On the development of corporate renewable energy procurement and economic modeling of hourly green certificate market

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Tiivistelmä – Referat – Abstract

Electricity is the fastest-growing final form of energy, and its demand is expected to increase rapidly in the coming decades. More transparent and accurate emission accounting is needed to accelerate green transition and achieve national decarbonization targets. Many organizations are currently developing strategies to reach carbon neutrality on an hourly basis as private renewable energy procurement is outpacing regulatory targets. The high standards of corporate sustainability management are driving the movement towards temporal matching or "24/7 matching" of renewable energy, which could also provide more credibility to net zero claims as well as decrease double-counting and greenwashing.

Thus far, electricity has been tracked with tradable green certificates, Guarantees of Origin in Europe, which enable matching electricity consumption on an annual or monthly basis with renewable energy. However, while the share of green power grows in the electricity generation mix, it also comes with problems of intermittent and variable production. All renewable energy technologies have unique resource profiles and seasonal and intra-day fluctuations. Thus, supply from green energy is unlikely to always align with the actual timing of consumption. In addition, the current green certificate systems do not adequately reflect the timely availability of renewable energy and hence do not drive investments that could provide system flexibility and around-the-clock availability of green energy. To address this issue, pilot versions of tradable certification instrument that would enable hourly or sub-hourly tracking of electricity are currently under development as the movement towards 24/7 matching of green energy is gaining more interest.

However, before introducing new instruments to the existing markets, it is essential to study the possible market effects. In this thesis, we introduce an economic model for the hourly certificate market and compare the volume and price effects of 24/7 matching with hourly renewable energy certificates with traditional certificate markets, where electricity consumption is matched on an annual basis. We also analyze how the consumer's utility from hourly green certificates varies between times with more available renewable energy generation and when green power is less abundant. We find that consumers utility from purchasing hourly certificates decreases when the share of renewable energy surges. Accordingly, the consumer's utility from hourly certificates is the highest when also the share of emitting energy is high. Therefore, hourly green certificates could provide the most benefit to both, consumers, and producers, in hours when renewable energy is less abundant.

We also find that hourly matching could either increase or decrease the consumer's procurement costs and the revenues of the producer within single hours or sub-hours than matching with an annual or monthly goal. Consequently, hourly certification could provide additionality to technologies needed for complete system-wide decarbonization, such as energy storage solutions. Thus, the scheme's development should focus on accentuating this effect that could further spur investments into system flexibility. However, more research is needed to examine the possible system effects especially in grids with already high renewable energy penetration, whether there is demand for such a system from the residential sector, and whether hourly certificates would lead to higher grid decarbonization than traditional schemes in a socially optimal way.

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24/7 matching, corporate renewable energy procurement, renewable energy certificates, hourly matching

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Yritysten uusiutuvan energian hankinnan kehittymisestä ja tuntikohtaisten vihreän sähkön sertifikaattimarkkinoiden taloudellisesta mallintamisesta

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Tiivistelmä – Referat – Abstract

Sähkö on nopeimmin kasvava lopullinen energiamuoto, ja sen kysynnän odotetaan kasvavan nopeasti tulevina vuosikymmeninä. Markkinoille tarvitaan läpinäkyvämpää ja tarkempaa päästölaskentaa, vihreän siirtymän ja kansallisten hiilidioksidipäästötavoitteiden nopeammaksi saavuttamiseksi. Monet organisaatiot kehittävät parhaillaan strategioita tuntitason hiilineutraaliuuteen, sillä monien yksityisten uusiutuvan energian hankintojen kunnianhimo ylittää olemassa olevan sääntelyn tavoitteet. Yritysten kestävyysjohtamisen korkeat standardit ohjaavat siirtymistä kohti uusiutuvan energian ajallista täsmäytystä tai "24/7-täsmäytystä", mikä voisi myös lisätä uskottavuutta hiilineutraaliusväitteisiin sekä vähentää päästöoikeuksien kaksinkertaista laskemista ja viherpesua.

Toistaiseksi sähkön alkuperää on seurattu markkinapohjaisilla vihreillä sertifikaateilla; Euroopassa Guarantees of Origin, jotka mahdollistavat sähkön vuosittaisen tai kuukausittaisen kulutuksen yhdistämisen uusiutuvaan energiaan. Vihreän sähkön osuuden kasvaessa sähköntuotannossa, sähköntuotanto kuitenkin siirtyy aiempaa ajoittaisemmaksi ja vaihtelevammaksi. Kaikilla uusiutuvan energian teknologioilla on omanlaisensa tuotantoprofiilit sekä kausittaiset ja päivänsisäiset vaihtelut. Täten vihreän sähkön kulutus ei aina vastaa sen tuntikohtaista saatavuutta. Lisäksi nykyiset vihreät sertifikaattijärjestelmät eivät heijasta riittävästi uusiutuvan energian oikea-aikaista saatavuutta eivätkä näin ollen edistä investointeja, jotka voisivat tarjota järjestelmän joustavuutta ja vihreän energian ympärivuorokautista saatavuutta. Tämän ongelman ratkaisemiseksi on parhaillaan kehitteillä pilottiversioita vihreän sähkön sertifikaattijärjestelmästä, joka mahdollistaisi sähkön tuotannon ja kulutuksen tuntikohtaisen täsmäytyksen, sillä siirtyminen kohti vihreän energian 24/7-täsmäytystä herättää yhä enemmän kiinnostusta.

Ennen uusien instrumenttien ottamista mukaan markkinoille on kuitenkin välttämätöntä selvittää niiden mahdolliset markkinavaikutukset. Tässä tutkielmassa esittelemme tuntisertifikaattimarkkinoiden taloustieteellisen mallin ja vertaamme 24/7-täsmäytyksen volyymi- ja hintavaikutuksia vihreän sähkön sertifikaateilla perinteisiin sertifikaattimarkkinoihin, joissa sähkönkulutusta täsmäytetään uusiutuvan energian kanssa vuosittain. Analysoimme myös, kuinka kuluttajan hyöty tuntikohtaisista vihreistä sertifikaateista vaihtelee eri ajankohtien välillä, kun uusiutuvan energian saatavuus vaihtelee. Havaitsemme, että kuluttajien hyöty tuntikohtaisten sertifikaattien hankinnasta laskee uusiutuvan energian tuotannon kasvaessa. Näin ollen kuluttajan hyöty sertifikaateista on suurin silloin, kun myös korkeapäästöisen energian osuus on korkea. Tuntikohtaiset vihreät sertifikaatit voisivat siis tarjota eniten hyötyä sekä kuluttajille että tuottajille niinä tunteina, jolloin uusiutuvaa energiaa on tarjolla vähemmän.

Havaitsemme myös, että tuntikohtainen täsmäytys voisi joko lisätä tai vähentää kuluttajan uusiutuvan energian hankintakustannuksia ja tuottajan tuloja yksittäisten tuntien sisällä verrattuna vuosittaiseen tai kuukausittaiseen täsmäyttämiseen. Näin ollen tuntikohtainen sertifiointi voisi tarjota lisähyötyä teknologioille, joita tarvitaan täydelliseen järjestelmän laajuiseen hiilidioksidipäästöjen nollaamiseen, kuten energian varastointiratkaisuille. Näin ollen tuntikohtaisen sertifikaattijärjestelmän kehittämisessä tulisi keskittyä tämän vaikutuksen korostamiseen, mikä voisi edelleen kannustaa investointeja sähkömarkkinajärjestelmän joustavuuteen. Tarvitaan kuitenkin lisätutkimusta mahdollisten vaikutusten selvittämiseksi erityisesti sähkömarkkina-alueilla, joissa uusiutuvan energian osuus on jo korkea. Lisäksi täytyy vielä selvittää, onko tällaiselle järjestelmälle kysyntää yksityissektorilla ja johtaisiko tuntikohtainen täsmäytys yhteiskunnan kannalta optimaalisesti korkeampiin päästövähennyksiin kuin perinteiset sertifikaattijärjestelmät.

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24/7 täsmäytys, yritysten uusiutuvan energian hankinta, uusiutuvan energian sertifikaatit, tuntikohtainen täsmäytys

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List of Abbreviations

24/7	24/7 matching of energy consumption with renewable sources
100/100/0	100% of electricity consumption, 100% of the time, matched by zero-carbon energy purchases
ACER	The European Union Agency for the Cooperation of Energy Regulators
AIB	Association of Issuing Bodies
EAC	Energy Attribute Certificate
EECS	European Energy Certificate Scheme
ENTSO-E	European association for the cooperation of transmission system operators (TSOs) for electricity
GO	Guarantee of Origin
PPA	Power Purchase Agreement
REC	Renewable Energy Certificate
RES	Renewable Energy Sources
TSO	Transmission System Operator

1 Introduction

The bulk of all human-originated greenhouse gas emissions is generated by burning fossil fuels, leading to significant economic and social damage. (Stern, 2007; Nordhaus, 2019; IPCC, 2022) Therefore, most governments are cutting their emissions and announcing net-zero targets. Consequently, swiftly developing technologies, decreasing costs, and more favorable policies have led to a significant ramp-up of renewable energy. In addition, for the past decade, an emerging effort for corporate sustainability has created a growing demand for renewable energy procurement and transparent carbon emissions tracking. These large electricity users can significantly impact green energy investments and the evolution of the future's electricity grid.

Electricity demand is growing rapidly, and it is the fastest-growing final form of energy. (Helgesen & Tomasgard, 2018; AFRY, 2020) However, the challenge in increasing the share of renewables in the electricity systems operations is their variability in time and space. Thereby, it can be questioned whether they manage to supply electricity when needed. In addition, it is impossible to track energy flows within the grid, making improving more transparent green products challenging. (Hamburger, 2019) Many governments have implemented green energy certificate schemes to promote renewable energy, that allow tracking the source of used electricity and generally traded on an annual basis. However, their prices in Europe have been remarkably low since implementation, excluding the development in 2022, when their prices started to grow significantly. (Greenfact, 2023) Even though, the certificates can be argued to bring some transparency into the electricity market, their historically low prices have not necessarily created a significant regulatory impact that would have incentivized investments in renewable energy. For the past few years, there has been an emerging trend of bringing their trading in synch with electricity markets, driven mostly by corporates with high sustainability goals. As electricity is traded in the markets in an hourly or sub-hourly basis, also trading of certificates is suggested to shift to take place also in this significantly shorter time span.

Ambitious environmental targets require serious measures in many economic sectors, particularly in the energy markets. According to IEA (2022a), global CO2 emissions from energy combustion and industrial processes soared in 2021 to thus far the highest annual level with 36,3 gigatons (Gt). The power exchange between countries is constantly increasing as they become more interconnected. International trade can significantly impact a country's GHG emissions (Peters & Hertwich, 2008; Davis & Caldeira, 2010; Peters et al., 2011). Soimakallio and Saikku (2012) argue that "consumption-based CO2 emission intensity of electricity differed significantly from the production-based intensity for some European countries such as Switzerland, Norway, Slovakia, and Austria", from which especially Norway is a significant producer and exporter of renewable energy. These countries sell electricity to surrounding price areas in which consumers are willing to pay more than within the area the electricity was generated in. However, as electricity demand grows, it becomes ever more important that the electricity generation occurs close to consumption. Even if the capacity additions are on track with the growing load, electricity transmission is not, and the amount of transmission bottlenecks is growing. This means that the industry and governments must invest extensively in strengthening the transmission grid, in addition to local electricity generation and flexibility. The energy crisis that resulted from Russian invasion to Ukraine and EU's sanctions on Russia, has brought the risks of interdependent electricity supply into reality. Countries reliant on electricity imports are faced with a higher risk of power outages during peak-demand hours than countries with more available domestic generation capacity. However, green transition is not only on how to add more renewable energy capacity but also on timely supply of green energy. Therefore, flexibility and shifting consumption to times when renewable energy is abundant will hold a crucial position in system-wide decarbonization. Flexibility also benefits large consumers, such as corporations, to hedge their electricity costs in addition to facilitation of hourly matching of renewables.

1.1 The objective of the study

The purpose of this study is to provide an overview of the corporate renewable energy procurement trend and an economic model for hourly green certificate markets. This thesis compares the volume and price effects of 24/7 matching with hourly renewable energy certificates with general green certificate markets, where electricity consumption is matched on an annual basis. We also analyze how the consumer's utility from hourly green certificates varies between times with more available renewable energy generation and when green power is less abundant. More specifically, the thesis attempts to answer the following questions:

Research question 1: What is the impact of 24/7 matching with hourly renewable energy certificates on electricity and certificate prices?

Research question 2: How does the consumer's utility from purchasing hourly green certificates vary in relation with the share of green and emitting energy in the grid?

In Chapter 2 we go through the key methodologies and economic theories applied in this thesis and fundamental energy market mechanisms. Additionally, the background of voluntary and compliance markets for renewable energy is introduced and we go through the evolution of renewable energy procurement standards, including general renewable energy certification, Power Purchase Agreements (PPAs), and 24/7 matching in more detail and discuss the performance of the European Guarantees of Origin markets. In Chapter 2.3 maximation problems of a producer and a consumer in hourly certificate market are modelled. We also analyze how the consumer's decision on the share of renewable energy procurement and utility from purchasing hourly certificates change in a relation to the prices in electricity and certificate markets, and the grid share of green and emitting energy. Lastly, the hourly certificate market is compared with existing green certificate market, considering changes in short-term demand and its relation to both consumer's and producer's utility as well as the consumer's green energy procurement costs. In Chapter 4, the results from Chapter 3 are discussed and further research suggestions are proposed.

As mentioned earlier, 24/7 matching envelopes multiple dimensions, approaches, and strategies. However, in this thesis, only hourly energy certificates are considered in more detail and modelled in economic terms. The terminology used in this thesis follows Google's, Microsoft's, and EnergyTag's pioneering concepts. (Google, 2018; Microsoft, 2020; EnergyTag, 2021)

1.2 Corporate renewable energy procurement

As consumers are becoming more environmentally conscious, also businesses and corporations are augmenting their efforts to become "carbon neutral" or "100 percent renewable". It is still almost impossible to know if a company marketing to be "100% renewably powered" is matching its consumption on a 24/7 basis with carbon-free generation or whether just buying unbundled Energy Attribute Certificates (EACs) on a yearly basis, meaning that the electricity consumed in a year is matched with certificates with electricity generated from renewable sources within that same year. However, 24/7 or hourly matching is a consumer-focused approach to purchasing electricity generation that matches to the consumer's hourly electricity consumption. It is argued that 24/7 matching could encourage investments into technologies that could provide clean energy any hour of the day and thus further accelerate the green transition while providing consumers with improved transparency. The current market-based method allows consumers to purchase a corresponding number of EACs to cover their annual energy consumption, claiming zero carbon emissions from purchased electricity by using annual accounting. Additionally, these EACs might have been produced far away from the location where they are needed and “unbundled” from long-term electricity purchases. Thus, generation and consumption are de-linked in both space and time, whereas 24/7 matching includes also bringing electricity generation closer to demand and vice versa.

Since the first EAC schemes were introduced 20 years ago, there has been an immense expansion of renewable energy deployment worldwide. They are currently the most used form of renewable energy procurement. (IEA, 2022b) However, the growth of renewables shares in the grid entails issues in grid integration, such as the need for curtailment in times of oversupply. An increased share of renewables might also create price cannibalization, which refers to electricity price crashes that stem from an oversupply of renewables, which decreases revenues available for new renewable energy projects generating electricity during the same hour. (EnergyTag, 2021) Thus, we need to also determine, how to absorb more when renewable energy is abundant. Fortunately, technologies such as energy storage, smart grids, and other demand response mechanisms are available to serve this purpose. Due to the flexibility which they bring into the power system, they are also an integral part of matching demand with 24/7 renewable energy.

The rapid increase of corporate renewable energy procurement has driven the movement towards 100% matching of renewable energy in each electricity market settlement period, meaning that the net consumption of the corporate equals the amount of renewable energy sourced on an hourly or sub-hourly basis. The main challenge in 24/7 matching is the variability and intermittency of renewable energy sources (RES), which all have different and unique resource profiles and seasonal and intra-day fluctuations. Thus, supply from green energy is unlikely to align with the actual timing of consumption. When the weather conditions are not optimal with low wind speeds, water reservoir levels, and solar output, consumers still need to rely on carbon-emitting power plants to meet their short-term demand. This mismatch between variable generation and variable demand limits the ability to reduce CO_2 emissions associated with a buyer's electricity consumption. Moreover, it fails to drive the deployment of other advanced clean energy technologies.

Nevertheless, there is increasing interest in procuring 100% of electricity consumed 100% of the time with zero emissions (100-100-0). Large corporations such as Google and Microsoft have set targets for 24/7 carbon-free electricity and 100/100/0. (Google, 2018; Microsoft, 2020) In addition, President Joe Biden issued an Executive Order in 2021, which declared that the US government, the world's largest buyer of electricity, will require 100 percent carbon-free electricity on a net annual basis, from which at least half would be sourced from local carbon-free energy on an hourly basis by 2030. (Executive Order No. 14507, 2021) The movement is also recognized by global organizations. For instance, Sustainable Energy for All and UN-Energy launched the 24/7 Carbon-free Energy Compact in September 2021, which has already been signed by more than 100 companies, organizations, and governments. (24/7 Carbon-Free Energy Compact, n.d.) Thus, it is evident that the sector's focus is turning to more granular carbon accounting and around-the-clock sourcing of green energy.

Initially, in the beginning of voluntary corporate renewable energy procurement, few market actors tried to harvest unique solutions to prove that their electricity supply is from carbon-free sources. Next, an increasing number of countries started to introduce regulations on reporting with differing certificates. These certificates were meant to provide traceability for each unit of electricity produced. (Hamburger, 2019) A few years later, the European Commission declared in article 3 of the Electricity Directive (2003/54/EG) that electricity suppliers must disclose their electricity portfolio with the source information and environmental impact. This information comprises so-called energy attributes, and they are currently working as a prerequisite for many EU policies. (Raadal et al., 2009)

From the beforementioned, Power Purchasing Agreements (PPAs) and Energy Attribute Certificates (EACs) form a standardized practice for zero carbon footprint claims and a mechanism for additional renewable energy investments. (Corradi et al., 2021) However, these claims can lead to overlapping certificates and, thus, double counting. Double counting occurs when multiple parties claim the same environmental benefit from the same unit of carbon-free energy. Consequently, the market is distorted due to falsely depicting more carbon-free energy claims, resulting in credibility issues and accusations of greenwashing. In 2013 the Finnish Government amended the law on the certification and disclosure of the origin of electricity by stating that Guarantees of Origin (GOs) would be regulated as the only method to certify that electricity is produced from renewable energy. Before the law amendment, several tracking systems were in force to verify the origin of electricity in Finland. Consequently, it was possible to double-count the renewable energy by selling GOs and utilizing the same renewable energy for marketing. Currently, it is possible to market electricity as renewable only if it is also granted a Guarantee of Origin. (Finlex, 2013)

2 Theoretical Background

In this chapter we will introduce equilibrium theory, which is the key economic theory applied in this thesis. Additionally, we will further examine the fundamental energy market mechanisms, such as electricity price formation in the markets. Since this thesis studies on renewable energy procurement particularly focusing on renewable energy certificates and hourly matching of renewables, we will also go through the development of renewable energy procurement. The latest trend in corporate renewable energy procurement is "24/7 matching" or "hourly matching" which includes multiple elements with a one being hourly green certificates. In this thesis, we focus on hourly green energy certificates and examine their possible market effects. After introducing the theoretical background in this chapter, we create an economic model for these hourly green certificates based on the equilibrium theory introduced in Chapter 3.

2.1 Equilibrium theory

The model used in this analysis is based on the market equilibrium theory by Alfred Marshallian (1842−1924) (Mas-Colell et al., 1995). The relation and balance of supply and demand are fundamental to all market mechanisms, represented by supply and demand curves. A supply curve illustrates the number of goods Q that a producer is willing to sell at a price P. The producer is generally willing to produce and sell more if the price of each sold good is high. A higher price might also eventually attract new producers to the market. The supply curve can be graphically illustrated in Figure 1(a), where we can see that the producer is willing to sell some number of produced goods in Q_1 with a price P_1. Moving along the supply curve illustrates a quantity change in response to a change in price. The supply curve can also move to the left or right if the production costs change. The aggregate supply curve has a similar effect as the total quantity of goods changes. Mathematically supply curve is a function of price, and it can be formulated as $Q_S(P)$.

The demand curve demonstrates how many products the consumers are willing to purchase at a specific price. Thus, the demand curve entails the relationship between the price and the demand quantity. In the case of only one consumer, the demand curve of that consumer represents the whole market demand. However, if there is more than one consumer, market demand consists of all consumers' demand curves that are combined, forming one aggregated demand curve. Market demand is mathematically formulated as a function of price $Q_D(P)$.

The demand curve can be illustrated graphically as in Figure 1(b). In this market setting, the consumer is willing to buy Q_1 amount of goods at a price P_1. Moving along the curve represents the shift in demanded quantity in response to price changes. For instance, the consumer is willing to purchase less as the price increases. On the other hand, lower prices encourage the consumer to increase consumption.

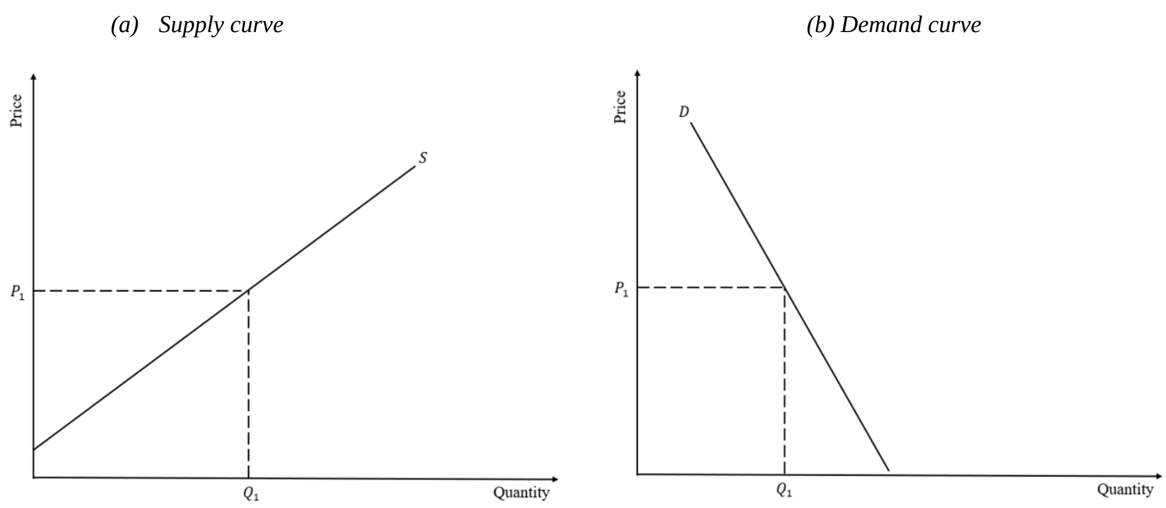

Figure 1: Supply and demand curves

In a free market, an equilibrium price P^*exists, which brings supply and demand into market equilibrium and solves $D(P^*) = S(P^*)$. Consequently, the intersection of the supply and demand curves determines the equilibrium price. All the produced units of a good will be exchanged in the market at this price. Thus, the price can also be referred to as the market-clearing price and the equilibrium market-clearing equilibrium, where all agents choose the best possible action for themselves, and each market participant's behavior is consistent with that of the other participants. The market equilibrium of demand and supply is illustrated in Figure 2.

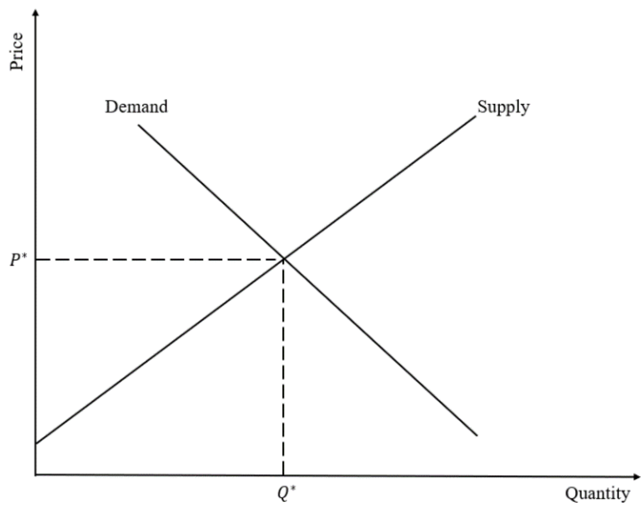

Figure 2: Market equilibrium

After finding the market equilibrium, we can analyze the effects of demand and supply changes in the market equilibrium and two different economic outcomes before and after a change in a given exogenous parameter. For instance, the supply curve shifts if the cost of production changes. Respectively, the demand curve can shift due to various reasons, including change in taste or preferences, changes in income, or price change of a related good.

In electricity markets, demand and supply vary every hour of day, depending on many factors, such as temperature and season. It can be also referred to as 'load', and it is the sum of all demands in each electricity market. In the current market operations, the demand curve is almost perfectly inelastic, and the demand curve can be illustrated as nearly vertical. Due to the constantly shifting electricity demand curve, the equilibrium price P^* also changes. In the analysis of this thesis in Chapter 3, we particularly focus on changes in consumer preferences in the hourly certificate market in each time period.

In a competitive electricity market, each energy supplier submits its own supply curve to its system operator, which entails how much of its electricity output it wants to sell at each price. The operator collects these so-called "bids" from each supplier day-ahead and arranges them into ascending price order, forming an aggregated supply curve. The cost basis of these bids is discussed in more detail in Section 2.2.3. Then, the system operator matches the demand in very settlement period with electricity generators in the aggregated supply curve that meet the load with the lowest cost.

2.2 Fundamental energy market mechanisms

2.2.1 Overview of the power markets

The structure and organization of the power market differ significantly globally and have changed over time. Generally, the power market value chain comprises electric energy generation, transmission, distribution, and consumption. These steps can be governed by individual companies, without or under competition, or by administrative agencies. Toward the end of the 21st century, many industries, such as electricity sector and forest industry started to liberalize around the world. Electricity utilities were reorganized from vertically integrated regulated monopolies to more liberalized and competitive markets. The generation part of the value chain was typically the first to be liberalized to stimulate investments and encourage competition. This was usually followed by "unbundling" the generation from the rest of the vertically integrated utility to ensure that transmission operators would not disfavor power plants separated from the utility. In the new structure of liberalized generation, transmission and distribution operators are still positioned as natural monopolies. This results from economies of scale, which means it is more profitable for one utility to set up the grid than to establish parallel grids. Along with generation, the supply of electricity is typically liberalized. The role of supply companies is then to procure electricity from the wholesale market, and manage metering, contracting, billing, and collecting payment from the end-users.

The goal of the power system is to generate and transfer electricity across long distances with minimized environmental impact and losses and maximized efficiency and reliability. Power system planners are responsible for balancing the load, also referred to as *demand*, and serving the grid's reliability. The power market is unique because the producer has only minor control over the demand due to a minimal share of storage possibilities. Therefore, electricity must be delivered whenever consumers demand it, meaning that the installed generation capacity must equal at least the peak demand. (Lin & Magnago, 2017) As the demand grows, it is increasingly challenging to meet the load peaks, especially with a growing share of renewables in the system. Moreover, the consumers' demand fluctuates throughout the day, within a week, and from season to season. Therefore, the power system operators must also forecast and anticipate possible demand peaks, such as unusually cold or hot days.

Electricity demand at different points of time and space creates variability in the produced emissions depending on, e.g., the prevalent season and energy supply portfolio of a specific node. (Holttinen and Tuhkanen, 2004; Hawkes, 2010; Amoret al., 2014; Olkkonen & Syri, 2016) In other words, the carbon intensity of the physical electricity grid varies over time and space. Electricity markets are highly interconnected between different nodes, providing a balance between demand and supply. Thus, a change of demand or supply in one node can affect the external market and marginal cost of electricity. Hence, tracking the initial source of electricity consumed in a particular location and time becomes even more challenging. Moreover, because electricity markets have been designed to match demand and supply, they also let the price form within the markets to reflect the current need for electricity while ensuring a stable power grid. However, as renewable energy support schemes started to emerge, policymakers needed to know the origin of electricity in the grid to allocate support to specific suppliers. (EnergyTag, 2021)

Electricity markets are becoming increasingly interconnected, generating further market couplings between countries, which creates a higher risk for emission leakage. (Olkkonen & Syri, 2016) The transfer of electricity between countries plays a crucial role in balancing load fluctuations and economic efficiency (IEA, 2010). However, trade between distant regions is limited due to losses in the transmission of electricity. The Finnish electricity market is a part of the multinational Nordic Pool Spot market, designed by an hourly auction. The Nordic electricity market has faced a total reconstruction since the 1990s, moving from vertically integrated monopolies to a free market structure, where consumers can choose freely between retailers and various supply offers. Together with other Nordic countries, Finland has been active in deregulating and liberalizing the electricity markets. (Bye & Hope, 2005; Hansson et al., 2020) In Finland, the market gradually started to open in 1995, and since 1998 all the consumers have been free to choose their suppliers. (Ministry of Economic Affairs and Employment in Finland, n.d.) However, national transmission and communal distribution networks still hold a position as natural monopolies. (Junttila et al., 2018)

In the wholesale power markets, most generated electricity is traded in the day-ahead market on the hourly timescale based on the predicted load for each hour of the next day. The system operators handle any deviations from the predictions for the intra-hour demand with 15 and 5-minute real-time markets. (Miller, 2020) In Nordpool, electricity is traded in a day-ahead spot market. The price is based on the bids by summarizing all purchases into a purchase curve. The same is done for sales. Then, the price is determined for each hour of the day with the sales and purchases of individual market participants. Without grid restrictions, the spot price would be the same within the Nordic region. (Energy Authority, 2020) Fingrid, the Transmission System Operator (TSO) in Finland, manages the real-time balancing of the markets. Other electricity market participants match supply and demand in each balance settlement period. Currently, the settlement period in Finland is one hour, but due electricity market transformation, the Finnish markets will move with other European countries to a 15-minute settlement period in 2023. (European Commission, 2017)

2.2.2 Levelized cost of electricity

The levelized cost of electricity (LCOE) is used to measure and compare the lifetime costs of generating electricity between technologies. It is the annual revenue per unit of generated electricity that is needed to recover the costs of constructing and operating a plant within its assumed financial lifetime. LCOE consists of capital costs (CAPEX), operation and maintenance costs (OPEX), and disposition costs. It is defined as the aggregated discounted lifetime cost of generating electricity per unit of output, and it is usually expressed as €/MWh. Capital costs generally include for example the cost of equipment, land, financing, project management, grid connection, and construction of the power plant. They can be also referred to as fixed costs since they include the cost of fixed assets. Operation and maintenance costs form the variable costs of electricity together with fuel costs. LCOE can be defined mathematically as follows:

$$LCOE = \frac{\sum of\ the\ costs\ over\ the\ lifetime}{\sum\ of\ electricity\ produced\ over\ lifetime}\frac{\sum_{t=1}^{n}\frac{I_t + M_t + F_t}{(1+r)^t}}{\frac{E_t}{(1+r)^t}}$$

Where I_t is investment expenditures, M_t operation and maintenance costs, F_t fuel costs, E_t amount of generated electricity, r the discount rate, and n the expected financial lifetime of the plant.

2.2.3 Marginal cost pricing of electricity

Marginal cost measures a change in total costs from producing one additional unit of output. Marginal costs are positive when the level of production is increasing and negative when the producer cuts its output. The producer chooses a level of input that maximizes its profits and minimizes costs. The costs vary depending on the output and input levels and change over time. In the short run, capital costs are fixed but producing electricity also has variable costs. Marginal costs can also be referred to as incremental costs.

Because the European power markets have been deregulated, Europe can be considered a single energy market. (Bye & Sentralbyrå, 2014) That is, without transmission capacity constraints. In this market, electricity generators have increasing marginal production costs due to a need for additional capacity. In the short run, it is impossible to influence the volume of generation capacity in the market. Thus, fixed costs or capital costs do not affect the production decision of the suppliers. Fixed costs are usually expressed per unit of installed capacity (per kW or per MW). The producer makes the generation decision solely based on the variable costs. The variable costs of the marginal plant in the merit-order curve also define the market price. While renewable technologies and nuclear power generally have low variable costs, they are ready to operate with lower prices. In the short run, the marginal cost of production must equal the variable cost of one unit of electricity. Then, power plants can be ordered "by merit", i.e., by increasing variable cost to illustrate a short-term supply curve, called the merit-order dispatch curve (Figure 3).

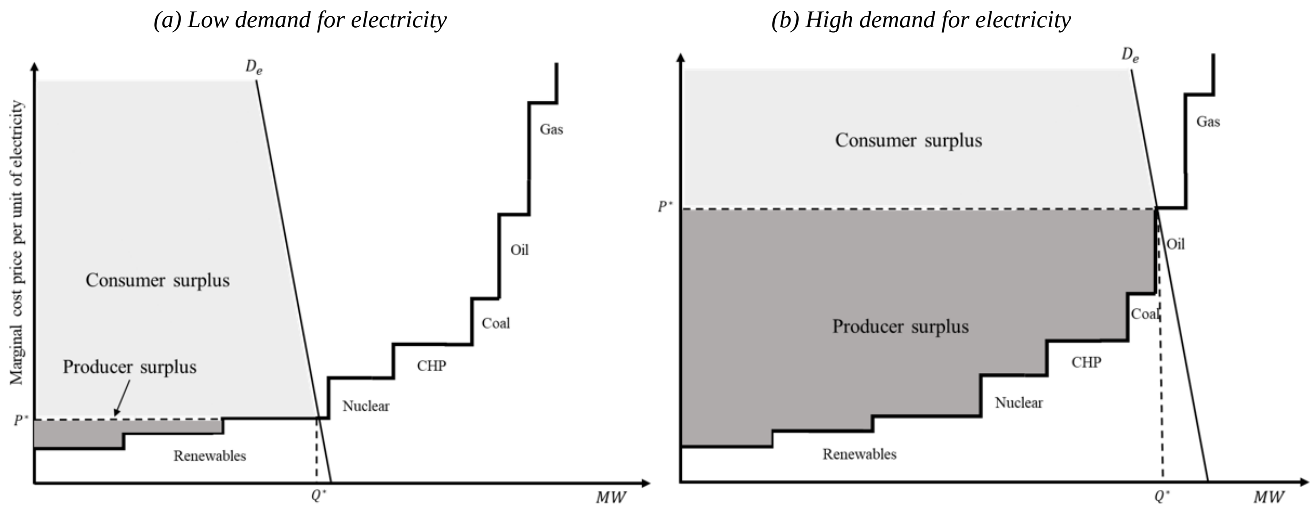

Figure 3: Merit-order curve for a) low demand of electricity and b) high demand for electricity

As illustrated in Figure 3, the producers' and consumers' surplus vary in relation to demand and position in the merit-order curve. The aggregated producer surplus increases as moved higher in the merit-order curve as all the producers willing to sell at market-clearing price P^* receive the same price from a unit of electricity. However, not all producers benefit alike. The producers with lowest variable costs benefit the most whereas the producers submitting the last accepted bid benefit the least. The market-clearing price P^* is a uniform price as also all consumers pay the same price in each settlement period. The aggregated consumer surplus is the highest when the demand can be met with generation plants with low variable costs. Consequently, also the market-clearing price stays low.

The aggregated consumer surplus decreases when moving to the right in the merit-order curve, leading to increasingly higher electricity prices.

2.2.4 Voluntary and compliance markets for renewable energy

Two separate markets can be distinguished for renewable energy, voluntary and compliance. In voluntary markets, consumers purchase green electricity to match their electricity demand on a voluntary basis. In the case of renewable energy certificates, this happens through unbundled EACs markets, where the certificates are unbundled from electricity, like in the European GO market. In an unbundled system, the consumer purchasing a certificate does not need to have access to a renewable energy product through their retailer. Thus, the certificates and electricity are traded separately, as illustrated in Figure 5. Correspondingly, EACs traded in compliance markets can be used to meet state renewable portfolio standards (RPS), where electricity retailers must procure a share of their electricity from green energy sources. An example of such a system is the North American Renewable Energy Certificate system for RECS.

Energy Attribute Certificates (EACs) are an example of a market-based instrument, which differs from pure subsidy-based schemes by being a quantity-based system. Market forces define the EAC market as they are left to determine the certificate price. The price is generally determined beforehand by the regulator, energy supplier, or grid operator in subsidy-based systems, such as feed-in tariffs. (Hustveit et al., 2017) Aune et al. (2008) define the EAC market as a subsidy for the generation of green energy and as a tax on energy consumption under the restriction of budget neutrality. Under the scheme, renewable energy producers receive additional revenue from a unit of electricity produced, while consumers are taxed through added certificate cost in their electricity bill. (Hustveit et al., 2017)

There are various subsidy schemes for renewable energy within each European country, whereas the market for renewable electricity certificates is a standard policy measure in most European countries. These certificates are referred to as Guarantees of Origin (GOs). According to the rules of AIB (Association of Issuing Bodies), electricity producers are obliged to disclose information about the energy source and the emission data of every produced unit of electricity. AIB is responsible of promoting and developing the use of the standardized European Energy Certificate System (EECS) to ensure its reliable operation. AIB also facilitates the international exchange of the certificates through its hub.

Currently, two different systems are in place for tracking the energy source of generated units: tracking and quota systems, of which Guarantees of Origin represent the first. There are a few different renewable certificate schemes around the world, such as Guarantees of Origin in the EU, El-certificates in Norway and Sweden, some national systems, for example in the United Kingdom and New Zealand, and i-RECs (International Renewable Energy Certificates), which are international and currently in force in Asia, the Middle East, Latin America, and some African countries (Figure 4).

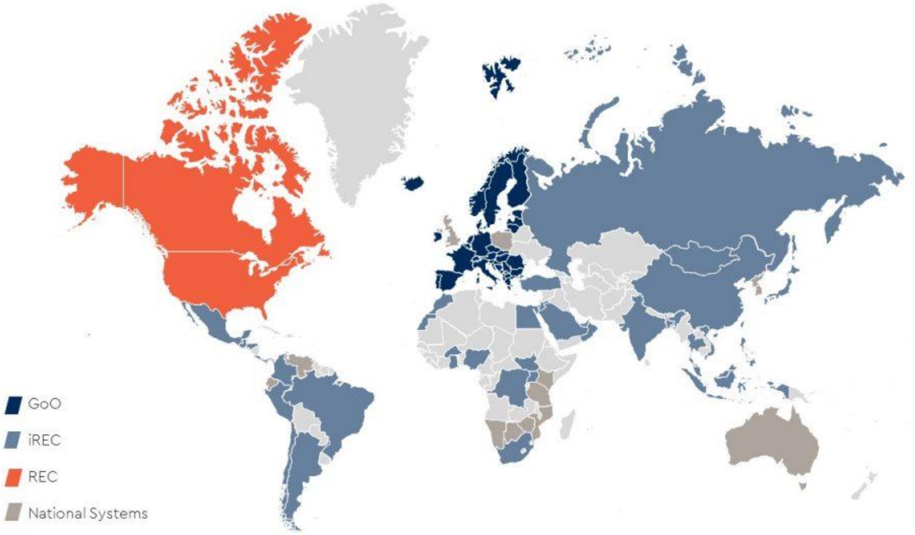

Figure 4: Renewable energy certificate schemes (STX Group, n.d.)

The effectiveness of the European Guarantees of Origin scheme has been discussed widely in the literature, for example by Hast et al. (2015), Mulder and Zomer (2016), Jansen (2017), and Hamburger (2019), but any actual system impacts of it are hardly measurable. However, it has become evident that the current Guarantees of Origin scheme does not contribute sufficiently to renewable energy procurement or timely and location-specific procurement of renewable energy. Consequently, in the ENTSO-E (European Network of Transmission System Operators for Electricity) Mission Statement (2022), it is declared that temporal matching of certificates is a necessity for the evolution of the European certification scheme as the current system "*does not demonstrate the green consumption of a GO buyer, because of the 18-month GO's validity period"* – – and "*sends wrong price signals to both GO buyers and RES developers as the GO price does not fluctuate as a function of the effective volume of RES energy produced at a specific moment in time*." In addition, hourly certificates could provide more accurate price signals as they catch the real-time generation mix and thus, they have great potential to accelerate investments into technologies that could provide around-the-clock renewable energy, such as different storage solutions.

Currently, the timely availability of renewable energy is not reflected in the GO system. Consequently, the potential of green energy certification scheme remains somewhat unharnessed as it does not provide sufficient incentive for system flexibility providers. As renewable energy is capacity is increasing, the challenge becomes whether we can provide carbon-free energy also when the weather conditions are not optimal. Thereby, storage solutions are needed to maintain system reliability. If the trading of green certificates would be brought to hourly basis, it could potentially provide new investment incentives for energy storages as they could sell stored carbon-free energy also within hours without any actual power generation from renewable sources.

The main goal of hourly certificates is to bring the process of contracting carbon-free electricity closer to the physical reality and timely availability. The current EAC systems do not need to specify the time or location of production. In addition, from a consumer perspective, hourly certificates would enable tracking of carbon footprints more accurately, which would further help plan actions to meet decarbonization goals.

Figure 5 portrays the electricity and renewable energy certificate markets in a simple manner. Essentially, renewable electricity producers can issue for each unit of electricity they produce, a green certificate, which specifies the technology by which the unit of electricity has been produced with. By selling these certificates through a registry, the producers receive additional revenue on top of electricity price. After the certificate takes a form or an electronic record, it can be transferred from consumer to another until it is used or “cancelled”, or expired after one year from the issuance.

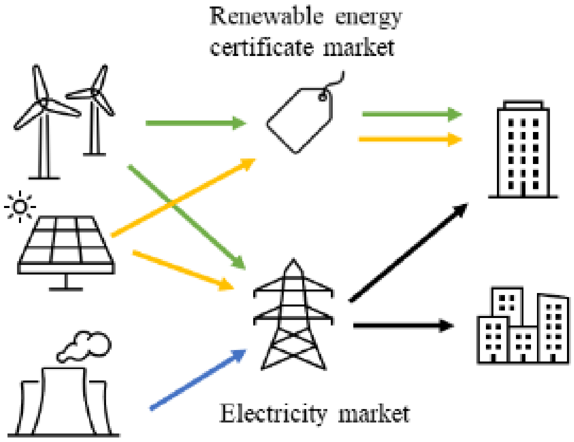

Figure 5: Trading in electricity and renewable energy certificate market

Even though electricity is a homogenous product, retailers can sell it in voluntary markets labeled to end-customers, for example, as *wind* or *green energy*. As most electricity markets are liberalized, the customers can freely choose the retailer and preferred contract type. Thus, customers can choose between traditional and green contracts in some markets. (Mulder & Zomer, 2016) Thus, a retailer that offers these contracts must have bought a corresponding number of these certificates that matches the consumption of its green customers' aggregated consumption. Certificates are canceled at the exact moment as electricity labeled *green* is sold to customers. This labeling system is thus referred to as a tracking system. (Lise et al., 2007; Mulder & Zoomer, 2016)

Markard & Truffer (2006) argue that green electricity markets are more compatible with liberalized electricity markets than national support schemes. In the liberalized Finnish markets, there are no regulations for the share of renewables in the electricity generation mix. This differs from many other European countries where the required generation share from RES can be sold to green energy customers, creating an issue of double counting, meaning that two different parties claim the environmental benefits from the same renewable energy unit. (Hast et al., 2015)

Most corporate renewable energy procurement is guided by Greenhouse Gas Protocol, which allows consumers purchasing renewable energy certificates to count them as zero-emissions attributes for the electricity consumed within the same year. This enables consumers, for example, corporates, to claim zero market-based scope two emissions if the number of canceled EACs equals the electricity demand from the reporting year. However, it is optional to disclose carbon emissions and avoided emissions information in the current GO scheme in Europe. Thus, they are usually only recorded for high-efficiency co-generation (EnergyTag, 2021). Avoided emissions are generally calculated from marginal emissions factors, which demonstrate the emission intensities of the marginal generators, which would be needed to meet demand at a given time. They are also the plants first affected by market interventions. The carbon impact of renewable energy procurement can be calculated by accounting the avoided emissions associated with purchased green energy that occur on an hourly basis, thus given the marginal impact of procurement. (CSR, 2020) Currently, the information on time and locational granularity for indirect emissions are not generally available for either systems, voluntary or compliance. However, in 2021 regional transmission organization PJM in the United States began to post a five-minute marginal emissions rate at the nodal level. (Hartman, 2022)

2.3 The evolution of renewable energy procurement standards

The motivations and sophistication of renewable energy procurement have evolved since the first EAC schemes. Within the last decade, pursuing 100% carbon-free energy goals on an annual basis has become a benchmark in sustainability management. However, especially large consumers have started gradually to take steps closer to “24/7 matching” or “100/100/0 renewable energy”. To backtrack this development, a few distinct stages can be observed that eventually led to the hourly matching of renewables, as illustrated in Figure 6.

At the beginning of the millennia, corporations started to get interested in more sustainable business practices, including decreasing the emission intensity of their electricity consumption (Figure 6). However, renewable technologies were not yet cost-competitive at the time, and many present-day practices, such as PPAs, were utilized only on a small scale. Thus, unbundled EACs, mostly from wind power, functioned as the primary mechanism for corporate renewable energy procurement. Since renewables became the lowest-cost technology in the merit order, another primary motivation for corporate renewable energy procurement has been to guarantee long-term profitability and cost savings through renewable energy. (IRENA, 2018) As the levelized cost of solar and wind power dropped while eliminating the “green” cost premium, it became increasingly popular to sign fixed-price PPAs, which enabled corporations to hedge their volatile electricity costs. (Miller, 2020) Later, the costs of renewable energy dropped due to technological development, reducing the overall cost of green power procurement, regardless the method.

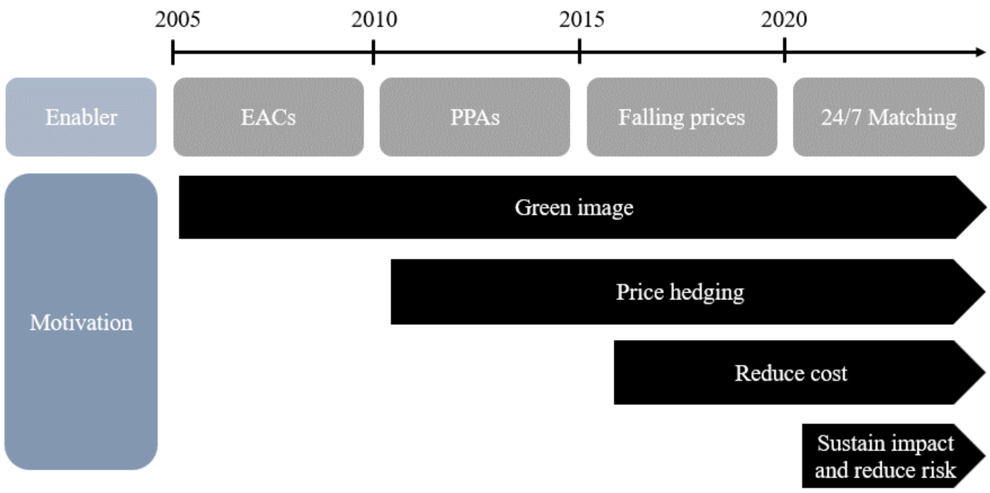

Figure 6: Development of renewable energy procurement over time. Adapted from Miller (2020).

In electricity markets, there are retail and project-specific options for green power supply. Retail options are generally more standardized options with a short-term commitment. In contrast, project-specific options demand longer commitment and are customized through negotiations between the customer and the supplier. Retail options include, for instance, unbundled renewable energy certificates, competitive green power products, and community choice aggregations. Whereas project-specific includes corporate PPAs, utility green tariffs, and self-supply. (Kent, 2022) The green electricity products in Finland are mainly from either wind or hydropower contracts, coming within Finland or other Nordic countries, where the possibilities for capacity increments are finite. (Hast et al., 2015)

Due to liberalized electricity market structure, consumers can choose to purchase power generated by a specific technology or close-by plants, which could provide additional assurance to the producer's decision-making and investment plans. In addition, there is a growing demand for more local and carbon-free energy, which can be seen as a growing number of 100-100-0 energy products. For instance, Vattenfall and Microsoft provide a service that enables customers to choose their own hourly consumption mix. Furthermore, it lets customers see their real-time consumption mix through smart meters. (Vattenfall, n.d.)

Meanwhile, neighboring electricity price areas are becoming more interconnected, and energy is being exchanged across long distances. Nevertheless, the magnitude of possible benefits of hourly matching still needs to be determined. Research is still needed, especially on whether it would be socially optimal to practice 24/7 matching on a national level.

2.3.1 Guarantees of origin

The first RES tracking certificate was introduced in the Netherlands in 1998, followed by the first EU directive 2001/77/EC, after it became evident that there was increasing consumer demand for renewable electricity. (Bertoldi & Huld, 2006; European Commission, 2000) The European governments decided to establish a Guarantees of Origin energy tracking system to address market information asymmetry. Ultimately, the information asymmetry stems from the impossibility for the end-customer to distinguish between energy from carbon-free and emitting sources. (Hulshof et al., 2019)

Although the system was not implemented on a mandatory basis, the practice became so widespread that the Association of Issuing Bodies (AIB) was established. Since then, AIB has aimed to harmonize the national and international markets of Guarantees of Origin. For this purpose, European Energy Certificate Scheme (EECS) was introduced, providing the methodology, regulations, and a standard for GOs. (AIB, 2018) The European GO scheme is the most extensive standardized renewable electricity certificate system and legally enforceable market for them (EnergyTag, 2021)

Renewable Energy Directive 2009/28/EC states that GOs are: "an electronic document which has the sole function of providing proof to a final customer that a given share or quantity of energy was produced from renewable sources." Thus, they are a tool for proving the source of a specific generated unit of electricity. (Raadal et al., 2011) They are created in the moment of production of one unit of electricity (MWh), issued in an electronic registry, and later canceled at the time of usage by end-users. (Hamburger, 2019) The GOs must be canceled within a year of their production time, which leads to some GOs expiring. Figure 7 demonstrates the issuance, cancellation, and expirations in 2019−2021.

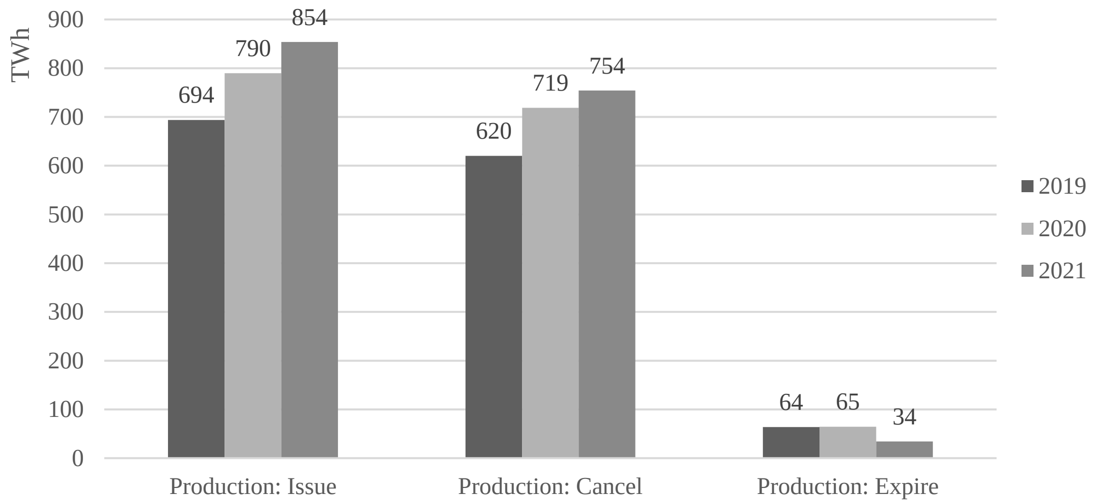

Figure 7: Annual transactions of Guarantees of Origin in Europe in TWh. (AIB, 2022)

The GO system represents a book and claim system, enabling the end-user to claim the source of the produced unit of electricity. Thus, not only individual consumers and households but also corporate consumers started to gain interest in GOs as they can use them for carbon-accounting purposes and sustainability claims. (Csutora & Harangozó, 2017; Hamburger, 2019) The disclosure of information is an essential aspect of GOs since one can avoid double-counting with it. When the origin of the electricity quantity is tracked, the same amount of electricity must be subtracted from the statistical electricity generation mix; otherwise, the share will be counted twice. The share left on the grid without GOs is called the *residual mix*. (Hamburger, 2019)

Those production devices that can issue GOs for electricity from renewable sources vary between countries, wind, hydropower, tidal, wave, solar, biomass, landfill gas, biogas, geothermal, and sewage treatment plant gases. (Mulder & Zomer, 2016) After issuance, the electricity unit can be labeled as "green" in the retail markets. However, if the GO is not used within 12 months, it is removed from the AIB registry, and the corresponding unit of electricity is fed into the grid. Thus, the "greenness" of the unit cannot be sold anymore. (Wimmers & Madlener, 2020) The GO system differs from the system in place in the US as carbon emissions and avoided emissions are only tracked for some high-efficiency co-generation, whereas the US REC scheme includes all environmental attributes associated with renewable energy generation. Additionally, GOs must provide information on the production site location and production's start and end dates. (Raadal et al., 2011) Through GOs and Electricity Disclosure processes, the electricity suppliers also receive additional monetary benefits by selling the certificates. (Raadal et al., 2011)

The most fundamental element of GO price formation is the law of supply and demand. (Jansen, 2017) However, as discussed above, the GO market has historically experienced oversupply. (AIB, 2020) The overall demand for green electricity in the European markets has been lower than the supply, leading to some certificates expiring each year. Therefore, the oversupply of certificates has resulted in low or even zero prices (AIB, 2019). Moreover, current schemes for traditional EACs have been criticized for making physically impossible energy flows theoretically possible. In extreme cases, EACs produced on an island have been virtually transferred to consumers without physical interconnection. (EnergyTag, 2022a)

The effectiveness and regulatory failures have been discussed in the literature, for example, by Hast et al. (2015), Mulder and Zomer (2016), Jansen (2017), and Hamburger (2019). Generally, GOs mainly function as a marketing instrument rather than an incentive for capacity expansion or increased electricity generation from renewables (Mulder & Zomer, 2016; Nordenstam et al., 2016; Jansen, 2017; Brander et al., 2018). These failures have been argued to increase double counting and undermine the reliability of the disclosure system.

For instance, according to Hast et al. (2015), GOs do not induce additional renewable energy investments due to their oversupply from existing plants, leading to lower-than-optimal certificate prices, subsequently decreasing the additional income of the supplier. Moreover, Mulder and Zomer (2016) came to similar conclusions in their study of Dutch markets, where the oversupply of GOs from Norwegian hydropower plants had a weak impact on RES development. Likewise, Dagoumas and Koltsakis (2017) analysis of Greek markets supported these arguments by confirming that GO prices were not high enough to provide positive investment signals. Furthermore, Jensen & Skytte (2002) argue that overall, the voluntary renewable energy certificate system is hard to manage if the government has parallel energy targets, which further underlines the need to harmonize all different emission accounting systems.

However, the discussion has focused solely on the voluntary market for contractual emission factors, such as Guarantees of Origin, rather than distinct compliance markets. Correspondingly, (Carley et al., 2017) state that renewable portfolio standards (RPS) – part of compliance markets have succeeded in creating additional renewable electricity generation worldwide. Their study suggests that countries with implemented RPS generated 4,1 TWh worth of additional annual renewable energy on average than countries without a similar scheme.

Nevertheless, voluntary carbon accounting can provide additional benefits besides electricity disclosure. For example, as GOs can be used in greenhouse gas protocols, they also help to improve greenhouse gas inventories. Moreover, they also enable carbon accounting of companies as well as households. (Jansen, 2017; Nordenstam et al., 2018b; H. Raadal et al., 2011; Wimmers & Madlener, 2020) Furthermore, Wimmers & Madlener (2020) argue that as demand for renewable energy certificates grows over time, the prices will likely increase. Consequently, as the producers receive higher revenue from producing renewable energy, certificate system such as Guarantees of Origin could contribute to the EU-wide transition to a carbon-free economy. And indeed, according to Greenfact (2023) statistics, the price of GOs finally started to surge in the second half of 2022, largely driven by the energy crisis that augmented the interest towards renewable energy in an unprecedented way.

2.3.2 Power Purchase Agreements (PPA)

A corporate power purchase agreement is a long-term contract under which a corporate consumer agrees to purchase carbon-free electricity straight from the producer, usually at a fixed price. PPAs are a national tool for large investors to procure renewable energy. They provide relatively good financial security for utility companies, which delivers better incentives for renewable energy investments. PPAs guarantee a specific revenue stream for the developer, helping to make the investment decision. PPAs have been standard practice in most European countries for over a decade. (DLA Piper, 2019) However, they arrived in Finland a few years later. Currently, all signed PPAs in Finland are wind power contracts. (RE-Source, n.d.) According to BloombergNEF (2022), corporations procured renewable energy through PPA contracts in a total of 31,1 GW in 2021, of which 65% occurred in the U.S. The total procurement share increased by 24% from the previous year with 25.1 GW.

However, ACER's (2022) report stresses the importance of making the PPA markets accessible for smaller actors, which would induce more investments and stimulate the market. ACER (2022) further suggests incorporating systems like supporting guarantees, where a government would facilitate the procurement. Such systems are already in place in Spain and Norway by The Spanish Export Credit Insurance Company (CESCE) and The Norwegian Export Credit Guarantee Agency (GIEK). They hedge the electricity producer's risk against the buyer's failure to honor the agreement.

Corporate PPAs are commonly assigned for 20−25 years. Consequently, Miller (2020) argues that corporate PPAs signed today might eventually become a liability as the grid evolves. Moreover, shape or covariance risk is aggravated when the amount of produced electricity and consumption needs do not match. (Lacey, 2019*)* Especially when a strong penetration from a single renewable energy source is observed at the markets – primarily solar – the wholesale market prices can drop or even reach negative prices during peak hours. Additionally, if only insufficient demand response technologies are available to store the surplus electricity, the production device operators might have to curtail their production. For instance, they might have to reduce the number of certificates produced to deliver PPA agreements. (Miller, 2020)

2.3.3 24/7 matching and hourly green certificates

The rapid increase of corporate renewable energy procurement has driven the movement towards 100% matching of carbon-free energy on 24/7 basis, meaning that the consumption must equal the amount of renewable energy sourced within the same settlement period, usually an hour or sub-hour. Thus, the corporate must match its electricity consumption within each hour with carbon-free generation produced within the same hour. In contrast, voluntary renewable energy procurement has generally involved matching the total consumption with the total purchased renewable electricity on an annual or monthly basis. 24/7 matching requires considering many factors that affect the consumers' demand and electricity supply. In this thesis we focus mostly only renewable energy procurement with green certificates. However, 24/7 matching also includes the following five key elements (Miller, 2020):

1. Energy demand analysis
2. Renewables portfolio diversification
3. Load shaping and shifting
4. Investing in local energy storage to balance the difference
5. Prioritizing action in regions with the most-carbon intensive grid mix

However, in this thesis we focus on sourcing renewable energy on an hourly basis with green certificates. Energy demand analysis includes understanding the daily and seasonal demand profiles as well as load characteristics. This requires hourly or sub-hourly data, which might reveal possible mismatches between the corporate renewable energy portfolio and consumption needs. Figure 8 illustrates a hypothetical demand profile of some corporation with a wind PPA contract, which matches the corporate's demand profile volumetrically (blue and grey area) within the day but not on each hour (black area). In order to achieve hourly matching of renewables, the corporate could, for instance, purchase hourly certificates for the amount of grid emitting energy (black area) each hour.

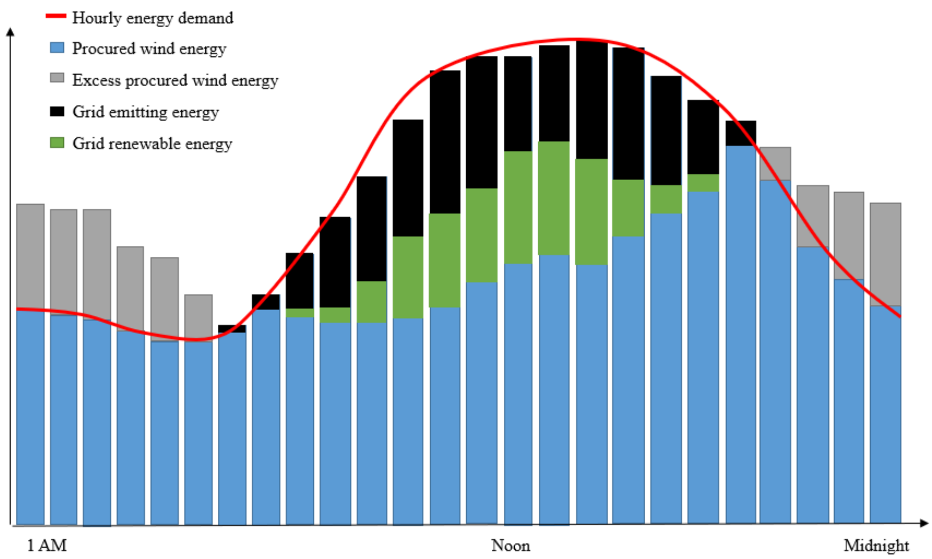

Figure 8: Hypothetical power demand profile and hourly-matching of renewables. Adapted from Miller (2020).

24/7 matching can also include local procurement, meaning that consumption is matched with purchased carbon-free energy from local generators operating on the local grid at the time of consumption. (Jones, 2021) Furthermore, according to ENTSO-E (2022), the absence of spatial dimension is causing adverse effects on RES investment decisions. Currently, most new renewable energy plants are installed in areas with limited transmission capacity. This is the case in Sweden, where most of the hydro and wind power production is located in the northern part of the country, but most of the consumption occurs in the southern part. This has increased electricity prices in the southern Sweden due to transmission capacity bottlenecks in the North-South linkages.

Possible benefits of 24/7 matching could be the following (Douglas & Hunt, 2021):

1. increased transparency of corporate sustainability claims
2. granularity of carbon accounting
3. increased renewable energy investments
4. accelerated decarbonization (by supporting the development of renewable energy assets to reflect better when and where RES generation is most needed)

5. innovative technologies and new business models
6. more closely aligned markets with the physics and economics of the grid and the variability of supply and demand.

Also, Gerber (2021) states that integrating more granular data into renewable energy certificates could lead to significant emissions reductions. Nevertheless, integrating such a system and methodology comes with many challenges. According to Miller (2020), the biggest challenge is the high volatility and intermittency of renewables. However, it is not only an issue for ambitious renewable energy procurement but also a fundamental challenge in complete grid decarbonization. In addition, accessibility of data is one of the most determinant factors in the successful introduction of 24/7 matching. Based on available data, each renewable energy buyer, such as corporates, are the best-informed market player to invest in cost-effective and demand-matched supply as they possess the best information and control of their internal costs and operational flexibility. (Miller, 2020)

Until now, voluntary renewable energy procurement has been mostly guided by policies that have focused to guarantee market access and prevent double counting of renewable energy attributes. These policies however can become costly, and they can only go thus far. Hence, prevalent market structure and rules need to evolve to recognize the timely value of renewable energy supply. This would further incentivize widespread adoption of 24/7 matching of renewables and system flexibility.

A market mechanism that would create an incentive and a price signal for storage and demand response is needed to accelerate timely matching. An independent industry-led initiative EnergyTag (2022b), has suggested as such an element the beforementioned granular or hourly green certificates, which would specify, in addition to the generation technology, for instance, a more detailed location of the power plant and the face value of the certificate. Furthermore, the scheme would not specify the allowed certificate size; in the standard certificate scheme, they are issued per produced MWh. The granular certificates might additionally record information on, for example, received renewable energy support, power plant emission factors (kg CO_2/MWh), and grid emission factors.

According to EnergyTag's Granular Certificate Scheme Standard (2022), the key purpose of Granular Certificates (referred to in thesis as hourly certificates) is to make the traceability of electricity closer to the physical reality and to provide consumers a possibility to match their consumption with a source of their choice on a (sub-)hourly basis. This way, the consumers can also maximize their avoided emissions. The resolution of hourly green certificate markets is planned to match the country's imbalance settlement period. For example, in Finland, it will be one hour until 22.5.2023, after which it will change to a 15-minute period. (Fingrid, 2021; ENTSO-E, 2022). The hourly certificate markets would be executed with a single auction for each market time unit for a relevant geographical, predefined area. The market price would then be determined for each imbalance settlement period. (ENTSO-E, 2022)

Demand for certificates is based on consumers' total electricity consumption within each hour and is exposed to plenty of variation. Respectively, the supply of certificates fluctuates in relation to renewable energy production every hour. As the short-term marginal cost of renewables is close to zero, electricity generation decisions are generally more affected by weather conditions rather than electricity prices. (Hustveit et al., 2017) Consequently, the prices of hourly certificates might become somewhat volatile. To my understanding, this thesis is the first to model the hourly certificate market in microeconomic terms. Previously, only few studies (e.g. Xu et al. 2021; Xu & Jenkins, 2022) have tried to model the system-wide effects of 24/7 matching, but not hourly certificate system. In 24/7 matching the method of matching consumption with green power generation is not specified, and thus it can be achieved with PPA’s and own generation, for instance, whereas hourly certificates are a market tool that could possibly bring more transparency and other new benefits to the electricity market. In Chapter 3, we examine the price effects in hourly certificate and electricity market. The effects on electricity and certificate prices as well as on the consumer’s utility from purchasing hourly certificates are analyzed. Lastly, in Chapter 3.3 the hourly certificate market is compared with existing EAC schemes. We explore how do the market equilibriums in both, electricity, and certificate market change after a demand shift and how it affects to the certificate and electricity prices as well as consumer’s and producer’s utility.

3 Results

The introduction of green energy certificates to the electricity markets affects the market equilibrium by shifting supply and demand curves. Without analyzing green certificates' effects on the markets, it is hard to know how they will affect the equilibrium price and quantity. In this section, we will analyze two interlinked markets: the electricity market without certificates and the others with them. First, we look at the producer's problem, where she maximizes the profits from generated electricity, following the consumer's utility maximization problem. Then, after discussing both problems, the price effects of the consumer's procurement decisions and the changes in the consumer’s utility in relation to share of green and fossil fuel sourced energy in the grid are examined and discussed. Lastly, we compare the traditional certificate markets with annual or monthly trading with the hourly one and review how a change in demand affects both markets on an hourly level regarding procurement costs and both consumer’s and producer’s utility.

3.1 The economic model for hourly green certificates

3.1.1 Maximization problem of the producer

In this thesis, we assume competitive markets where the market actors cannot influence prices and take the price of electricity p_t^e and certificates p_t^c as given in every settlement period and closed economy, meaning that the supply must equal the demand within the market and there exists no trade with other markets. The electricity producer wants to maximize her profits from every unit of energy that is generated while choosing the amount of electricity produced and taking electricity prices and green certificates as given. Therefore, the producer decides to issue hourly certificates from each unit of green electricity x^G produced at time t. She then sells homogenous electricity to the market clearing price p_t^e. Additionally, she wants to get additional revenue from hourly green certificates x_t^c by issuing a certificate for each unit of green electricity x_t^G produced at time t ($x_t^c = x_t^G$), which she then sells to the consumer with a price p_t that guarantees $p_t = p_t^e + p_t^c = C_G'(x_t^G)$, where p_t^c is the price of hourly certificates and ${C_G}'(x_t^G)$ is the marginal cost of green energy at time t. The maximization problem of the producer can be then written as follows:

$$\max_{x_t^F, x_t^G} \pi = \sum_{t=1}^{T} \left(p_t^e x_t^F + (p_t^e + p_t^c) x_t^G - \left(C_F(x_t^F) + C_G(x_t^G) \right) \right) \tag{1}$$

The equation is also subject to a positive output constraint, $x_t^e \geq 0$, of energy produced with technology $e = F, G$, where F refers to emitting technologies such as coal-powered electricity and G to green or carbon-free energy available at a time t. Here π is the producer’s profit from producing energy from mixed technologies, p_t^e is the market clearing price of electricity at a settlement time t (usually hourly or sub-hourly), p_t^G is the price of carbon-free energy, and $C_F(x_t^F) + C_G(x_t^G)$ is the cost function of different technologies. Because electricity from green and emitting sources require distinct investments, we can assume that the cost function $C_F(x_t^F) + C_G(x_t^G)$ is separable with respect to x_t^F and x_t^G. We also assume that the cost function is quadratic and that derivates C_F' and C_G' are linear functions. Furthermore, both technologies have increasing marginal costs:

$$\frac{\partial C_F(\cdot)}{\partial x^F} > 0, \qquad \frac{\partial C_G(\cdot)}{\partial x^G} > 0, \qquad \frac{\partial^2 C_F(\cdot)}{\partial x^F} > 0, \qquad \frac{\partial^2 C_G(\cdot)}{\partial x^G} > 0 \tag{2}$$

The producer chooses optimal generation levels for emitting x_t^F and green energy x_t^G to maximize equation (1). First, we derive the first-order condition for emitting energy:

$$\frac{\partial \pi}{\partial x_t^F} = p_t^e - C_F'(x_t^F) = 0 \tag{3}$$

$$C_F'(x_t^F) = p_t^e \tag{4}$$

Thereby, the marginal cost of electricity generated from emitting sources equals the electricity price at time t. We can solve the supply function for fossil fuel energy by rewriting the first-order condition (4):

$$x_t^F \equiv C_F'(p_t^e)^{-1} \equiv S_F(p_t^e) \tag{5}$$

Where we define $S_F(p_t^e)$ as the supply function for emitting energy. Similarly, the producer wants to choose the optimal level of green energy generation x_t^G that maximizes equation (1). We can solve the first-order condition for green energy:

$$\frac{\partial \pi}{\partial x_t^G} = p_t^e + p_t^c - C_G'(x_t^G) = 0 \tag{6}$$

$$C_G'(x_t^G) = p_t^e + p_t^c \tag{7}$$

Thus, the marginal cost of green electricity equals the sum of electricity cost and the price of certificates. We can solve the supply function for green energy by rewriting the first-order condition (7):

$$x_t^G \equiv C_G'(p_t^e + p_t^c)^{-1} \equiv S_G(p_t^e + p_t^c) \tag{8}$$

Where we define $S_G(p_t^e + p_t^c)$ as the supply function for green energy. Thus, the supply of green energy depends both, on the price of electricity and the price of certificates. The aggregated supply of emitting and green energy at a specific time t is then the following:

$$S_{F+G} \equiv x_t^F + x_t^G \equiv S_F(p_t^e) + S_G(p_t^e + p_t^c) \tag{9}$$

As illustrated above, the aggregated supply depends on the price of electricity and the price of certificates at a given time t.

3.1.2 Maximization problem of the consumer

The consumer benefits from electricity consumption as well as green certificates. Demand for electricity and hourly certificates is based on consumers' total demand within a specific hour or sub-hour. The consumer of hourly green certificates acts as a price taker and maximizes his utility U from the demanded quantity of electricity x_t^e, where $e = F, G$, and demanded quantity of green certificates x_t^c within each settlement period t. The consumer procures a share of his electricity consumption from renewables with hourly green certificates x_t^c and benefits from this amount of $\alpha U_c(x_t^c)$, where $\alpha = [0,1]$ is a coefficient representing the consumer's procurement decision on green energy. Thus, the consumers utility from purchasing hourly green certificates $U_c(x_t^c)$ varies depending on α, i.e., α represents the share of utility from purchasing hourly certificates at a time period t. The consumer receives utility $U_c(x_t^c)$, for instance, from more accurate carbon footprint tracking and verified sustainability claims. The maximization problem of the consumer can be then written as follows:

$$\max_{x_t^e, x_t^c} U \sum_{t=1}^{T} \left(U_e(x_t^e) + \alpha U_c(x_t^c) - (x_t^e p_t^e + x_t^c p_t^c) \right) \tag{11}$$

We assume that the utility function for both, electricity $U_e(x_t^e)$ and certificates $U_c(x_t^c)$ is growing but concave so that the utility decreases from each additional unit that is consumed.

$$\frac{\partial U_e(\cdot)}{\partial x^e} > 0, \qquad \frac{\partial U_c(\cdot)}{\partial x^c} > 0, \qquad \frac{\partial^2 U_e(\cdot)}{\partial x^e} < 0, \qquad \frac{\partial^2 U_c(\cdot)}{\partial x^c} < 0 \tag{12}$$

In a closed economy, supply needs to equal demand at every settlement period t. Because electricity is a homogenous product for the consumer, we do not separate the demand for emitting and green energy but only for the hourly green certificates. Thus, the demanded quantity of electricity x_t^e at time t needs to equal the combined supply from emitting and green energy sources, as follows:

$$x_t^e \equiv x_t^F + x_t^G \tag{13}$$

The consumer wants to choose optimal demand levels for electricity x_t^e and hourly certificates x_t^c to maximize equation (11). First, we can solve the first-order condition of electricity demand:

$$\frac{\partial U_e}{\partial x_t^e} = U_e'(x_t^e) - p_t^e = 0 \tag{14}$$

$$U_e'(x_t^e) = p_t^e \tag{15}$$

Thus, the marginal utility of the consumer's electricity demand x_t^e equals the price of electricity p_t^e at a time t. We can solve the demand for electricity by rewriting the first-order condition (15):

$$x_t^e \equiv U_e'(p_t^e)^{-1} \equiv D_e(p_t^e) \tag{16}$$

Where we define $D_e(p_t^e)$ as the demand function for electricity for technologies $e = F, G$. Then, we can derive the marginal utility for certificates x_t^c. The first order condition is the following:

$$\frac{\partial U_c}{\partial x_t^c} = \alpha U_c'(x_t^c) - p_t^c = 0 \tag{17}$$

$$\alpha U_c'(x_t^c) = p_t^c \tag{18}$$

$$U_c'(x_t^c) = \frac{p_t^c}{\alpha} \tag{19}$$

Thus, the marginal utility for green certificates equals green certificate price p_t^c divided by the share α of procured green energy by hourly certificates in the consumer's electricity demand. Demand for certificates can then be solved by rewriting (19) as follows:

$$x_t^c \equiv U_c'\left(\frac{p_t^c}{\alpha}\right)^{-1} \equiv D_c\left(\frac{p_t^c}{\alpha}\right) \tag{20}$$

Where we define $D_c\left(\frac{p_t^c}{\alpha}\right)$ as the demand function for green certificates at time t.

3.1.3 Market equilibrium

Then, we can solve the market equilibrium for both, electricity generated from fossil fuel sources x^F and electricity from carbon-free sources x^G. The market clearing condition (21) for the electricity market can be derived by combining (4) and (15) because the market players act in a closed economy $x_t^e \equiv x_t^F + x_t^G$. Similarly, we can derive the market clearing condition for certificate (22) market by combining (4), (7), and (18).

$$C_F'(x_t^F) = U_e'(x_t^F + x_t^G) \tag{21}$$

$$C_G'(x_t^G) - C_F'(x_t^F) = \alpha U_c'(x_t^c) \tag{22}$$

where $C_G'(x_t^G) - C_F'(x_t^F)$ is the additional marginal cost of certificates. The electricity market equilibrium is illustrated in Figure 9(a), where D_e is the demand curve for electricity from both technologies $e = F, G$. Similarly, the supply curve S_e demonstrates the aggregated electricity supply from both technologies $e = F, G$. The market equilibrium can be found in (x_t^e, p_t^e) and the optimal price of electricity can be found where demand D_e equals supply S_e, i.e.

$$D_e(p_t^e) = S_F(p_t^e) + S_G(p_t^e + p_t^c) \tag{23}$$

The market equilibrium for certificate market is illustrated in Figure 9(b). The producer issues a certificate for each generated unit of green electricity. Thus, the supply of green electricity equals the supply of certificates $S_G = S_c$. As illustrated in Figure 9(a)–(b), demand for hourly certificates is more elastic than demand for electricity because we assume that the consumer's procurement decision of is not constant and thus can vary across time. With hourly certificates, the share of certificates that the consumer decides to buy might vary in relation to price fluctuations. Hence, when the price of certificates is low, the consumer might decide to procure more green electricity through certificates and vice versa, depending on his demand flexibility at a specific time t. We can find the optimal price for green certificates at a point where the supply of green electricity equals the demand for certificates, i.e., green energy.

$$S_G(p_t^e + p_t^c) = D_c\left(\frac{p_t^c}{\alpha}\right) \text{ or } S_G(p_t^e + p_t^c) = D_G\left(\frac{p_t^c}{\alpha}\right), \tag{24}$$

Where we define $D_G\left(\frac{p_t^c}{\alpha}\right)$ as the demand function for green energy at time t.

(a) Electricity market *(b) Hourly certificate market*

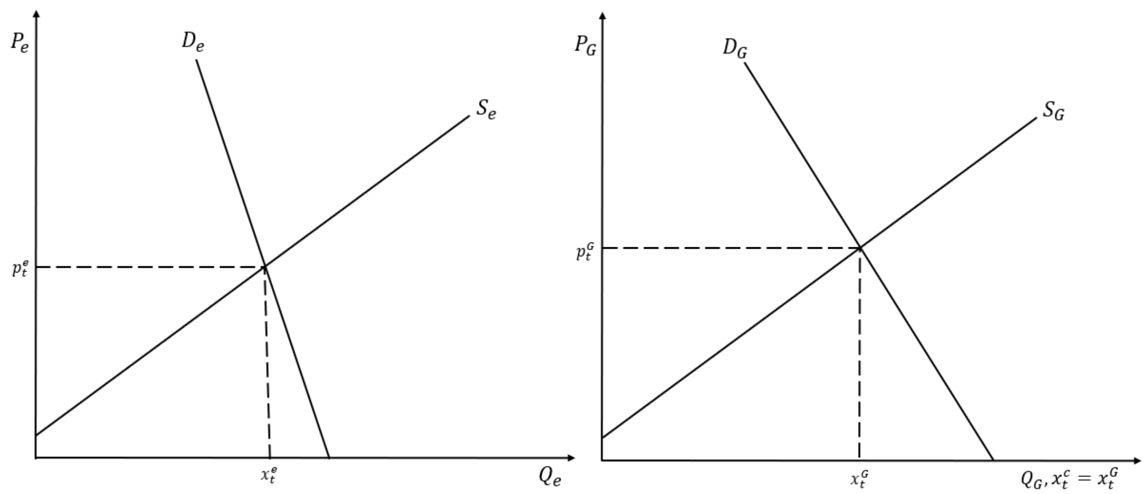

Figure 9: Electricity and hourly certificate market equilibrium

Notes: (a) D_e demand for electricity, S_e supply of electricity, x_t^e optimal amount of generated electricity that is sold to the consumer at time t, p_t^e price of electricity at time t, and in (b) D_G demand for green electricity, S_G supply of green electricity, $x_t^c = x_t^G$ optimal amount of green electricity at time t, which equals the corresponding value of hourly green certificates x_t^c in MWh, p_t^G price of green electricity that includes the cost of hourly certificates as well the settlement price of electricity at time t.

3.2 Sensitivity analysis

In order to analyze the effect that changes in the volume of renewable energy procurement have on the share of emitting and green energy in the markets, as well as electricity and green certificate prices, we perform a sensitivity analysis. As the producer issues a certificate for all produced green energy, i.e., $x_t^G = x_t^c$, and the market players act in a closed economy so that all units of energy and certificates are sold in the markets, we can rewrite (22). The market equilibriums of electricity market x_t^e and certificate market x_t^c are then the following:

$$C_F'(x_t^F) = U_e'(x_t^F + x_t^G) \tag{25}$$

$$C_G'(x_t^G) - C_F'(x_t^F) = \alpha U_c'(x_t^G) \tag{26}$$

Then, we can differentiate both equations with respect to the share α of consumer's procured green electricity and thus certificates by using implicit differentiation:

$$C_F''(x_t^F)\frac{\partial x_t^F}{\partial \alpha} = U_e''(x_t^F + x_t^G)\frac{\partial x_t^F}{\partial \alpha} + U_e''(x_t^F + x_t^G)\frac{\partial x_t^G}{\partial \alpha} \tag{27}$$

$$C_G''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} - C_F''(x_t^F)\frac{\partial x_t^F}{\partial \alpha} = U_c'(x_t^G) + \alpha U_c''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} \tag{28}$$

Next, we can solve the group of equations for $\frac{\partial x_t^F}{\partial \alpha}$ and $\frac{\partial x_t^G}{\partial \alpha}$:

$$\frac{\partial x_t^F}{\partial \alpha} = \frac{U_e''(x_t^F + x_t^G)\frac{\partial x_t^G}{\partial \alpha}}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)} \tag{29}$$

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{U_c'(x_t^G) + \alpha U_c''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} + C_F''(x_t^F)\frac{\partial x_t^F}{\partial \alpha}}{C_G''(x_t^G)} \tag{30}$$

We can rewrite (30) by inserting $\frac{\partial x_t^F}{\partial \alpha}$ into the equation.

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{U_c'(x_t^G) + \alpha U_c''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} + C_F''(x_t^F)\frac{U_e''(x_t^F + x_t^G)\frac{\partial x_t^G}{\partial \alpha}}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)}}{C_G''(x_t^G)} \tag{31}$$

Then, we solve the equation for $\frac{\partial x_t^G}{\partial \alpha}$ (see Appendix A).

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{-U_c'(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}{\alpha U_c''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right) - C_F''(x_t^F)\left(U_e''(x_t^F + x_t^G) - C_G''(x_t^G)\right) + U_e''(x_t^F + x_t^G)C_G''(x_t^G)} \tag{32}$$

Then, we can solve the effect of α to the share of green energy in the grid in time period $t.$ Because $U_c'(x_t^G) > 0, \alpha > 0, U_c''(x_t^G) < 0, \frac{\partial x_t^G}{\partial \alpha} > 0$ $C_F''(x_t^F) > 0, U_e''(x_t^F + x_t^G) < 0,$ and $C_G''(x_t^G) > 0,$ it follows that $\frac{\partial x_t^G}{\partial \alpha} < 0.$ Thus, when α increases, x_t^G decreases i.e., when the share of consumer's green energy procurement and utility from purchasing hourly green certificates at time period t increases, the amount of green energy decreases in the market. Similarly, we can solve alpha's effect on the share of emitting energy. Because $U_e''(x_t^F + x_t^G) < 0,$ $C_F''(x_t^F) > 0,$ and $\frac{\partial x_t^G}{\partial \alpha} < 0,$ it follows that $\frac{\partial x_t^F}{\partial \alpha} > 0$. Thus, when α increases, x_t^F also increases, i.e., when the consumer decides to procure more green energy, following that the utility from purchasing hourly green certificates increases, also the amount of emitting electricity in the market increases.

As shown above, the consumer benefits more from purchasing hourly green certificates in a time period t when renewable energy is less abundant. This can happen due to unfavorable weather conditions, nigh-time hours, or when the demand for renewable energy is high. In that case, and if the consumer's demand is not elastic, he is increasingly willing to purchase additional hourly green certificates, knowing that the share of emitting energy in the grid is higher but still wanting to procure a share of his electricity consumption from renewable energy sources. Conversely, when renewable energy is abundant and supplies a major part of demand in a given time, the consumer does not benefit as much from purchasing hourly green certificates and decides to procure less green energy through certificates because the certificates provide then less additionality. The consumer knows that the grid's energy mix is already low-carbon and thus, the utility from renewable energy procurement is lower.

Similarly, we can derive the effect on prices p_t^e and p_t^c from the supply and demand equations, as follows:

$$C_F'(x_t^F) = p_t^e \tag{33}$$

$$C_G'(x_t^G) = p_t^e + p_t^c \tag{34}$$

We can differentiate both equations with respect to α using implicit differentiation and solve for $\frac{\partial p_t^e}{\partial \alpha}$ and $\frac{\partial p_t^c}{\partial \alpha}$.

$$\frac{\partial p_t^e}{\partial \alpha} = C_F''(x_t^F)\frac{\partial x_t^F}{\partial \alpha} \tag{35}$$

$$\frac{\partial p_t^c}{\partial \alpha} = C_G''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} - \frac{\partial p_t^e}{\partial \alpha} \tag{36}$$

We can rewrite (35) by inserting the value of $\frac{\partial p_t^e}{\partial \alpha}$ into the equation:

$$\frac{\partial p_t^c}{\partial \alpha} = C_G''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} - C_F''(x_t^F)\frac{\partial x_t^F}{\partial \alpha} \tag{37}$$

Because $C_F''(x_t^F) > 0$ and $\frac{\partial x_t^F}{\partial \alpha} > 0$, it follows that $\frac{\partial p_t^e}{\partial \alpha} > 0$. Thus, the price of electricity p_t^e increases when the utility from purchased green electricity increases. Typically, the price of electricity is high when renewable energy is less abundant or demand for electricity is high, as illustrated in Chapter 2.2.3. Conversely, as $C_G''(x_t^G) > 0, \frac{\partial x_t^G}{\partial \alpha} < 0$, $C_F''(x_t^F) > 0$ and $\frac{\partial x_t^F}{\partial \alpha} > 0$, it follows that $\frac{\partial p_t^c}{\partial \alpha} < 0$, meaning that when the utility from purchasing hourly green certificates increases, their price decreases. The consumer wants to maximize his utility from purchased hourly green certificates by also minimizing his procurement costs. Consequently, as the price of hourly green certificates decreases, his utility increases, because the consumer spends less capital on green energy procurement.

In Figure 10(a) the price of electricity declines when the share of green energy increases in the grid. However, as renewable energy is more abundant and its' share from electricity demand is higher, the utility that the consumer benefits from purchasing additional hourly certificates decreases as well. Respectively, Figure 10(b) illustrates an increase in the price of green energy as a result of surged electricity demand. In this case, the consumer's procurement costs increase. Thereby, he benefits less from purchasing certificates and might shift his consumption to times with lower demand.

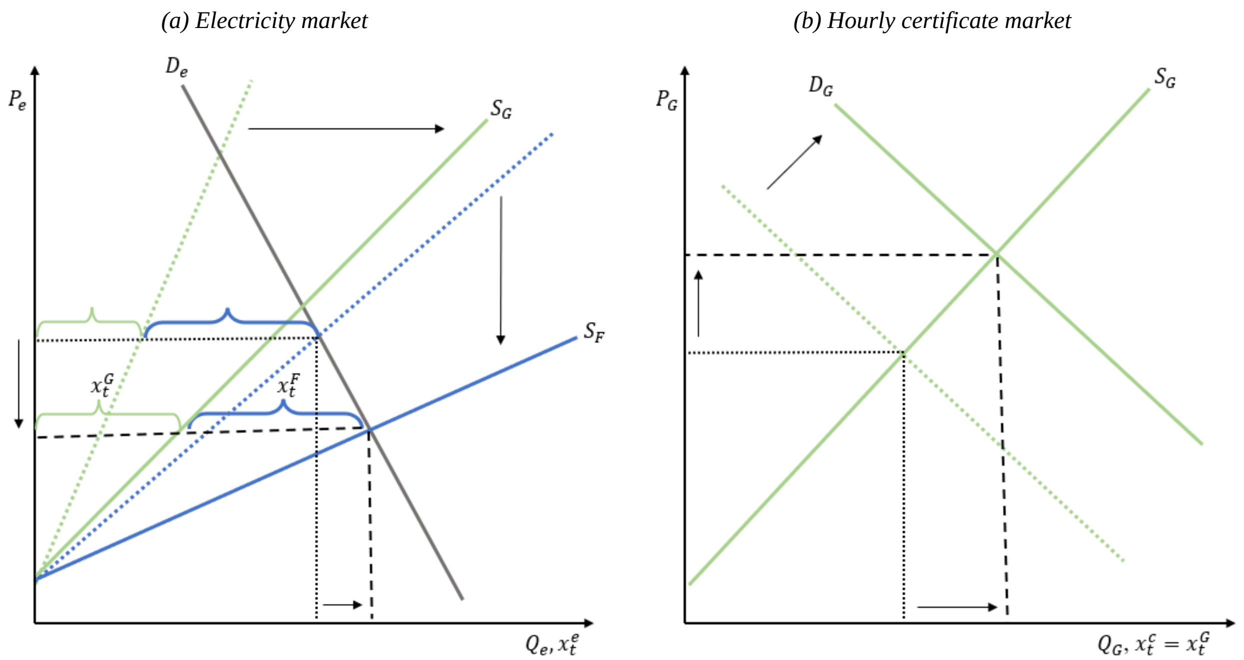

Figure 10: Consumer's procurement share's effect on prices in (a) electricity market and (b) hourly certificate market.

Notes: (a) D_e electricity demand, S_G supply of green electricity, S_F supply of emitting electricity, P_e price of electricity, Q_e quantity of supply or demanded electricity, x_t^G amount of green electricity at time t, x_t^F amount of emitting electricity at time t, and in (b) P_G price of green electricity that includes the cost of certificates and settlement price of electricity at time t, and x_t^c number of hourly certificates at time t.

If the supply of electricity would be perfectly elastic $\frac{\partial x_t^G}{\partial \alpha} = 0$ and $\frac{\partial x_t^F}{\partial \alpha} = 0$, meaning that the electricity generation would be abundant at a price p_t^e, then $\frac{\partial p_t^e}{\partial \alpha} = 0$ and $\frac{\partial p_t^c}{\partial \alpha} = 0$. Hence, a change in the procurement share would not affect the price of electricity or the price of certificates. However, the likelihood of such a case is negligible.

3.3 Comparison of hourly green certificate and general EAC markets

Then we can analyze graphically how hourly matching differs from traditional certificate markets. We assume that the supply of traditional certificates is perfectly price elastic within time t. However, consumer's demand can vary within this period. In the hourly certificates market, the share $\alpha = [0,1]$ that is utility from purchased certified renewable electricity can change each time period t. In regular compliance certificate markets, changes in certificate demand can be affected, for example, by demand-side policies such as the government's decision to increase the obligatory quota for certificates. We assume that the consumer's renewable energy share from total amount of consumption is constant over time in the general green certificate scheme as the consumer or the government sets an annual or monthly goal for the renewable energy procurement. In this model, the consumer only buys renewable energy solely with energy attribute certificates and not with any other green power products.

Markets for traditional certificates x_t^z and hourly certificates x_t^c are illustrated in Figure 11(a)−(b) and Figure 12(a)−(b), where D_1 represents the old demand curve in both markets, and D_2 the new demand curve after the change in demand. The supply curve for hourly certificates is illustrated as S_c, and the supply curve for general certificates as S_z. We assume that the supply of general certificates x_t^z is perfectly price elastic within time period t (an hour or sub-hour). Thus, the producer will supply any number of certificates at a constant price, and the supply curve is horizontal. Consequently, the equilibrium price is determined solely by the supply conditions, while the demand curve determines the equilibrium quantity. In this case, the determination of price and quantity are separated.

In Figure 11 (a)−(b), the certificate demand increases in both markets from D_1 to D_2. In the general certificate markets (Figure 11(a)), the new price p_2^z remains at the initial level p_1^z due to perfectly price elastic supply. Thus, the producer's profits from certificates do not reflect the demand at a given time t and do not lure other producers into the market. On the contrary, the consumer benefits excessively from separated market price and quantity determination. However, this is not necessarily the case in the longer time horizon, where the supply might vary in relation to market price. In the case of hourly certificate markets (b), the price increases from the initial level p_1^c to p_2^c due to the grown demand D_2 in the new market equilibrium. Thus, the exchanged number of certificates is less in hourly certificate markets than in the general one.

In Figure 11, demand in both certificate markets increases from D_1 to D_2. In general certificate markets, the price of certificates p_2^z does not change as a response to demand decrease, because it is determined by average supply and demand over a longer period. Consequently, the exchanged number of certificates in the traditional market is higher than in the hourly one, raising the cost of certificates. Thus, hourly matching becomes more expensive for the consumer than annual or monthly matching with general green certificates. Therefore, it can be argued that it provides better price signal to new market entrees than the general green certificate market, where the producers do not benefit from the increased short-term demand through increased certificate prices.

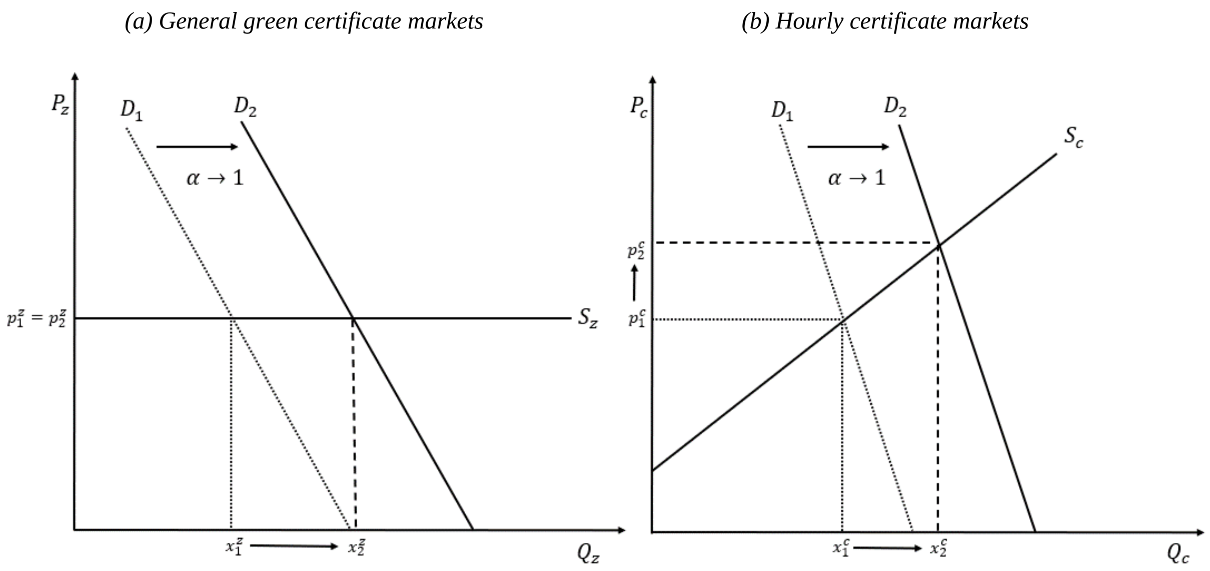

Figure 11: Effect of demand increase in (a) general and (b) hourly certificate markets.

Notes: D_1 old demand and D_2 new demand of certificates after demand increase (both markets) p_1^z price of general certificates in period 1, p_2^z price of general certificates in period 2, S_z supply of general certificates, x_1^z and x_2^z number of exchanged general certificates in periods 1 and 2, p_1^c and p_2^c prices of hourly certificates in periods 1 and 2, S_c supply of hourly certificates, x_1^c and x_2^c number of exchanged certificates in periods 1 and 2.

In Figure 12 (a)−(b), demand in both markets decreases from D_1 to D_2. In general certificate markets, the price of certificates again stays the same as it is determined independently from the short-term demand. Respectively, as the demanded quantity of hourly certificates drops, the price also decreases in the hourly certificate market. The effect of demand decrease on the exchanged number of certificates is more significant in general certificate markets than in an hourly one. Consequently, the consumer in the hourly certificate market benefits from cheaper certificate price p_2^c but the producer receives less profit from issuing hourly certificates than in the general market.

Therefore, as the supply of certificates is reflective to the demand, 24/7 matching with hourly certificates becomes cheaper for the consumer in case of low demand or abundant green energy than renewable energy procurement with an annual or monthly target within time t, as it can be seen in Figure 12. Consequently, low price of certificates might encourage consumers to shift their demand to hours when renewable energy is abundant as it lowers their procurement costs. Hence, the daily demand fluctuations might become more flattened, and the market would experience less particularly high demand peaks.

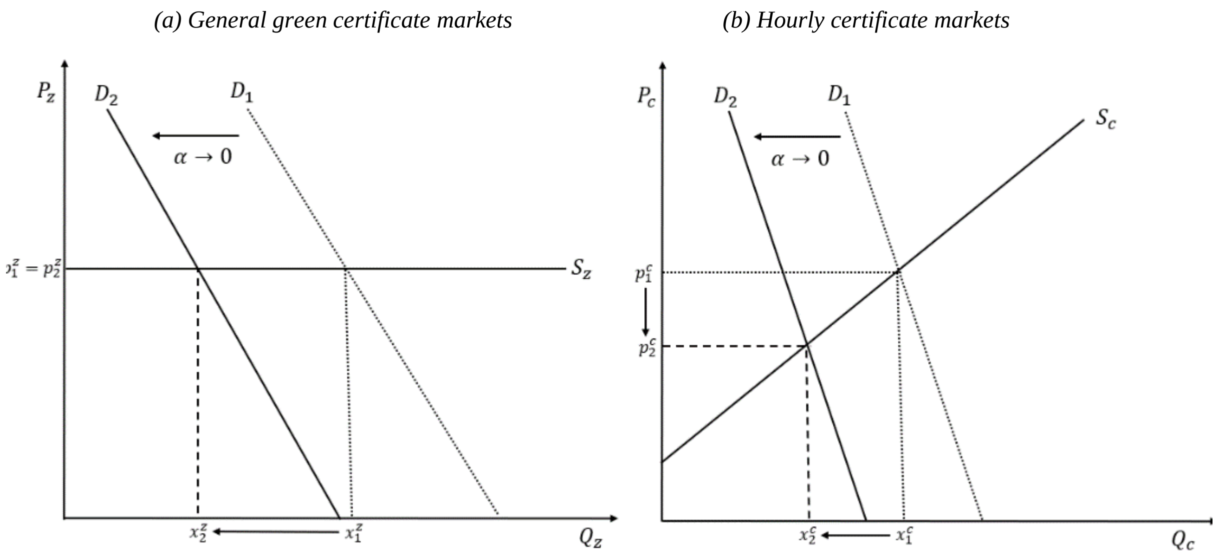

Figure 12: Effect of demand decrease in (a) general and (b) hourly certificate markets

Notes: D_1 old demand and D_2 new demand of certificates after demand decrease (both markets), p_1^z and p_2^z prices of general certificates in periods 1 and 2, S_z supply of general certificates, x_1^z and x_2^z number of exchanged general certificates in periods 1 and 2, p_1^c and p_2^c prices of hourly certificates in periods 1 and 2, S_c supply of hourly certificates, x_1^c and x_2^c number of exchanged certificates in periods 1 and 2.

4 Discussion

The effectiveness of annual renewable energy certificates has been widely researched and criticized in the literature. Previous studies (e.g., Hast et al. (2015), Mulder and Zomer (2016), Jansen (2017), and Hamburger (2019)) have shown that European system of Guarantees of Origin have not significantly influenced renewable energy investments, albeit it was initially established to provide information on the disclosure of used electricity. Power markets have always had asymmetric information as the end-users cannot be sure of what the consumed electricity consists of. Electricity is traded in the markets as a homogenous product; thus, the consumer cannot know the origin of the used electricity. To address this issue, the current system in force in Europe is the Guarantees of Origins allows the matching of green power generation with consumption on a yearly or monthly basis. Consequently, consumers can match their winter-night consumption, for instance, with solar power generated during a summer day. Therefore, it can be argued that the current GO system does not reflect the time-specific demand for green energy. Thus, it can be argued that GOs do not create a sufficient incentive for developing technologies that could provide system flexibility, such as storage solutions.

To address this issue, as well as greenwashing and double counting of energy attributes, many organizations and corporations are developing strategies to reach carbon neutrality on an hourly basis. More granular data integrated into the electricity market could provide additional benefits for achieving green transition, as the power market operations would be tracked more systematically. As illustrated in Chapter 3, hourly green certificates reflect better the short-term demand and supply of green energy than traditional certificate systems because the price of hourly certificates is determined by their supply and demand at a given time. Thus, the price of certificates is high when their supply is low compared to the demand. Correspondingly, producers are willing to sell hourly certificates at a low price when the supply is high in contrast to demand. Consequently, it can be argued that hourly green certificates provide investors with a better price signal than annually traded certificates. This, with hourly green certificates the time period when consumption of an energy unit happens is linked with the corresponding time period of green energy. In addition to providing better incentives for flexibility solutions, hourly green certificates could courage consumption to shift to times when the demand of certificates is low or renewable energy is abundant, as illustrated in 3.3.

However, it is yet to be determined whether hourly green certificates would lead to additional grid decarbonization than annually or monthly traded certificates, especially in electricity grids with high renewable energy penetration. The energy crisis and record-high power prices resulting from a gas supply shortage in Europe further raise the question of whether consumers will have any excess resources to allocate to voluntary green energy procurement. Thus, it is uncertain if there is a more extensive demand for such a system. Furthermore, introducing hourly certification might become expensive and socially non-optimal if only large corporations adopt the practice to meet their sustainability targets. Nevertheless, corporations and nations also have carbon-neutrality targets to achieve, which will only be reached with increased system flexibility and a diverse technology portfolio, in which 24/7 matching and hourly emissions tracking could function as a key element. Later, with an increasing number of consumers shifting to hourly tracking, 24/7 matching could potentially have even system-wide effects.

As 24/7 matching helps to identify consumers' demand profiles and electricity consumption mix, demand peaks might become more flattened as consumers shift their load to times when electricity and renewable energy procurement is cheaper. Generally, there is less available green energy during night hours but also the demand for electricity and certified green energy is lower than during day-time hours. As the demand is lower, making the price of certificates also to fall, some consumers might shift their load to these lower demand time frames. Additionally, as the hourly certificates are traded on an hourly basis, they could encourage investments in technologies that provide carbon-free energy at any hour of the day, such as P2X and storage technologies, as the producers could receive additional revenue by selling these certificates. Annual matching does not incentivize such investments as electricity consumption during night hours can be matched with certificates produced in the daytime with existing generators.

Before implementing new procurement standards, examining the possible market effects stemming from these changes is crucial. This thesis demonstrates that renewable energy procurement through hourly green certificates might lead to raised electricity costs compared to annual or monthly matching when the demand for renewable energy and certificates is high. However, when demand for hourly certificates is low, for example, when grid renewable energy is abundant, the certificate price would be lower than annual or monthly traded certificates'. Thus, hourly matching could become either more expensive or cheaper within single hours or sub-hours, depending on the demand for hourly certificates, than matching with an annual or monthly goal. However, in the long-term it is not likely to lead to cheaper procurement costs. Thus, the scheme's attractiveness is difficult to predict as typically all market participants strive for minimized expenses. There is a possibility that hourly green certificates would only gain interest among large market participants with ambitious sustainability standards and thus, willingness to pay extra for verified sustainability claims, but to fail to gain enthusiasm among residential consumers. Consequently, a similar issue could surface as with Guarantees of Origin scheme, where the historically low prices have not sufficiently incentivized renewable energy investments. If there are not enough market participants from the consumer side, the price of certificates might fall below optimal, leading hourly green certificates to become an ineffective market instrument. Thus, before bringing green energy certification into hourly operations, interest of residential consumers for such system should be estimated so that the scheme would not become a market failure.

Additionally, as illustrated in Chapter 3.2, the consumer's utility from hourly green certificates is higher when the share of emitting energy is high in the electricity market. Therefore, hourly green certificates could provide benefit to both, consumers and producers, in hours when renewable energy is less abundant, such as nigh-time hours. Thus, the scheme's development should focus on accentuating this effect that could further spur investments, for instance, into system flexibility. Moreover, as the penetration of renewable energy grows over time, the long-term potential utility from hourly procurement declines. As seen in Chapter 3, the consumer's utility decreases when the share of green energy in the grid increases. Thus, more research is needed to determine, whether there is still need for such system, especially in market areas with already high renewable energy share, such as the Nordic countries.

Nevertheless, hourly green certificates could enable temporally more precise and transparent emission accounting and potentially increase capital flows to investments that could provide an around-the-clock carbon-free grid. Albeit this thesis compares hourly certification with existing EAC systems, it does not necessarily imply that annual or monthly matching of renewables is insufficient or lacking. 24/7 matching provides transparency to the electricity market and emissions accounting as well as supports specific customers, such as corporates, to achieve their sustainability targets. However, if hourly green certificates are to be implemented on a system-wide scale, more research and legislative support are needed to bring hourly certification together with existing systems to accommodate a smooth transition and stepwise implementation of temporal matching of renewables. In addition, the system effects of hourly certificates and 24/7 matching are still somewhat uncertain, especially in grids with already high renewable energy penetration. Hence, the effects should be studied carefully within the electricity market price area in question before broader implementation.

5 Conclusions

Electricity markets and emissions accounting need more transparency, especially considering national net zero emission targets and a high grid share of renewable energy. Moreover, as the cost of renewables is constantly declining, the challenge changes from how to install more renewable capacity to providing timely supply of green energy when needed. The main goal of hourly certificates is to bring the process of contracting carbon-free electricity closer to the physical reality and timely availability. Thus, it can be argued that they could augment investments in renewable and flexibility technologies that could provide renewable energy around-the-clock. In addition, from a consumer perspective, hourly certificates would enable tracking of carbon footprints more accurately, which would further help plan actions to meet either private or nationwide decarbonization goals.

In Chapter 3 we saw that depending on the timely demand for green power, hourly green certificates could either increase of decrease the procurement costs compared to annually or monthly matching, depending on the hourly demand and supply of certificates. This brings volatility into the market and might affect the scheme's attractiveness to market participants. Furthermore, as analyzed in Chapter 3, hourly certificates provide a better price signal of the timely availability of renewable energy when compared to existing EAC markets. However, as seen in Chapter 3, when renewable energy is abundant, consumers gain less utility from purchasing hourly certificates. As the share of renewable energy is constantly increasing in the electricity generation, the additionality that hourly certificates could bring to the markets is declining. Thus, the attractiveness of the scheme is still uncertain apart from businesses with ambitious sustainability targets. Nevertheless, hourly certificates could accelerate grid decarbonization on hours when the weather conditions are not optimal for green power generation by providing additional revenue to flexibility providers, such as different storage solutions. Thus, this aspect should be in the center of the certificate scheme development.

Evidently, hourly matching could enable more closely aligned electricity and certificate markets with the physics and economics of the grid and the variability of supply and demand. However, the possible system effects still need to be determined in each electricity market area and how the hourly green certificate system can be combined with the existing system. It is also still unclear whether hourly green certificates would provide greater grid decarbonization than annually or monthly traded certificates. Thus, the additionality of the scheme should be evaluated carefully before broader implementation to avoid system inefficacies and market failure.

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Appendix A

We solve the equation (31) for $\frac{\partial x_t^G}{\partial \alpha}$:

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{U_c'(x_t^G) + \alpha U_c''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} + C_F''(x_t^F)\frac{U_e''(x_t^F + x_t^G)\frac{\partial x_t^G}{\partial \alpha}}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)}}{C_G''(x_t^G)}$$

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{U_c'(x_t^G)}{C_G''(x_t^G)} + \frac{\alpha U_c''(x_t^G)\frac{\partial x_t^G}{\partial \alpha}}{C_G''(x_t^G)} + \frac{\frac{C_F''(x_t^F)U_e''(x_t^F + x_t^G)\frac{\partial x_t^G}{\partial \alpha}}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)}}{C_G''(x_t^G)}$$

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{U_c'(x_t^G)}{C_G''(x_t^G)} + \frac{\alpha U_c''(x_t^G)\frac{\partial x_t^G}{\partial \alpha}}{C_G''(x_t^G)} + \frac{\frac{\partial x_t^G}{\partial \alpha}C_F''(x_t^F)U_e''(x_t^F + x_t^G)}{C_G''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}$$

$$C_G''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} = U_c'(x_t^G) + \alpha U_c''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} + \frac{\frac{\partial x_t^G}{\partial \alpha}C_F''(x_t^F)U_e''(x_t^F + x_t^G)}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)}$$

$$-U_c'(x_t^G) = \alpha U_c''(x_t^G)\frac{\partial x_t^G}{\partial \alpha} + \frac{\frac{\partial x_t^G}{\partial \alpha}C_F''(x_t^F)U_e''(x_t^F + x_t^G)}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)} - C_G''(x_t^G)\frac{\partial x_t^G}{\partial \alpha}$$

$$-U_c'(x_t^G) = \frac{\partial x_t^G}{\partial \alpha}\left(\alpha U_c''(x_t^G) + \frac{C_F''(x_t^F)U_e''(x_t^F + x_t^G)}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)} - C_G''(x_t^G)\right)$$

$$-U_c'(x_t^G) = \frac{\partial x_t^G}{\partial \alpha}\left(\frac{\alpha U_c''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)} + \frac{C_F''(x_t^F)U_e''(x_t^F + x_t^G)}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)} - \frac{C_G''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)}\right)$$

$$-U_c'(x_t^G) = \frac{\partial x_t^G}{\partial \alpha}\left(\frac{\alpha U_c''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right) + C_F''(x_t^F)U_e''(x_t^F + x_t^G) - C_G''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}{C_F''(x_t^F) - U_e''(x_t^F + x_t^G)}\right.$$

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{-U_c'(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}{\alpha U_c''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right) + C_F''(x_t^F)U_e''(x_t^F + x_t^G) - C_G''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}$$

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{-U_c'(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}{\alpha C_F''(x_t^F)U_c''(x_t^G) - C_F''(x_t^F)C_G''(x_t^G) - \alpha U_e''(x_t^F + x_t^G)U_c''(x_t^G) + U_e''(x_t^F + x_t^G)C_G''(x_t^G) + C_F''(x_t^F)U_e''(x_t^F + x_t^G)}$$

$$\frac{\partial x_t^G}{\partial \alpha} = \frac{-U_c'(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right)}{\alpha U_c''(x_t^G)\left(C_F''(x_t^F) - U_e''(x_t^F + x_t^G)\right) - C_F''(x_t^F)\left(U_e''(x_t^F + x_t^G) - C_G''(x_t^G)\right) + U_e''(x_t^F + x_t^G)C_G''(x_t^G)}$$