Master's Thesis – Sustainable Business and Innovation

The Inefficiency of the Dutch Electricity Market

The Curtailment of Renewable Energy and the Role of Green Power Purchase Agreements

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Abstract

The inefficiency of the Dutch electricity market poses significant challenges, particularly for renewable energy (RE) producers, and is defined as any requirement to pay for the production of RE. This research focuses on the financial and curtailed impacts of these inefficiencies on solar parks with and without Green Power Purchase Agreements (GPPAs). GPPAs are bilateral agreements where consumers purchase electricity directly from producers, which can shield them from market inefficiencies during synchronized intervals. The study explores how these agreements influence the curtailment of RE and the financial viability of solar parks.

To address this, the research employs a dual approach based on longitudinal data, combining quantitative analysis and case study evaluations. The study examines four groups of solar parks: those without GPPAs or energy steering software, those with energy steering software only, those with GPPAs only, and those with both GPPAs and energy steering software. Data is sourced from the EPEX and Imbalance markets, as well as from specific solar parks, to analyze the extent to which market inefficiencies impact these groups.

The study identifies several triggers for curtailment in the Dutch energy market, including market regulations like the SDE++ subsidy, which limits the inverter capacity to 50% of the solar park's total power. This regulation alone resulted in a 5.43% energy loss compared to previous requirements. Both the EPEX and Imbalance markets exhibit strong correlations between negative price intervals during the daytime in the spring and summer, aligning with the solar energy generation profile.

The results show that solar parks with GPPAs are less impacted by market inefficiencies, both financially and in terms of curtailment. Specifically, solar parks with GPPAs are financially better off by €2.09 per MWh compared to those without GPPAs, representing a 19.12% reduction in financial impact. When comparing the groups with energy steering software, the financial benefit is €1.36 per MWh for solar parks with GPPAs, indicating an 18.45% reduction. Additionally, solar parks utilizing GPPAs reduce energy curtailment by 58.4% compared to those without.

The findings underscore the importance of GPPAs in mitigating the financial and curtailed impacts of market inefficiencies. They also highlight the benefits of energy steering software resulting in decreased costs. This research provides valuable insights for stakeholders in the renewable energy sector, policymakers, and investors, emphasizing the need for strategic investments in GPPAs and energy steering technologies to enhance the financial viability and sustainability of solar energy projects.

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Abbreviations

- DAM – Day-Ahead Market
- DSO – Distribution system operators
- EJ – Exajoule
- ENDEX – European Energy Derivatives Exchange
- ETS – European Trading System
- GoO – Guarantees of Origin
- GPPA – Green Power Purchase Agreement
- GW – Gigawatt
- HHI – Herfindahl-Hirschmann Index
- IDM – Intra-day market
- kV – Kilovolt
- kWh – Kilowatt-hour
- MWh – Megawatt-hour
- PPA – Power Purchase Agreement
- GPPA – Green Power Purchase Agreement
- PV – Photovoltaic
- RE – Renewable Energy
- PRPs – Program Responsible Party's
- SDE – Stimulering Duurzame Energieproductie
- TSO – Transmission system operator
- TWH – Terawatt-hour

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1. Introduction

In the current global landscape, the increase of the average surface temperature to more than 1.2 °C above pre-industrial levels has unleashed a series of consequences, from intensified heatwaves and extreme weather events to a surge in greenhouse gas (GHG) emissions that are yet to peak [1]. The primary driver of global warming is the emission of GHG released by the energy sector [2]. The Stated Policies Scenario, a projection used in energy modeling, expects global energy demand to increase from around 630 exajoules (EJ) in 2022 to 670 EJ by 2030 [1]. This critical moment demands a restructuring of our energy systems, better known as the energy transition. The energy transition is characterized by a simultaneous shift towards low-carbon sources and a growing emphasis on electricity [1].

The Netherlands is increasingly committed to reducing its reliance on fossil fuels, driven by concerns about global warming and the pursuit of self-sufficiency [3]. This commitment has resulted in the widespread adoption of a substantial number of solar photovoltaics (PV) and windmills. In 2022, the total installed solar PV capacity grew by 4.2 GWp, resulting in a remarkable 46% increase in energy production compared to 2021 [4]. Additionally, the total installed wind capacity expanded by 1.06 GW, contributing to a 13.1% increase in energy production compared to 2021 [5]. The Dutch Environmental Assessment Agency (Planbureau voor de Leefomgeving) has set a target for 2030, aiming to achieve an installed solar PV capacity of 25.8 GW and a wind capacity of 21 GW [6]. As a consequence of this shift, the Dutch electricity market is evolving from its traditional model, in which producers and consumers interact separately, towards a more prosumer[1]-oriented paradigm [7].

Wind and solar energy distinguish themselves from conventional generation technologies in several key aspects. The output of renewable energy (RE) fluctuates due to the inherent variability of their primary energy source (sunlight and wind), which is unpredictable. Furthermore, solar PV and wind systems are typically smaller in scale compared to conventional generation technologies and are constrained by their specific geographic locations [8]. These unique characteristics lead to multiple challenges within the current power system, including issues such as insufficient transmission grid capacity and a shortfall in generation adequacy. The substantial increase in installed wind and solar capacity amplifies the impact, as it hinders the occurrence of high solar production overlapping with elevated wind production [9], [10]. This causes inconsistencies in the supply and demand of electricity [11], [12], [13].

Electricity is traded in four markets in the Netherlands. The most common markets are the Day-Ahead and the Imbalance market. The EPEX Market operates as an auction determining day-ahead electricity prices for each 24-hour period in the upcoming day based on forecasts. The Imbalance Market functions as a mechanism to address discrepancies between forecasted and actual electricity generation and consumption. It operates in real-time, allowing grid operators to balance supply and demand to maintain system stability.

Due to growing RE sources with intermittent supply, the Netherlands saw 315 hours of negative electricity prices on the EPEX Market in 2023, up from 85 hours in 2022. Furthermore, the Imbalance Market experienced a 27.73% increase in negative prices in 2023 compared to 2022 [14]. The surplus in forecasted electricity generation results in negative prices on the EPEX Market. Negative prices in the Imbalance Market take place when the allocated (actual generated) electricity exceeds the consumption [15]

[1] Prosumer: A prosumer in the energy sector is an actor that both consumes and produces electricity.

In the energy transition, ensuring the effective functioning of the electricity market is crucial. Ideally, it would require the implementation of true pricing, where the costs of polluting emissions are incorporated. Consequently, fossil electricity becomes more expensive than RE. It is contradictory to encounter a situation where, in an energy transition aimed at promoting clean electricity and ideally taxing fossil fuels, we find ourselves having to pay for the production of sustainable energy while, at the same time, electricity is still being produced by fossil-driven sources. In the Netherlands in 2023, electricity was continuously generated from fossil-driven sources at any given point [9]. Therefore, any requirement to pay for the production of renewable energy within the electricity market indicates an inefficiency.

Negative prices in the electricity market signify a market inefficiency. This inefficiency encourages RE owners to equip their assets with energy steering hardware and software which allows them to curtail RE production in response to financial incentives (negative electricity prices). Currently, an increasing number of RE sources are being equipped with energy steering software. However, the integration of this technology is a gradual process. RE plants without energy steering capabilities are only financially affected by market inefficiencies. When RE plants are equipped with energy steering technology, they still experience financial impacts, although to a lesser extent due to the curtailment of RE during inefficient moments in the market. Consequently, solar parks equipped with energy steering technology are not only financially affected by the inefficiencies of the electricity market but also by the degree to which RE is curtailed.

The inefficient market will lead to more frequent curtailment of RE, raising concerns about economic and operational challenges for the energy sector [16]. Furthermore, when RE sources are curtailed, fossil energy sources will continue to be produced, exacerbating the situation where RE is curtailed while GHG-emitting fossil energy sources remain active [9].

In addition to market influences, regulations also contribute to the curtailment of RE, notably through the stringent criteria of the SDE++ subsidy, a governmental initiative designed to promote RE adoption while phasing out fossil fuel reliance. This subsidy now mandates that the inverter capacity be limited to 50% of the solar panel's peak power. This marks a significant change from the previous capacity allowance of 100% before 2021 and 70% since then [17].

Curtailing RE poses a significant threat to our sustainable energy objectives, especially considering the current shortfall in meeting RE targets. The consequence is a missed opportunity to harness and utilize clean energy sources fully. Moreover, as we strive to increase the percentage of RE in our overall energy portfolio [18], curtailment becomes an even more pressing concern. A higher share of RE in the mix signifies a larger potential for curtailment, as the intermittency and unpredictability of certain renewable sources, such as solar and wind, may contribute to more periods of oversupply and therefore negative prices in the market [19].

The curtailment of RE is triggered by the inefficiency of the electricity market. The electricity market is a multifaced market with different components. One of the components are Power Purchase Agreements (PPAs). PPAs are contracts closed between producers and consumers of electricity, in which electricity is directly traded, bypassing the electricity market and therefore its inefficiency. Nowadays more and more PPAs are involving RE. In the Dutch electricity market, conventional green PPAs (GPPAs) involve consumers purchasing all the generated electricity from a producer. This type of GPPA, better known as electricity purchased as produced, is feasible primarily for energy-intensive consumers since all generated energy must be consumed to ensure the arrangement. Notably, in the Netherlands these GPPAs are predominantly held by energy-intensive corporations like Amazon, BASF, Google, Microsoft, and NS [20].

The focus of this research is on GPPAs with a different structure, in which electricity is purchased as consumed. This type of GPPA means that if, within the span of the same 15-minute interval, there is a synchronization of electricity generation and consumption between the producer and the consumer, the contractual terms of the GPPA come into effect. In instances of surplus or deficit electricity, either the consumer or the producer must engage in trading the surplus or deficit on the electricity market. In this structure, not all produced energy has to be consumed to maintain the agreement's viability, making it accessible to a broader range of consumers. Although this structure of GPPAs reduces the vulnerability of RE producers to market inefficiencies compared to relying solely on market functioning, there is still some remaining exposure to market dynamics.

This research seeks to explore how inefficiencies within the Dutch GV[2] electricity market impact solar parks consisting of GPPAs, focusing on the Day-Ahead (EPEX) and Imbalance Market. The influence of the impact can be assessed through both the quantity of energy curtailed, and the financial losses as a result of the inefficiency. Therefore, this research will answer the following question:

To what extent are solar PV parks with contractual Green Power Purchase Agreements (GPPAs) influenced by the inefficiency of the Dutch electricity market in 2023 compared to solar parks without such agreements?

The research strategy will utilize a dual approach based on longitudinal data, employing both quantitative analysis and case study evaluations, to investigate the impact of GPPAs on the curtailment of RE. The analysis will explore differences between solar parks with and without GPPAs, as well as those with or without energy steering systems.

Sub-questions:

1. What triggers curtailment in the Dutch electricity market, leading to the underutilization of renewable energy potential?
    a. To what extent is curtailment influenced by the SDE++ subsidy?
    b. To what extent does the EPEX Market's structure trigger curtailment?
    c. To what extent does the Imbalance Market's structure trigger curtailment?
    d. What effect do negative prices have on the electricity production mix in the market?
2. What are the financial and energy losses, for solar park owners without contractual GPPAs, due to the inefficiency of the electricity market?
    a. Financially, due to negative income?
    b. Energy loss, due to energy steering?
3. What are the financial and energy losses, for solar park owners with contractual GPPAs, due to the inefficiency of the electricity market?
    a. To what extent do GPPAs influence the financial loss established by the inefficiency of the Dutch electricity market?
    b. To what extent do GPPAs influence the curtailment rate of renewable energy in the Dutch market?

The social importance lies in evaluating the impact of GPPAs on curtailment rates in RE production, exploring how these contractual agreements may mitigate or exacerbate RE curtailment challenges in the Dutch energy landscape.

[2] GV: all the electricity connections that have a capacity above 3 x 80 ampere

Sub-question 1 explores various factors contributing to the curtailment of RE. Sub-question 2 establishes the baseline of the issue. Consequently, the findings from sub-question 1b and 1c are used to define the effects across different solar parks in sub-question 2. Once the baseline is established, sub-question 3 will determine the impact of GPPAs on solar parks that obtain these contractual agreements.

My hypothesis is that solar parks with GPPAs will be less influenced by market inefficiencies. Consequently, it is expected that the rate of curtailment and the financial costs will be lower for solar parks with GPPAs compared to those without such agreements.

If the projected findings are confirmed, this research holds significance as it elucidates a framework where solar-based electricity exhibits reduced reliance on inefficient periods within the electricity market. Consequently, the volume of curtailed RE is expected to diminish.

The structure of this research proposal is as follows. Section 2 will explain the mechanism of the electricity market, focusing both on the system infrastructure as well as the financial market. In Section 3, a comprehensive review of existing literature has been conducted. Section 4 encompasses the methodology of the proposed analyses. Section 5 comprises the data section, detailing various datasets and their respective sources. Section 6 presents the analysis findings. In Section 7, the discussion and conclusions of this thesis are addressed.

2. The Electricity System in the Netherlands

The Dutch electricity system is a network comprising various stakeholders that work harmoniously to ensure a reliable and sustainable power supply. The system encompasses electricity generation, transmission, distribution, and consumption [21].

The Dutch electricity system can be split up into two sections, namely the system infrastructure and the financial market.

2.1 Electricity System Infrastructure

Currently, six independent entities oversee the core process of supplying electricity to consumers in the Netherlands [22]. Figure 1 provides an overview of the electricity supply chain.

The production company produces electricity using various sources such as fossil fuels, uranium, biomass, hydro, solar, and wind. The Program Responsible Party (PRP) is responsible for planning electricity production, transportation, and consumption in 15-minute intervals throughout the day [22]. This interval is referred to as the Program Time Unit (PTU).

The Transmission System Operator (TSO) is government-owned and operated by TenneT. The TSO is responsible for overseeing and managing the high-voltage grids, specifically the 220 kV and 380 kV grids [23]. The TSO plays a crucial role in ensuring the efficient transmission of electricity between the high-voltage grid and various stakeholders, including generators and consumers.

TenneT manages real-time imbalances between electricity demand and supply through PRPs. This mechanism aims to align scheduled electricity programs[3] with actual consumption or generation. PRPs are economically incentivized to minimize imbalances, as they are charged for net deviations on the Imbalance Market [24]. The Distribution System Operators (DSOs) oversee the electrical transportation and distribution networks connecting the high-voltage grid (TSO) to end-users [22].

Metering companies are also part of the electricity infrastructure. They are responsible for determining and validating the energy consumption and transferring this data to the grid operators [25].

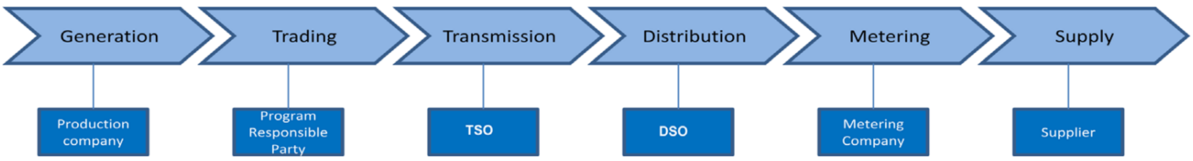

Figure 1: Electricity supply chain [22]

[3] E-programs: PRPs inform TenneT daily about the planned transactions for the next day and the networks they will use for transport. The sum of all transactions of a PRP is called an energy program (e-program) [70].

2.2 The Electricity Mix

A critical aspect to consider is the transformation of the Dutch electricity mix. Illustrated in Figure 2 is the evolution of electricity generation size and composition over three years (2015, 2020, and 2023). As shown, there has been a substantial increase in renewable electricity generated from solar parks and windmills, contrasted with a decrease in coal-generated electricity [26]. This progressive shift towards RE sources signifies that inefficiencies in the market will have a more pronounced impact on a greater range of renewable energy sources.

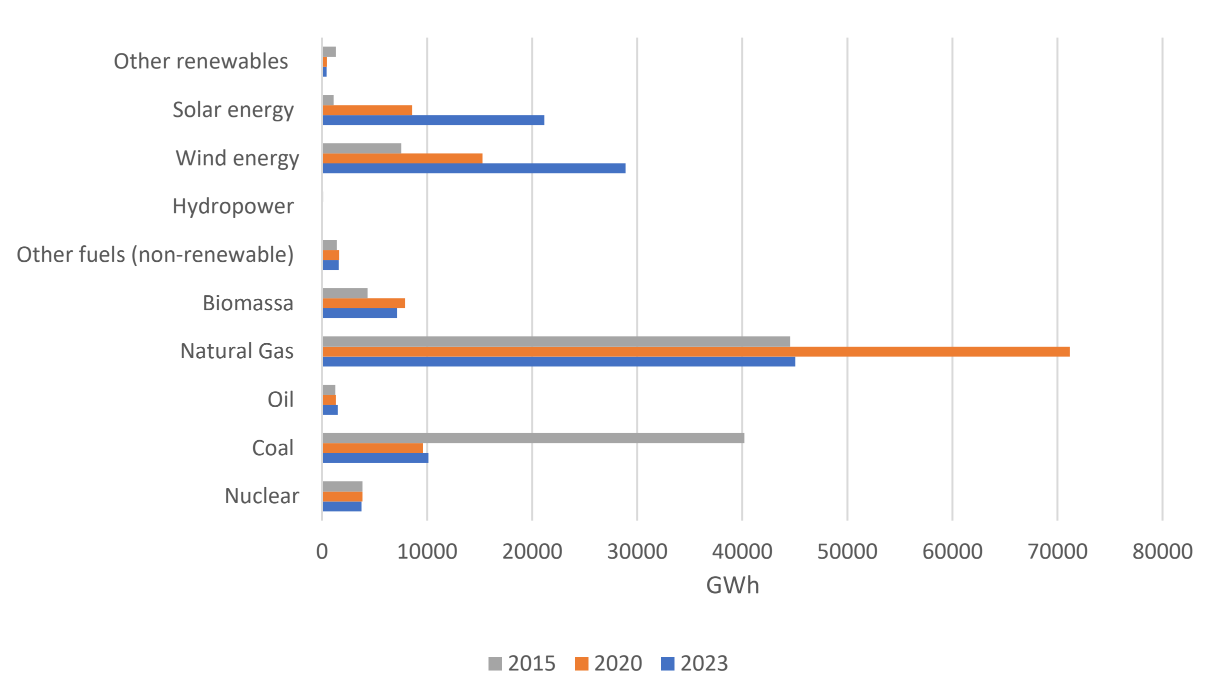

Figure 2: The Dutch electricity production [26]

2.3 The Electricity Market

The Netherlands consists of four primary electricity markets, each consisting of a different timeframe. The different markets are discussed based on their timeline compared to their physical delivery.

A Program Responsible Party (PRP) permit is a necessity for trading on all four markets. PRPs exclusively handle the physical delivery of electricity. Delivery is permitted to any connection within the Dutch network, treated as a unified market [27]. Table 1 shows an overview of the timeline within the electricity market.

The ENDEX Futures Market

Contracts for the future are exchanged on the regulated platform known as the European Energy Derivatives Exchange (ENDEX) and expire two days before the physical delivery. Future contracts facilitate the physical delivery of 1 MW of electric energy to the Dutch high voltage grid, spanning from 00:00 on the first day of the delivery period to 24:00 on the last day of the delivery period [28]. These contracts are additionally categorized based on their durations, including monthly, quarterly, and yearly classifications [28].

ENDEX's futures market provides two standardized electricity delivery hour products, namely Base Load and Peak Load. The distinction between Base Load and Peak Load lies in the delivery time of electricity. Base Load spans from 20:00 to 8:00, while Peak Load encompasses the hours from 8:00 to 20:00 every day.

The EPEX Spot Market

Contracts for the spot market are exchanged on the EPEX market. This market can be separated into two markets: the Day-Ahead Market (DAM) and the Intra-Day Market (IDM). DAM, the more extensive of the two markets, operates as an auction determining day-ahead electricity prices for each 24-hour period in the upcoming day. The second market, IDM, grants participants the flexibility to modify their spot positions up to 5 minutes before the actual delivery of electricity [28].

The DAM serves as a spot market where companies engage in the buying and selling of spot electricity for delivery the following day. Operating as a two-sided, double-blind auction, the DAM allows both buyers and sellers to submit anonymous orders with varying prices and quantities on an hourly basis [28]. These orders lead to the formation of demand and supply curves for each hour of the following day, better known as a market bid ladder, influencing the prices for each hour [29].

Between establishing Day-Ahead positions and the actual delivery of electricity, market participants have the option to revise their physical positions. This adjustment process occurs through the IDM. Unlike the DAM, prices for the IDM are based on a 15-minute interval instead of the one-hour interval. Market participants have the flexibility to modify their spot positions up to 5 minutes before the actual electricity delivery in the Intra-day Market. It's important to note that the cost of purchasing electricity in the intraday market typically exceeds that of the Day-Ahead Market [28].

The Passive Imbalance Market

The ENDEX-, Day-Ahead-, and Intra-Day Market derive their prices based on forecasted energy projections. The Imbalance Market functions as a mechanism to address discrepancies between forecasted and actual electricity generation and consumption. It operates in real-time, allowing grid operators to balance supply and demand to maintain system stability.

The TSO assesses the imbalances of all PRPs by comparing their submitted E-programs[3]. In cases where a PRP deviates from its E-program, representing the total electricity taken from or supplied to the grid, the TSO functions as an artificial market participant. It engages in buying (for electricity shortage) or selling (for electricity excess) with the PRP at a dynamic and volatile price in the Imbalance Market [28]. The Imbalance Market provides both a buy (take) and a sell (feed) price every minute. The price for each 15-minute interval is determined by the price of the last minute within that interval. The specific prices for these transactions exhibit significant variability [30].

When this is translated in terms of this research it means that when a solar park deviates from its forecast the imbalance can either be positive (more produced than forecasted) or negative (less produced than forecasted). The prices for the Imbalance Market can also be positive (when there is a shortage of energy on the market) or negative (when there is an excess of energy on the market). Solar park owners can generate additional revenue during negative imbalance prices by curtailing solar energy production, and thereby deviating from their forecasted output. More details on the functioning of the Imbalance Market can be found here [31].

Table 1: Timeline of the Electricity Markets

All Days Before	Two Days Before	Day Before	Delivery Day	After Delivery Day
(T-n) ENDEX	(T-2) ENDEX	(T-1) APX DAM	(T)APX IDM	(T+1)

The Effect of Inefficiencies

As previously stated, negative prices are present in the Day-Ahead, Intra-Day, and Imbalance Market, but their impact varies across them. The Day-Ahead and Intra-Day Market derive their prices based on forecasted energy projections, whereas the Imbalance Market sets its price according to actual electricity generation. This clear distinction sets apart the Imbalance Market from the others.

In the Day-Ahead and Intra-Day Market, negative prices result in decreased income for energy producers. However, in the Imbalance Market, negative prices trigger the curtailment of energy production. It's important to note that the curtailment of RE is dependent upon the presence of energy steering hardware and software in RE sources.

3. Theory

In Chapter 1, the question arises to what extent solar PV parks with GPPAs are influenced by the inefficiency of the Dutch electricity market. In Chapter 2, the infrastructure and market mechanisms of the Dutch electricity system are explained. The central emphasis of this theory chapter will be on uncovering the origins of market inefficiency. It will start by examining market imperfections, considering the perspectives of consumers, producers, and market regulations. From the producer's perspective, the market is defined as an oligopoly. This analysis aims to determine the entry barriers present in the market, as well as the roles of regulations and consumers.

After the examination of the imperfect market players, the functioning of the EPEX bid ladder is discussed. The goal is to determine what influences the functioning of the EPEX Market and how negative prices are established. The research will then transform the EPEX bid ladder from an economic perspective to an environmental one, showcasing the shift that would occur and how curtailment of RE would become a last resort. However, even with this transformation, the hindrance posed by the dynamics of the ENDEX Market will still persist, as discussed in Chapter 3.4.

In addition to the influence of forecasted markets (ENDEX & EPEX), the technical limitations of the electricity infrastructure, such as capacity shortages and grid congestion, also contribute to market inefficiency (Chapter 3.5). The exploration of these constraints, together with forecast deviations, are particularly evident in the Imbalance Market and result in negative prices on the Imbalance Market as discussed in Chapter 3.6.

Finally, after thoroughly examining the causes of market inefficiency, Chapter 3.7 will focus on the functioning of GPPAs, illustrating how they are less dependent on market functioning and therefore less influenced by its inefficiency.

Due to the innovative nature of the concept, where power is procured based on simultaneous consumption and production, there is a lack of academic research conducted on it. Therefore, this research aims to explore the research gap concerning how inefficiencies within the Dutch electricity market impact solar parks with contractual GPPAs.

3.1 The imperfect Electricity Market structure

The electricity market is a multifunctional market with different actors as already explained in Chapter 2. The Dutch market reveals that certain independent roles are already eliminated from market operations, either because a company is government-owned (TenneT) or due to monopoly market conditions (DSOs) [32]. This subsection delves into the structure of the electricity market, considering the producers, consumers, and market regulations.

The Producers

Analysis of the Dutch retail electricity market reveals characteristics indicative of an imperfect market structure, deviating from the assumptions of perfect competition. The market exhibits a significant level of concentration, with the three largest retailers commanding 80% of the electricity production market share [21].

The Herfindahl-Hirschman Index (HHI) is a measure of market concentration used to assess the competitiveness of the market. The index ranges from 1, indicating a fully competitive market, to 10,000, signifying a monopoly market. Concentration measurements, using the HHI, confirm heightened concentration levels (1.800 < HHI < 10.000), portraying the electricity market as an oligopoly [33], [34]. Overall, the electricity markets lack typical constraints, such as competition, and regulatory actions cause significant obstacles for potential entrants in this influential and complex market [35]. This concentration suggests a lack of a multiplicity of firms: a key condition for perfect competition is to have many sellers/buyers in a market. In a perfectly competitive market, no single entity should have substantial control over the market, and consumers should have numerous choices [36]. These factors underscore the challenges faced by new entrants attempting to break into the market.

The Consumers

Lewis and Marvel concluded that consumers present a stronger motivation to explore alternative energy suppliers in response to price increases compared to their response when prices decrease [37]. Despite efforts to promote competition and consumer choice, only roughly 10% of Dutch households have switched suppliers within the period spanning from June 2022 to June 2023 [38]. This inertia among consumers indicates barriers to effective competition, such as information asymmetry, transaction costs, or other imperfections hindering the switching process [21].

The presence of dormant consumers[4] further underscores market imperfections. These consumers, who have not actively participated in the competitive market, tend to remain on more expensive default offers. This phenomenon suggests that, despite regulatory oversight, certain market imperfections persist, preventing all consumers from fully benefiting from competitive alternatives [21].

Market Regulations

In 2022, Renewable Energy (RE) accounted for just 15% of the total energy consumption [39]. The Dutch government has established RE targets for 2030, aiming for 30% of the country's energy to be generated from renewable sources [40]. To reach this target, different policies have been introduced, some influence the RE market directly, and some indirectly. The next section will discuss two regulations that are implemented by the Dutch (SDE++) or European authorities (GoOs).

[4] Dormant consumer: consumers who have not changed their supplier or contractual agreement.

Both the GoOs and the SDE++ subsidy are beneficial for solar PV parks. Therefore, the presence of these regulations can significantly impact market dynamics by introducing government intervention, which alters the natural flow of the market. The statistics below highlight the considerable influence applied by these regulatory measures.

The SDE++ subsidy, officially the Stimulering Duurzame Energieproductie en Klimaattransitie (SDE++), is a Dutch governmental incentive aimed at fostering RE adoption and phasing out fossil fuel-based energy on a large scale. The subsidy administered by the Netherlands Enterprise Agency (RVO) depends on the installed capacity and production efficiency of eligible entities in the industrial and utility-scale sectors [41]. Strict criteria must be met, emphasizing a reduction in GHG emissions. The subsidy, allocated through competitive bidding, includes variable premium contracts that last for 15 years and adapt to market dynamics and the performance of the applicants [42].

The SDE++ subsidy serves as a crucial safety net for solar park owners, ensuring them a reliable income based on market averages. In 2022, the total installed capacity reached an impressive 19.14 GWp, with a substantial portion, 11.05 GWp, attributed to the utility-scale (GV) segment. Remarkably, approximately 85% of this GV solar PV capacity, totaling 9.37 GWp, was established with the support of the SDE++ subsidy [43].

Guarantees of Origin (GoO) function as a digital certificate, providing evidence that the respective energy carrier originates from a sustainable source. Each GoO represents 1 MWh of sustainably generated energy. The certificate contains details about the energy source, the production installation, as well as the production date and location [44].

The current GoOs, valued at €6 per certificate, constitute a substantial component of the business model for RE providers. This valuation equates to approximately 0.7 percent of the internal rate of return (IRR), emphasizing the significance of GoOs within the financial outlook of RE projects [45]. Within the European Union, countries are allowed to meet their target by purchasing the deficit in their RE generation from other nations with a surplus. This EU-wide trade involves the exchange of GoOs [46].

The deviation from perfect markets

In typical markets, factors like storability, informed buyers, and supply elasticity act as constraints preventing a single firm with a small production share from inflating prices significantly [36]. Storable goods provide a defense mechanism as middlemen can stockpile products [47]. Informed buyers and supply elasticity discourage sellers from demanding exorbitant prices, maintaining market competitiveness [36]. However, the electricity markets deviate from these norms due to a distinctive oligopolistic structure with entry barriers for producers (high investment cost; technical disadvantages). The rapid demand nature and limited storage make these markets vulnerable to market power, even by firms with modest market shares [35]. Meanwhile, the large share of dormant consumers indicates barriers to effective competition. Therefore, these market participants, alongside regulations, disrupt the smooth functioning of the ideal market, resulting in deviations in the electricity market.

3.2 The Economic functioning of the Day-Ahead Market bid ladder

In this research, the Day-Ahead Market is referred to as the EPEX Market. In the Netherlands, the EPEX price is determined each hour by the functioning of a bid ladder, which is better known as a demand and supply curve. The electricity price is determined by price elasticity, which originates from the marginal electricity generation costs, illustrated in Figure 3. Elevated electricity prices are typically observed during periods of high demand coupled with low renewable energy generation, occasionally accompanied by sudden power plant failures. Conversely, negative price spikes occur in situations of oversupply, characterized by low demand but a high penetration of RE [27]. The EPEX price determination is based on both the forecasted energy supply and demand.

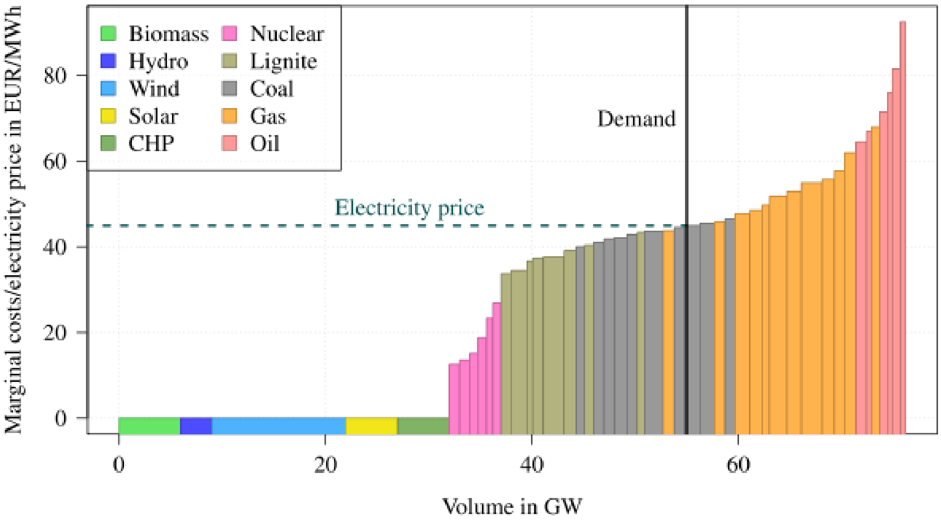

Figure 3: Simple supply stack model with inelastic demand (merit order model), featuring various power plant types [27]

Forecasting electricity prices presents several challenges, as extensively discussed in detailed review papers by Weron [48]. In recent years, there has been a rapid increase in focus on probabilistic forecasting, as it holds significant relevance for various applications in energy trading, risk management, storage optimization, and predictive maintenance [49], [50]. The research conducted by Petropoulos and colleagues emphasizes the primary challenges in electricity price forecasting [27]. The study indicates that these challenges can be influenced by external factors, including the complexities associated with forecasting RE production. The main energy sources for RE are weather-dependent, relying heavily on forecasted weather information [8], [27]. Given that most RE forecasting relies on the same weather data, and the amount of RE capacity is substantial, inaccuracies in these forecasts can lead to significant fluctuations in energy production, resulting in extreme price spikes or drops [14]. Therefore, these forecast errors in the EPEX Market have a major impact on the Imbalance Market.

Petropoulos and colleagues also explain that the complexity of electricity price data, influenced by regulations, adds an additional layer of intricacy [27]. Nevertheless, electricity trading persists through auctions and continuous trading mechanisms. Several markets, including those in the Netherlands, organize Day-Ahead auctions for electricity prices, as explained in paragraph 2.3 The Electricity Market.

Due to the impact of GoOs and SDE++ regulations, RE producers can place their bids below € 0 and still benefit from the production of their energy. An EPEX price below € 0 will only occur when the demand for electricity on the EPEX Market equals the supply stemming from RE sources. Such a scenario is only possible during certain times, such as when there is high solar irradiance combined with high wind speed [9], [14]. Consequently, energy prices on the EPEX market are sometimes negative. Fossil fuel-based electricity producers often respond to this negative offer with an even lower one, as the maintenance costs associated with shutting down power plants are higher than the negative income observed from the EPEX market, combined with the variable cost of fuel [51].

Solar parks with contractual GPPAs experience a reduced impact from the market dynamics and, consequently, its inefficiencies. A greater proportion of GPPAs in RE portfolios will result in reduced RE trading on the market, consequently leading to a shift in the supply curve. The decreased market impact resulting from a GPPA will also contribute to a reduction in the curtailment rate of RE.

3.3 The bid ladder optimized for Environmental Impact

In its conventional setup, the bid ladder is optimized for financial considerations as discussed in chapter 3.2. The bid ladder would undergo a significant transformation if it were not founded on marginal cost, emphasizing financial considerations (€/ kWh), but rather on environmental impact. Instead of the financial price, the metric of CO_2 per unit of energy (g CO_2/kWh) would be employed. This shift would result in a different bid ladder, placing the most sustainable production type at the forefront, with the energy producer exhibiting the highest emissions positioned at the end. This bid ladder based on the emissions would be optimal for social consideration, leading to lower GHG emissions. Figure 4 gives an overview of the CO_2 equivalent for each generation type.

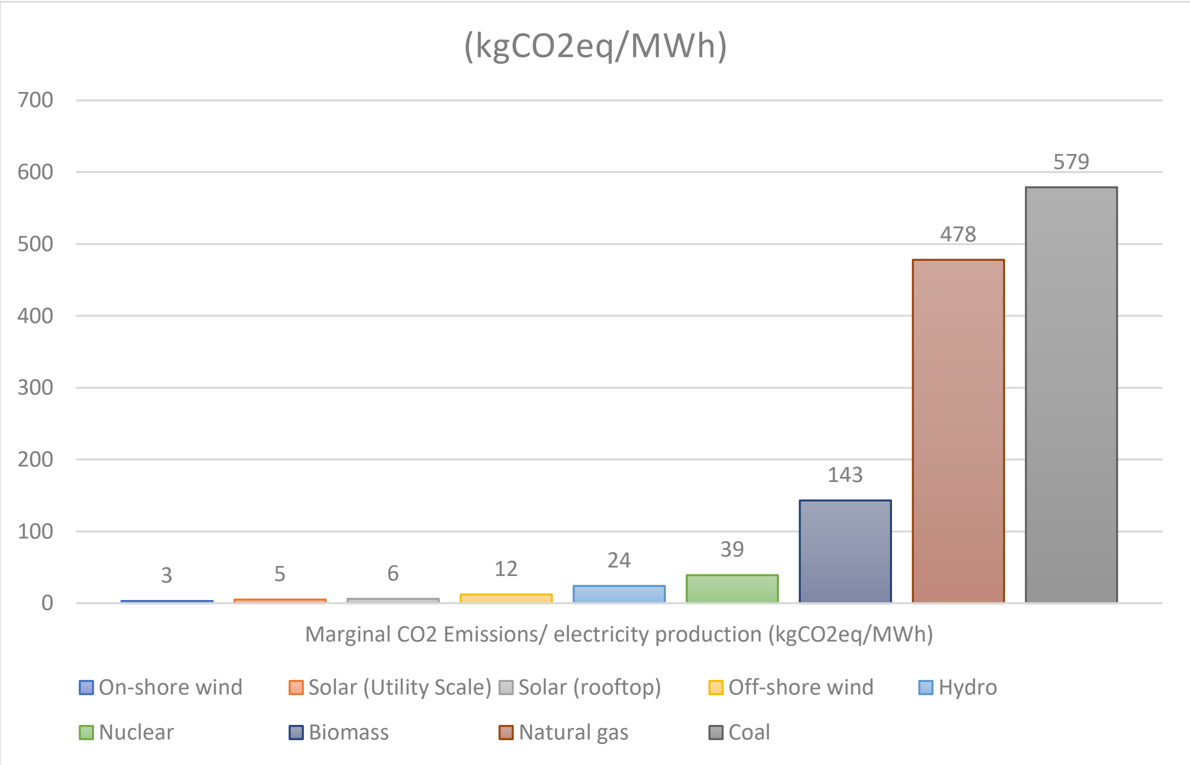

Figure 4: Emissions factors for electricity generation [52]

By using the insights derived from Figure 4, an opportunity presents itself to construct a bid ladder centered on environmental impact rather than financial considerations. This is shown in Figure 5 and Figure 6, based on this information and the production data from the ENTSO-E [9]. The winter data corresponds to information from January 21, 2024, while the summer data is derived from July 4, 2023. Both datasets are timestamped on the production at 12:00. Figure 5 and Figure 6 illustrate the optimal dispatch order determined by the environmental impact of electricity production during these specific time intervals.

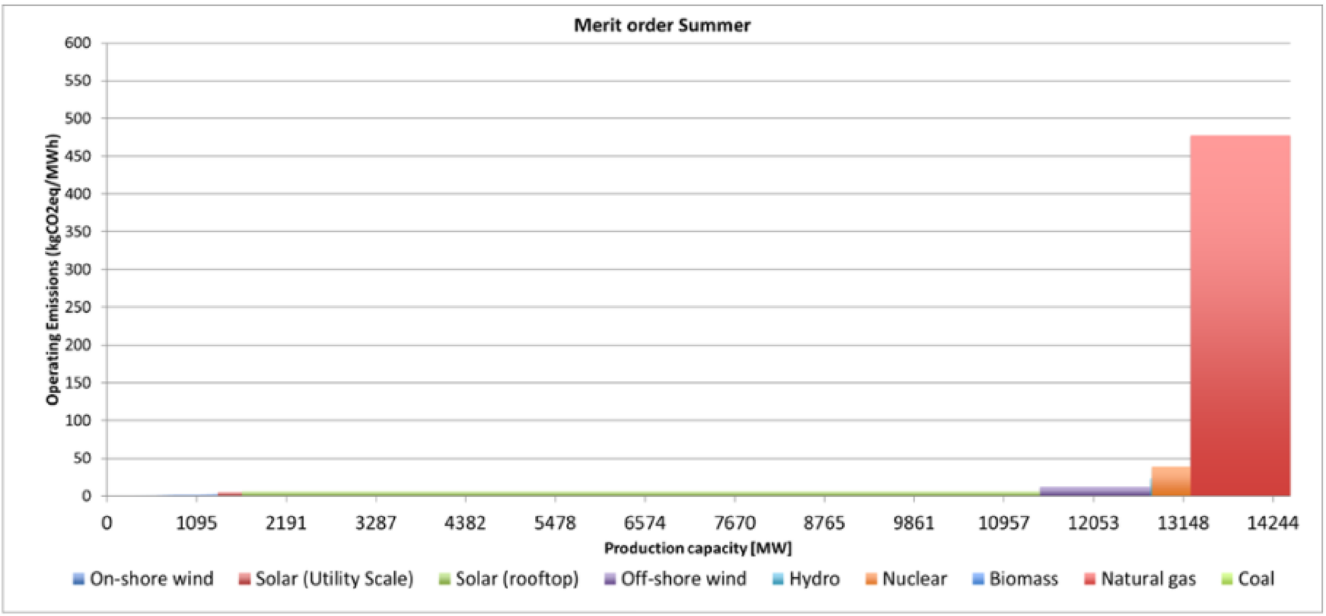

Figure 5: Electricity merit order summer based on the environmental impact

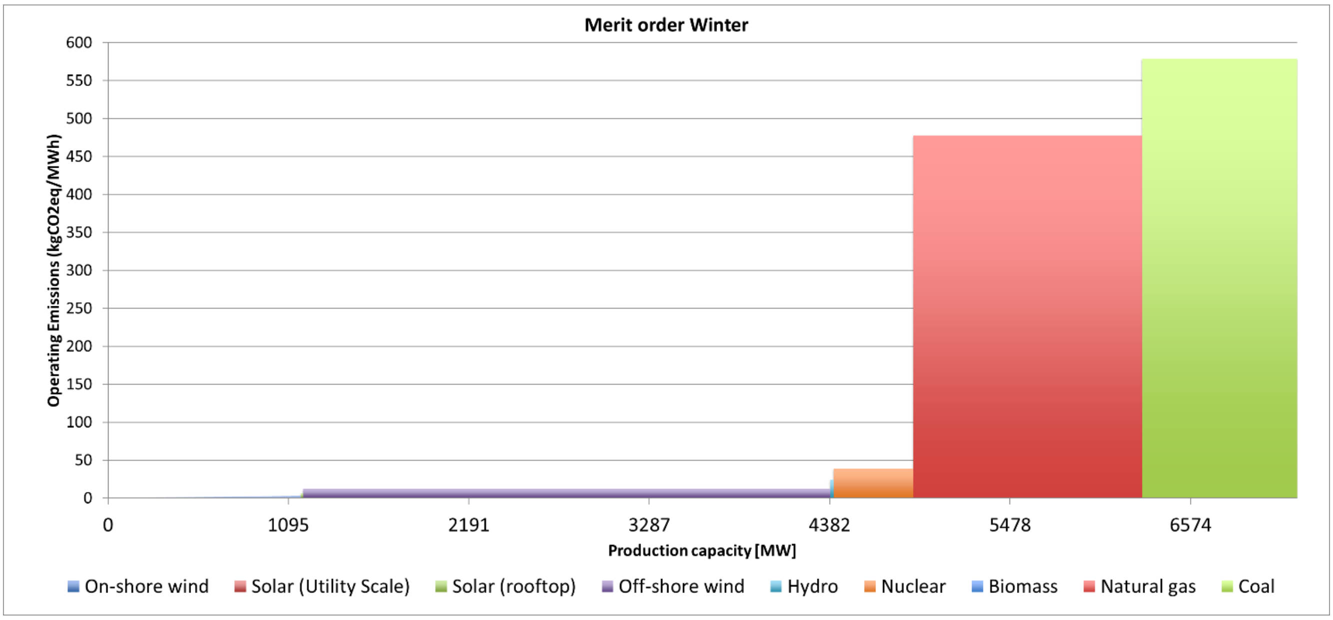

Figure 6: Electricity merit order winter based on the environmental impact

Based on the merit order[5] in which the environmental impact is the key factor, the Dutch electricity market avoids curtailing renewable electricity over fossil during periods of excess, as these energy sources have the least environmental impact. Curtailment will be applied to electricity generation types that emit a significant amount of CO2 equivalent (natural gas- and coal plants).

[5] Merit order: A merit order is a ranking of available electricity generation sources normally based on the marginal costs of production. In this case, the order is based on the environmental impact of production.

3.4 The hindering of the ENDEX Market

Switching the EPEX Market bid ladder from a marginal cost perspective to an environmental cost perspective wouldn't resolve the issue completely, as it would still be hindered by the dynamics of the ENDEX Market. This is because not all electricity in the Netherlands is traded through the Day-Ahead, Intra-Day, and Imbalance Market; a limited share is traded via the ENDEX Market [53].

As detailed in The ENDEX Futures Market, future contracts facilitate the physical delivery of 1 MW of electricity to the Dutch high-voltage grid over a defined period [28]. Additionally, long-term agreements in future contracts between producers and consumers specify a predetermined electricity price over a defined period, avoiding engagement with the Day-Ahead bid curve [54]. This further diminishes the motivation for curtailing operations during periods of electricity surplus. ENDEX contracts, largely dominated by fossil fuel-driven producers, may include certain producers with long-term contracts, excluding them from the benefits of production curtailment [54].

Energy traded on the ENDEX Market remains unaffected by the negative prices of the EPEX Market and less influenced by the Imbalance Market. Consequently, negative prices in the market lead to the curtailment of RE rather than fossil fuel-derived energy [9].

The decreased demand on the EPEX Market is attributed to the allocation of a portion of the electricity demand through the ENDEX Market. During certain periods, the supply of RE on the EPEX market surpasses the demand leading to negative prices. However, it is crucial to note that most of the time, the supply of RE does not exceed the total demand of the electricity market (ENDEX and EPEX) [9]. Therefore, the trading of energy on the ENDEX Market is a significant factor contributing to the inefficiency of the electricity market.

If the total electricity demand were to occur on the EPEX market, the price elasticity would shift to the right. Additionally, some supply methods, predominantly from fossil fuels, would also need to be incorporated from the ENDEX Market to the EPEX Market. Figure 7 provides an overview of the new price elasticity based on the total demand, resulting in a higher price. This change leads to a wider gap from the negative prices, reducing the likelihood of reaching the inefficient moments in the market. In an optimal social consideration, all the electricity would be traded in the same market. That way one market wouldn't interfere with the other and the inefficiency of the market would become less.

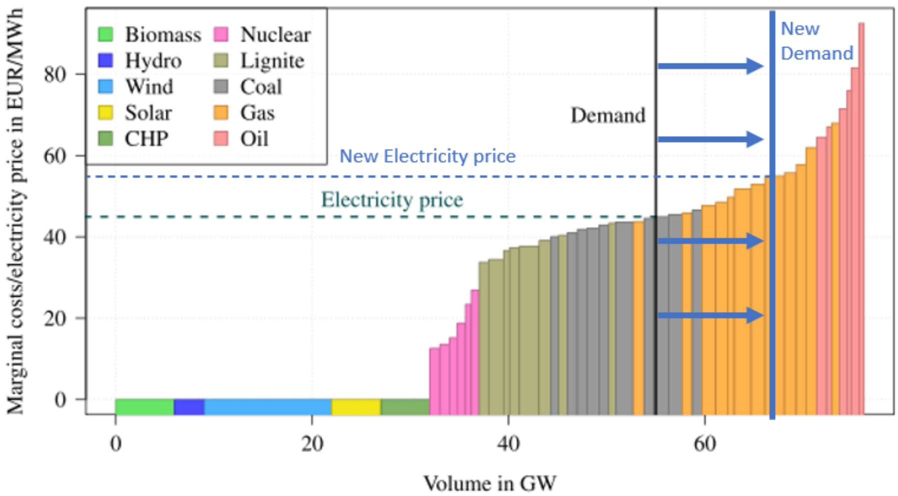

Figure 7: The demand of the ENDEX Market added to the merit order model

3.5 Technical limits of the Electricity Infrastructure

Now that the forecasted market functioning has been discussed (ENDEX- & EPEX Market), it's time to start looking at the impact of technical limitations due to the electricity infrastructure. The technical constraints of the electricity infrastructure can be attributed to both capacity shortages and grid congestion. These limitations within the electricity grid introduce imbalances within the energy network. Consequently, it is crucial to delve deeper into this issue.

Capacity Shortage

There is an increased electrification of society. On the demand side, electric transport, heating, and industrial processes are increasingly being driven by electricity. This results not only in an expansion of electrical devices in the system but also in a growing demand for sustainable electricity [55]. On the supply side, the unpredictable nature of RE generation has intensified market imbalances. The variability in energy production, particularly with solar PV, where generation ceases at night, compounds the challenge [56]. The increase in renewable electricity sources in combination with the higher electricity demand has led to peakiness of our electricity use [57].

On average, grid utilization in the Netherlands ranges from 25% to 30%, with increased utilization during peak moments [58]. One strategy to alleviate congestion issues is to optimize the utilization of the existing network closer to 100%.

Figure 8 & Figure 9 provide an overview of the state of the electricity supply and demand network in December 2023 [59]. The restricted areas are marked by their severity levels indicated by red (no transport capacity available), orange (no transport capacity available for the time being), and yellow colors (limited transport capacity available) [59].

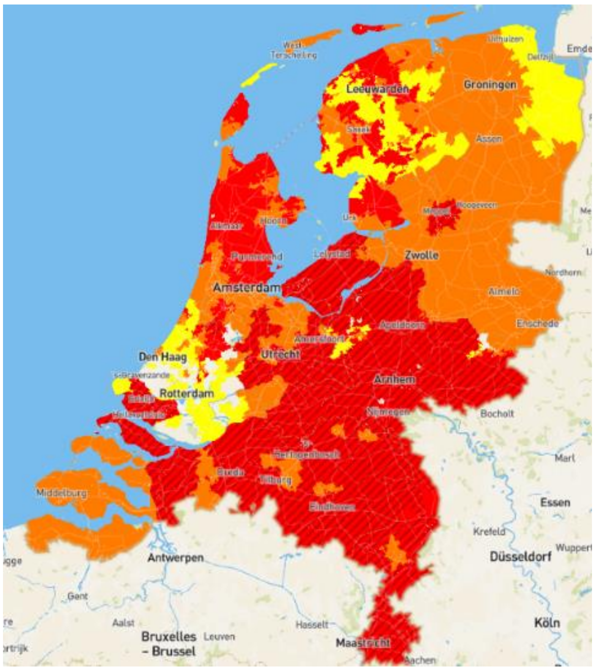

Figure 9: Capacity map of output in the electricity grid [59]

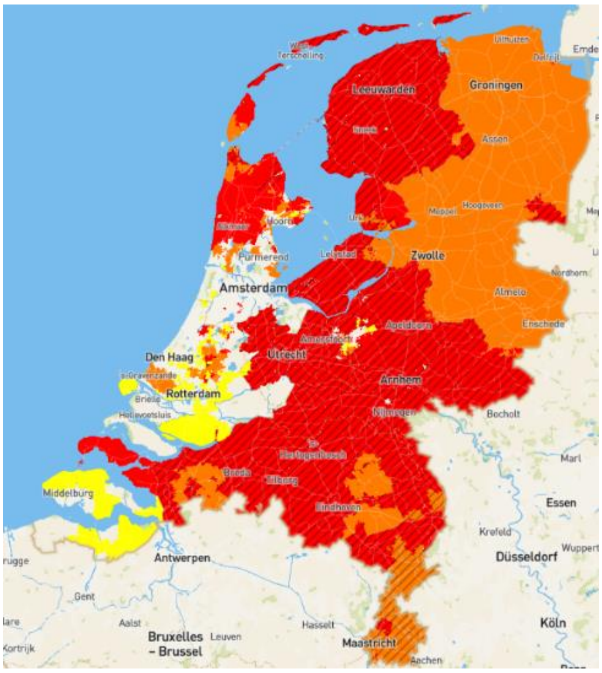

Figure 8: Capacity map of input in the electricity grid [59]

Congestion

Congestion presents a two-sided operational challenge, characterized by the incapacity of the existing transport infrastructure to transmit electricity from one area to another, leading to a twofold imbalance scenario [60].

The functioning of present electricity systems, relying on stable and controllable energy sources, is built upon the principle that the supply aligns with the demand. Nevertheless, achieving this is not feasible with solar and wind as electricity sources, given our inability to control their availability. The electricity output of a solar facility, for instance, can swiftly shift from generating a substantial amount to none at all, dependent on the weather. The inertia of the heavy, rotating rotor in a traditional power plant's generator is very different from the quick responsiveness of solar panels in generating electricity. This swift response can result in abrupt fluctuations in energy supply, posing a threat to the overall stability of the electricity grid [55].

Laan demonstrates an illustrative instance of congestion that emerges following the implementation of the technical 110% rule (Figure 10). The transport requirements of 60 MVA at node C and 50 MVA at node D cannot be fulfilled due to the 100 MVA limit from node A to B. Consequently, grid congestion occurs, characterized by an excess of electricity at node A and a deficiency of electricity at nodes C and D [61]. More information on congestion can be found here [60].

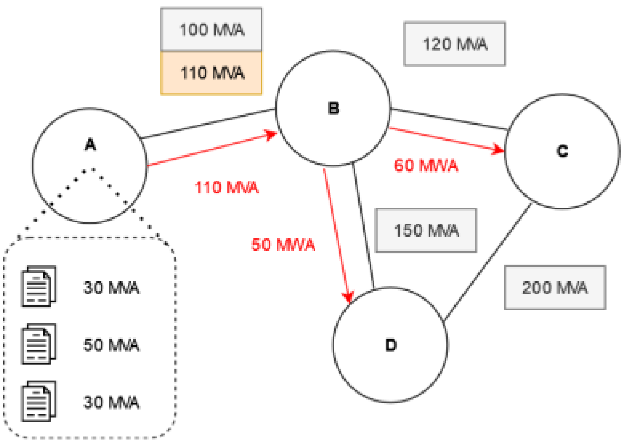

Figure 10: Illustrative example of congestion after applying the technical 110% rule [61]

Capacity shortage and congestion can lead to imbalances between electricity supply and demand. When there is excess supply and limited capacity to transport electricity to areas with high demand, negative prices may occur within the Imbalance Market as producers attempt to offload surplus electricity. Researchers have identified a correlation between the increased amount of RE (TWh production) and the quantitative increase in the imbalance of the Dutch electricity market (MWh) [56].

3.6 The Imbalance Market

If every producer and consumer were to stay within their capacity limitations, then negative prices on the Imbalance Market could be attributed to forecast errors. If no producer or consumer were to deviate from its forecast, then there wouldn't be an imbalance to manage in the first place. On the producer side, forecasting errors primarily occur with RE production [27].

The main energy sources for RE are weather-dependent, relying heavily on forecasted weather information [8], [27]. Since most RE forecasting relies on the same weather data, inaccuracies in these forecasts can result in significant fluctuations in RE production. Due to the substantial share of RE capacity in the mix, any forecast error promptly results in a significant impact on the Imbalance Market. This forecast error will result in either an energy excess or shortage, requiring balance through the operation of the Imbalance Market. In times of energy excess, the Imbalance Market will have negative prices. These negative prices should motivate producers to curtail their energy production, while they could also encourage consumers to increase their energy usage. Conversely, during energy shortages, the Imbalance Market will experience positive prices, encouraging producers to increase their energy production, while they could also prompt consumers to decrease their energy usage [62].

When this is translated into the means of RE production, the Imbalance Market only triggers the curtailment of RE because of the fact that production can't be increased (the sun can't shine brighter or the wind can't blow harder than it is already doing).

As mentioned before, negative prices in the EPEX Market (Day-Ahead) result in decreased income for energy producers. However, in the Imbalance Market, negative prices trigger the curtailment of energy production.

3.7 Green Power Purchase Agreements

Based on the aforementioned theory, the inefficiency of the electricity market is caused by multiple factors. Firstly, the market's oligopolistic structure with entry barriers for producers contributes to its imperfection. The rapid changes in demand and limited storage make it vulnerable to manipulation by dominant market players. Secondly, regulations like SDE++ and GoOs, along with hindrances from the ENDEX market, result in negative prices on the EPEX Market. Thirdly, grid limitations such as capacity constraints and congestion, combined with forecast errors, lead to negative prices in the Imbalance Market. These factors collectively contribute to the inefficiency of the Electricity Market.

Now that the causes that lead to the inefficiency of the market have been discussed, it's time to investigate what the expected effect of the inefficient market is on the GPPAs.

GPPAs play a pivotal role in various forms of bilateral energy trading, depending on the types of sellers and buyers [63]. Specifically, a GPPA constitutes a bilateral agreement between an energy-consuming company, committing to procure future energy generation from a RE producer at prearranged prices [64]. These contracts offer financial benefits to both producers and consumers by offering price certainty for the future unpredictable energy generation of producers, in contrast to the volatility of uncertain electricity market prices [65].

GPPAs are only possible when both the producer and the consumer are clients of the same PRP. This requirement is needed because the forecast and allocation need to be monitored by the same party. The forecast is needed for the E-program while the allocation is needed to determine the PRP's deviation from it. The impact of the allocation is further explained in the Methods section.

GPPAs with fixed prices are not linked to the EPEX or Imbalance Market. These fixed prices are effective during specific time intervals (15 minutes) when there is a synchronization of electricity supply and demand between the producer and the consumer. Consequently, during these synchronized intervals, these contractual arrangements remain unaffected by inefficiencies in the electricity markets.

In instances of surplus or deficit electricity, either the consumer or the producer must engage in trading on the DAM, IDM, or Imbalance Market to address the surplus or deficit. This surplus or deficit leads to uncertainty within the GPPAs. The higher the concurrency rate[6] is, the less dependent a consumer or producer is on the market functioning. The concurrency rate can be calculated both from the perspective of the consumer and the producer. A lower concurrency rate on GPPAs presents financial and technical challenges for buyers and sellers [66].

[6] Concurrency rate: The amount of energy that is simultaneously produced and consumed in the same 15 min interval, over a period of 1 year. This rate will be calculated individually for each energy consumer based on the data of the energy producer.

Figure 11 provides a graphical representation of the energy exchanged between a consumer and a solar PV producer involved in a GPPA. The producer's production is depicted in grey, while the consumer's consumption is shown in green. During these three days, the electricity production from the producer exceeded the electricity demand from the consumer during solar hours. Therefore, all the forecasted electricity was delivered from the producer to the consumer against the set agreement. In this scenario, the excess of generated electricity is traded on the EPEX Market, while forecast errors for both consumption and production are traded on the Imbalance Market. During these three days, the producer achieved a concurrency rate of 67%. This means that only 33% of the produced energy is traded on the EPEX Market, thereby reducing the producer's reliance on the inefficiencies of the electricity market.

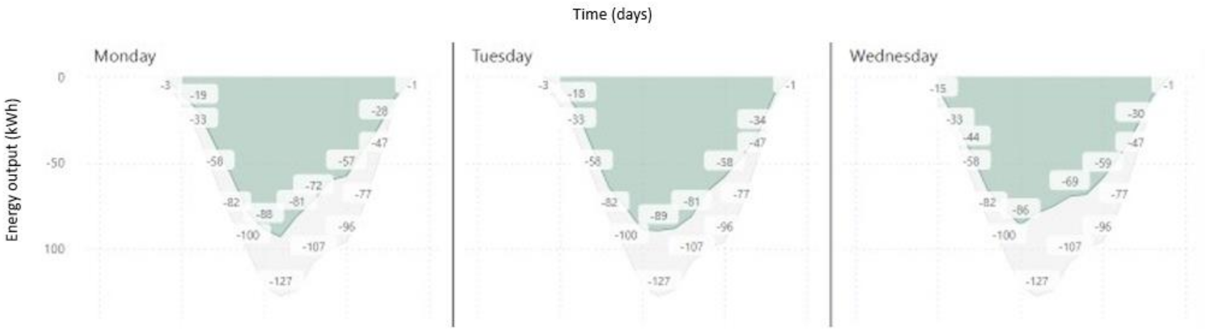

Figure 11: GPPA allocation between a consumer and a producer (67% concurrency rate)

4. Methodology

The research question aims to explore the multifaceted impact of the inefficiency of the Dutch electricity market on solar parks consisting of contractual GPPAs. Specifically, it seeks to investigate how GPPAs influence the curtailment of renewable energy.

4.1 Definitions

The following methods are used to answer **sub-question 1**:

Curtailment

The total energy curtailed due to the regulations of the SDE++ subsidy is calculated based on the production data of different solar parks. For each solar park, a simulation is made in which the inverter capacity is limited to 50%. Therefore, the amount of energy is capped for each 15-minute interval if it would have exceeded 50% of the maximum output. To determine this capacity, the installed capacity of the solar park (P_{solar}) is multiplied by 50%. The following formula is used to calculate the new power output of the solar park:

$$Power_{new} = P_{solar} * 0.5 \qquad (1)$$

For each 15 minute interval (PTU) the maximum energy production is calculated as follows:

$$Energy_{max} = Power_{new} / 4 \qquad (2)$$

When the actual energy production exceeds the $Energy_{max}$, it is scaled back to the maximum production based on the 50% inverter capacity ($E_{50\%}$). Based on this new energy production ($E_{50\%}$), the curtailed energy due to the limited inverter capacity is calculated as a percentage of the original energy output, with the inverter capacity averaging 80%.

$$Curtailed\ energy\ \% = \frac{E_{80\%} - E_{50\%}}{E_{80\%}} \qquad (3)$$

The following methods are used to answer **sub-question 2a:**

EPEX revenue

Each hour has its own EPEX price, determined through the process explained on page 12. Each interval of prices ($EPEX\ price_t$) is multiplied by the energy forecasted ($Nomination_t$) for the same interval. The revenue obtained from the EPEX Market is calculated as follows:

$$EPEX\ revenue = \sum_t Nomination_t * EPEX\ price_t \qquad (4)$$

Therefore, this calculation is made for each solar park for each hour, comprising 8,760 different intervals (365 days * 24 hours).

Imbalance

The Imbalance Market is explained in subparagraph 2.3 The Electricity Market. The Imbalance Market provides both a buy (take) and a sell (feed) price every minute. The price for each 15-minute interval is determined by the price of the last minute within that interval.

The forecast (nomination) for every producer is traded against the EPEX market. Frequently, there exists a variance between the forecasted (nomination) and actual (allocation) electricity generation, known as an imbalance. The formula for imbalance is as follows:

$$Imbalance_t \;=\; Allocation_t\;(production) -\; Nomination_t\;(forecast) \qquad (5)$$

Imbalance revenue

The prices for the Imbalance Market can vary, being positive when there is a shortage of energy on the market or negative when there is an excess of energy. These prices differ for each time interval. The Imbalance Market provides a final buy (take) and sell (feed) price at the end of each 15-minute interval. Imbalance can occur in either a positive (more produced than forecasted) or negative (less produced than forecasted) direction.

The revenue obtained from the Imbalance Market can be calculated for each interval as follows:

$$Imbalance\ revenue = \sum_t Imbalance_t *\; Imbalance\ price_t \qquad (6)$$

This calculation is made for each solar park for every quarter, comprising 35.040 different intervals (365 days * 24 hours * 4 quarters).

In the event of an excess of energy produced (allocation > nomination), leading to a positive imbalance, the feed price is utilized to determine the value of the created imbalance. Conversely, in the case of a shortage of energy produced (allocation < nomination), resulting in a negative imbalance, the take price is employed.

Financial loss

The financial loss is calculated by summing the negative prices within both the EPEX and Imbalance Market. Each interval of negative prices (P_t) is multiplied by the energy quantity (E_t) traded during the corresponding negative interval by the solar park:

$$Financial\ loss = \sum_t [MIN(0, P_t)] *\; E_t \qquad (7)$$

The following methods are used to answer **sub-question 2b:**

Energy steering

Energy steering operates based on a predefined threshold, which represents the minimum price required by the Imbalance Market before energy steering is initiated. The system sends signals based on an algorithm that tracks Imbalance Market prices every second. This process leads to the curtailment of energy, and the outcome is the duration of curtailment within the same time interval. Energy steering solely relies on data from the Imbalance Market and is therefore based on 15-minute intervals (900 seconds). The total duration of curtailed energy is defined as "*Seconds Curtailed*".

Curtailment each Interval

For each interval, the energy curtailed is calculated by the following equation:

$$Curtailment_t\ (PTU) = (Seconds\ Curtailed_t/900) * Allocation_t \qquad (8)$$

This equation is used to calculate the new allocation data for solar parks without GPPAs when energy steering is applied, as opposed to when it is not applied. The following equation is used to determine the allocation when energy steering is applied:

$$Allocation\ steering_t\ (PTU) = Allocation_t - Curtailment_t \qquad (9)$$

Imbalance

Due to the steering, the allocation changes and therefore the imbalance needs to be calculated with the new allocation (Allocation steering) for each time interval (t):

$$Imbalance_t\ (PTU) = Allocation\ steering_t - Nomination_t \qquad (10)$$

Additionally, the revenue obtained by the Imbalance Market needs to be recalculated. This equation utilizes the formula for Imbalance Revenue as given on page 23.

Total Curtailment

Curtailment is presented both in absolute terms (MWh) and as a percentage of potential PV output. This percentage signifies the proportion of PV output that was curtailed compared to the total potential energy production [67]:

$$Curtailment\ \% = \frac{E_{Curtailed}}{E_{Produced} + E_{Curtailed}} * 100 \qquad (11)$$

The following methods are used to address **sub-question 3a**:

EPEX revenue

The difference between sub-question 2a and 3a is that a certain amount of energy isn't traded via the EPEX market, but via the GPPA. Therefore, each interval of forecasted energy production ($Nomination_t$) will first be subtracted by the amount of energy directly sold to the GPPA for the same interval ($GPPA_t$) and then multiplied by the EPEX price ($EPEX\ price_t$). The revenue obtained from the EPEX Market is calculated as follows:

$$EPEX\ revenue = \sum_t MAX(0,\ Nomination_t - E_{GPPA\ t}) *\ EPEX\ price_t \qquad (12)$$

When the nomination of the solar park is smaller than the nomination towards the GPPA (nomination $< E_{GPPA\ t}$), the nomination accounted to the EPEX will automatically be set to 0 and therefore the revenue obtained from the EPEX is € 0.

GPPA revenue

The revenue obtained by the GPPA is calculated based on the GPPA price (P_{GPPA}) which is set at a rate that is agreed upon by both parties (consumer and producer). This price is multiplied by the quantity of energy that is directly traded against the GPPA consumer (E_{Gppa}). When, within a specific interval, the solar park's power allocation falls below the E_{Gppa} demand ($allocation_t < E_{Gppa\ t}$), the entire allocation is attributed to the GPPA. This is calculated as follows:

$$GPPA\ revenue_t = \sum_t IF(Allocation_t > E_{GPPA\ t}\ ;\ E_{GPPA\ t}\ ;\ Allocation_t) *\ P_{GPPA\ t} \qquad (13)$$

Because both the energy producer and the energy consumer are clients of the same Program Responsible Party (PRP), the simultaneous energy provision from the producer to the consumer in the GPPA is an administrative act. Therefore, the Allocation and the Nomination of the GPPA are the same.

The following methods are used to address **sub-question 3b:**

Curtailment per Interval

For each interval, the energy curtailed is calculated. For solar parks consisting of contractual GPPAs, not the entire allocation (production) is available for curtailment because some energy is allocated to the GPPA and not traded via the market. Therefore, the energy allocated to the GPPA needs to be subtracted from the allocation (production) data before the curtailment can be calculated. When the allocation of the solar park is smaller than the nomination towards the GPPA (allocation < GPPA), curtailment will automatically be set to 0 seconds and therefore avoided. With the new curtailment per PTU, the imbalance is calculated. Subsequently, based on the new imbalance, the revenue obtained from the Imbalance Market is calculated. This formula is as follows:

$$Curtailment\ _t(PTU): IF\big(Allocation_t > GPPA_t; \big((900 - SecondsCurtailed_t)/900\big) * (Allocation_t - GPPA_t); 0\big) \quad (14)$$

This equation includes the energy allocated to the GPPA, and is used to calculate the new allocation data for solar parks without GPPAs when energy steering is applied. Each interval (*t:* 15 minutes) has its own amount of curtailed energy and therefore its curtailment rate.

4.2 Data analysis

Based on the methods, the following analysis was used to answer each sub-question:

1. *What triggers curtailment in the Dutch electricity market, leading to the underutilization of renewable energy potential?*

Quantifying the energy curtailed due to regulations attached to the SDE++ subsidy (sub-question a) involved a thorough examination of 11 solar parks. The criteria for selecting these 11 solar parks were as follows: solar parks without contractual GPPAs and energy steering software. The methods attributed to sub-question 1 were used to determine the energy curtailment due to new SDE++ regulations.

To address the extent to which the EPEX Market's structure and the Imbalance Market's structure triggered curtailment (sub-questions b and c), the research delved into the occurrences of negative prices within both markets. The first phase entailed pinpointing the intervals marked by negative pricing. This data is graphically presented, facilitating clear comprehension and visualization of the identified issues.

To address the effect of negative prices on the actual electricity mix (sub-question d), data sourced from the ENTSO-E transparency platform was used to examine the energy production types in operation during intervals marked by negative prices on both the EPEX and Imbalance Market. Based on this information, an analysis was conducted to ascertain whether negative prices led to the curtailment of fossil fuel-driven energy production. The data is presented in graphs, providing a clear overview of the different energy producers during negative time intervals.

2. *What are the financial and energy losses, for solar park owners without contractual GPPAs, due to the inefficiency of the electricity market?*

Figure 12 presents an overview of the identification strategy used for the various solar parks from which the data for this research is obtained.

For sub-question 2, forecast (nomination) and production (allocation) data from eight different solar parks for the year 2023 were used. The solar parks used for Groups 1 and 2 were identical. The difference between Group 1 and Group 2 was that Group 2 underwent an energy steering simulation. This was necessary because Groendus did not have annual data for solar parks with energy steering in 2023.

The criteria for selecting these eight solar parks were as follows: they lacked energy steering software, didn't have contractual GPPAs, meaning all energy was traded via the market, and had to have a minimum capacity of 300 kWp. This last requirement was chosen based on the need for the energy steering effect to be measurable. Smaller solar parks would have a smaller effect on these measurements.

Financial losses (question 2a) occurred in both groups (Group 1 & 2 in Figure 12). The baseline for financial loss was set based on the financial performance of the group which was completely dependent on the market functioning and therefore didn't consist of energy steering hardware and software (Group 1 in Figure 12). Quantifying the financial loss involved extracting the amount of energy produced during the negative prices on both the EPEX and Imbalance Market.

From these solar parks, the revenue streams allocated to the EPEX and Imbalance Market were calculated. To determine the financial losses (question 2a) each negative EPEX interval was multiplied by the forecast and each negative imbalance interval was multiplied by the quantity of imbalance (the method is explained on page 22). To be able to perform a clean measurement, negative revenue from the Imbalance Market was only accounted for when the production (allocation) exceeded the forecast (nomination) and led to a negative income obtained from the production of RE. Therefore, negative income stemming from a shortage of energy production (allocation < nomination) was excluded from the calculation.

Quantifying the energy loss (question 2b) required extracting the curtailment loss from the data. For Group 2, the forecast (nomination) data remained unchanged, while the production data varied (allocation). This discrepancy arose because energy steering software leveraged the imbalance signal to evaluate whether deviating from the nomination could yield additional revenue. In the context of renewable energy production, this often results in encountering negative take prices and the subsequent curtailment of renewable energy output.

The reference group, designated as Group 1, contained solar parks lacking energy steering and without contractual GPPAs. To determine the electricity loss caused by curtailment, generation data from Group 2, comprising solar parks with energy steering and without contractual GPPAs, was utilized. Energy loss occurred when solar parks were equipped with energy steering hardware and software (Group 2 in Figure 12).

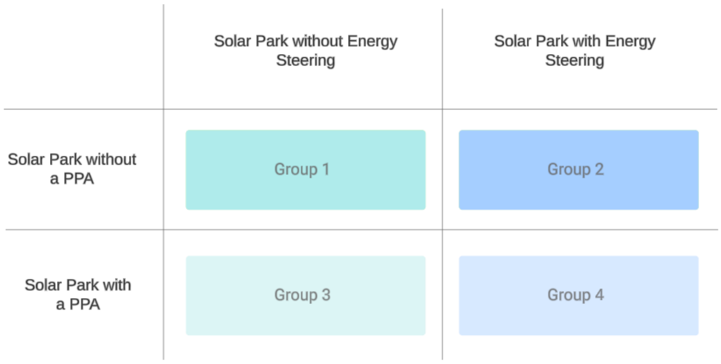

Figure 12: Identification strategy of different solar parks

3. *What are the financial and energy losses, for solar park owners with contractual GPPAs, due to the inefficiency of the electricity market?*

Groups 1 and 2 have been established in sub-question 2. After, Groups 3 and 4 were established (see Figure 12).

For sub-question 3, forecast (nomination), production (allocation), and GPPA allocation data from 10 different solar parks for the year 2023 were used. Again, the solar parks used for Groups 3 and 4 were identical. The difference between Group 3 and Group 4 was that Group 4 underwent an energy steering simulation. This was necessary because Groendus did not have annual data for solar parks with energy steering in 2023.

The criteria for selecting these 10 solar parks were as follows: they lacked energy steering software, did have contractual GPPAs, meaning not all energy was traded via the market, and had to have a minimum capacity of 300 kWp. As already mentioned, this last requirement was chosen based on the need for the energy steering effect to be measurable. Smaller solar parks would have a smaller effect on these measurements.

Financial losses (question 3a) occurred in both groups (Group 3 & 4 in Figure 12). This time, both groups were less dependent on the functioning of the market. This was because a substantial part of the energy production was sold via the GPPA. For group 3, the results only obtained financial effects due to the absence of energy steering hardware and software. Quantifying the financial loss involved extracting the amount of energy produced during the negative prices on both the EPEX and Imbalance Market.

For sub-question 3a, forecast (nomination), production (allocation), and GPPA allocation data from 10 solar parks for the year 2023 were used. From these parks, the revenue streams allocated to the EPEX, GPPA, and Imbalance Market were calculated. Each negative EPEX interval was multiplied by the forecast minus the GPPA and each negative imbalance interval was multiplied by the quantity of imbalance (the method is explained on page 29). Again, to perform a clean measurement, negative revenue from the Imbalance Market was accounted for only when the production (allocation) exceeded the forecast (nomination) and resulted in negative income from renewable energy production. Therefore, negative income resulting from an energy production shortfall (allocation < nomination) was excluded from the calculation.

Quantifying the energy loss (question 3b) required extracting the curtailment loss from the data. For Group 4, the forecast (nomination) data remained unchanged, while the production data varied (allocation). Again, this discrepancy arose because energy steering software leveraged the imbalance signal to evaluate whether deviating from the nomination could yield additional revenue. In the context of renewable energy production, this often results in encountering negative take prices and the subsequent curtailment of renewable energy output.

The reference group, designated as Group 3, comprised solar parks with GPPAs but lacking energy steering. To determine the electricity loss caused by curtailment, generation data from Group 4, comprising solar parks with energy steering and contractual GPPAs, was utilized. Energy loss occurred when solar parks were equipped with energy steering hardware and software (Group 4 in Figure 12).

4.3 Data comparison

Several requirements were imposed on each group. Figure 12 illustrates the identification strategy along with the requirements for each group.

For sub-question 3a, the analysis focused on solar parks comprising contractual GPPAs but lacking energy steering software (Group 3 in Figure 12). Forecast (nomination), production (allocation), and GPPA allocation data from the 10 solar parks for the year 2023 were used. The baseline for this group was determined based on the financial performance of solar parks that were completely dependent on the market functioning and therefore didn't consist of energy steering hardware and software (Group 1 in Figure 12).

For sub-question 3b, the analysis focused on solar parks comprising contractual GPPAs and energy steering software (Group 4 in Figure 12). Forecast (nomination), production (allocation), and GPPA allocation data from the same 10 solar parks for the year 2023 were used. Energy steering was only applied to a substantial part of the production (allocation). First, the GPPA allocation was subtracted from the solar park allocation to determine the energy used for curtailment. Therefore, the potential curtailment was smaller. The baseline for energy loss was established based on the curtailed energy of solar parks that are dependent on the market functioning and include energy steering hardware and software (Group 2 in Figure 12).

When the results from each group were finalized, a comparison was made in section 6.4 Overview of the Results to determine to what extent solar PV parks with contractual GPPAs are influenced by the inefficiency of the Dutch electricity market compared to solar parks without contractual GPPAs. This comparison was made for each group and expressed in the amount of negative revenue obtained per MWh of electricity (€ / MWh).

5. Data Section

The research utilized a dual approach based on longitudinal data, employing both quantitative analysis and case study evaluations, to investigate the impact of GPPAs on the curtailment of RE. First, national data on the Dutch electricity market was gathered. The EPEX prices for the year 2023 were extracted from the EPEX database and the Imbalance prices were from the TenneT database [14], [68]. Both these databases were used to examine the Dutch electricity market for the year 2023. Annual data on the actual generation per production type was extracted from the ENTSO-E transparency platform [9].

Data for the solar parks were extracted from the Groendus database. For the solar parks that were in the possession of contractual GPPAs, data on the nomination, allocation, and GPPA allocation were extracted.

This chapter will discuss the datasets that were used for answering each sub-question. A distinction is made between public and private data. Descriptive statistics for each dataset are presented here, including the number of intervals, the average, the standard deviation, the minimum, and the maximum. This analysis allows for an examination of the distribution, central tendency, and variability within each dataset, contributing to the understanding of the behavior and characteristics of the variables used in this study.

5.1 Public data

By examining the descriptive statistics provided in Table 2 for the EPEX and Imbalance prices, a difference in the number of intervals is observed. This variation arises from the difference in Program Time Units (PTUs). The EPEX Market operates with PTUs of 1 hour, resulting in 8,760 intervals per year. In contrast, the Imbalance Market operates with PTUs of 15 minutes, resulting in four times as many intervals, totaling 35,040 per year.

The Imbalance Market exhibits a significantly higher standard deviation of €194.95, compared to the EPEX Market's standard deviation of only €49.04. Additionally, the price range on the EPEX Market spans from €-500 to €463.77, whereas prices on the Imbalance Market vary more widely, ranging from €-1,549.47 to €2,037.74.

Table 2: EPEX and Imbalance prices for the year 2023

Dataset	Intervals	Average (price)	Standard deviation	Minimum	Maximum
EPEX prices	8,760	€ 95.83	€ 49.04	€ -500.00	€ 463.77
Imbalance Take prices	35,040	€ 103.43	€ 195.69	€ -1,549.47	€ 2,037.74
Imbalance Feed prices	35,040	€ 93.61	€ 194.95	€ -1,549.47	€ 2,037.74

Table 3 presents the descriptive statistics for actual generation by production type, expressed in power (MW). The data is segmented into 15-minute PTUs. The maximum energy generated from a single source within one PTU is 28,237 MW, categorized under "Other." This volume is anticipated to be imported energy and, as such, is not attributed to a specific generation source.

Table 3: Actual Generation per Production Type from the ENTSO-E [9]

ENTSO-E production	Average (MW)	Standard deviation	Minimum	Maximum
735,840	591.00	1,436.35	0	28,237.00

5.2 Private data

Table 4 provides an overview of the data used to determine the new energy production if the inverter capacity would be set at 50%. Data from 11 different solar parks was used to determine the outcome.

Table 4: Generation data of 11 solar parks with an inverter capacity above 70%

Intervals	Average (kWh)	Standard deviation	Minimum	Maximum
385,440	20.87	50.66	0.00	490.225

Table 5 provides an overview of the different requirements for each group as detailed in section 4.2, Data Analysis. Table 6 presents the descriptive statistics for the different groups. Groups 1 and 2 contain data from the same solar parks, as do Groups 3 and 4. The difference between Groups 1 and 2, and between Groups 3 and 4, are due to the energy steering software, which influences the allocation data and, consequently, the descriptive statistics.

Groups 1 and 2 provide data attributed to eight solar parks, while Groups 3 and 4 cover data from ten solar parks. This difference can be observed in the number of intervals. Additionally, the installed capacity of the ten solar parks is 2.8 times greater than that of the eight solar parks. As a result, the average production data for the ten solar parks (Groups 3 and 4) is larger than that of the eight solar parks (Groups 1 and 2). Additionally, within the data presented in Groups 3 and 4, the largest solar park is approximately 3.6 times larger than the largest solar park represented in Groups 1 and 2.

Table 5: Requirements for each group

Group	Requirements
1	Solar parks without GPPAs and without energy steering
2	Solar parks without GPPAs and with energy steering
3	Solar parks with GPPAs and without energy steering
4	Solar parks with GPPAs and with energy steering

Table 6: Allocation, Nomination, and GPPA data of each group

Dataset	Intervals	Average (kWh)	Standard deviation	Minimum	Maximum
Allocation of Group 1	280,320	11.06	19.62	0.00	120.00
Nomination of Group 1	280,320	12.06	20.17	0.00	133.91
Allocation of Group 2	280,320	9.70	18.01	0.00	120.00
Nomination of Group 2	280,320	12.06	20.17	0.00	133.91
Allocation of Group 3	350,400	24.45	52.93	0.00	438.75
Nomination of Group 3	350,400	26.22	53.94	0.00	438.45
GPPA nomination of Group 3	350,400	15.39	34.87	0.00	363.25
Allocation of Group 4	350,400	22.95	50.03	0.00	438.75
Nomination of Group 4	350,400	26.22	53.94	0.00	438.45
GPPA nomination of Group 4	350,400	15.39	34.87	0.00	363.25

6. Results

The following section presents both quantitative results derived from the analysis of diverse datasets and qualitative findings stemming from theoretical and practical research.

6.1 The different triggers that cause curtailment

Understanding the challenges of curtailment in electricity markets is crucial for optimizing resource use and improving operational efficiency. This chapter delves into the complex factors that influence curtailment. The influence of regulatory frameworks, and market mechanisms, including the EPEX and the Imbalance Market, on the phenomenon of curtailment is examined. Through a comprehensive analysis, valuable insights for stakeholders in the energy sector seeking to mitigate curtailment and improve overall market performance are aimed to be provided.

The influence of the SDE++ subsidy

The Dutch Minister for Climate and Energy has introduced stricter requirements for solar panel projects participating in the SDE++ subsidy scheme, mandating that the inverter capacity be limited to 50 percent of the solar panel's peak power. This marks a significant change from the previous capacity allowance of 100% before 2021 and 70% since then [17]. The rationale behind this adjustment stems from research indicating that a grid connection comprising 45% to 50% of the PV peak capacity represents an optimal balance between cost efficiency and sustainable energy production [69]. Based on these requirements, RE will be curtailed because the inverter capacity is unable to convert all the generated renewable energy during peak moments.

This study examined the government's assertion through an analysis of production data from 11 solar parks in 2023, with an average inverter capacity of 80%. This enabled quantification of the potential energy loss if the inverters had operated at 50% of the installed capacity. The methodologies for these calculations are detailed in 4.1 Definitions. The findings indicate an overall loss of energy production of 5.43% compared to the original inverter capacities. Table 7 provides an overview of the aggregated values for the 11 solar parks.

Table 7: Solar park inverter details

Details of the 11 solar parks	Result
Installed solar capacity (kWp)	9,111.79
installed inverter capacity (kWp)	7,263.80
Inverter capacity	80%
Generation (kWh)	8,044,515.14
Invertercapacity 50% (kWp)	4,643.30
Generation with 50% inverter capacity(kWh)	7,607,992.75
% losses due to 50% inverters	5.43%

The EPEX Market

This section will dive into the influence of the EPEX Market on the curtailment of solar energy. As defined in the introduction, negative prices in the electricity market are established as the inefficiency of the market. This paragraph will look further into the occurrence of inefficient moments in the EPEX market. In 2023, the EPEX Market recorded 315 hours of negative prices. The data is initially organized by the frequency of negative EPEX prices for each month, as illustrated in Figure 13, and further detailed in Figure 14, which outlines the distribution of negative prices by the hour they occurred [14]. In February and November, there were no instances of inefficiency observed in the EPEX Market.

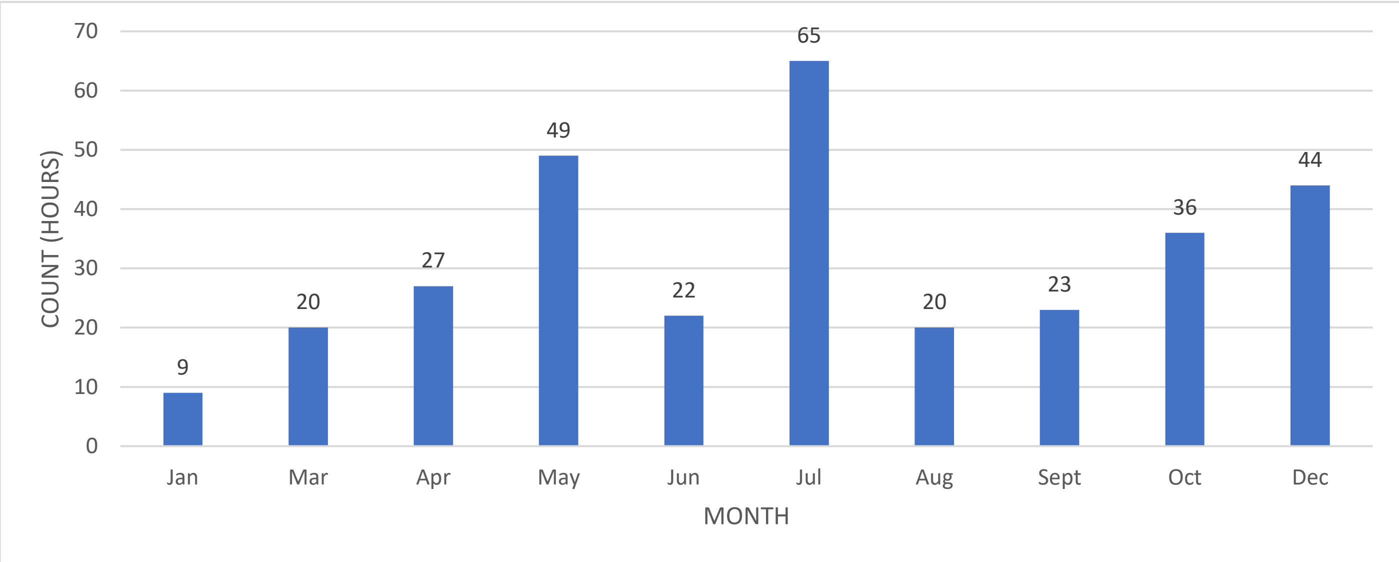

Figure 13: Count of negative EPEX prices in 2023 divided over the months

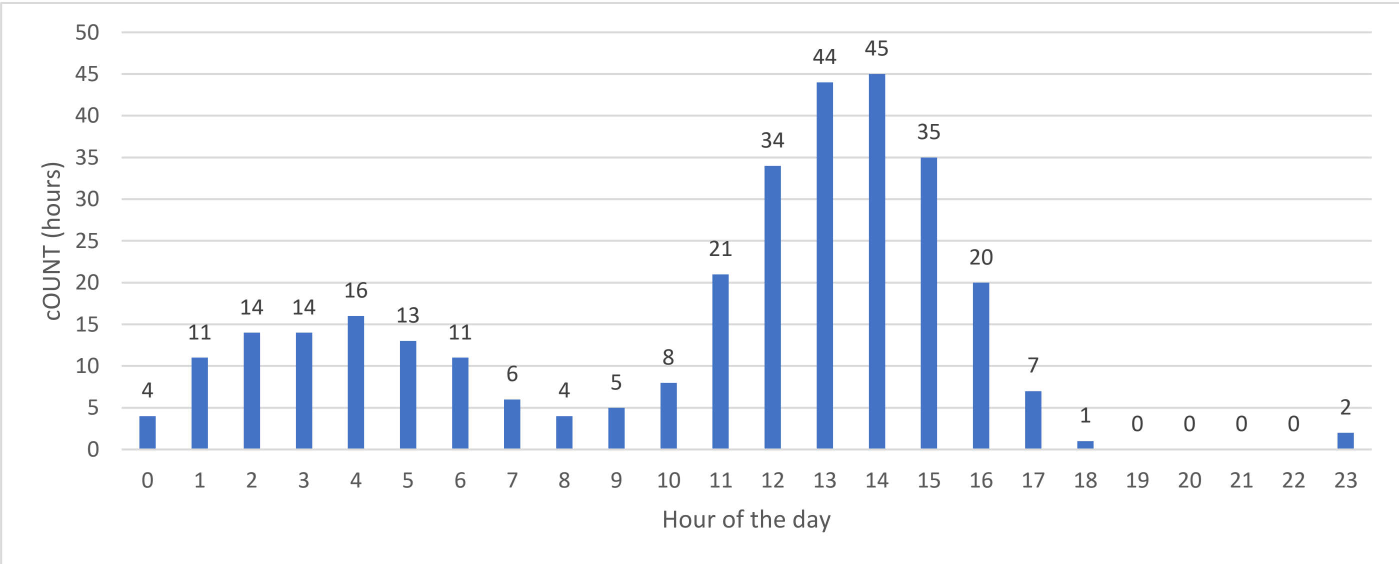

Figure 14: Count of negative EPEX prices in 2023 divided over the hours of the day

The data distinctly reveals a correlation between negative prices in the winter season, with occurrences predominantly observed during nighttime hours (11 PM – 7 AM). Similarly, in spring and summer, negative prices are primarily recorded during daytime hours (11 AM – 5 PM). Figure 15 provides a comprehensive overview of negative price occurrences during the winter months, while Figure 16 offers a detailed analysis of negative price occurrences in the spring and summer months [14].

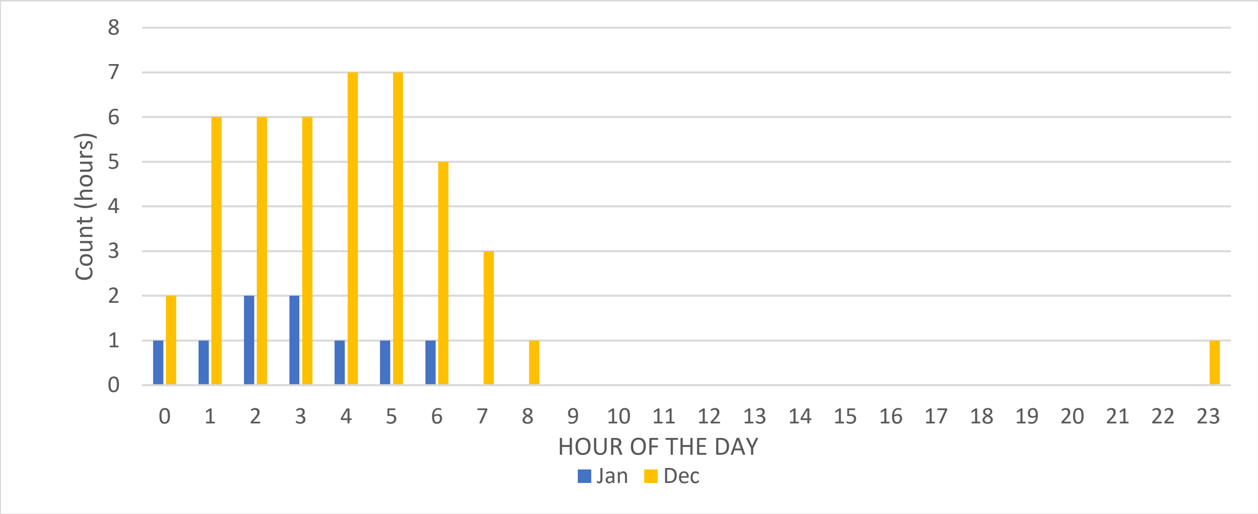

Figure 15: Negative EPEX hours during November-January

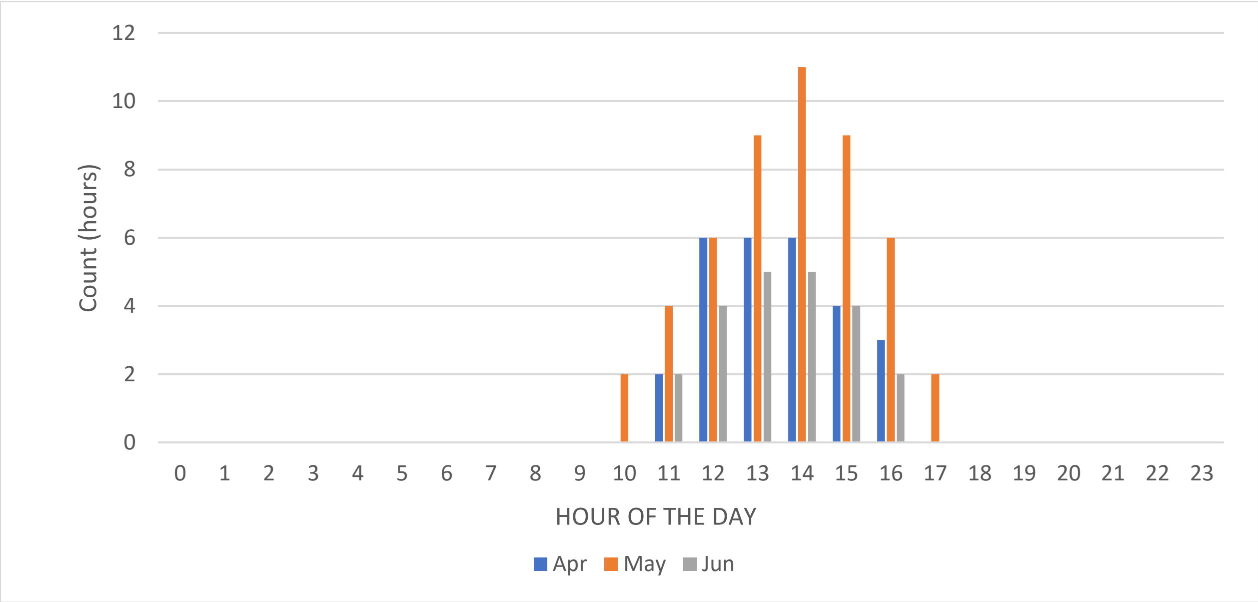

Figure 16: Negative EPEX hours during April-June

A distinction has been made between negative EPEX hours in winter and summer. Negative hours in winter are characterized primarily by a large quantity of wind energy combined with low demand. In the spring and summer, negative hours are predominantly influenced by solar energy in combination with wind energy. Most of these negative intervals in the spring and summer occur on weekends, with low electricity demand and high renewable energy penetration. Consequently, the excess electricity produced is higher in the spring and summer months compared to the winter months, leading to higher negative prices in the spring and summer [14].

The Imbalance Market

This section will dive into the influence of the Imbalance Market on the curtailment of solar energy. On the electricity market, solar parks are initially subject to the EPEX market, relying on forecasts generated the day before at 12 pm. These forecasts dictate the required electricity generation. If there is an excess or shortage of electricity within the 15-minute interval, companies are obligated to buy or sell their surplus or deficit on the Imbalance Market.

Negative prices on the Imbalance Market can result in either financial losses or quantitative energy losses due to energy steering, which is financially incentivized. This subparagraph will look further into the occurrence of negative prices in the Imbalance Market.

Unlike the EPEX market, the Imbalance Market operates on a 15-minute interval instead of a one-hour interval. The data is initially organized by the frequency of negative imbalance prices for each month, as illustrated in Figure 17, and further detailed in Figure 18, which outlines the distribution of negative prices by the hour they occurred.

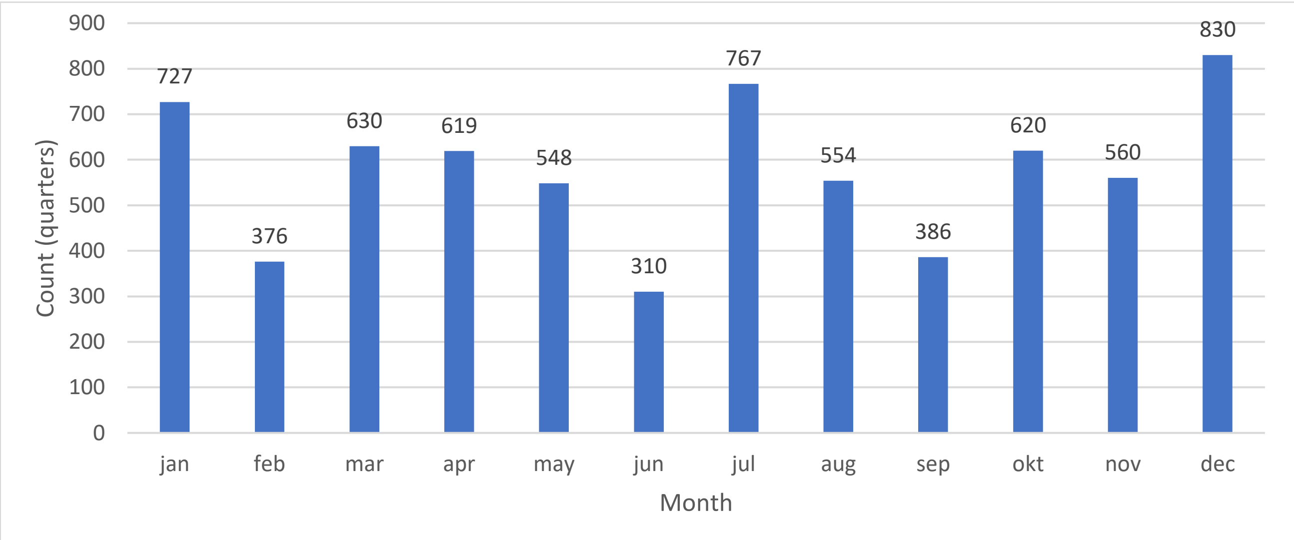

Figure 17: Count of negative Imbalance prices in 2023 divided over the months of the year

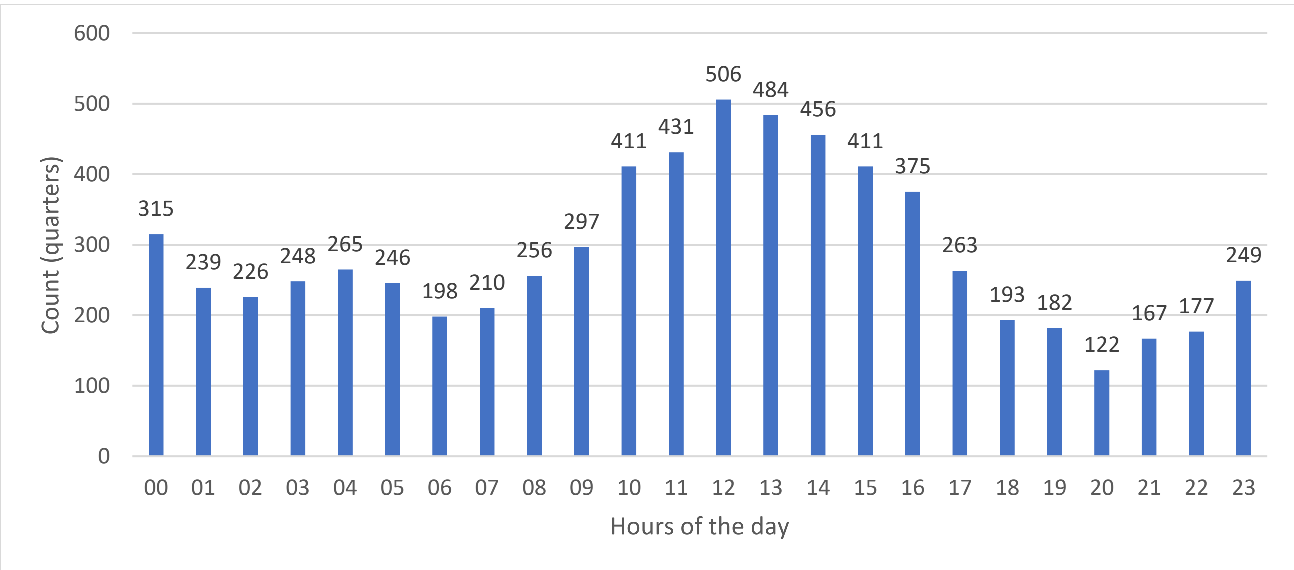

Figure 18: Count of negative Imbalance prices in 2023 divided over the hours of the day

Unlike the EPEX Market, there is a weaker correlation between negative hours and the nighttime in the fall and winter seasons. However, during the spring and summer months, negative hours predominantly occur during daytime hours, corresponding to the generation profile of solar energy. Figure 19 provides a comprehensive overview of negative price occurrences during the fall and winter months, while Figure 20 offers a detailed analysis of negative price occurrences in the spring and summer months.

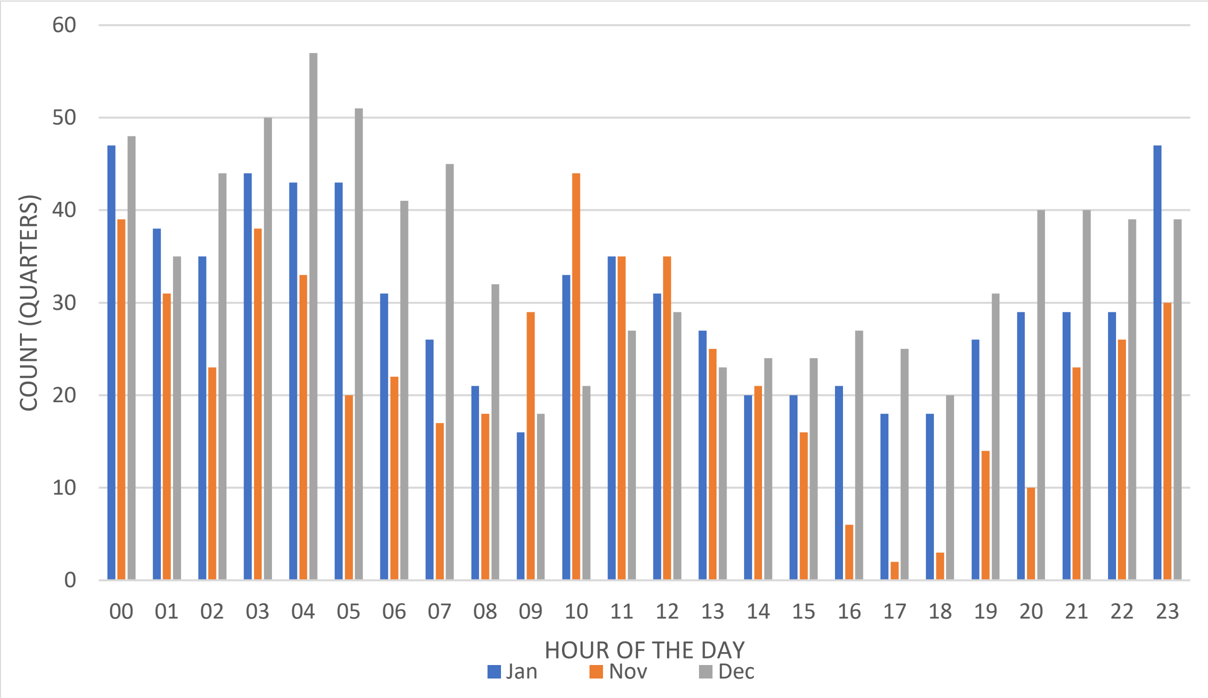

Figure 19: Negative Imbalance quarters during November-January

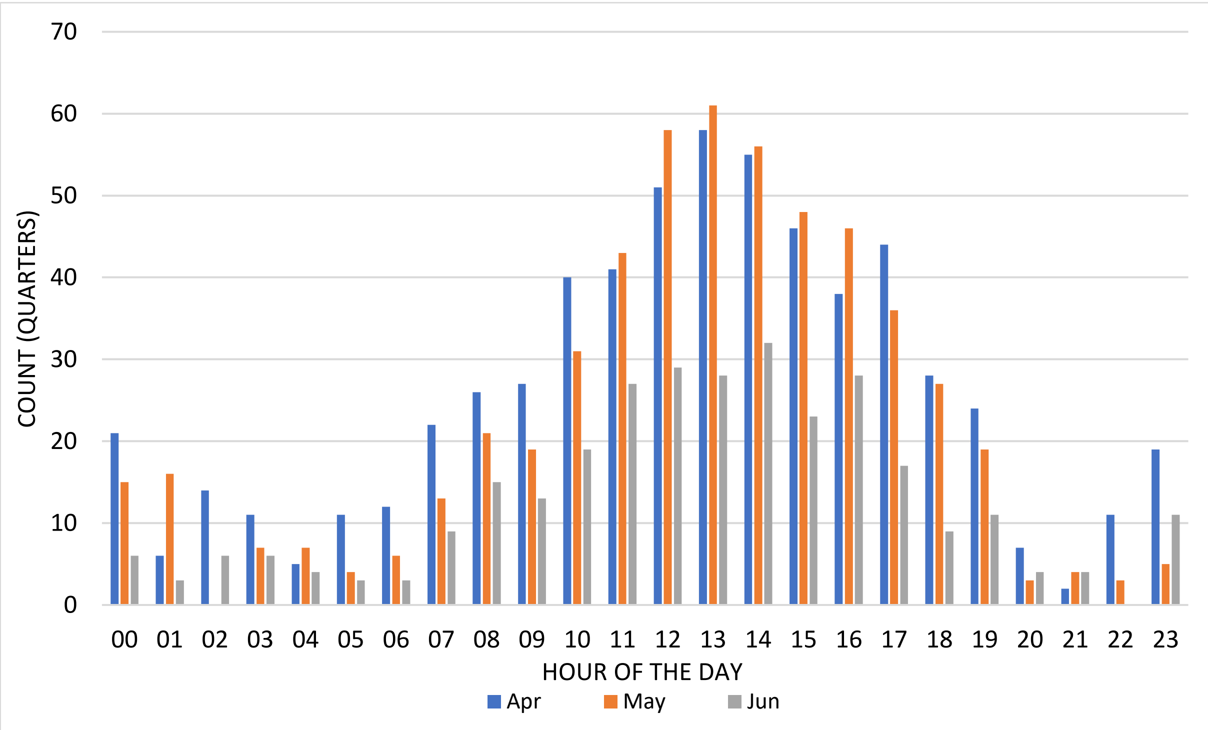

Figure 20: Negative Imbalance quarters during April-June

Analyzing the impact of Negative Prices on the Electricity Market

The question arises: What is the effect of negative prices on the actual generation of electricity within the Dutch electricity market? Figure 21 provides an overview of the different prices on both the Imbalance and EPEX markets for July 2, 2023, between 12:15 and 16:45. It's evident that all hours show extremely negative prices on the EPEX market, while the feed prices for the Imbalance Market are also negative but to a lesser extent. Figure 22 offers insight into the actual electricity generation stemming from fossil gas and solar. Despite the negative prices on both the EPEX and the Imbalance Market, a substantial amount of electricity stemming from gas (+/- 8%) is still generated during these periods.

The impact of energy steering on solar assets is evident in Figure 22. Energy steering operates based on a predefined threshold, which represents the minimum price required by the Imbalance Market before energy steering is initiated. Solar energy production decreases when the Imbalance Market reaches higher negative prices. Consequently, the threshold at which energy steering operates is reached for a greater number of solar parks, leading to a larger decrease in solar energy production. As shown in Figure 21, the imbalance price becomes almost positive at 16:45, resulting in an increase in solar energy production once again.

This indicates the inefficiency of the electricity market in which we find ourselves having to pay for the production of sustainable energy while, at the same time, electricity is still being produced by fossil-driven sources.

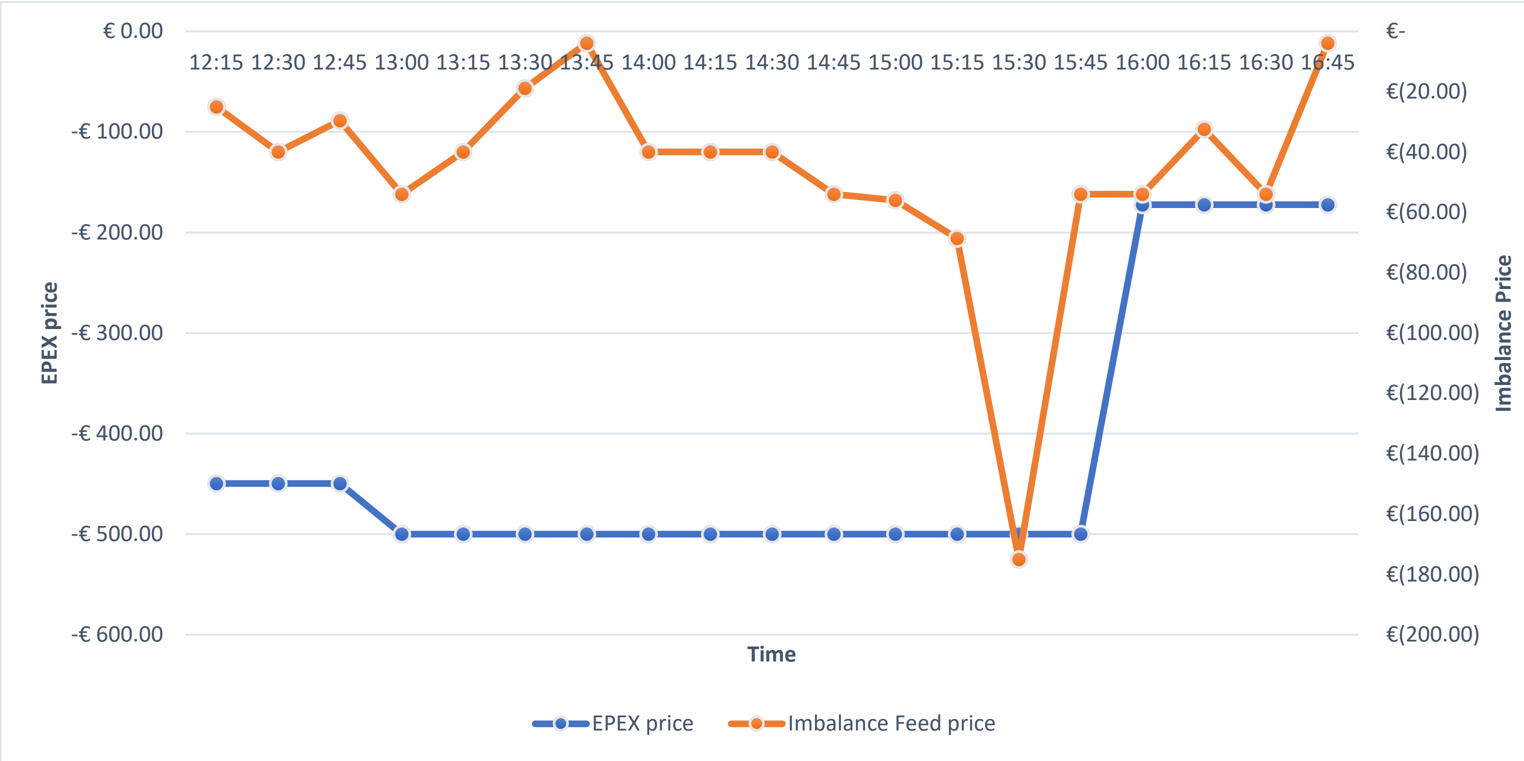

Figure 21: EPEX and Imbalance prices (€) from 02-07-2023

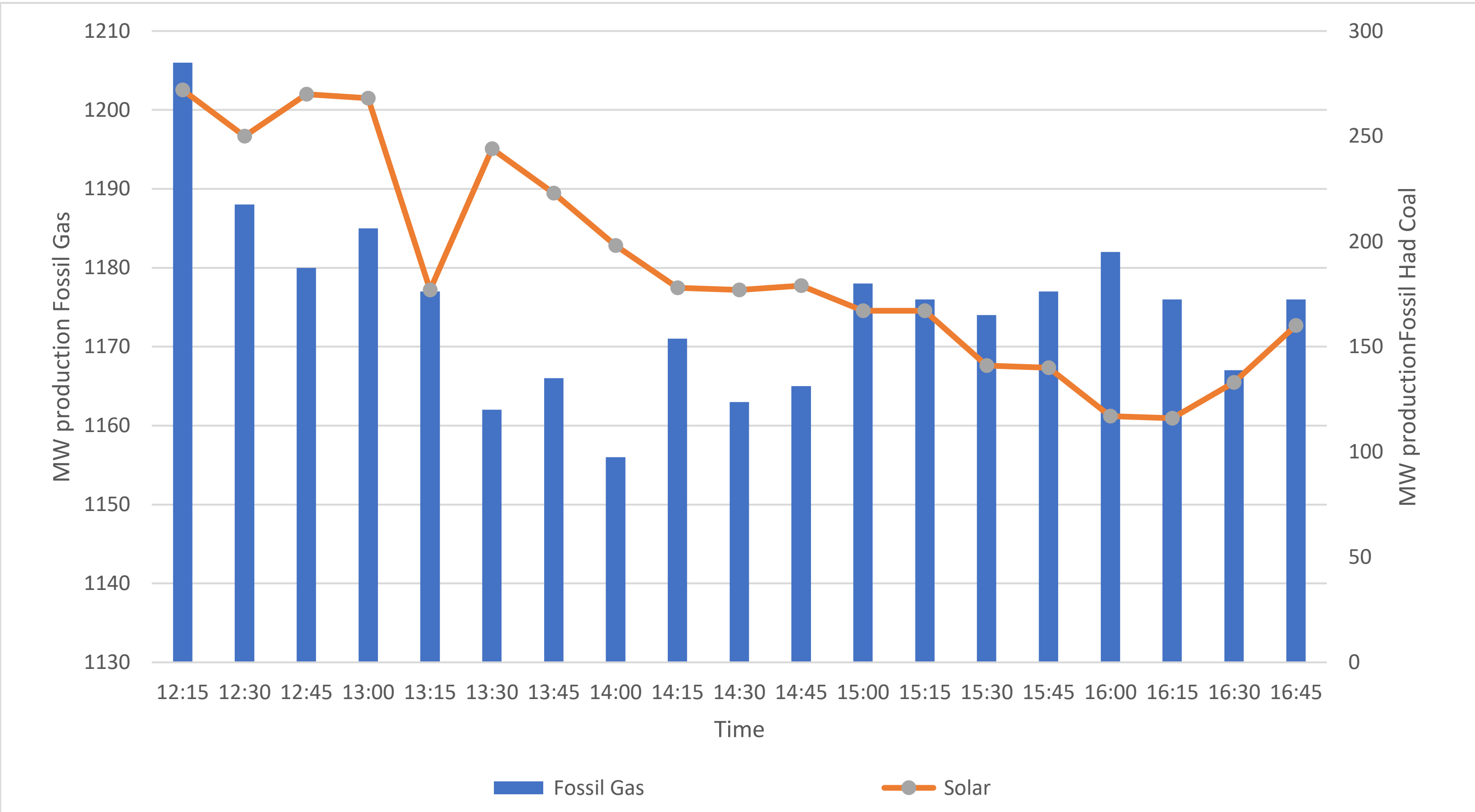

Figure 22: Production per generation type (MW) from 02-07-2023

6.2 The Economic impact for solar parks without GPPAs

In exploring the economic landscape for solar park owners operating without contractual GPPAs, it is essential to examine the impact posed by the inefficiencies in the electricity market. These costs often translate into concrete financial burdens for solar park owners, impacting their bottom line and operational viability. The findings, outlined in subparagraphs The EPEX Market and The Imbalance Market, illustrate the timing and frequency of inefficiencies within the electricity market. This section aims to analyze and clarify the various financial burdens faced by solar park owners without the security of GPPAs as a consequence of the inefficient electricity market.

First, the economic losses for solar parks without contractual GPPAs and energy steering software are assessed (Group 1 in Figure 12). Subsequently, the economic losses for solar parks equipped with energy steering software but without contractual GPPAs are determined (Group 2 in Figure 12). The economic losses for solar parks with energy steering encompass not only financial aspects but also the quantity of energy curtailed.

Quantifying the energy loss requires extracting the curtailment loss from the data. Consequently, the data from the eight solar parks is simulated to determine the potential outcomes if energy steering is utilized. The energy management software solely relies on data sourced from the Imbalance Market for its inputs.

The deviation in results between solar parks within a single group can be attributed to differences in size and location. Since these deviations are not significant, the results from each solar park are aggregated into one table. This aggregation allows for a clearer comparison between groups. An overview of the individual results for each solar park within a group is provided in Appendix A: Results.

Economic losses for solar parks without energy steering

The identification strategy is given in Figure 12. This sub-paragraph entails Group 1 from Figure 12 comprising solar parks without contractual GPPAs and energy steering software.

Table 8 presents an overview of the energy allocation and nomination for the 8 solar parks that are not in the possession of either GPPAs or energy steering.

Table 8: Aggregated Allocation, and Nomination of 8 solar parks

Solar Parks	Allocation (kWh)	Nomination (kWh)
Total	3,100,995.43	3,315,090.36

For these solar parks, revenue is derived from two places: the EPEX, and the Imbalance Market. Initially, the forecast is traded against EPEX prices. This happens the day before delivery at 1 pm. Imbalances arise during the actual energy delivery due to disparities between forecasted (nomination) and actual (allocation) electricity generation. These discrepancies result in both positive and negative income, contingent upon the energy balance within the electricity market.

Based on the data provided in Table 8, Table 9 presents the aggregated revenue streams obtained from all solar parks in Group 1.

Table 9: Revenue streams of 8 solar parks

Solar Parks	Epex	Imbalance	Total
Total	€ 234,678.45	€ -74,091.55	€ 160,586.90

To investigate market inefficiencies, data from eight distinct solar parks are analyzed. Across all parks, negative incomes are observed on both the EPEX and Imbalance Market. Notably, the negative revenue from the Imbalance Market exceeds the positive revenue, resulting in a negative revenue obtained from the Imbalance Market.

The inefficiency of the electricity market is defined as the situation in which we have to pay for the production of renewable energy (RE) while electricity is still being produced by fossil-driven sources. Therefore, inefficiency in the electricity market occurs when a RE producer incurs costs for the electricity forecasted on the EPEX Market and for the surplus of electricity traded on the Imbalance Market. When production data surpasses the forecasted figures, it results in an excess of electricity being generated. Consequently, an analysis is conducted to investigate the occurrence of negative prices.

Table 10 gives an overview of the negative revenue obtained from both the EPEX and the Imbalance Market. These are negative revenue streams that can be attributed to the inefficiency of the electricity market. All the negative revenue stemming from the EPEX Market can be attributed to the inefficiency. For the Imbalance Market, a distinction is made between negative income resulting from the excess of renewable energy (allocation > nomination) and the negative income resulting from a shortage of renewable energy (nomination > allocation). The Imbalance column in Table 10 only represents the negative income stemming from an excess in renewable energy.

Table 10: Negative revenue of 8 solar parks

Solar park	Epex	Imbalance
Total	€ -15,251.85	€ -18,690.68

The negative revenue obtained from the EPEX Market is lower than the negative revenue obtained from the Imbalance Market. This can be explained by the lower volatility of the EPEX Market in comparison to the Imbalance Market. By examining the descriptive statistics provided in Table 2 for the EPEX and the Imbalance prices (page 31), it is evident that the negative revenue from the Imbalance Market is higher. The larger negative revenue from the Imbalance Market is attributed to its greater standard deviation of € 194.95, compared to the EPEX Market's standard deviation of only € 49.04. Furthermore, prices on the EPEX Market range between € -500 and € 463.77, while prices on the Imbalance Market fluctuate between € -1,549.47 and € 2,037.74.

Economic losses for solar parks with energy steering

The identification strategy is given in Figure 12. This sub-paragraph entails Group 2 from Figure 12 comprising solar parks equipped with energy steering software but without contractual GPPAs.

As explained, energy losses occur due to the effect of negative prices in the Imbalance Market. The negative revenue obtained from the Imbalance Market in Group 1 (see Table 9) explains why solar park owners would like to have their assets equipped with energy steering hardware and software.

The formula for imbalance is provided in the Methods section as follows:

$$Imbalance_t = Allocation_t\,(production) - Nomination_t\,(forecast) \qquad (15)$$

The imbalance can either be positive (more produced than forecasted) or negative (less produced than forecasted). The prices for the Imbalance Market can also be positive (when there is a shortage of energy on the market) or negative (when there is an excess of energy on the market).

The key indicator for energy steering software is the data from the Imbalance Market. Energy steering occurs when the renewable producers are financially incentivized by the Imbalance Market. When this is translated into the means of RE production, the Imbalance Market only triggers the curtailment of RE because of the fact that production can't be increased (the sun can't shine brighter, or the wind can't blow harder than it is already doing). Therefore, energy steering only leads to reduced energy production for solar parks.

Energy steering operates based on a predefined threshold, which represents the minimum price required by the Imbalance Market before energy steering is initiated. Determining this threshold involves considering the revenue streams obtained from market regulations. As explained in Chapter 3.1 The imperfect Electricity Market structure, market regulations significantly influence the revenue stream obtained by solar park owners. Therefore, the influence of GoOs and SDE needs to be considered to determine the threshold.

By looking at the negative prices on the Imbalance Market, the financial benefits of curtailing need to outweigh the financial benefits of the GoO + SDE. Based on the experience within Groendus, this price is set at € -40.00 / MWh. So when the take price of the imbalance exceeds € -40.00, the solar parks will curtail their energy production.

To explore energy loss stemming from market inefficiencies, data from the same eight solar parks undergo simulation using energy steering software. Table 11 presents an overview of the energy allocation and nomination for the eight solar parks equipped with energy steering software but without contractual GPPAs.

Table 11: Aggregated Allocation, and Nomination of 8 solar parks consisting of energy steering

Solar Parks	Allocation (kWh)	Nomination (kWh)
Total	2,645,556.58	3,315,090.36

A particularly notable observation when comparing the results from Group 1 (Table 8) with those from Group 2 (Table 11) is the visible decrease in the allocation from Group 2 compared to Group 1. The nomination and revenue obtained from the EPEX Market for both groups stay the same, due to the fact that energy steering only influences the allocation.

Table 12 provides an overview of the revenue streams obtained from the eight solar parks equipped with energy steering software but without contractual GPPAs.

Table 12: Revenue streams of 8 solar parks consisting of energy steering

Solar Parks	Epex	Imbalance	Total
Total	€ 234,678.45	€ -18,475.72	€ 216,202.73

Another difference when comparing the results from Group 1 (Table 9) with those from Group 2 (Table 12) is the decrease in costs resulting from the Imbalance Market. Consequently, the cost stemming from the Imbalance Market for these 8 parks has decreased by € 55,615.62 (34.6% increase in total revenue), despite a decrease in energy production by 455.44 MWh (14.69% decrease in total energy production).

One correction that needs to be made is the missed revenue stemming from the SDE and GoOs, this number has been set at € -40.00 / MWh. Therefore, the energy losses need to be multiplied by this number and subtracted from the extra revenue of the Imbalance Market. The new revenue therefore is € 37,398.28 higher (23.29% increase).

Furthermore, the difference in negative revenue obtained for each group can be compared between solar PV parks with and without energy steering (Group 1 & Group 2 in Figure 12). As previously explained, the inefficiency of the electricity market is defined as the situation in which we have to pay for the production of renewable energy (RE). Inefficiency in the electricity market occurs when an RE producer incurs costs for the electricity forecasted on the EPEX Market and for the surplus of electricity traded on the Imbalance Market. When production data surpasses the forecasted figures, it results in an excess of electricity being generated. Consequently, an analysis is conducted to investigate the occurrence of negative prices.

Table 13 presents the negative revenue generated by each solar park consisting of energy steering. These negative revenue streams can be attributed to the inefficiency of the electricity market. The forecasts of the solar parks remain the same, and therefore the negative revenue stemming from the EPEX Market is identical for solar parks with or without energy steering (Table 10 & Table 13).

For the Imbalance Market, again the distinction is made between negative income resulting from the excess of renewable energy (allocation > nomination) and the negative income resulting from a shortage of renewable energy (nomination > allocation). The Imbalance column in Table 13 only represents the negative income stemming from an excess in renewable energy.

Table 13: Negative revenue of 8 solar parks with energy steering

Solar park	Epex	Imbalance
Total	€ -15,251.85	€ -4,196.19

When comparing the results from Group 1 and Group 2 (Table 10 & Table 13), a difference in negative imbalance revenue of €14,494.49 is observed (78.1% decrease), resulting in a better financial outcome for the solar parks equipped with energy steering software.

6.3 The Economic impact for solar parks with GPPAs

The first sub-question delved into market inefficiencies, while the second sub-question examined the impact of it on two groups of solar parks without contractual GPPAs. This impact was assessed both financially and in terms of the quantity of curtailed energy that would have been curtailed with the use of energy steering. This last paragraph aims to analyze and clarify the various financial burdens faced by solar park owners with the security of GPPAs as a consequence of the inefficient electricity market.

First, the economic losses for solar parks without energy steering are determined (Group 3 of Figure 12). Subsequently, the economic losses for the solar parks with energy steering are calculated (Group 4 of Figure 12). The economic losses for solar parks with energy steering encompass not only financial aspects but also the quantity of energy curtailed.

Quantifying the energy loss requires extracting the curtailment loss from the data. Consequently, the data from the 10 solar parks is simulated to determine the potential outcomes if energy steering is utilized. The energy management software solely relies on data sourced from the Imbalance Market for its inputs.

Economic losses for solar parks without energy steering with GPPAs

The identification strategy is given in Figure 12. This sub-paragraph entails Group 3 from Figure 12 comprising solar parks with contractual GPPAs but lacking energy steering software.

For these solar parks, revenue is derived from three places: the GPPA, the EPEX, and the Imbalance Market. Table 14 presents an overview of the energy allocation, nomination, and GPPA volume. The average concurrency rate of the GPPA is provided for the group of solar parks, indicating the proportion of energy produced that is traded under the GPPA. These rates vary within the group, ranging from 25% to 80%, signifying low to high concurrency, respectively.

Table 14: Allocation, Nomination, and GPPA volume of 10 solar parks consisting of GPPAs

Solar park	Allocation (kWh)	Nomination (kWh)	PPA_volume (kWh)	PPA Match
Total	8,564,827.06	9,186,666.14	5,390,743.52	63%

Based on the data provided in Table 14, Table 15 illustrates the aggregate revenue stream obtained from all 10 solar parks in the group.

Table 15: Revenue streams of 10 solar parks consisting of GPPAs

Solar park	PPA Price / MWh	PPA	Epex	Imbalance	Total
Total	€ 148.58	€ 800,951.98	€ 288,917.09	€ -218,179.26	€ 871,689.81

Table 16 provides an overview of the negative revenue obtained from both the EPEX and the Imbalance Market. The same requirements, used in Groups 1 and 2, have been used to determine the results.

Table 16: Negative revenue of 10 solar parks consisting of GPPAs

Solar park	Epex	Imbalance
Total	€ -24,070.86	€ -51,748.42

Economic losses for solar parks with energy steering and GPPAs

The identification strategy is given in Figure 12. This paragraph entails Group 4 from Figure 12 comprising solar parks equipped with both contractual GPPAs and energy steering software.

The same threshold, that is used for Group 2, compromising solar parks without GPPAs but equipped with energy steering software, is used to determine when energy steering will be applied. This threshold is set at € -40.00 / MWh.

A particularly notable observation when comparing the results from Group 3 (Table 14) with those from Group 4 (Table 17) is the visible decrease in the allocation from Group 4 compared to Group 3. The nomination and GPPA volume for both groups stay the same, due to the fact that energy steering only influences the allocation. As a result of the decrease in allocation combined with the same GPPA volume, the percentage of GPPA Match has increased.

Table 17 provides an overview of the new allocation, nomination, and GPPA data.

Table 17: Allocation, Nomination, and GPPA volume of 10 solar parks consisting of GPPAs and energy steering

Solar park	Allocation (kWh)	Nomination (kWh)	PPA_volume (kWh)	PPA Match
Total	8,041,101.78	9,186,666.14	5,390,743.52	67%

Based on the data provided in Table 17, Table 18 illustrates the aggregate revenue stream obtained from all 10 solar parks in the group.

Table 18: Revenue streams of 10 solar parks consisting of GPPAs and energy steering

Solar Parks	PPA Price / MWh	PPA	Epex	Imbalance	Total
Total	148.58	€ 800,951.98	€ 288,917.09	€ -136,555.02	€ 953,314.04

Another difference when comparing the results from Group 3 (Table 15) with those from Group 4 (Table 18) is the decrease in costs resulting from the Imbalance Market. Consequently, the cost stemming from the Imbalance Market for this group has decreased by € 81,624.24 (9.36% increase in total revenue), despite a decrease in energy production by 523.73 MWh (6.11% decrease in total energy production).

Again, the correction for the missed revenue stemming from the SDE and GoOs needs to be made, this number has been set at € -40.00 / MWh. Therefore, the energy losses need to be multiplied by this number and subtracted from the extra revenue of the Imbalance Market. The new revenue therefore is € 60,675.22 higher (6.96% increase).

Table 19 illustrates the aggregate negative revenue stream obtained from all 10 solar parks in the group.

Table 19: Negative revenue of 10 solar parks consisting of GPPAs and energy steering

Solar park	Epex	Imbalance
Total	€ -24,070.86	€ -24,132.85

When comparing the results from Group 3 and Group 4 (Table 16 &Table 19), a decrease in negative imbalance revenue of € 27,615.56 is observed (53.4% decrease), resulting in a better financial outcome for the solar parks equipped with energy steering software compared to the group without.

6.4 Overview of the Results

This paragraph presents a graphical overview of the results from all four groups. This makes it clearer to distinguish differences between groups.

First Figure 23 provides an overview of the allocation, nomination, and GPPA volume of each group.

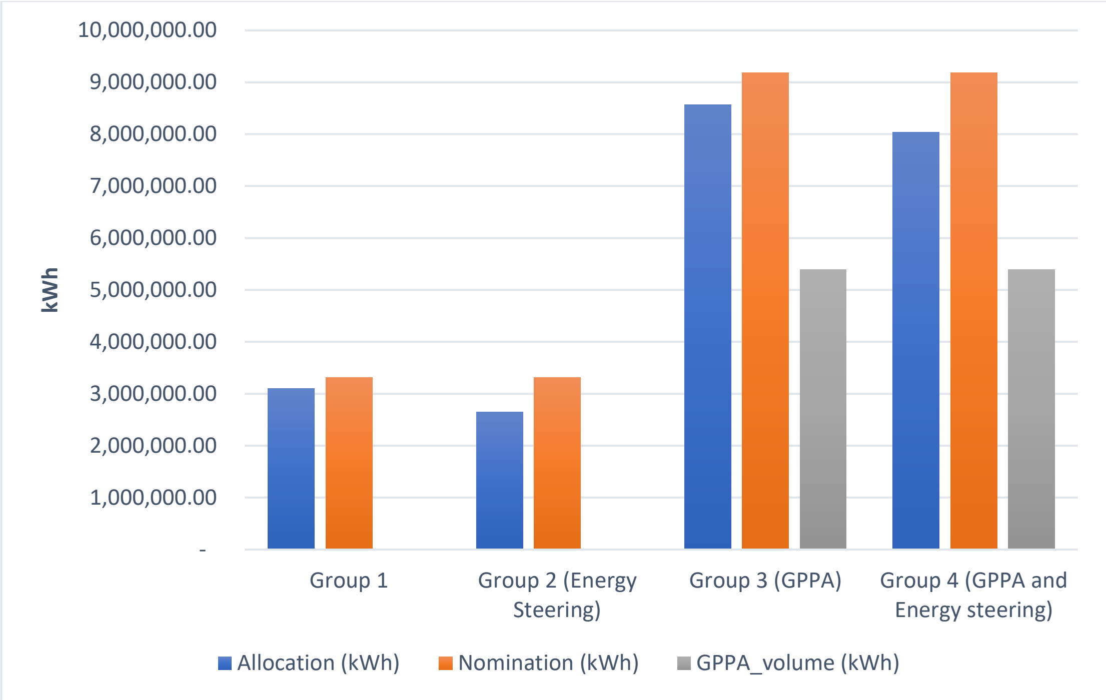

Figure 23: Allocation, Nomination, and GPPA Volume for each group

The discrepancy in allocation between Group 1 and Group 2, and between Group 3 and Group 4, is attributed to the curtailed energy resulting from the energy steering software. Figure 24 illustrates the quantity of energy curtailed in kWh, while Figure 25 provides an overview of the additional revenue generated from the Imbalance Market due to the curtailment of renewable energy production.

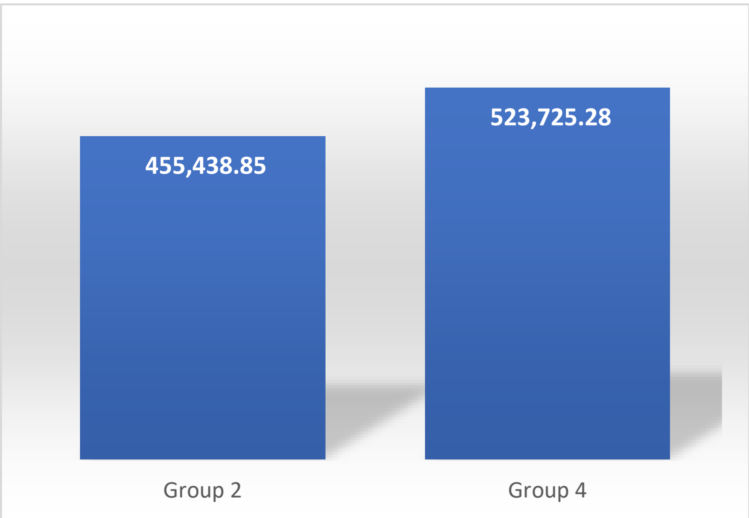

Figure 24: Curtailed energy (kWh)

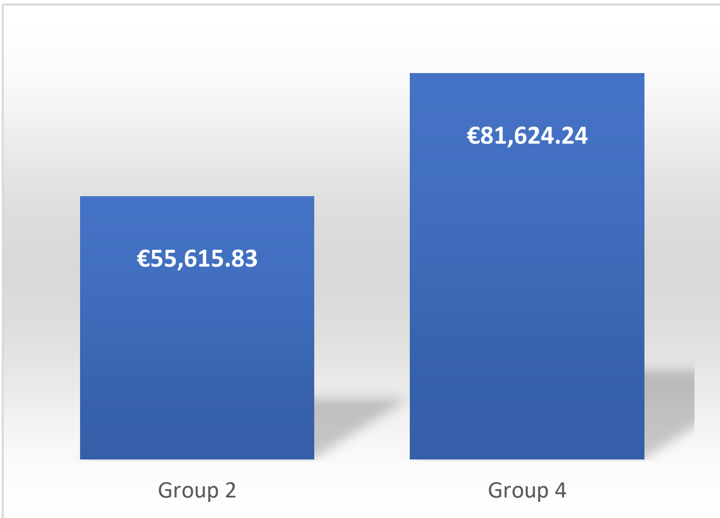

Figure 25: Additional revenue generated (€)

Figure 26 presents the revenue streams from each group categorized by market and also compiled. As illustrated, the revenue obtained from market regulation (SDE and GoOs) is also included for each group. The differences in total revenue obtained between Groups 1 and 2, and Groups 3 and 4, correspond to the additional revenue generated due to the energy steering.

As evident, Groups 1 and 2 derive no revenue from GPPAs. Their revenue is generated through the EPEX Market, market regulations (SDE + GoOs), and the Imbalance Market. Conversely, Groups 3 and 4 generate revenue from GPPAs. Consequently, their revenue is generated through the same channels as Groups 1 and 2, with the additional revenue stemming from the GPPA.

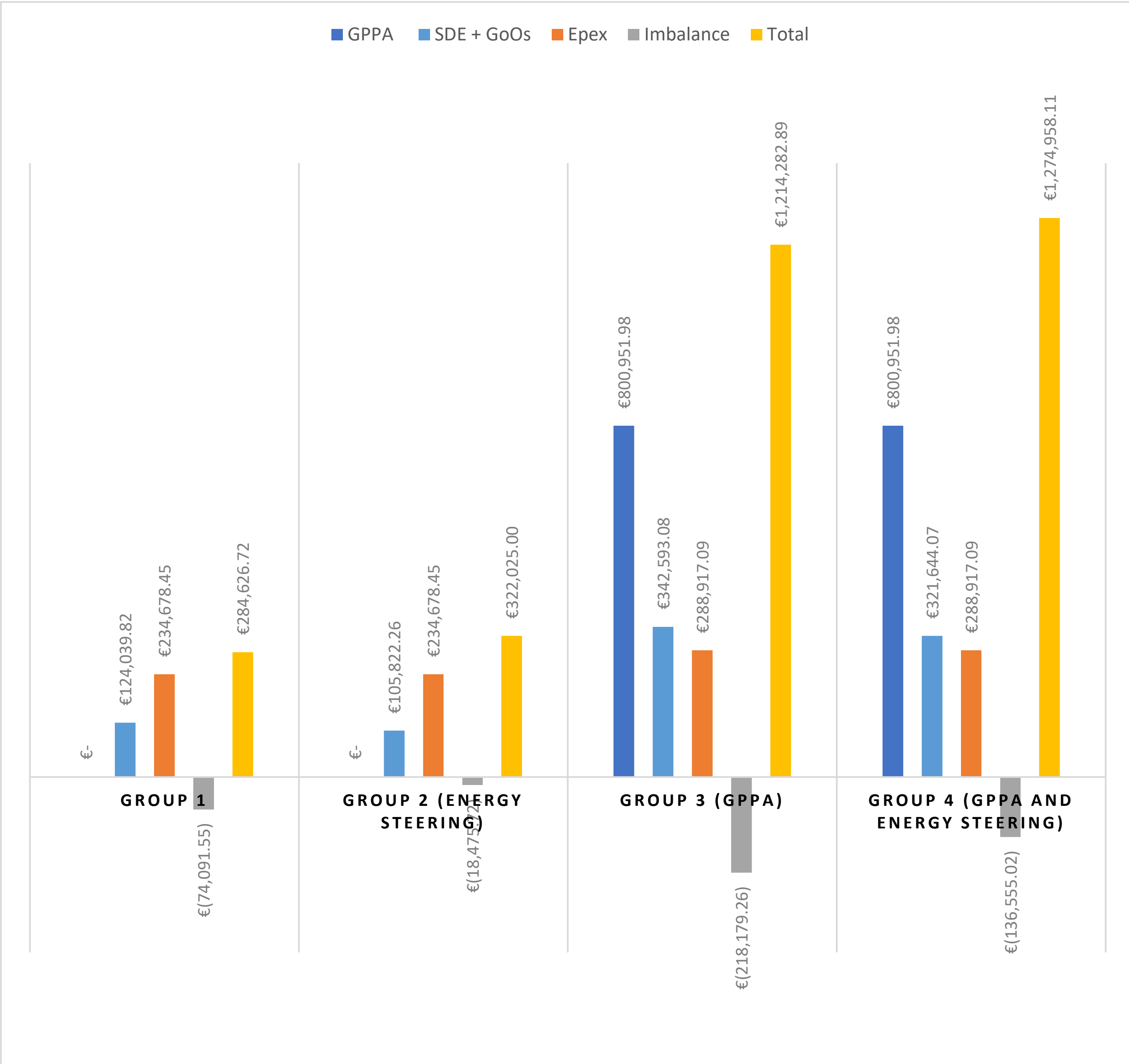

Figure 26: Revenue obtained from each group

Figure 27 provides an overview of the negative revenue obtained from the EPEX and the Imbalance Market for each group. This data can be traced back to Table 10, Table 13, Table 16, and Table 19. As observed, Group 1 experienced more negative revenue than Group 2, mirroring the trend seen between Group 3 and Group 4. The results obtained in Figure 27 provide an overview of the effect that energy steering has. To determine the effect of the GPPA, a weighted overview of these results based on the amount of energy produced needs to be made.

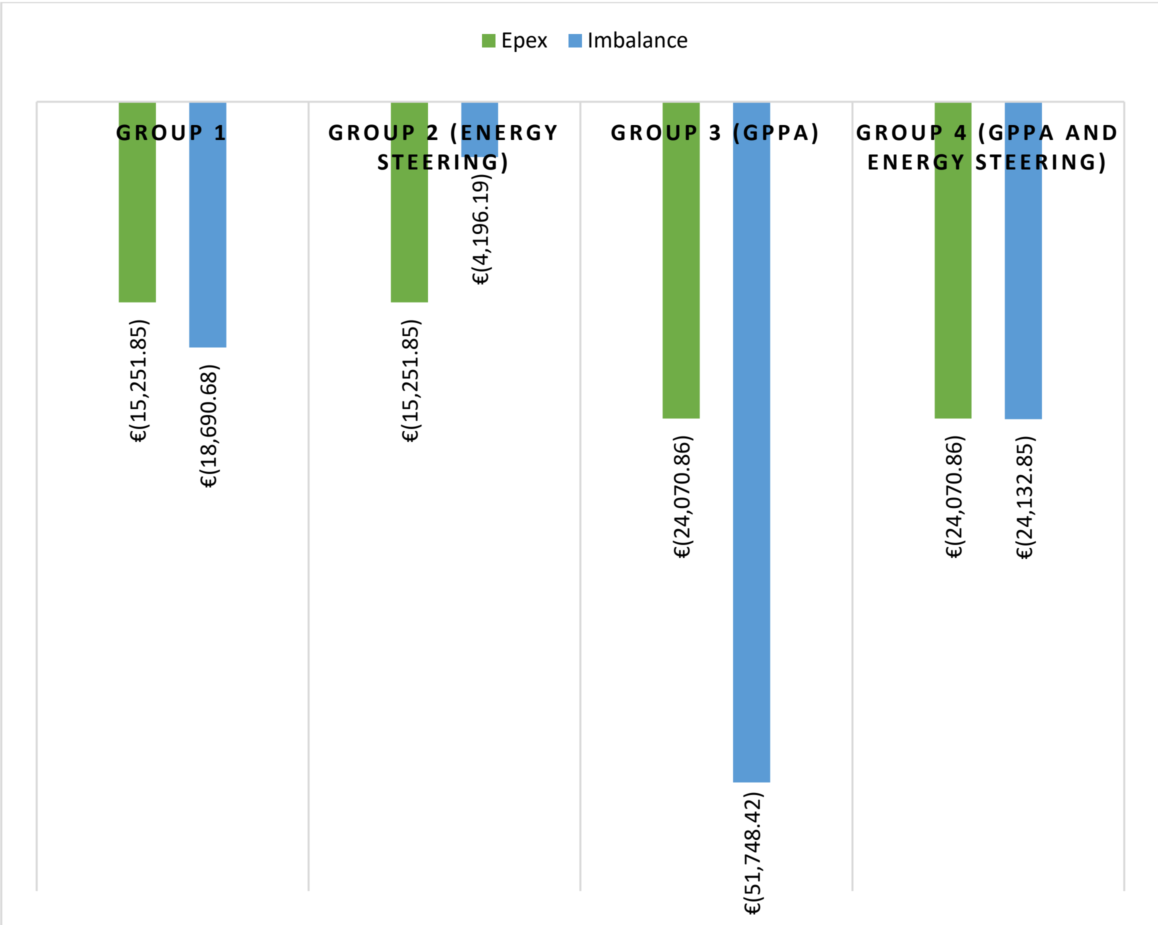

Figure 27: Negative revenue stemming from each group

By correlating the information from Figure 23 and Figure 27, the negative revenue obtained per MWh of electricity produced can be determined. This data is presented in Figure 28.

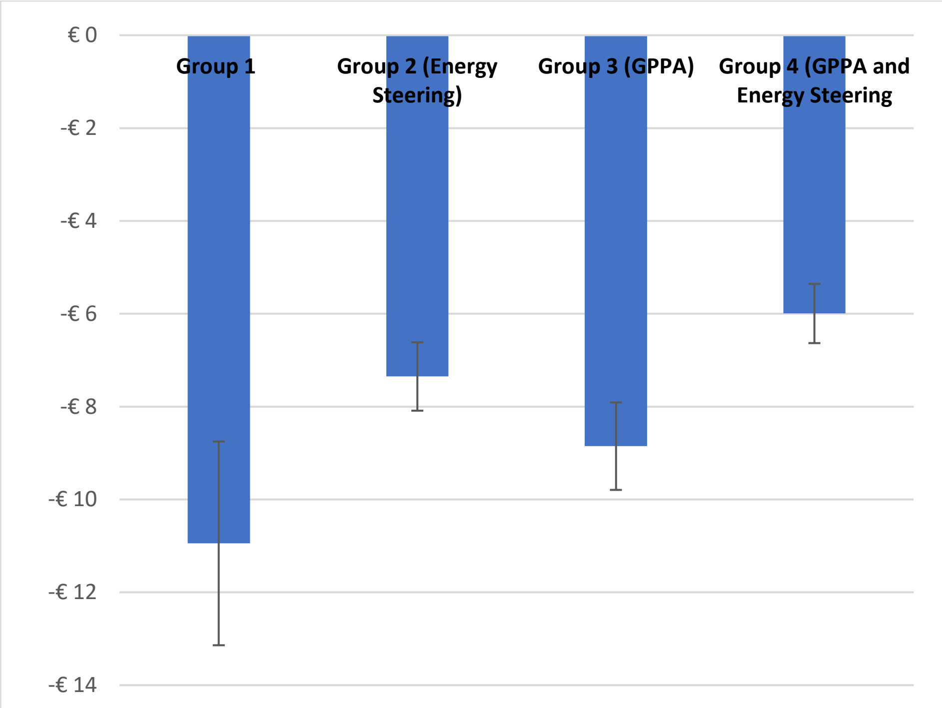

Figure 28: Negative revenue obtained per MWh production

By comparing Group 1 and Group 3, the financial impact of the GPPA becomes evident. Solar parks with GPPAs are financially better off by €2.09 per MWh compared to those without GPPAs. When comparing Group 2 and Group 4, both of which include energy steering hardware, with Group 4 also incorporating contractual GPPAs, the financial benefit of the solar parks consisting of GPPAs is €1.36 per MWh. The energy loss attributable to the energy steering software accounts for 14.69% of the total energy in group 2 compared to group 1. While in Group 4 it only accounts for 6.11% of the total energy compared to Group 3.

The results of this research clearly show that solar parks with GPPAs are less impacted by the inefficiencies of the Dutch electricity market compared to those without GPPAs. This advantage is evident both financially and in terms of reduced energy curtailment. In 2023, solar parks with GPPAs experienced more stable revenue and fewer instances of energy curtailment, as shown by revenue stemming from the EPEX and Imbalance Market. Consequently, GPPAs provide a significant benefit for solar park owners by protecting them from the negative effects of market inefficiencies.

Figure 28 also presents the standard deviation within each group. It is evident that the deviation between Groups 2, 3, and 4 is greater than the deviation between individual solar parks of each group. However, the deviation between individual solar parks of Group 1 is slightly larger than the deviation between groups. This deviation is due to one solar park in Group 1, which has high forecast errors resulting in low EPEX revenues and high imbalance costs. If this solar park were excluded from the standard deviation calculation, the standard deviation for Group 1 would be 0.81 instead of 2.19. Therefore, the use of aggregated results is justified.

6.5 Extraordinary data

Upon examining the data, a notable observation emerged. A significant portion of the negative revenue obtained from the EPEX Market was allocated to the date 7-2-2023. This raises the question of what would happen if this day is excluded from the dataset.

This section compares the negative revenue from the EPEX market on July 2, 2023, with the annual negative revenue. The findings are presented in Figure 29.

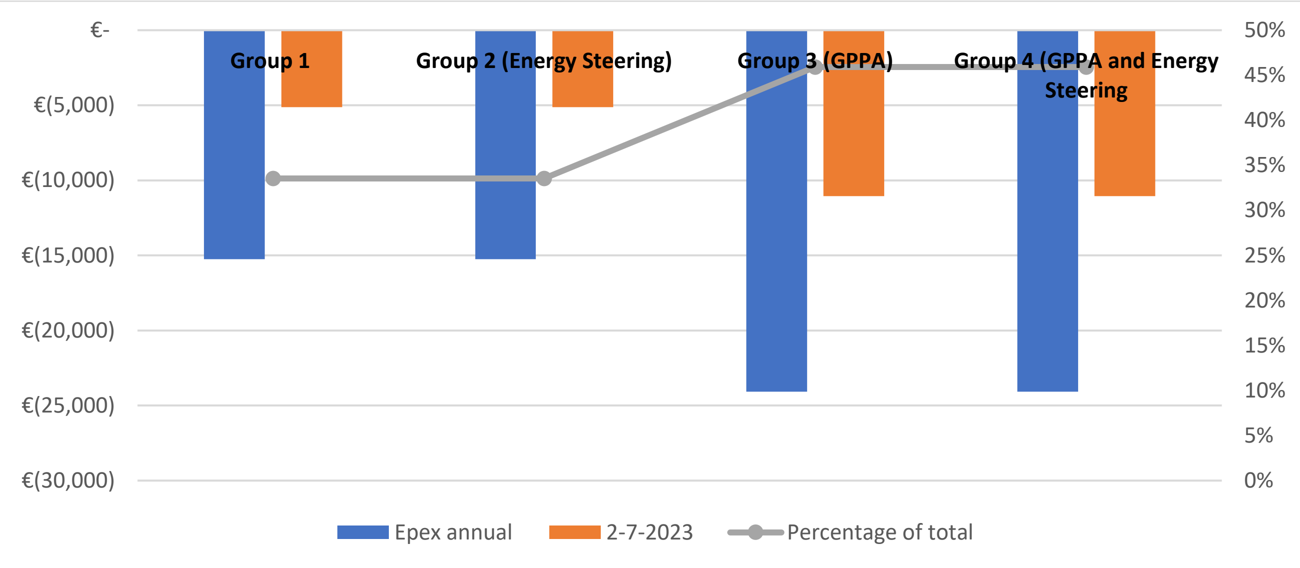

Figure 29: Negative revenue stemming from the EPEX annually vs 2-7-2023

The data for Groups 1 & 2 are the same, the same applies for Groups 3 & 4. This is logical because the difference between groups does not affect the nomination and therefore the revenue obtained from the EPEX Market.

For Groups 1 & 2, 33.54% (€ -5,116.07) of the negative revenue obtained from the EPEX market is attributed to the 2nd of July. For Groups 3 & 4, this percentage is even higher, at 45.91% (€ -11,052.01).

My hypothesis is that solar parks with GPPAs are less influenced by market inefficiencies, specifically Groups 3 & 4 in this research. The negative revenue obtained from the solar parks consisting of GPPAs can be explained when looking at the date: the 2nd of July is a Sunday. On weekends, work-life largely comes to a standstill, resulting in lower electricity demand from consumers bound by GPPAs. Therefore, solar parks have a lower concurrency rate with their consumers on weekends and consequently experience a greater impact from market dynamics.

If this day were a Monday, Groups 3 and 4 would have been less dependent on market dynamics, thus experiencing a reduced impact from the extreme negative prices on the EPEX market. Additionally, the negative prices would likely have been less severe due to increased electricity demand.

Given the significant impact of July 2nd on the dataset, it is crucial to consider the implications for the validation of our findings. Excluding this day might provide insights into how market dynamics behave under more typical conditions. However, to maintain the generality and robustness of the findings, July 2nd is included in the data. Including these data points maintains the dataset's integrity and allows for the analysis of extreme cases, resulting in a more comprehensive understanding of market behavior and the impact of specific days on revenue outcomes.

Including July 2nd acknowledges that outliers and extreme events play a crucial role in understanding market inefficiencies and their impacts on solar parks with GPPAs. This approach ensures that the findings remain applicable to real-world scenarios, where such abnormalities can significantly affect revenue.

7. Discussion & Conclusions

This chapter presents the conclusions of this thesis, addressing the initially stated research questions. The results are validated, and their implications on the theory are discussed. Additionally, the chapter offers concrete recommendations for private companies in this sector and policymakers. Following this, the limitations of the study are outlined, and suggestions for improvements are provided. Finally, based on the knowledge and insights gained during this research, recommendations for future research are offered.

7.1 Answers to the research questions

This research explored how inefficiencies within the Dutch GV electricity market impacted solar parks with contractual GPPAs, focusing on the EPEX and Imbalance Market. The study assessed the influence of these inefficiencies through the resulting financial losses and the quantity of energy curtailed. The analysis specifically considered solar PV parks with contractual GPPAs compared to those without, emphasizing the financial and curtailed impacts throughout the year 2023.

The study identified several triggers for curtailment in the Dutch energy market. Firstly, the influence of market regulations was explored. Market regulations played a significant role in the electricity market. The stricter requirements for new solar park projects under the SDE++ subsidy scheme, which mandated that the inverter capacity be limited to 50% of the total power of the solar park, resulted in a 5.43% energy loss compared to previous requirements.

Secondly, both the EPEX and Imbalance Markets exhibited a strong correlation between negative price intervals during daytime in the spring and summer, aligning with the solar energy generation profile. This underscored the seasonal and daily patterns of negative price occurrences in the electricity market.

Lastly, the research revealed a critical imbalance in the Dutch electricity market. Despite persistent negative prices, electricity generation from fossil gas remained significant, while solar energy production decreased. This discrepancy underscored a market inefficiency where sustainable energy generation was curtailed while fossil-fueled electricity persisted. This highlighted the urgent need for improved market mechanisms aligned with the goals of the energy transition towards renewable energy sources.

This research benefited from access to unique data sourced from the Dutch electricity market and specific solar parks, enabling in-depth exploration of how inefficiencies within the market impact solar parks with GPPAs compared to those without, specifically for the year 2023. This unique data includes detailed performance metrics and contractual information that are typically not publicly available, allowing for a more precise analysis. The following results, regarding the financial and energy losses, detail the impacts on different groups of solar parks due to the inefficiency of the energy market.

The financial results were measured and expressed in negative revenue obtained per MWh production (€ / MWh). By comparing Group 1, which comprised solar parks without contractual GPPAs and energy steering software, and Group 3, which comprised solar parks with contractual GPPAs but without energy steering software, the financial impact of the GPPA became evident. Solar parks with GPPAs were less impacted by the inefficiencies of the electricity market, resulting in a financial advantage of €2.09 per MWh compared to those without GPPAs, representing a 19.12% reduction in financial impact. When comparing Group 2 and Group 4, both of which included energy steering hardware, with Group 4 also incorporating contractual GPPAs, the financial benefit for the solar parks with GPPAs was €1.36 per MWh compared to the group without GPPAs, representing an 18.45% reduction in financial impact. The financial reductions are significant, resulting in increased profitability for solar parks with contractual GPPAs compared to those without. These results underscore the effectiveness of GPPAs in mitigating the financial risks associated with market inefficiencies in the energy sector.

The energy loss attributable to the energy steering software accounted for 14.69% of the total energy in Group 2 compared to Group 1. In Group 4, it accounted for only 6.11% of the total energy compared to Group 3. This represented a relative reduction of 58.4% in curtailed energy, despite both groups experiencing the same market inefficiencies. This substantial reduction in curtailed energy highlights how GPPAs effectively mitigate the inefficiencies of the market, enhancing the overall efficiency and viability of solar energy production despite current market challenges.

After a comprehensive examination, the data revealed a substantial concentration of negative revenue within the EPEX Market on July 2, 2023, which shed light on the influence of weekend dynamics on solar park financial performance. Specifically, 33.54% (€ -5,116.07) of negative revenue for Groups 1 & 2 and 45.91% (€ -11,052.01) for Groups 3 & 4 were recorded on that Sunday. The discrepancy in concurrency rates between solar parks and consumers during weekends, stemming from reduced electricity demand, emphasized the heightened financial vulnerability to market inefficiencies during such periods. This finding underscored the importance of implementing strategies to mitigate the impact of reduced demand and market fluctuations on solar park revenue, particularly on weekends.

7.2 Validation of results

This research breaks new ground by exploring the innovative concept of power procurement based on simultaneous consumption and production, a topic with minimal academic coverage. It addresses a significant research gap by analyzing how inefficiencies in the Dutch electricity market in 2023 impact solar parks with contractual GPPAs compared to those without, thus contributing new insights to the field.

To ensure the generalizability of the results from this research, they were compared with data from solar parks equipped with energy steering systems. The comparison showed that both the curtailed volume and the relative added value are in line with the research findings. This alignment justifies the use of the small sample sizes of n: 8 (Groups 1 & 2) and n: 10 (Groups 3 & 4), supporting the validity of the research despite the limited dataset. Therefore, this research holds significance as it provides a framework where solar-based electricity exhibits reduced reliance on inefficient periods within the electricity market. Consequently, the volume of curtailed RE has declined.

7.3 Implications of the Theory

The results of this research confirm the theory of an imperfect market, emphasizing the impact of market regulations on the curtailment threshold for solar energy, which is influenced by the value of the SDE++ and GVO. The findings neither confirm nor deny the hindering effects of the ENDEX Market or the technical limitations of the electricity infrastructure. Further research is required to determine the impact of these factors on the inefficiency of the electricity market. The results of this study illustrate how electricity pricing on both the EPEX and Imbalance Market is weather-dependent. Additionally, the theory regarding GPPAs is validated, as solar parks with contractual GPPAs are less affected by the inefficiency of the electricity market, both financially and in terms of energy curtailment. These solar parks remain unaffected by market inefficiencies during synchronized intervals. In cases of electricity surplus, the producer must trade on the DAM, IDM, or Imbalance Market to manage these fluctuations, leading to uncertainty within GPPAs. The results confirm that a higher concurrency rate reduces a producer's reliance on market functioning, thereby decreasing exposure to inefficient periods in the electricity market.

7.4 Recommendations

The motivation for this research, as stated in the introduction, arises from the pressing need for an energy transition centered on low-carbon sources and greater reliance on electricity. The findings underscore that solar parks equipped with GPPAs experience reduced vulnerability to inefficiencies within the Dutch electricity market, both in terms of financial impacts and curtailment rates. This increased resilience helps improve the financial performance of solar parks, making them more attractive investment opportunities. Moreover, GPPAs play a crucial role in mitigating the curtailment of renewable energy, thereby increasing the share of renewable sources in the overall electricity supply. In summary, GPPAs decrease greenhouse gas emissions stemming from the energy sector by enhancing incentives for solar park projects and reducing the curtailment of renewable energy.

The results of this research underscore the importance of adopting contractual GPPAs for solar parks within the Dutch electricity market. While GPPAs are currently in use, their availability remains limited, posing a significant barrier. Additionally, another challenge lies in reaching a mutual agreement between producers and consumers on the traded electricity volume.

The following recommendations for policymakers rely on the findings of this study:

1. **Oblige energy trading companies to provide GPPAs for solar asset parks.**

The results clearly show that GPPAs experience reduced vulnerability to inefficiencies within the Dutch electricity market, both in terms of financial impacts and curtailment rates. An increase in the number of GPPAs will result in a decrease in solar energy curtailment. However, this recommendation may involve a trade-off: while curtailed RE decreases, the energy grid's balance could diminish. This imbalance stems from the reduction in easily curtailed energy assets, such as solar parks, thereby increasing the volatility in the imbalance market.

2. **Implement true pricing in the electricity market**

My analysis indicates that implementing true pricing will guarantee a positive price for renewable energy in the EPEX bid ladder, rather than a negative one. True pricing should encompass not just the cost of emissions but also the expenses linked to maintenance required during energy plant shutdowns or startups. This approach ensures that fossil energy is only used when the demand for electricity exceeds the supply from renewables on the EPEX Market. This highlights the growing price difference between renewable and fossil electricity. Overall, this would increase the price of fossil fuels and enhance the feasibility of contracting GPPAs for consumers and consequently boost sales.

These two recommendations aim to increase the amount of contractual GPPAs in the Dutch Electricity Market. An expansion in GPPAs will increase the renewable energy production stemming from solar parks, thereby reducing greenhouse gas emissions and advancing progress toward the goals of the Paris Agreement.

For private companies in this sector, such as Groendus, several recommendations are made:

3. **Equip all solar assets with energy steering software and hardware.**

Based on the financial results from the groups using energy steering, and considering the current economic landscape, companies with solar assets should equip all their solar parks with energy steering software and hardware. This will reduce costs and thereby increase profitability. Awareness about this technology varies among companies, with some unsure about available solutions or providers in the market.

4. Contract Green Power Purchase Agreements for all solar assets.

Based on the findings of this research, companies with solar assets should prioritize equipping their asset base with contractual GPPAs. Given the current economic landscape, energy steering software emerges as crucial. Therefore, GPPAs not only improve financial performance but also help reduce curtailed energy, offering a dual benefit of enhanced economic viability and lower curtailment rates. In the current electricity market, many companies are either unaware of these agreements or do not know which electricity providers offer them.

5. Contract consumers with a high weekend consumption

The data indicates that extremely negative prices for solar asset production profiles predominantly occur during the daytime on weekends. Consequently, companies with solar assets can benefit from contracting consumers who have high consumption profiles over the weekend. Companies in the retail, hospitality, food service, and entertainment sectors are typically consumers with high weekend consumption.

7.5 Limitations

The data used for the calculations in this study contains certain shortcomings, requiring several assumptions in the methodology to derive the results. These limitations will be discussed in the chronological order of the research process.

Data on solar park production was obtained at 15-minute intervals, leading to the assumption that energy production is evenly distributed over each interval. In reality, production patterns can vary, such as instances of high production in the first 5 minutes followed by significantly lower production in the subsequent 10 minutes, possibly due to cloud cover. This assumption affects the calculation of the curtailment rate due to stricter SDE subsidy requirements and the simulation of energy steering software. Real-time data, with its higher accuracy and second-by-second intervals, would mitigate this issue but was unavailable.

The financial calculations are based on revenue from the EPEX and Imbalance markets, excluding the Intraday Market because Groendus does not trade on it. Including this market could alter the results, as it allows for imbalance corrections up to 15 minutes before energy delivery, potentially reducing imbalance costs for solar park owners.

To determine the effect of energy steering, data from solar parks without energy steering was used to simulate its effects. This was necessary because actual generation data from solar parks with energy steering was not yet available for 2023, as its implementation began in July 2023 and has not spanned a full calendar year. The simulation also assumed evenly distributed energy production over 15-minute intervals.

The concurrency rate of each solar park within the GPPA group varies, with an average concurrency rate of 63%. Results may differ if solar parks with different concurrency rates were used. Higher concurrency rates generally lead to better financial outcomes compared to lower rates. Additionally, the agreed price between the producer and consumer impacts the financial results.

All results are based on historical data, which does not guarantee future outcomes. The market has changed significantly during the course of this research. For instance, there were 74 instances of negative EPEX prices in May 2024 compared to 49 in May 2023, an increase of 51%. The volatility of the Imbalance Market has also led to substantial negative revenue for solar parks without energy steering.

7.6 Suggested improvements

This research could be enhanced through several key improvements. First, utilizing real-time production data instead of 15-minute interval data would provide more accurate insights. Second, incorporating trading activities on the Intraday Market would offer a more comprehensive understanding of market dynamics. It would also allow for imbalance corrections up to 15 minutes before energy delivery, potentially reducing imbalance costs for solar park owners. Third, using actual data from solar parks equipped with energy steering software and hardware, rather than relying on simulations, would provide more reliable results. This would allow for a more precise assessment of both the allocation and nomination differences in revenue obtained from the EPEX and Imbalance Markets.

7.7 Future research

Knowledge and insights obtained during this research suggest several promising avenues for future research.

This research delves into the inefficiency of the market in 2023. As explained, the electricity market is continuously changing. Therefore, continuous monitoring is essential to understand the impact of GPPAs in the current economic environment.

Further research is required to determine the impact of both the ENDEX Market and technical limitations of the electricity infrastructure on the inefficiency of the electricity market. By doing this, the theory can be confirmed or denied.

Additionally, research into the effects of a consolidated GPPA is needed. In this kind of GPPA, multiple solar park producers and multiple consumers are bound. The data suggests that this could lead to an improved concurrency rate for both producers and consumers. Consequently, the performance of the solar park will improve, leading to a decrease in the impact of market inefficiencies.

The thesis also observed that prohibiting the use of renewable energy sources to balance the electricity grid in the Imbalance Market could have a significant impact. System designers and policymakers are advised to investigate the effects of such a prohibition. By ensuring that renewable energy is directly traded on the EPEX and Intraday markets and is prohibited from participating in the Imbalance Market, renewable energy will always be utilized. This could make the curtailment of RE an outdated topic.

A solution could be that the correction of imbalances will be facilitated by fossil fuel-driven sources. To achieve this, TenneT could increase the number of flexible assets in the Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFFR), and manual Frequency Restoration Reserve (mFFR) markets, ensuring efficient management of demand and supply fluctuations under the Balance Service Provider framework. However, this finding cannot be fully substantiated from the analysis. While there appears to be merit to this observation, further research is needed to confirm it.

Reference list

[1] IEA, "World Energy Outlook 2023," 2023. [Online]. Available: www.iea.org/terms

[2] Statista, "Global carbon dioxide emissions from 1970 to 2022, by sector." Accessed: Dec. 07, 2023. [Online]. Available: https://www.statista.com/statistics/276480/world-carbon-dioxide-emissions-by-sector/

[3] Ministerie van Economische Zaken, "Climate Change," Ministerie van Economische Zaken, Landbouw en Innovatie. Accessed: Dec. 07, 2023. [Online]. Available: https://www.government.nl/topics/climate-change/climate-policy

[4] CBS, "46 percent more solar energy production in 2022." Accessed: Dec. 07, 2023. [Online]. Available: https://www.cbs.nl/en-gb/news/2023/24/46-percent-more-solar-energy-production-in-2022

[5] Karen Brandenburg *et al.*, "Hernieuwbare energie in Nederland 2022," Oct. 2023. Accessed: Dec. 12, 2023. [Online]. Available: https://www.cbs.nl/nl-nl/longread/rapportages/2023/hernieuwbare-energie-in-nederland-2022#:~:text=In%202022%20was%20het%20aandeel,het%20totale%20energieverbruik%20in%20Nederland.

[6] Planbureau voor de Leefomgeving, "Klimaat- en Energieverkenning 2022." [Online]. Available: www.pbl.nl/kev

[7] Inês Campos, Guilherme Pontes Luz, Esther Marín-González, Swantje Gährs, Stephen Hall, and Lars Holstenkamp, "Regulatory challenges and opportunities for collective renewable energy prosumers in the EU," *Energy Policy*, vol. 138, p. 111212, Mar. 2020, doi: 10.1016/j.enpol.2019.111212.

[8] IEA, *The Power of Transformation*. OECD, 2014. doi: 10.1787/9789264208032-en.

[9] ENTSO-E, "Actual Generation per Production Type." Accessed: Jan. 12, 2024. [Online]. Available: https://transparency.entsoe.eu/

[10] ComCam, "Record aantal uren negatieve stroomprijs 2023." Accessed: Dec. 07, 2023. [Online]. Available: https://www.comcamenergy.com/blog/record-negatieve-stroomprijs-2023/

[11] A. von Meier, "Challenges to the Integration of Renewable Resources at High System Penetration," 2014.

[12] E. Pean, M. Pirouti, and M. Qadrdan, "Role of the GB-France electricity interconnectors in integration of variable renewable generation," *Renew Energy*, vol. 99, pp. 307–314, Dec. 2016, doi: 10.1016/J.RENENE.2016.06.057.

[13] R. A. Rodríguez, S. Becker, G. B. Andresen, D. Heide, and M. Greiner, "Transmission needs across a fully renewable European power system," *Renew Energy*, vol. 63, pp. 467–476, Mar. 2014, doi: 10.1016/j.renene.2013.10.005.

[14] Groendus, "Groendus EPEX prijzen 2023." 2024.

[15] R. Kiesel and F. Paraschiv, "Econometric Analysis of 15-Minute Intraday Electricity Prices," *SSRN Electronic Journal*, 2015, doi: 10.2139/ssrn.2671379.

[16] J. Zheng, A. A. Chien, and S. Suh, “Mitigating Curtailment and Carbon Emissions through Load Migration between Data Centers,” *Joule*, vol. 4, no. 10, pp. 2208–2222, Oct. 2020, doi: 10.1016/j.joule.2020.08.001.

[17] Planbureau voor de Leefomgeving, “EINDADVIES BASISBEDRAGEN SDE++ 2021,” Den Haaf, May 2021. Accessed: Mar. 18, 2024. [Online]. Available: https://www.pbl.nl/sites/default/files/downloads/pbl-2021-eindadvies-basisbedragen-sde-plus-plus-2021_4032.pdf

[18] IEA, “The energy world is set to change significantly by 2030, based on today’s policy settings alone.” Accessed: Jan. 11, 2024. [Online]. Available: https://www.iea.org/news/the-energy-world-is-set-to-change-significantly-by-2030-based-on-today-s-policy-settings-alone

[19] S. Hussain, C. Lai, and U. Eicker, “Flexibility: Literature review on concepts, modeling, and provision method in smart grid,” *Sustainable Energy, Grids and Networks*, vol. 35, p. 101113, Sep. 2023, doi: 10.1016/j.segan.2023.101113.

[20] AURORA, “PPAs in the Netherlands: Developments in an emerging PPA market,” Amsterdam, Nov. 2023.

[21] M. Mulder and B. Willems, “The Dutch retail electricity market,” *Energy Policy*, vol. 127, pp. 228–239, Apr. 2019, doi: 10.1016/j.enpol.2018.12.010.

[22] F. Tanrisever, K. Derinkuyu, and M. Heeren, “Forecasting electricity infeed for distribution system networks: An analysis of the Dutch case,” *Energy*, vol. 58, pp. 247–257, Sep. 2013, doi: 10.1016/j.energy.2013.05.032.

[23] TenneT, “Over TenneT”, Accessed: Dec. 21, 2023. [Online]. Available: https://www.tennet.eu/nl/over-tennet

[24] TenneT, “Balanceringsmarkten”, Accessed: Dec. 21, 2023. [Online]. Available: https://www.tennet.eu/nl/balanceringsmarkten

[25] TenneT, “Meetverantwoordelijkheid.” Accessed: Dec. 21, 2023. [Online]. Available: https://www.tennet.eu/nl/meetverantwoordelijkheid

[26] CBS, “Elektriciteitsbalans; aanbod en verbruik.” Accessed: Apr. 08, 2024. [Online]. Available: https://opendata.cbs.nl/#/CBS/nl/dataset/84575NED/table

[27] F. Petropoulos *et al.*, “Forecasting: theory and practice,” *Int J Forecast*, vol. 38, no. 3, pp. 705–871, Jul. 2022, doi: 10.1016/j.ijforecast.2021.11.001.

[28] F. Tanrisever, K. Derinkuyu, and G. Jongen, “Organization and functioning of liberalized electricity markets: An overview of the Dutch market,” *Renewable and Sustainable Energy Reviews*, vol. 51. Elsevier Ltd, pp. 1363–1374, Aug. 01, 2015. doi: 10.1016/j.rser.2015.07.019.

[29] D. J. Swider, “Simultaneous bidding in day-ahead auctions for spot energy and power systems reserve,” *International Journal of Electrical Power & Energy Systems*, vol. 29, no. 6, pp. 470–479, Jul. 2007, doi: 10.1016/j.ijepes.2006.11.005.

[30] L. Vandezande, L. Meeus, R. Belmans, M. Saguan, and J.-M. Glachant, “Well-functioning balancing markets: A prerequisite for wind power integration,” *Energy Policy*, vol. 38, no. 7, pp. 3146–3154, Jul. 2010, doi: 10.1016/j.enpol.2009.07.034.

[31] TenneT, “De onbalansprijssystematiek.”

[32] Energievergelijken.nl, “Netbeheerders Nederland (stroom en gas).” Accessed: Jan. 05, 2024. [Online]. Available: https://www.energievergelijk.nl/onderwerpen/netbeheerders

[33] A. Cretì and F. Fontini, “Market Power in Electricity Markets,” in *Economics of Electricity*, Cambridge University Press, 2019, pp. 171–182. doi: 10.1017/9781316884614.014.

[34] M. Naldi and M. Flamini, “The CR4 Index and the Interval Estimation of the Herfindahl-Hirschman Index: An Empirical Comparison,” *SSRN Electronic Journal*, 2014, doi: 10.2139/ssrn.2448656.

[35] S. Borenstein and J. Bushnell, “An Empirical Analysis of the Potential for Market Power in California’s Electricity Industry,” *J Ind Econ*, vol. 47, no. 3, pp. 285–323, Sep. 1999, doi: 10.1111/1467-6451.00102.

[36] L. Makowski and J. M. Ostroy, “Perfect Competition and the Creativity of the Market,” *J Econ Lit*, vol. 39, no. 2, pp. 479–535, Jun. 2001, doi: 10.1257/jel.39.2.479.

[37] M. S. LEWIS and H. P. MARVEL, “WHEN DO CONSUMERS SEARCH?*,” *J Ind Econ*, vol. 59, no. 3, pp. 457–483, Sep. 2011, doi: 10.1111/j.1467-6451.2011.00459.x.

[38] ACM, “Energiemonitor Klantbeleving – 2023.” Accessed: Jan. 15, 2024. [Online]. Available: https://www.acm.nl/nl/publicaties/energiemonitor-klantbeleving-2023

[39] CBS, “How much of the energy we consume is renewable?”

[40] J. Winkler, B. Breitschopf, M. Ragwitz, M. Mistre, S. Cail, and M. Harmelink, “DIRECTORATE GENERAL FOR INTERNAL POLICIES POLICY DEPARTMENT A: ECONOMIC AND SCIENTIFIC POLICY Renewable Energy Directive Target STUDY,” 2018.

[41] V. Fuentes Verastegui, “‘The political, economic and environmental impacts of the SDE++ subsidy scheme by introducing solar PV technologies in the Dutch electricity market.’”

[42] A. Podesta and G. Astuti, “State aid: Commission approves €30 billion Dutch scheme to support projects reducing greenhouse gas emissions,” European Commission. Accessed: Jan. 18, 2024. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2410

[43] RVO, “Monitor zon-PV 2023 Datum september 2023 Status Definitief.”

[44] Verticer, “What are Guarantees of Origin?” Accessed: Jan. 18, 2024. [Online]. Available: https://verticer.eu/en/guarantees-of-origin/

[45] McKinsey & Company, “Guarantees of origin.” Accessed: Jan. 16, 2024. [Online]. Available: https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/guarantees-of-origin-playing-a-vital-role-in-decarbonization

[46] M. Ragwitz, P. del Río González, and G. Resch, “Assessing the advantages and drawbacks of government trading of guarantees of origin for renewable electricity in Europe,” *Energy Policy*, vol. 37, no. 1, pp. 300–307, Jan. 2009, doi: 10.1016/j.enpol.2008.07.032.

[47] M. Mulder, "Competition in the Dutch Electricity Market: An Empirical Analysis over 2006-2011," *The Energy Journal*, vol. 36, no. 2, pp. 1–28, Apr. 2015, doi: 10.5547/01956574.36.2.1.

[48] R. Weron, "Electricity price forecasting: A review of the state-of-the-art with a look into the future," *Int J Forecast*, vol. 30, no. 4, pp. 1030–1081, Oct. 2014, doi: 10.1016/j.ijforecast.2014.08.008.

[49] J. Nowotarski and R. Weron, "Recent advances in electricity price forecasting: A review of probabilistic forecasting," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1548–1568, Jan. 2018, doi: 10.1016/j.rser.2017.05.234.

[50] F. Ziel and R. Steinert, "Electricity price forecasting using sale and purchase curves: The X-Model," *Energy Econ*, vol. 59, pp. 435–454, Sep. 2016, doi: 10.1016/j.eneco.2016.08.008.

[51] N. Kumar, P. Besuner, S. Lefton, D. Agan, and D. Hilleman, "Power Plant Cycling Costs," 2012. Accessed: Dec. 12, 2023. [Online]. Available: https://www.nrel.gov/docs/fy12osti/55433.pdf

[52] P. Silva Ortiz, D. Flórez-Orrego, S. de Oliveira Junior, R. Maciel Filho, P. Osseweijer, and J. Posada, "Unit exergy cost and specific CO2 emissions of the electricity generation in the Netherlands," *Energy*, vol. 208, p. 118279, Oct. 2020, doi: 10.1016/j.energy.2020.118279.

[53] EPEX SPOT, "Market Data." Accessed: Feb. 07, 2024. [Online]. Available: https://www.epexspot.com/en/market-data?market_area=NL&trading_date=2024-03-06&delivery_date=2024-03-07&underlying_year=&modality=Auction&sub_modality=DayAhead&technology=&product=60&data_mode=graph&period=&production_period=

[54] "Energy Products and the Time Dimension of Electricity Markets," in *Economics of Electricity*, Cambridge University Press, 2019, pp. 59–71. doi: 10.1017/9781316884614.006.

[55] M. Zeman, "Developing the future electricity grid," *Europhysics News*, vol. 52, no. 5, pp. 32–35, Nov. 2021, doi: 10.1051/epn/2021505.

[56] M. Farrokhseresht and F. Nobel, "The impact of RES integration on balancing markets," in *2022 18th International Conference on the European Energy Market (EEM)*, IEEE, Sep. 2022, pp. 1–6. doi: 10.1109/EEM54602.2022.9921068.

[57] S. Mertens, "Design of wind and solar energy supply, to match energy demand," *Clean Eng Technol*, vol. 6, p. 100402, Feb. 2022, doi: 10.1016/j.clet.2022.100402.

[58] NOS, "Reservecapaciteit hoogspanningsnet in gebruik voor duurzame energie," Feb. 2022, Accessed: Jan. 15, 2024. [Online]. Available: https://nos.nl/artikel/2416856-reservecapaciteit-hoogspanningsnet-in-gebruik-voor-duurzame-energie

[59] Netbeheer Nederland, "Capaciteitskaart invoeding elektriciteitsnet." Accessed: Jan. 03, 2024. [Online]. Available: https://capaciteitskaart.netbeheernederland.nl/

[60] TenneT, "Congestie Management." Accessed: Jan. 11, 2024. [Online]. Available: https://www.tennet.eu/nl/de-elektriciteitsmarkt/congestie-management

[61] J. Laan, “Faculty of Engineering Technology Sustainable Energy Technology Electricity grid congestion and application of a novel tariff in the Netherlands,” 2023.

[62] S. Goodarzi, H. N. Perera, and D. Bunn, “The impact of renewable energy forecast errors on imbalance volumes and electricity spot prices,” *Energy Policy*, vol. 134, Nov. 2019, doi: 10.1016/j.enpol.2019.06.035.

[63] P. Wallace, “Long-term power purchase agreements: the factors that influence contract design,” in *Research Handbook on International and Comparative Sale of Goods Law*, Edward Elgar Publishing, 2019. doi: 10.4337/9781786436153.00023.

[64] Ç. Aslan and T. Irwin, “Power to the Fiscal? An Exploration of the Use of Credit Ratings to Estimate the Expected Cost of a Guarantee of a Power-Purchase Agreement,” 2020. Accessed: Jun. 12, 2024. [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3620554

[65] Y. Ghiassi-Farrokhfal, W. Ketter, and J. Collins, “Making green power purchase agreements more predictable and reliable for companies,” *Decis Support Syst*, vol. 144, p. 113514, May 2021, doi: 10.1016/j.dss.2021.113514.

[66] PWC, “Corporate renewable energy procurement survey insights,” 2016. [Online]. Available: www.pwc.com/us/renewables

[67] E. O’Shaughnessy, J. R. Cruce, and K. Xu, “Too much of a good thing? Global trends in the curtailment of solar PV,” *Solar Energy*, vol. 208, pp. 1068–1077, Sep. 2020, doi: 10.1016/j.solener.2020.08.075.

[68] TenneT, “Exporteer data.” Accessed: Jan. 12, 2024. [Online]. Available: https://www.tennet.org/bedrijfsvoering/ExporteerData.aspx?exporttype=Onbalansprijs

[69] Planbureau voor de Leefomgeving, “FOTOVOLTAÏSCHE ZONNE-ENERGIE OP EEN KLEINERE NETAANSLUITING Eindadvies SDE++ 2022.”

[70] TenneT, “Balanceringsverantwoordelijkheid,” TenneT. Accessed: Dec. 22, 2023. [Online]. Available: https://www.tennet.eu/nl/de-elektriciteitsmarkt/nederlandse-klanten/balanceringsverantwoordelijkheid

Appendix A: Results

Solar parks without contractual GPPAs and energy steering software:

Table 20: Allocation, Nomination, and Revenue streams of 8 solar parks

Solar park	Allocation (kWh	Nomination (kWh)	Epex	Imbalance	Total
1	469,860.27	510,344.22	€ 36,838.52	€ -11,976.63	€ 24,861.88
2	495,954.33	526,914.73	€ 37,602.45	€ -11,514.21	€ 26,088.24
3	274,669.26	297,344.51	€ 21,687.82	€ -6,354.21	€ 15,333.60
4	274,451.36	268,420.06	€ 16,594.10	€ -7,591.77	€ 9,002.32
5	258,170.14	284,471.65	€ 20,266.41	€ -6,866.65	€ 13,399.76
6	361,043.77	380,573.07	€ 27,617.90	€ -8,912.12	€ 18,705.77
7	384,676.06	421,834.88	€ 31,465.82	€ -7,803.13	€ 23,662.69
8	582,170.24	625,187.22	€ 42,605.45	€ -13,072.82	€ 29,532.63
Total	**3,100,995.43**	**3,315,090.36**	**€ 234,678.45**	**€ -74,091.55**	**€ 160,586.90**

Table 21: Negative revenue of 8 solar parks

Solar park	Epex	Imbalance
1	€ -2,297.98	€ -2,641.53
2	€ -2,415.43	€ -3,353.90
3	€ -1,258.67	€ -1,479.47
4	€ -1,552.35	€ -2,995.35
5	€ -1,306.07	€ -1,397.31
6	€ -1,619.73	€ -2,258.35
7	€ -1,733.20	€ -1,628.55
8	€ -3,068.42	€ -2,936.23
Total	**€ -15,251.85**	**€ -18,690.68**

Solar parks equipped with energy steering software but without contractual GPPAs:

Table 22: Allocation , Nomination, and Revenue streams of 8 solar parks with energy steering

Solar park	Allocation (kWh)	Nomination (kWh)	Epex	Imbalance	Total
1	411,574.76	510,344.22	€ 36,838.52	€ -3,540.03	€ 33,298.49
2	435,290.64	526,914.73	€ 37,602.45	€ -2,761.53	€ 34,840.92
3	241,427.18	297,344.51	€ 21,687.82	€ -1,492.28	€ 20,195.53
4	234,854.99	268,420.06	€ 16,594.10	€ -1,543.26	€ 15,050.84
5	225,922.81	284,471.65	€ 20,266.41	€ -2,125.58	€ 18,140.83
6	316,348.24	380,573.07	€ 27,617.90	€ -2,439.61	€ 25,178.29
7	268,420.06	421,834.88	€ 31,465.82	€ -1,747.28	€ 29,718.54
8	511,717.90	625,187.22	€ 42,605.45	€ -2,826.15	€ 39,779.30
Total	**2,645,556.58**	**3,315,090.36**	**€ 234,678.45**	**€ -18,475.72**	**€ 216,202.73**

Table 23: Negative revenue of 8 solar parks with energy steering

Solar park	Epex	Imbalance
1	€ -2,297.98	€ -604.26
2	€ -2,415.43	€ -717.12
3	€ -1,258.67	€ -342.24
4	€ -1,552.35	€ -583.13
5	€ -1,306.07	€ -309.80
6	€ -1,619.73	€ -529.43
7	€ -1,733.20	€ -397.97
8	€ -3,068.42	€ -712.24
Total	**€ -15,251.85**	**€ -4,196.19**

Solar parks with contractual GPPAs but lacking energy steering software:

Table 24: Allocation, Nomination, and GPPA volume of 10 solar parks consisting of GPPAs

Solar park	Allocatie (kWh)	Nominatie (kWh)	GPPA_volume	PPA Match
1	779,942.60	866,825.13	578,753.04	74%
2	2,159,842.68	2,207,579.14	1,722,985.68	80%
3	1,768,782.75	1,951,846.38	1,160,036.68	66%
4	494,493.29	546,407.71	275,300.24	56%
5	261,356.52	295,475.41	152,639.72	58%
6	890,396.00	949,434.67	511,700.20	57%
7	436,094.47	472,994.95	110,076.28	25%
8	185,670.30	195,346.36	69,296.40	37%
9	580,065.25	619,295.47	246,599.60	43%
10	1,008,183.20	1,081,460.94	563,355.68	56%
Total	**8,564,827.06**	**9,186,666.14**	**5,390,743.52**	

Table 25: Revenue streams of 10 solar parks consisting of GPPAs

Solar park	PPA Price / MWh	PPA	Epex	Imbalance	Total
1	€ 169.20	€ 92,129.20	€ 22,935.87	€ -22,424.12	€ 92,640.95
2	€ 150.00	€ 239,100.16	€ 46,524.38	€ -58,078.34	€ 227,546.20
3	€ 162.00	€ 179,490.23	€ 57,241.13	€ -44,922.16	€ 191,809.20
4	€ 177.00	€ 46,591.08	€ 20,319.12	€ -13,271.73	€ 53,638.47
5	€ 170.00	€ 24,674.32	€ 11,225.42	€ -7,325.70	€ 28,574.04
6	€ 150.00	€ 73,438.72	€ 32,734.48	€ -19,172.35	€ 87,000.86
7	€ 138.50	€ 13,997.04	€ 24,466.54	€ -12,235.60	€ 26,227.97
8	€ 178.00	€ 12,334.76	€ 8,761.49	€ -5,182.25	€ 15,914.00
9	€ 118.13	€ 27,892.52	€ 25,139.51	€ -10,242.45	€ 42,789.58
10	€ 170.00	€ 91,303.96	€ 39,569.14	€ -25,324.57	€ 105,548.54
Total		**€ 800,951.98**	**€ 288,917.09**	**€ -218,179.26**	**€ 871,689.81**

Table 26: Negative revenue of 10 solar parks consisting of GPPAs

Solar park	Epex	Imbalance
1	€ -2,932.02	€ -4,263.86
2	€ -552.92	€ -17,510.50
3	€ -6,303.78	€ -8,633.56
4	€ -1,645.43	€ -2,702.31
5	€ -890.63	€ -1,277.40
6	€ -2,895.52	€ -5,247.39
7	€ -2,117.72	€ -2,554.49
8	€ -778.29	€ -1,307.77
9	€ -2,570.57	€ -2,541.21
10	€ -3,383.98	€ -5,709.94
Total	**€ -24,070.86**	**€ -51,748.42**

Solar parks equipped with both contractual GPPAs and energy steering software:

Table 27: Allocation, Nomination, and GPPA volume of 10 solar parks consisting of GPPAs and energy steering

Solar park	Allocatie (kWh)	Nominatie (kWh)	PPA_volume	PPA Match
1	740,664.60	866,825.13	578,753.04	78%
2	2,062,614.12	2,207,579.14	1,722,985.68	84%
3	1,672,930.84	1,951,846.38	1,160,036.68	69%
4	461,853.12	546,407.71	275,300.24	60%
5	244,444.77	295,475.41	152,639.72	62%
6	831,252.86	949,434.67	511,700.20	62%
7	386,860.46	472,994.95	110,076.28	28%
8	168,638.92	195,346.36	69,296.40	41%
9	532,823.53	619,295.47	246,599.60	46%
10	939,018.58	1,081,460.94	563,355.68	60%
Total	**8,041,101.78**	**9,186,666.14**	**5,390,743.52**	

Table 28: Revenue streams of 10 solar parks consisting of GPPAs and energy steering

Solar park	PPA Price / MWh	PPA	Epex	Imbalance	Total
1	€ 169.20	€ 92,129.20	€ 22,935.87	€ -15,967.44	€ 99,097.63
2	€ 150.00	€ 239,100.16	€ 46,524.38	€ -41,201.29	€ 244,423.25
3	€ 162.00	€ 179,490.23	€ 57,241.13	€ -30,235.40	€ 206,495.96
4	€ 177.00	€ 46,591.08	€ 20,319.12	€ -8,341.10	€ 58,569.10
5	€ 170.00	€ 24,674.32	€ 11,225.42	€ -4,750.73	€ 31,149.00
6	€ 150.00	€ 73,438.72	€ 32,734.48	€ -9,776.26	€ 96,396.94
7	€ 138.50	€ 13,997.04	€ 24,466.54	€ -4,918.21	€ 33,545.36
8	€ 178.00	€ 12,334.76	€ 8,761.49	€ -3,224.22	€ 17,872.02
9	€ 118.13	€ 27,892.52	€ 25,139.51	€ -3,435.65	€ 49,596.38
10	€ 170.00	€ 91,303.96	€ 39,569.14	€ -14,704.71	€ 116,168.39
Total		**€ 800,951.98**	**€ 288,917.09**	**-136,555.02**	**€ 953,314.04**

Table 29: Negative revenue of 10 solar parks consisting of GPPAs and energy steering

Solar park	Epex	Imbalance
1	€ -2,932.02	€ -2,085.02
2	€ -552.92	€ -9,848.44
3	€ -6,303.78	€ -4,164.75
4	€ -1,645.43	€ -1,008.77
5	€ -890.63	€ -557.51
6	€ -2,895.52	€ -2,033.51
7	€ -2,117.72	€ -764.50
8	€ -778.29	€ -531.27
9	€ -2,570.57	€ -991.21
10	€ -3,383.98	€ -2,147.88
Total	**€ -24,070.86**	**€ -24,132.85**