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Shedding Light on Green Claims: The Impact of a Closer Temporal Alignment of Supply and Demand in Voluntary Green Electricity Markets

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Shedding light on green claims: the impact of a closer temporal alignment of supply and demand in voluntary green electricity markets

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Abstract

Consumers purchase green energy via certificates independent from the physical good. The system's current structure, primarily based on annual volumetric matching, is critiqued for neither being transparent nor incentivizing necessary system improvements. By applying the pattern of European electricity demand and renewable electricity supply to the GO certificate market from 2016-2021, we test quarters, months, weeks, days, and hours as periods for a more granular matching. Our analysis reveals major shortages of green electricity due to seasonal and day-night volatility in generation. We argue that the current annual matching mechanism weakens market signals for investments in renewable energy and flexibility measures to cover under-supplied periods. We recommend a shift towards quarterly matching for the short- and hourly matching for the long term to balance the incentives of the matching mechanisms with system costs. Furthermore, storage solutions should be enabled to act as consumers and issuers of certificates.

Keywords: energy transition, market-based mechanisms, energy attribute certificates, green electricity, guarantees of origin, variable renewable energy integration

1 Introduction

In the belief that they are behaving more sustainably, consumers worldwide switch to sustainable energy suppliers. These suppliers advertise their energy as green or renewable. However, they usually cannot guarantee that the physical energy consumed is indeed produced from renewable sources [17, 45]. It may also be accounted for by renewable (excess) production from another day or another geographical location via energy attribute certificates (EACs). As the timely overlap of supply and demand of green energy is of no matter, these certificates can provide additional returns for renewable generation independent from current energy prices. The time-independent returns decrease the overall relative price volatility of the green energy supply [46]. By that, these certificates may, however, reduce the incentives to install flexibility measures such as battery storage systems and demand-side management that would otherwise help balance supply and demand over time. Certificates that provide time-independent returns also slightly curb pricing signals that foster off-peak green electricity generation, e.g. via west- or east-angled photovoltaic units. Within this paper, we analyze the current certificate-matching scheme for green electricity and showcase the impact of different certificate-matching frequencies within the largest standardized voluntary green electricity market, the European guarantees of origin (GO) market [53].

The green-labeling of energy usually requires the cancellation of certificates like renewable energy certificates (RECs) in the United States or GOs in Europe, proving that an equivalent amount of renewable energy has been generated [24, 25]. Energy labeled as green often relies on an annual volumetric accounting through certificates. These EACs can be traded independently from the physical product in certificate markets that exist, amongst others, for gas and electricity within the US and the EU. Prior literature has outlined many advantages of this system:

1) The ability to trade EACs independently from the physical product enhances market flexibility [46]. The EACs ease the process for renewable energy producers to sell their certificates to different consumers, including those in distant geographic locations [17, 42]. Hence, this system helps consumers relieve the energy consumption burden on the environment and contribute to sustainability goals regardless of their local grid's energy composition [48].

2) The additional returns generated through EAC certificates can directly increase revenue [60] and support renewable energy projects financially [48], encouraging increased investment in renewable technologies [33, 51]. This helps accelerating the transition towards a sustainable energy mix by enhancing the financial viability of green energy sources.

However, many researchers also criticize these markets in terms of their efficacy. According to Bird et al [9] and Markard and Truffer [44], certificates such as GOs only have a limited impact on increasing renewable generation. They therefore advocate for additional regulatory support schemes (e.g., feed-in tariffs) [44]. Gillenwater [28, 29] and Gillenwater et al [30] find similar problems with RECs failing additionality effects as they are not providing significant economic returns for wind power facilities. A. Hast et al [1] criticize the high utilization of GOs from cost-amortized hydropower plants, where these payments have little potential to increase further expansion of renewable production. Moreover, the abundant supply of GOs reduces the price premiums to a level too low to incentivize further investments in new capacity [47]. Winther and Ericson [57] also draw attention to the danger of consumers in countries with high RES generation to refrain from purchasing green electricity as they perceive their national electricity as green anyway. Picking up on such criticism, Mulder and Zomer [47] propose restricting international trade or limiting the issuance of new certificates. Similarly, Hamburger [31] and Herbes et al [32] see lacking incentivization of investments and no additionality in renewable generation capacity due to the oversupply of GOs from Norway. Thus, they propose to consider physical barriers of electricity transportation and to align disclosure information with official energy statistics or to simplify the system with a state-led labeling scheme with minimum performance criteria. The systemic failure of considering the actual physical flows of electricity by accounting for 100% renewable claims via EACs such as RECs is also addressed by Monyei and Jenkins [45]. They express great concern about the superficial distancing of companies from fossil fuel issues through accounting tactics that ignore the broader implications for energy justice and policy. Nordenstam et al [48] and Brander et al [14] even find that EAC-based greenhouse gas inventories of corporate consumers are unlikely to actually lead to emission reductions. Recent papers like Bjørn et al [10], thus, demand a revision of current accounting guidelines as they fear an inflated estimate of the effectiveness of mitigation efforts due to the widespread usage of EACs. de Chalendar and Benson [16] also call for a revision in corporate carbon accounting that allows to consider the benefits of different types of renewable energy depending on the local grid mix at a certain time of day. They point out that due to daily fluctuations in availability in solar-dominated grids such as California's, new wind capacity may have a greater carbon reduction impact than new solar capacity. Enhancing a capacity expansion planning model, Xu et al [59] find that the combination of a closer geographical and temporal alignment of green electricity generation and -demand can prove beneficial: When corporate consumers match their carbon-free electricity procurement within the same grid region on an hourly basis, they achieve higher CO2 emission reductions per MWh compared to 100% annual volumetric matching. Yet, the system costs increase with the imposition of hourly matching within the same grid region. The more players engage in it, the higher the costs [59]. With the EnergyTag Initiative, an industry-led initiative has formed that works on guidelines for 24/7 clean electricity procurement on the basis of granular energy certificates [53]. Yet, academic literature is lagging behind with empirical studies on the temporal interplay between green electricity demand and green electricity supply [49]. Moreover, past studies have focused on corporate consumers taking advantage of reporting zero emission for their electricity consumption [10, 14, 48]. Those have, however, not been the only ones showing an increasing interest in sourcing green electricity. Demand has grown across sectors [1, 9, 31, 32, 34, 37, 39, 43, 44, 47, 58], such as in the German residential sector, where the share of green electricity purchased has increased from 14% to 43% over the past decade [15]. Biden's executive order from December 8th, 2021, that federal agencies have to consume 100% carbon-free electricity by 2030, is another example of increasing demand for green electricity[55]. According to Xu et al [59], hourly matching within the same grid region is associated with higher system costs. Thus, considering softer, less-costly matching requirements might be worthwhile. To the best of our knowledge, past literature has not evaluated the isolated impact of different levels of closer temporal alignment between green electricity supply and the increasing cross-sectoral demand. We, therefore, aim to contribute to a better understanding of (voluntary) green electricity markets by asking: (1) how sound would green electricity claims be with the imposition of a closer temporal alignment of green electricity supply and demand? (2) How should the matching frequency be structured to best incentivize additional renewable energy source (RES) installations and flexibility measures?

To answer these questions, we study the isolated effect of a gradually increasing temporal alignment of green electricity supply and demand in a market where all sectors engage in green electricity consumption as they do in in general electricity consumption. We use real-world GO-data of 2016-2021 with data on European electricity demand and renewable supply to study the quarterly, monthly, weekly, daily, and hourly matching of green electricity supply with demand. Based on our findings, we discuss the effects on RES installations and flexibility measures and give policy recommendations for an incentive-efficient certificate scheme. Section 2 highlights the most important characteristics of the GO market and gives a brief method overview. Section 3 starts with an illustration and description of the intervals uncovered by renewable production in 3.1 and closes with a detailed description of the results with hourly matching in 3.2. We conclude our study in section 4. For reproduction purposes and deeper understanding, we provide a comprehensive method description in section 5.

2 Important Characteristics of the GO Market and Method Overview

The European GO market was initially introduced in 2001 [21]. In 2009, GOs were legally defined as "an electronic document [...] providing proof to a final customer that a given share or quantity of energy was produced from renewable sources" [22]. Producers of renewable energy may receive such a document per MWh of renewable electricity generation, and its reception is commonly referred to as GO issuance. Energy released from storage systems may only issue GOs if the respective systems are located next to a renewable energy generation facility and no GOs have been issued by that facility [8]. Within the same year, the EU stipulated that the disclosure of the share of electricity from renewable sources over the preceding year should be done using GOs [23]. The act of using a GO for a green claim is referred to as GO cancellation. Any GOs that have not been canceled 18 months after issuance expire (2018/2001/EU). Providing an electronic hub, the Association of Issuing Bodies (AIB) sits at the interface of GO-trade within Europe. By 2021, its hub connected 24 European countries [4], which in total issued GOs for 748 TWh of green electricity. In the past, the market has shown a structural oversupply. Over the last years, however, annual GO supply and demand have become increasingly balanced (from 26% oversupply in 2016 to merely 3% in 2021) [2, 3]. While annual GO supply relates to the GOs issued within a year, annual GO demand relates to the canceled GOs that were issued in the respective year. Due to the focus of our study on the GO market, we use GO supply and demand interchangeably with green electricity supply and demand within this paper.

To contrast green electricity supply and demand on an hourly level, we interpolate sub-yearly GO-demand and sub-monthly GO-supply data by assuming a direct correlation with overall European electricity consumption and renewable generation. For example, we use data on the sub-monthly renewable electricity generation to draw conclusions on the sub-monthly supply of GOs. However, not all renewable generation also issues GOs (about 60% in 2020) [54]. Member states can decide not to issue GOs for renewable energy installations that receive financial support [25]. Because different renewable energy sources depend on financial support to varying degrees [31], there are differences in the composition of energy sources between GO-issuing generation and total renewable electricity generation. Most noteworthy is that the share of hydropower within the GO-issuing generation is over-proportional. As a result, the generation pattern of total renewable electricity generation partially differs from that of GO-issuing generation. However, both generation profiles show the same trend: a decline in the dominance of hydropower in favor of wind and solar, more non-dispatchable, variable renewable energy (VRE)[2–4, 27, 36]. Using the pattern of total renewable electricity generation, hence, allows us to study the impact of a closer temporal alignment on the backdrop of the shifting energy mix for future energy scenarios.

Aiming to reflect all sectors involvement in the sourcing of green electricity [1, 9, 14, 31, 32, 34, 37, 39, 43, 44, 47, 58], we approximate the sub-yearly demand of GOs by means of fitting total load data. Thereby, we assume all sectors to consume green electricity in the same manner and proportion as they consume electricity.

3 Results

3.1 Uncovered Intervals depending on imposed matching periods

In line with current regulations, green electricity supply consistently meets green electricity demand when accounting on annual volumetric basis. If we, however, introduce more granular matching periods, we observe severe discrepancies between green electricity supply and demand (see Fig. 1). The shorter the imposed matching periods, the more the supply falls short of the demand. With the increase in green electricity demand and the shift in the energy mix towards more and more VRE, we face a yearly increasing mismatch. In recent years, already one out of four quarters is showing insufficient coverage under a quarterly matching scheme. On average, 1.2% of the demand remained uncovered in Quarter 1, while Quarter 4 experienced a 2.6% shortfall. Monthly matching sheds further light on the months at risk within the quarters, with January, February, September, October, and November being particularly prone to shortages. As evident in 2020, even a single month with a significant deficit can be sufficient to cause a quarterly shortage if the other months of the respective quarter do not compensate with substantial overcoverage. While October registers the lowest average shortage (2.4%), with 6.5%, November shows the highest. December shows reduced demand, as large manufacturing companies typically take a holiday break over Christmas and, hence, faces less under-coverage. Even more extreme, the imposition

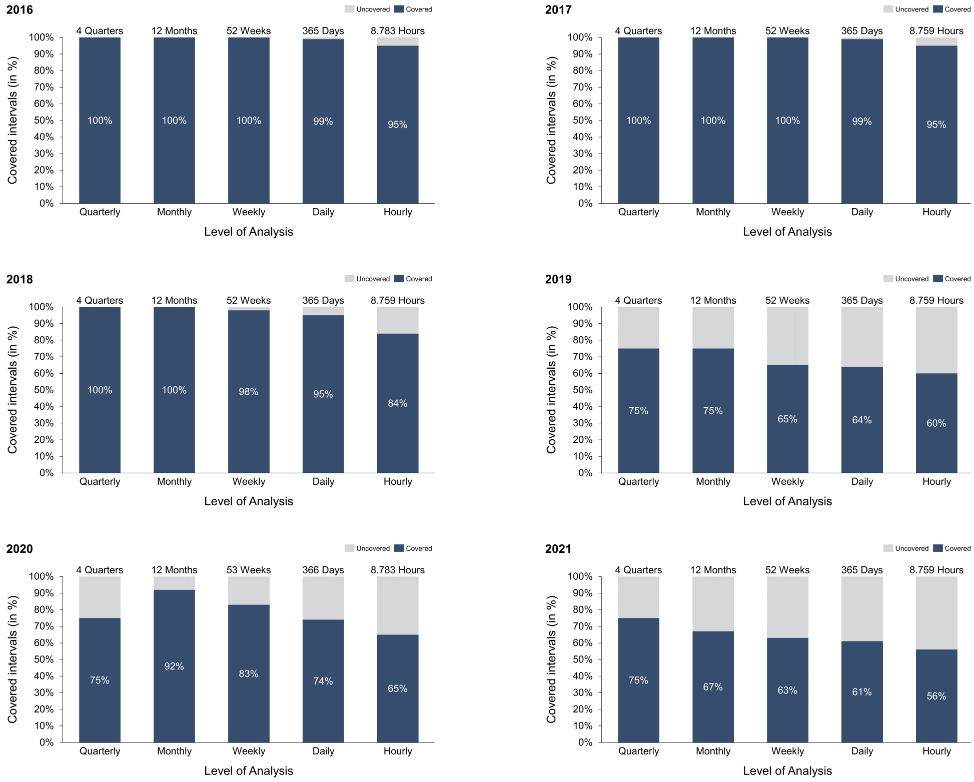

Fig. 1 Share of intervals where green electricity demand was covered with green electricity supply produced within the same interval from 2016 to 2021, depending on the imposed matching period (in % of all intervals at respective level of analysis)

of an hourly matching would, in the worst case, only allow 56% of all intervals to be covered with green electricity.

Our findings highlight the critical influence of - especially in the case of solar - existing seasonal fluctuations in renewable energy generation. Although there is coverage of green electricity demand with green electricity supply at the aggregated annual level, the reality diverges significantly during winter. A mismatch that stays hidden under the current annual volumetric matching scheme. In the future, decarbonization efforts in the transport sector could further aggravate green electricity shortages in the winter quarters as achieving low carbon footprints for electric vehicles requires powering them with green electricity [7]. Low ambient temperatures, however, increase the energy demand due to the use of auxiliaries significantly reducing vehicle ranges [6]. While the literature focuses on the advocacy of 24/7 matching, our study reveals that shifting to quarterly matching could already be beneficial. Adopting quarterly matching would increase the demand for EACs from the winter quarters, potentially increasing their value. This shift might incentivize the construction of renewable capacity, such as wind, which is less prone to winter shortages. Assuming increasing administrative and system costs the shorter the matching period, moving to quarterly matching would entail only a minimal change in the market and may cause only minor administrative efforts compared to the complexities associated with hourly matching. Balancing market scheme effects and operational system costs, quarterly matching, hence, may be a good choice for the short term. While ramping up appropriate renewable generation capacity is one solution to increasing the supply of green electricity in uncovered quarters, taking advantage of overproduction in summer quarters with the help of long-term storage solutions could be another. In power systems with a penetration of VRE above 80%, storage - particularly long-term storage - may become an attractive option to meet demand [11, 56]. Incorporating long-term and seasonal storage solutions into the EAC value chain under a quarterly matching framework could reduce costs and enhance attractiveness even at lower VRE penetration levels by facilitating additional arbitrage opportunities. An update of current regulation which severely restricts the possibilities of storage systems in EAC issuance, could allow storage systems to take on a dual role in green electricity markets. During periods of surplus (summer quarters), they could act as EAC consumers, storing green electricity at lower EAC prices. Conversely, during winter quarters, they could act as EAC producers, releasing stored energy volumes when the green electricity market faces supply shortages. This approach would allow them to benefit from higher EAC prices, mirroring the situation in systems with significant VRE penetration, where shortages in renewable generation lead to general supply constraints and translate into high electricity prices.

3.2 Hourly matching and the Course of Uncovered Intervals

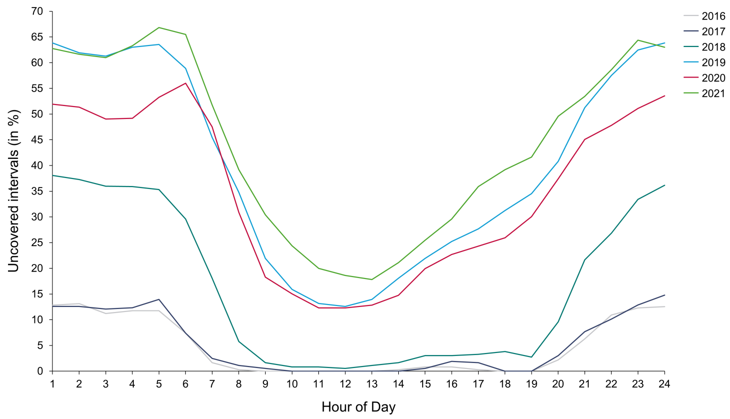

Fig. 2 Distribution of hours with a shortage in green electricity supply over the day, from 2016-2021 (in % of all intervals at respective hour of day)

Within our analysis, we find total shortages in uncovered intervals in relation to the yearly green electricity demand to peak at 4.3% in 2021 at the imposition of an hourly matching scheme. Figure 2) illustrates two major trends on the hourly level of analysis:

Firstly, there has been an overall increase in the share of intervals with insufficient coverage over recent years. In 2016, shortages from 7 a.m. to 7 p.m. have been almost nonexistent. By contrast, in 2021, shortages are even observed in 18% of all intervals at 1 p.m. This development reflects the increasing demand for green electricity. The only year that falls out of line is 2020. However, this was the only year in which the increase in overall demand was smaller than that in supply. Moving forward, we expect the undercoverage to increase as the electrification for decarbonization purposes advances, marked by the increased coupling of the electricity sector with the transport, building, and industrial sector, boosting green electricity demand [38, 40, 52].

Secondly, the night hours exhibit a higher number of shortages than the day hours. This disparity between day and night hours has grown more pronounced over the years, with the range of uncovered intervals expanding significantly — from a 13 to a 49 percentage-point difference. For instance, in 2021, the share of uncovered intervals peaks at 66% at the fifth hour of the day. Notably, this hour of the day, on average, also records the largest volumetric shortfall in meeting green electricity demand with supply (11.4%). The role of the increase of VRE, in particular wind and solar, in the increase of the day-night disparity becomes particularly evident through the analysis of three hypothetical scenarios, one with solar-only and one with wind-only electricity generation, and one combining generation from both production types (see Fig. 3).

The day-night disparity climaxes in a system powered exclusively by solar energy, with the proportion of uncovered intervals rising to 100% during nighttime. The surplus generated during the daytime, however, sufficiently offsets the shortages of the night on an annually aggregated level. Different dynamics are at play in a system relying solely on wind energy. The incidence of uncovered intervals at night is notably lower. Instead, we see a tendency for shortages to peak in the morning. Interestingly, a hybrid system that integrates both solar and wind resources does not eliminate the day-night dichotomy. Instead, it moderates the extremities, curtailing the frequency of uncovered intervals at night at the expense of an increase during the day. If we view our baseline scenario against this background, the intensification of the share of uncovered intervals over the years appears to reflect a convergence towards our hypothetical solar and wind system. The increasing share of solar and wind energy is beginning to outweigh the smoothing effects of more firm renewable energy sources such as hydropower. This will become even more apparent in the future as those energy sources are already being deployed at their natural limits [1]. The EU's plan to become climate neutral by 2050 (2021/1119/EU), hence, builds heavily on a further expansion of VRE. In comparison to 2020, at least a doubling in onshore wind capacity and a quadrupling in solar and in offshore wind capacity is planned [1]. Today, the GO-issuing electricity generation may still show a higher proportion of hydropower than the total renewable generation in Europe, which we used to approximate the hourly supply and demand. Consequently, the carve-out of the day-night disparity in the European green electricity market is likely to lag somewhat behind compared to our results. However, in the long run, the increased reliance on solar and wind will also significantly come into play here. In addition, the decarbonization efforts in the transportation sector

[1]See REPowerEU, EU solar strategy (COM(2022)221, EU strategy on offshore renewable energy (COM(2020)741) and European Wind Power Action Plan (COM(2023)669).

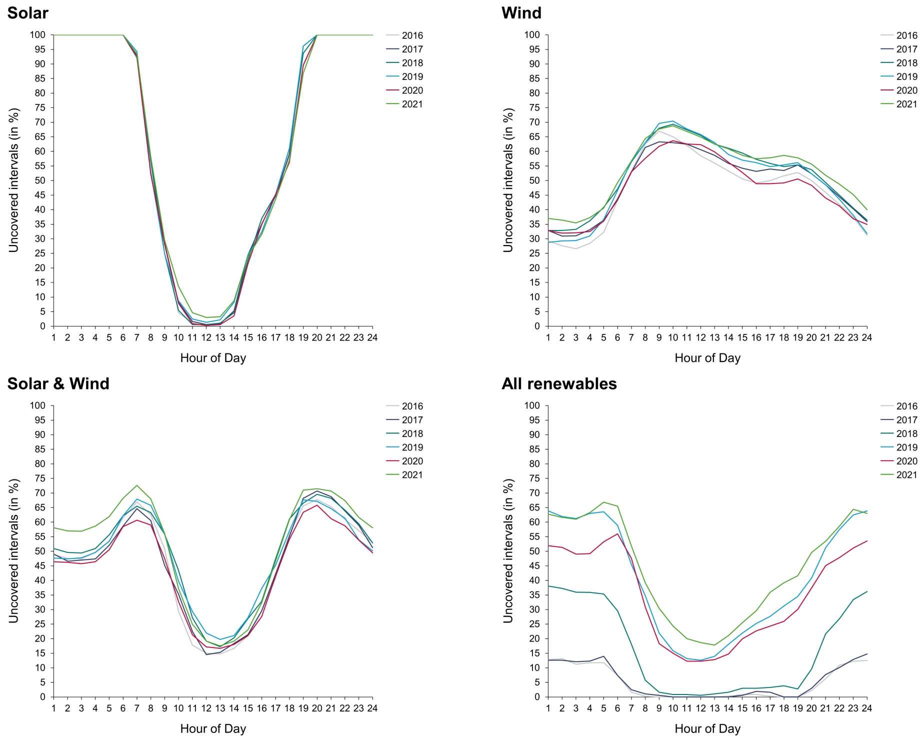

Fig. 3 Distribution of hours with a shortage in green electricity supply over the day, from 2016-2021, for the hypothetical scenarios of solar-only electricity generation, wind-only generation, and combined solar and wind generation, in comparison to the baseline scenario

are likely to be accompanied by a particular increase in demand for electricity in the evening and at night due to the charging preferences of users [41, 50].

At some point, the imposition of merely a quarterly matching will, thus, no longer provide the right incentives. While facilitating the building of RES installations and flexibility measures that help tackle seasonal variations, it will not target overcoming the increasing carve-out of the day-night disparity. The imposition of hourly matching would, however, raise the value of EACs issued within the night or the early morning hours. Short-term storage solutions - if integrated into the EAC value chain with a dual role as outlined above - could benefit. Similarly, these relative price increases may trigger more installations of west or east-angled photovoltaic units for higher production outside the peak hours. On the demand side, hourly matching may help facilitate the shifting of demand from hours with high EAC prices to hours with low EAC prices and abundant green electricity supply (see Blaschke [12]). Similarly to Xu et al [59], we find hourly matching to be beneficial but only see a necessity for it in the long-run. Given the high system costs associated with hourly matching, we recommend moving to quarterly matching as a first step. It would also enable us to take advantage of expected advances in digitization and data availability [13] before switching to hourly matching. Our two-pronged approach enriches prior literature on the lacking additionality of EACs [1, 9, 10, 28–32, 44, 47] with a viable improvement of the much-criticized status quo in voluntary green electricity markets. A shift in incentives could foster a more sustainable energy mix in EAC-issuing generation. It could also spur more beneficial demand-side management, an element crucial for the improvement of greenhouse gas implications [14, 48].

4 Conclusion

This study investigates the certificate market mechanism of green energy products. Since green energy products are traded via certificates independent of the physical energy flow, the current market rules allow the acquisition of green energy that was or will be produced at another location and at another time. We discuss the lack of timely overlap between the certificate supply and demand and showcase our thoughts on the European voluntary green electricity market. We find the current market rules to provide wrong incentives and advocate for a reevaluation of the matching periods in green electricity markets. The current annual volumetric matching via EACs may be convenient from an accounting perspective but does not provide incentives to improve the resilience of the systems further. As the certificates can be used time-independent, over-production in summer will likely cover up missing supply in winter months. Switching towards a quarterly matching frequency would already open up the potential to address the seasonal imbalances in green electricity supply and demand more effectively. To trigger the right investments in the long run, we, however, require hourly matching. Currently, photovoltaic investors, for example, may maximize their returns on certificates with southwards-angled systems for maximum output. From a market perspective, however, it may be very important to have more renewable production in the early morning and late evening hours with photovoltaic units angled to the east and west. Hence, the annual volumetric approach with the corresponding time-independent returns reduces market signals required for a more resilient energy system. Shorter matching frequencies would stimulate market dynamics that provide incentives for more market-oriented solutions like time-optimized renewable generation capacity or flexibility measures like storage systems. In terms of storage system, we call for an overall strengthening of the position of such systems in the EAC value chain. To fully utilize the potential of a closer temporal alignment of green electricity demand with green electricity supply, storage systems must be enabled to issue EACs independent of their location if EACs have been canceled for the stored electricity volumes before. Together, these adjustments could pave the way for a more sustainable green energy certificate framework and a higher validity of green energy claims. While we took an overall market view, approximating the sub-yearly green electricity consumption pattern by that of total electricity consumption, future research could further look into the differences between both. Accounting for variations in how different sectors prioritize or have access to green electricity could shed further light on the impacts of temporal alignment in different sectors.

5 Method

5.1 Merging GO-data with data on the European electricity market

We evaluate historical GO and electricity market data from 24 European GO trading countries from 2016-2021 to calculate the hypothetical quarterly, monthly, weekly, daily, and hourly coverages of green electricity demand by actual green electricity supply. Therefore, we combine data from the Association of Issuing Bodies (AIB) and the European Network of Transmission System Operators for Electricity (entso-e). The AIB reports statistics on historical GO issuance, cancellation and trade of GOs. Entso-e provides up to quarter-hourly data on historical electricity generation and consumption within Europe [5, 20].

From the AIB production statistics [2, 3][2] we derive data on the cumulative monthly GO issuance per production type from 2016 to 2021 aggregated over all AIB member states connected via the AIB hub[3] *(GO-supply)*. We also use the AIB production statistics for yearly cumulative data over the respective AIB member states on the GOs issued and cancelled within each year from 2016-2021 *(GO-demand)*. Considering only GOs issued for renewable production, we omit all other types of GOs.

To increase the granularity of the AIB data on GO-supply, we use entso-e data on the actual generation per production type for the years 2016-2021 [18]. Depending on the country, the generation data points refer to different measurement intervals (15min, 30min, or 60min). As our analysis requires an hourly frequency, we harmonize the different measurement intervals. By using the mean of all measurements within a respective hour, we derive a data set of the hourly electricity generation per production type and country. Subsequently, we aggregate the generation per country over all renewable sources that could have led to the issuance of renewable GOs. For the few missing values within the data set, we apply a structured data imputation strategy (see section 5.2). We then aggregate the data on renewable generation per hour for all countries that, at the respective time, had been connected via the AIB hub and were, thus, reflected in the AIB statistics. Since GOs have not been issued for every MWh of renewable electricity generation, the monthly GO-supply only makes up a fraction $(a_{m,y})$ of the monthly renewable electricity generation $(reg_{m,y})$. Hence, to finally derive the hourly ***green electricity-supply*** *(ge-supply)*, we scale each hourly value in the modified entso-e data set with $a_{m,y}$ (see equation 1).

$$\textit{ge-supply}_{h,d,m,y} := \textit{GO-supply}_{h,d,m,y} = a_{m,y} \cdot reg_{h,d,m,y} \tag{1}$$

where,

$$\begin{aligned} h \in H &:= \{1, 2, ..., 24\} \\ d \in D_{m,y} &:= \text{All days of month } m \text{ in year } y \\ m \in M &:= \{1, 2, ..., 12\} \end{aligned}$$

[2] As the AIB changed the format of the statistics in 2019, we used the statistics in the old format for data on the years 2016-2018 (Tab "Monthly - Fuel"), and the statistics in the new format from 2019 onwards (Tab "All statistics").

[3] An overview of the countries and periods of analysis can be found in appendix A.

$$y \in Y := \{2016, 2017, ..., 2021\}$$

Similarly, we use entso-e data on the actual total load for the years 2016-2021 [19] to derive the hourly ***green electricity-demand*** *(ge-demand)*. Due to the differences in resolution, we also harmonize the data to an hourly level per country. For the missing values, we apply a structured data imputation strategy (see section 5.2). After artificially imputing the missing data, we aggregate the consumption data per hour for all countries that were connected via the AIB hub at the respective time. Since, doing so, we consider the overall consumption of electricity *(ec)*, instead of solely that of green electricity, also here the annual GO demand only makes up a fraction (b_y) of the yearly electricity consumption (ec_y). Scaling each hourly demand value in the modified entso-e data set by means of b_y, we derive the hourly *ge-demand* as follows:

$$ge\text{-}demand_{h,d,m,y} := GO\text{-}demand_{h,d,m,y} = b_y \cdot ec_{h,d,m,y} \tag{2}$$

where,

$$\begin{aligned} h \in H &:= \{1, 2, ..., 24\} \\ d \in D_{m,y} &:= \text{All days of month } m \text{ in year } y \\ m \in M &:= \{1, 2, ..., 12\} \\ y \in Y &:= \{2016, 2017, ..., 2021\} \end{aligned}$$

5.2 Imputing missing values in the data on the European Electricity market

While the entso-e data is very granular and comprehensive data on European electricity generation and consumption, it also shows some limitations - not only does it lack Icelandic data for both the generation and the demand side, but it also shows sporadic data gaps in the other 23 countries (two major gaps larger than a month and multiple minor gaps).[4] We impute the data for Iceland and the other sporadic data gaps (in total 7.2% of the data points contributing 2.4% of the renewable electricity generation and 5.5% of the data points contributing 0.9% of the electricity consumption) by applying a structured and transparent data imputation strategy. We therefor draw on related values within the data set and incorporate additional data from other providers such as the International Energy Ageny (IEA) [35] and EUROSTAT [26]:

Due to the lack of any other provider of hourly data for the two major gaps (renewable generation in Croatia (HR) from 2016 to 2018 and electricity consumption in Cyprus (CY) from January to September 2016) we impute the missing data by using scaled generation and consumption data from the time after the data gap. For Croatia, we use the net electricity production data from the IEA's Monthly Electricity Statistics [35], derive the required scaling factors by putting the monthly Croatian 2019 total renewable generation in relation to the 2016 to 2018 total renewable generation, and, finally, calculate the missing hourly values displayed in equation 3.

[4] The lack of Icelandic data originates from the lack of any physical connections to other entso-e members. As, however, Iceland was connected to the AIB-hub for the years of our analysis, engaging in the issuance and cancellation of GOs, we require its electricity generation and consumption data despite the absence of any physical connections.

$$reg(HR)_{h,d,m,y} = \frac{reg_{IEA}(HR)_{m,y}}{reg_{IEA}(HR)_{m,2019}} \cdot reg_{entso-e}(HR)_{h,d,m,2019} \tag{3}$$

where,

$$\begin{aligned} h \in H &:= \{1, 2, ..., 24\} \\ d \in D_{m,y} &:= \text{All days of month } m \text{ in year } y \\ m \in M &:= \{1, 2, ..., 12\} \\ y \in Y &:= \{2016, 2017, 2018\} \end{aligned}$$

As the IEA's Monthly Electricity Statistics do not feature Cypriot electricity consumption data, we use 2016 and 2017 data from EUROSTAT on the electricity available to the internal market for Cyprus [26]. We derive the scaling factors based on the relation of the Cypriot monthly electricity consumption in 2016 to that in 2017 and calculate the hourly values as follows:

$$ec(CY)_{h,d,m,2016} = \frac{ec_{EUROSTAT}(CY)_{m,2016}}{ec_{EUROSTAT}(CY)_{m,2017}} \cdot ec_{entso-e}(CY)_{h,d,m,2017} \tag{4}$$

where,

$$\begin{aligned} h \in H &:= \{1, 2, ..., 24\} \\ d \in D_{m,y} &:= \text{All days of month } m \text{ in year } y \\ m \in M &:= \{1, 2, ..., 9\} \end{aligned}$$

For the minor gaps within the data set, we apply a two-pronged approach: Wherever solely one timestamp is missing, we linearly interpolate its value with the mean of the value of the data point before and after the gap (approach A). If more than one data point is missing, we use the mean of the values of the closest available surrounding data points at the same time of day (approach B).

For the missing Icelandic data, we use the generation and consumption of selected reference countries as a proxy, scaling them to the Icelandic level: Iceland primarily builds on hydro and geothermal sources [35]. We, therefore, use Norwegian hydro and Italian geothermal generation data as a reference, since these countries show an equally high share of hydro/geothermal generation in their renewable electricity generation [35].[5] Besides, we also use the data on Norwegian electricity consumption. We address gaps in the data of both generation subsets by applying the same two-pronged approach also used for the total renewable generation and electricity consumption data per country. Drawing on the Monthly Electricity Statistics of the IEA [35], we derive time-dependent scaling factors by putting the IEA data of the reference countries in

[5] We use the aggregated Norwegian hydro generation ("Hydro Pumped Storage", "Hydro Run-of-river and poundage", "Hydro Water Reservoir" and "Marine") and the Italian geothermal generation ("Geothermal") per hour.

contrast to the IEA Icelandic data. [6] We finally calculate the hourly Icelandic values for renewable electricity generation and electricity consumption as follows:

$$
\begin{aligned}
reg(IS)_{h,d,m,y} = &\Big(\frac{reg_{IEA}(IS, hydro)_{m,y}}{reg_{IEA}(NO, hydro)_{m,y}} \cdot reg_{entso\text{-}e}(NO, hydro)_{h,d,m,y}\Big) \\
&+\Big(\frac{reg_{IEA}(IS, geothermal)_{m,y}}{reg_{IEA}(IT, geothermal)_{m,y}} \cdot reg_{entso-e}(IT, geothermal)_{h,d,m,y}\Big)
\end{aligned} \tag{5}
$$

$$
ec(IS)_{h,d,m,y} = \frac{ec_{IEA}(IS)_{m,y}}{ec_{IEA}(NO)_{m,y}} \cdot ec_{entso-e}(NO)_{h,d,m,y} \tag{6}
$$

where,

$$
\begin{aligned}
h \in H &:= \{1, 2, ..., 24\} \\
d \in D_{m,y} &:= \text{All days of month } m \text{ in year } y \\
m \in M &:= \{1, 2, ..., 12\} \\
y \in Y &:= \{2016, 2017, ..., 2021\}
\end{aligned}
$$

Table 1 provides a conclusive overview of which share of total renewable electricity generation and electricity consumption within the final data set is based on which type of data imputation.

Table 1 Impact of data imputation in relation to total renewable electricity generation and electricity consumption (in %)

		Generation	Demand
Iceland		1.94	0.81
Major	Croatia	0.43	/
	Cyprus	/	0.02
Minor	Approach A	0.01	0.02
	Approach B	0.03	0.05
TOTAL		2.41	0.91

5.3 Calculating green electricity coverages from 2016-2021 at different levels of analysis

We finally calculate the green electricity coverages by contrasting *ge-demand* with *ge-supply* at an hourly level of analysis (see equation 7). Subsequently, we aggregate the coverages to a daily, monthly, weekly and quarterly level.

[6]We use the following IEA data: "Net electricity production Hydro" in Iceland and Norway for scaling the modified entso-e Norwegian Hydro generation data, "Net electricity production Geothermal" in Iceland and Italy for the modified entso-e Italian geothermal generation data, and "Final Consumption Electricity" Iceland and Norway for the modified entso-e Norwegian electricity consumption data.

$$ge\text{-}coverage_{h,d,m,y} := ge\text{-}supply_{h,d,m,y} - ge\text{-}demand_{h,d,m,y} \tag{7}$$

where,

$$\begin{aligned} h \in H &:= \{1, 2, ..., 24\} \\ d \in D_{m,y} &:= \text{All days of month } m \text{ in year } y \\ m \in M &:= \{1, 2, ..., 12\} \\ y \in Y &:= \{2016, 2017, ..., 2021\} \end{aligned}$$

5.4 Compiling additional scenarios: in-depth analysis of the role of the VRE wind and solar

With the aim to study the increasing share of wind and solar, we additionally calculate the hourly coverages of *ge-demand* by *ge-supply* for three hypothetical generation scenarios: one with solar-only generation, one with wind-only generation, and one combining generation from both production types.

For solar-only generation, we filter the entso-e data for the production type "solar" and harmonize the different measurement intervals to an hourly level. We complement missing values with our structured data imputation strategy outlined in section 5.2. For reasons of simplicity, we ease the threshold value between minor and major data gaps from one to two months and use the same scaling factors as before for the Croatian data gap in this analysis as imputed values only make up 0.05% of total solar generation. We aggregate the solar generation per hour for all countries that, at the respective time, were connected via the AIB hub. Considering the relation between total solar generation and GO-issuing solar generation ($a(solar)_{m,y}$) and total electricity consumption and Solar GO cancellations ($b(solar)_{y}$), we calculate the hourly supply and demand values. For wind-only generation, we proceed the same way but initially filter the entso-e data for the production types "wind offshore" and "wind onshore" instead. Imputed MWhs here also only make up a small fraction (0.4%). We finally calculate the coverages for all intervals at an hourly level of analysis as displayed in equations 8-10 for solar exemplarily.

$$ge\text{-}coverage(solar)_{h,d,m,y} := ge\text{-}supply(solar)_{h,d,m,y} - ge\text{-}demand(solar)_{h,d,m,y} \tag{8}$$

$$\begin{aligned} ge\text{-}supply(solar)_{h,d,m,y} := GO\text{-}supply(solar)_{h,d,m,y} = \\ a(solar)_{m,y} \cdot reg(solar)_{h,d,m,y} \end{aligned} \tag{9}$$

$$\begin{aligned} ge\text{-}demand(solar)_{h,d,m,y} := GO\text{-}demand(solar)_{h,d,m,y} = \\ b(solar)_{y} \cdot ec_{h,d,m,y} \end{aligned} \tag{10}$$

where,

$$
\begin{aligned}
h \in H &:= \{1, 2, ..., 24\} \\
d \in D_{m,y} &:= \text{All days of month } m \text{ in year } y \\
m \in M &:= \{1, 2, ..., 12\} \\
y \in Y &:= \{2016, 2017, ..., 2021\}
\end{aligned}
$$

Besides, we calculate the hourly coverages for combined solar and wind generation as follows:

$$
\begin{aligned}
\textit{ge-coverage}(\textit{solar\&wind})_{h,d,m,y} = &\Big(\textit{ge-supply}(\textit{solar})_{h,d,m,y} + \textit{ge-supply}(\textit{wind})_{h,d,m,y}\Big) \\
&-\Big(\textit{ge-demand}(\textit{solar})_{h,d,m,y} + \textit{ge-demand}(\textit{wind})_{h,d,m,y}\Big)
\end{aligned}
\tag{11}
$$

Appendix A Supplementary materials

Table A1 Countries within our analysis and analysis period, based on their connection to the AIB-hub between 2016-2021 [4]

No.	Country	From	Until
1	Austria	2016	2021
2	Belgium	2016	2021
3	Switzerland	2016	2021
4	Cyprus	2016	2021
5	Czech Republic	2016	2021
6	Germany	2016	2021
7	Denmark	2016	2021
8	Estonia	2016	2021
9	Spain	2016	2021
10	Finland	2016	2021
11	France	2016	2021
12	Croatia	2016	2021
13	Ireland	2016	2021
14	Iceland	2016	2021
15	Italy	2016	2021
16	Luxembourg	2016	2021
17	Latvia	2018	2021
18	Netherlands	2016	2021
19	Norway	2016	2021
20	Portugal	2020	2021
21	Serbia	Oct 2019	2021
22	Sweden	2016	2021
23	Slovenia	2016	2021
24	Slovakia	Oct 2019	2021

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