewable energy producers to compensate for inaccuracies in their estimated production, thereby affecting imbalance market and intraday market prices. If this hypothesis were to be investigated, a correlation between high imbalance prices and errors in the SARIMAX or ARIMAX should be found. However, as the details of these forecast algorithms remain industry secrets, they cannot be further examined.

3.3 Risk Management Approaches

As in any market, the mentioned risks that involve the whole market and not just specific projects, or in other words, systematic risks, cannot be eliminated by diversification. This is one of the key characteristics of market risk, in contrast to technical or timing risks, which can be diversified by investing at different times or across multiple solutions.

Many of these risks are acknowledged in the industry, to some extent, even as the energy transition is still a relatively new phenomenon. Understanding the underlying causes and outcomes of these market inefficiencies is crucial to developing efficient support schemes for renewable energy. Even as these risks cannot be completely avoided, power producers can substantially mitigate their impact through different technical setups, contractual arrangements, and hedging strategies.

As outlined in the previous section, renewable energy sources suffer from 2 key market inefficiencies: negative or low prices during periods of high production and high imbalance prices due to poor predictability of power production. First, one of these can be mitigated with a direct power purchase agreement (PPA), bypassing auction markets and selling electricity directly to the user (Mittler et al., 2025, p. 12).

Most often, PPA agreements include a fixed price that the power purchaser is willing to pay for the power plants' production. In exchange, the power purchasers can publicly declare that they have used the agreed-upon amount of renewable electricity. This structuring allows the power producer to avoid the market price fluctuations and eliminate the risk of negative hourly rates.

This structuring is researched to provide an incentive for sustainable energy production. Furthermore, PPA agreements provide long-term visibility into pricing, which is a mutual benefit for both sides' risk management. As these are commonly long-term commitments, the risk of technical obsolescence and, thus, price falls shifts from the power producer to the power purchaser. (Stanitsas & Kirytopoulos, 2023, p.1)

While the research consensus suggests that PPA agreements have a direct effect in minimising risks related to market price fluctuations and policy shifts, there are controversies regarding the risks associated with PPA agreements. Primarily, the risks highlighted in the scientific literature focus on the long-term commitment in PPA agreements, which can leave the power supplier locked into a fixed price for an extended period. Furthermore, as PPA agreements have for the most part acted as a response to the increased volatility after 2020, the structure is still relatively new and lacks standardisation (Mittler et al., 2025, p.17).

The current literature lacks detailed categorisation of a wide range of PPA agreements in the transitioning European electricity market, possibly leaving some risks outside the scope of appropriate research. In the study, the researchers conducted a literature review of the risks of green PPAs and compared it with interview data from experts in the field. The research found that some risks associated with PPA agreements, as noted by experts in the field, are not yet reflected in the scientific literature. Even as PPAs can protect renewable projects from market fluctuations, they can also create new contractual risks (Mittler et al., 2025, p.17).

Moreover, to minimize the second risk, high imbalance prices, providing the BRP party with direct access to create and adjust curtailments to the power plant, the predictability of production and, thus, the imbalance fees can be improved. However, this does not entirely eliminate the risk, but research has concluded that if the BRP can flexibly adjust the site's power output, it will correlate with lower imbalance fees (De Heer et al., 2021, pp. 17-19).

So, in theory, combining the PPA agreement with the correct technical setup can provide an efficient framework for avoiding market-related risks. However, as there is no single outstanding trading strategy, the research is inconsistent if continuous curtailment of the site’s production is the optimal way to maximise revenue.

Price fluctuations can be hedged against, as in any business, and in the energy sector. The most common instruments used in the energy sector besides PPAs are CfDs, options, forwards, and futures. From these, options and futures are the most well-known hedging instruments because they are also widely used in other commodity markets. Due to grid bottlenecks, CDFs are more specific to electricity markets and are most commonly used in the Nordic region (Ferkingstad & Løland, 2014, p. 1).

Futures, options, and forwards are used to hedge against shifts in the system price, providing a level of certainty similar to that of PPAs. These financial instruments eliminate the risks encountered in day-ahead and intraday auction markets, enabling electricity producers to lock in prices for future dates at predetermined quantities. Forward contracts are typically traded in OTC (over-the-counter) markets and are not publicly traded. This allows solutions to be tailored to meet the criteria that power producers demand and, as a result, often demand larger premiums. Contrary to futures and options, which are standardised financial tools traded publicly and typically hold a smaller premium. These are traded on several exchanges, such as the European Energy Exchange, the Intercontinental Exchange, and Nasdaq Commodities (ETPA, n.d.).

CfDs differ from futures and forwards in several key ways. CfDs or contracts for difference are forwards for the spread between area price and system price and are publicly traded only in areas that are most keen to spread between system and area prices. With CfDs, a power producer can hedge against unfavourable area prices and close the gap between the system and area prices. Most commonly, the majority of DfCs range from 2 months to 3 years, so they are substantially shorter commitments than PPAs. In theory, if DfCs are combined with futures or forwards hedging for the system price, can the risk of price fluctuations be efficiently eliminated (Ferkingstad & Løland, 2014, p. 1).

3.4 Governmental support programs

As noted in previous sections, market inefficiencies are widely acknowledged within the industry. Given that the green transition is essential to our future well-being, these issues have also been taken into account in the design of support schemes for the electricity transition. In response to these challenges, public authorities have launched a range of subsidies and incentives for renewables. Simultaneously, the requirements for operating traditional power plants have increased. These changes strive to support the energy transition but also place additional financial and technical pressure on conventional energy producers.

In the article titled “Prices versus quantities: choosing policies for promoting the development of renewable energy,” published in 2003 by Philippe Menanteu, Dominique Finon, and Marie-Laure Lamny, the support schemes have been divided into two categories: quantity supporting schemes and price supporting schemes (Menanteau et al., 2003, pp. 802-804).

In this research, quantity-promoting policies include “green certificates” that power producers receive based on the amount they have supplied to the grid. These include certificates such as Guarantee of Origin (GO) and Elcerts, a ladder available only in Sweden and Norway. By fundamental nature, these two certificates are very similar. The power producer will receive one certificate for each MWh produced that can later be sold separately. The main difference between these two is that GOs are traded in a voluntary market. In contrast, Elcerts must be purchased by electricity suppliers in proportion to the electricity they sell (Statnett, n.d.). Companies can voluntarily buy GOs to promote the use of green energy (Statkraft, n.d.).

The researchers' other category included price-support schemes, such as Feed-in Tariffs, in which the government guarantees a specific price per MWh. There are many implementations across EU countries. According to the article “Evaluation of different fee-in tariff design options – Best practice paper for the international Feed-In Cooperation”, published in 2008 by Global Climate Action Partnership, 20 out of 27 EU countries had implemented some form of feed-in tariff (Klein et al., 2008, p.10).

Feed-in Tariffs provide the same certainty regarding a fixed electricity price as PPAs do. However, as Feed-in Tariffs rely on governmental policy, they include political risk. Basing investment decisions on a specific policy can be risky, as a newly elected government might abruptly cancel it, leaving the power producer once again reliant on market fluctuations. Furthermore, as these policies are intended to serve the community, they may result in some deviations for power producers. For example, the Finnish Feed-in-

Tariff system will not compensate for production during negative energy prices (Energiavirasto, 2025).

Research, however, has established inefficiencies in both quantity-based and price-based incentives. Price-based incentives, such as feed-in tariffs, do not incentivize lower costs but, in terms of installed capacity, yield much better results than quantity-based support, such as green energy incentives. However, according to the article, a quantitative approach is far more effective at controlling the cost of government incentives (Menanteau et al., 2003, pp. 810-811).

Even as price-based support policies play a key role in the energy transition, the scientific literature is inconsistent on the adverse effects of these market interventions. Some research suggests that FIT policies have already driven extraordinary, unsustainable growth in renewable production beyond the capacity of the current market system. By guaranteeing renewable projects with certainty of revenue independent of price variability that the projects cannot sustain on their own, it eventually leads to artificially inflated investments in such projects (Milanés-Montero et al., 2018, pp. 13-14). In theory, this, in turn, increases the price of such a policy, eventually leading to its abolition.

Another approach to categorizing support policies is to divide them into production-based and capacity-based mechanisms. In this categorisation, both green energy certificates and feed-in tariffs are included in production-based mechanisms. This categorisation is more intuitive, enabling separate research into the benefits of capacity and production incentives. Research indicates that production-based mechanisms can distort competition in the electricity market and may not necessarily provide power producers with incentives to act efficiently in ways that would be collectively beneficial.

In contrast, capacity-based incentives do not cause the same market distortions. Capacity-based incentives, such as those to lower initial setup costs, would not have a direct effect on the markets in which the farms operate (Huntington et al, 2017, pp. 479-480).

In response to Russian invasion of Ukraine European Union launched set of capacity-based incentives under the REPowerEU initiative. In October 2022, the European Investment Bank Group committed an additional €30 billion in loans and equity financing to support this plan, focusing on renewables, energy efficiency, grid enhancements, storage units, and low-carbon technologies (European Commission, 2022). The outcome of this incentive has further accelerated the integration of renewable production in large quantities.

Although capacity-based incentives alone cannot fully resolve inefficiencies in electricity markets, combining them with production-based incentives appears to have created a positive momentum in expanding renewable energy. These mechanisms accelerate the growth of renewable capacity as well as enhance investor confidence by reducing financing risks. This also supports EU's long-term goal of achieving decarbonized energy system.

4 Conclusion

The demand for energy transition is inevitable and as a significant part of that, the current energy production infrastructure must evolve with changing world. Transforming such critical infrastructure is a complex task to undertake. Overhauling the entire market system and grid infrastructure can create significant bottlenecks and challenges that can be already observed in the changing energy market. As the whole market operates in capitalist framework, this transition must therefore be guided by well-designed incentives that promote both investment and the broader well-being of society.

It can be observed that different transition speeds in power production methods and electricity market systems have led to several market inefficiencies during the transition period. The concept of generating electricity with minimal environmental effect and theoretically zero marginal cost is highly compelling, but the fundamental characteristic of weather-dependent renewable energy has created a new challenge for the market system to adapt to. As the electricity market has historically developed with production methods that can be controlled to meet dynamic demand, it can be expected that market dynamics might not support large quantities of production during fast integration process.

In this thesis, two key market risks arising from these fundamentals in renewable production methods have been identified. As observed earlier in this thesis, renewable energy capacity can largely meet and even exceed energy demand under strong conditions, consequently pushing electricity prices down. In extreme cases, this can even lead to negative energy prices during high production periods. Furthermore, the negative correlation between residual load and electricity prices indicate that traditional power plants benefit from this phenomenon. As such, the first hypothesis was supported by the theoretical framework, real world data as well as scientific research. However, the extreme price fluctuations are expected to stabilize as the grid infrastructure adapts to the characteristics of the renewable methods of producing power.

The second risk concerns the poor predictability of renewable production compared to conventional power plants. Fundamentally, electricity differs from other commodities in that it is difficult to store and with current infrastructure, it cannot be stored in large quantities. The challenging predictability of renewables can create substantial imbalance costs realised from frequency and intraday markets. These findings support the second hypothesis of the thesis. Empirical findings as well as scientific research indicate that forecasting errors significantly affect imbalanced prices, thereby also affecting the whole profitability of renewable projects.

As these risks are highly systemic in the renewable energy sector, diversification cannot eliminate them. However, the impact of these risks can be minimised through appropriate technical setup and contractual management. Alternatively, some derivatives can reduce the financial risks of price fluctuations but cannot reduce the risk of high imbalance prices. A PPA agreement can reduce both imbalance and price fluctuation risks, whereas a properly configured technical and trading strategy can reduce only imbalance risks.

Furthermore, eliminating these market inefficiencies is also in the interest of governments in promoting energy transition. This thesis has briefly touched upon FIT policies that guarantee power producers a fixed price to mitigate market price fluctuations. In addition to FIT policies, the green energy certificate system and capacity-based incentives can further mitigate these risks. As observed, green energy promotion schemes may distort competitive positions in the electricity market, but they have proven to incentivize new projects and investments efficiently. These observations confirmed the third hypothesis of the thesis.

To conclude, the hypothesis that market efficiencies are likely to arise during the transition period was supported by both academic research as well as the theoretical framework. As the current market system has not been optimised to support renewable energy projects, inefficiencies cannot be expected to disappear with pure market competition. Thus, supporting the green transition requires government intervention and the availability of the right financial tools to support renewable energy in coping with these risks.

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