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Guarantees of Origin: Does the Origin matter? Exploring Pricing Dynamics and Product Transparency in the Renewable Electricity Market

Sofie van Dooren
Applied Economics and Sustainability

Abstract

This study analyses the historic development of Guarantee of Origin (GO) market prices and the impact of information disclosure on GO prices. A GO is a certificate that documents the generation of one-megawatt hour (MWh) of electricity. It allows for transparency and differentiation based on the origin of electricity, reducing information asymmetry, and enabling consumer choice. Literature points to low GO prices as a significant barrier to the positive impact of the GO market on renewable electricity production, yet the literature on GO price determinants is limited. Therefore, this study aims to shed light on GO prices from two perspectives. Firstly, an exploratory analysis of GO issuance, cancellation, and prices reveals increasing market volatility as the oversupply of GOs in the market shrinks. This trend is expected to continue, with potentially higher average prices in the long term. Secondly, a linear regression model is used to analyse the extent to which product transparency in the form of information disclosure impacts GO prices. The analysis reveals price premiums based on attribute information disclosure, with GOs from certain renewable energy sources and countries commanding higher prices. However, there is a risk of selection bias, as GOs with "negative" attributes may be hidden by generic labels. In conclusion, our study highlights two main insights regarding GO market prices: increasing market price volatility and the dependence of individual GO prices on product transparency. While product transparency can increase GO prices, further research is needed to investigate whether this holds for "negative" attributes, if they can benefit from greater transparency through improved trust in and credibility of the GO market. Given that low GO prices limit the market's ability to positively impact renewable electricity production, these avenues for higher prices may aid the GO market in fostering sustainable energy production.

Keywords: renewable electricity; guarantee of origin; energy attribute certificate; market prices; volatility; transparency

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List of Abbreviations

AIB	Association of Issuing Bodies
Any RES	Any Renewable Energy Source
EAC	Energy Attribute Certificate
EECS	European Energy Certificate System
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
GO	Guarantee of Origin
MWh	Megawatt hours
NVE	Norges Vassdrags- og Energidirektorat
PPA	Power Purchasing Agreement
RE	Renewable Electricity
RECS	Renewable Energy Certificate System
RED	Renewable Energy Directive
RES	Renewable Energy Source
RQ	Research Question
TWh	Terawatt hours
YOC	Year of Commissioning

1. Introduction

The landscape of energy consumption is undergoing a profound shift, marked by a rapid ascent in the production and utilisation of renewable energy sources. In this energy transition, renewable electricity has played a significant role, as increasingly more electricity is generated by renewable sources, and electrification of processes is a common way of addressing environmental concerns. As the demand for cleaner energy rises, the role of the renewable electricity market grows with it.

Electricity has two inherent characteristics that shape the market for electricity. For one, electricity is homogeneous in its functionality. This means that regardless of its production source, electricity shares the same physical characteristics. Each electron that enters the grid performs the exact same, no matter where or how it was produced. Furthermore, electricity is non-traceable. Once an electron enters the grid, there is no way of tracing it back to its original source. In essence, feeding electricity into the grid is like pouring a bucket of water into the ocean.

The combination of these two aspects poses a problem. After all, electricity might perform the same, but there is a large difference in, among other things, the environmental aspects associated with different production methods of electricity. This creates a demand for electricity based on its production origin. But, if electricity cannot be traced, it is impossible to facilitate a market for that demand. In Europe, this led to the creation and implementation of the "Guarantee of Origin" (GO) system in 2001. The concept is simple; a GO is a certificate that documents the generation of one-megawatt hour (MWh) of (renewable) electricity. A producer may then request the issuance of a GO in their national registry for every MWh of electricity they have fed into the grid. Such a GO can then be sold, traded, and claimed by a buyer, completely independent of the physical electricity itself. Upon such a claim, the GO is cancelled and removed from the national registry. GOs provide transparency and allow for differentiation based on the origin of electricity. This reduces information asymmetry, facilitates a market for renewable electricity and allows consumer choice by informing the consumer about the origin of the electricity (Hulshof et al., 2019).

Simple as the concept may be, there are challenges that harm the market's efficiency. The system is heavily criticized for its questionable environmental impact. Both the public and academic literature are predominantly concerned with whether the GO system contributes to additional renewable electricity production or not. In academic literature, the conclusion is typically that it does not, primarily due to historically low GO prices.

However, knowledge of what those GO prices are and what determines them is limited. A key obstacle lies in the fact that the market suffers notoriously from a lack of transparency. Prices are not publicly available, intermediaries capture a large share of the revenue (Oslo Economics, 2018), and the system is incomprehensible to many (Snoeck, 2019). Furthermore, the disclosed information on GOs rarely reaches consumers (Aasen et al., 2010), and GOs are often bundled with other attributes and products, hindering product comparability (Oslo Economics, 2018). Consequently, the lack of transparency undermines the market's ability to facilitate consumer choice and product differentiation. This all leads to a lack of trust and credibility.

In light of this, the main research question of this research reads as follows: "How do market dynamics and information disclosure influence the prices of Guarantees of Origin in the European renewable energy market?"

This research will thus encompass two primary objectives related to GO prices. First, despite the low prices of GOs hindering their ability to contribute to additional renewable energy production, there is a lack of an analysis of price development in the existing literature. Therefore, the aim is to explore the general dynamics of pricing, supply, and demand in the GO market from the past 15 years. The first research question (RQ1) reads as follows:

RQ1: How have GO demand, supply and price dynamics developed over the past 15 years? And why?

Second, the research will analyse the impact of product transparency on the pricing of GOs. Literature suggests a positive impact of transparency on the trust in and credibility of the market. As a result, transparency could result in higher GO prices. However, a quantitative assessment of that claim has, to my knowledge, not yet been conducted. This research will focus on product transparency, measured by the extent to which information on GO attributes is disclosed. The second research question (RQ2) reads as follows:

RQ2: What is the effect of disclosing information on GO attributes on the pricing of GOs?

The hypotheses for RQ2 are formulated as follows:
H2a: Increased transparency in the GO attributes positively influences trust and credibility, thereby leading to higher prices.

H2b: Disclosure of information on the GO attributes leads to price differentiation among GOs based on their energy source and country of origin.

The research uses data primarily from the Association of Issuing Bodies (AIB) and from Becour AS, a company active in the GO market. Becour AS, founded in January 2018, aims to increase the value of renewable energy by marketing its product as a transparent, high-quality product. Through Becour AS, this research gets the unique opportunity to use extensive GO price data. General market price data, as employed for RQ1, ranges from 2008 to 2023. The analysis of the development of demand, supply and prices in the market is exploratory in nature. A more detailed dataset is employed for RQ2, which includes price information on a diverse range of primarily GO price offers, but also bids and trade prices, varying in the degree of information disclosure. The degree to which such information is included in the transaction will function as a key indicator of the level of transparency provided in the trade, offer or bid. A linear regression analysis forms the core of the statistical methodology, allowing for the examination of how changes in transparency influence GO pricing. In the context of this approach, "transparency" then refers to the disclosure of information on the attributes of a GO to the consumer.

The findings of this research hold implications for both academia and the renewable energy industry. By delving into the relationship between transparency in Guarantees of Origin (GO) and pricing dynamics, this study contributes valuable insights to the evolving discourse on renewable energy markets. By employing a quantitative approach, the research addresses a notable gap in existing literature. Therefore, the results are expected to enhance our understanding of how GO prices have developed historically and how transparent information disclosure on the attributes of GOs influences pricing dynamics.

In practical terms, the findings of this research offer insights for stakeholders within the renewable energy sector, including policymakers, market regulators, and industry stakeholders. Understanding the impact and relevance of transparency, may not only enable consumers to make informed decisions, but may also aid renewable electricity producers. If transparency allows for higher pricing and competition through market differentiation, it can incentivize renewable electricity producers to invest in cleaner and more sustainable energy sources.

The research is structured as follows. Chapter 2 provides an in-depth background to the Guarantee of Origin market. Chapter 3 presents an overview of the existing literature on the topic of Guarantees of Origin, especially concerning notable market developments and transparency. Then, in Chapter 4, I develop a theoretical framework on which the statistical analysis and hypotheses are based. The methodology and results of RQ1 will be discussed in Chapter 5, followed by RQ2 in Chapter 6. Chapter 7 includes the discussion, followed by the conclusion which answers the research question in Chapter 8.

2. Background

This Chapter will provide the background information required for this study. After a brief overview of the status of renewable energy in Europe, the Guarantee of Origin market will be discussed thoroughly, as a good understanding of how this market operates is crucial to the interpretation of the results. The regulatory framework around the market (Renewable Energy Directives) will be discussed, combined with an overview of the market size and structure.

2.1 Renewable Electricity in Europe

The European Union (EU) has emerged as a global leader in setting ambitious targets to address climate change and transition towards a more sustainable economy. In 2020, the European Green Deal was launched. The Green Deal is a package of policy initiatives, comprising the EU's strategy for a climate-neutral EU by 2050 (Council of the European union, n.d.-a). "Fit for 55" is a legislative package unveiled in July 2021, that operationalises the goals of the Green Deal through concrete legislative measures and targets for the next decade. With the implementation of Fit for 55, the target for cutting greenhouse gas emissions compared to 1990 levels by 2030 was set to 55 percent. For energy production, this means that by 2030, 42,5 percent of total energy needs to come from renewable sources (Council of the European union, n.d.-b).

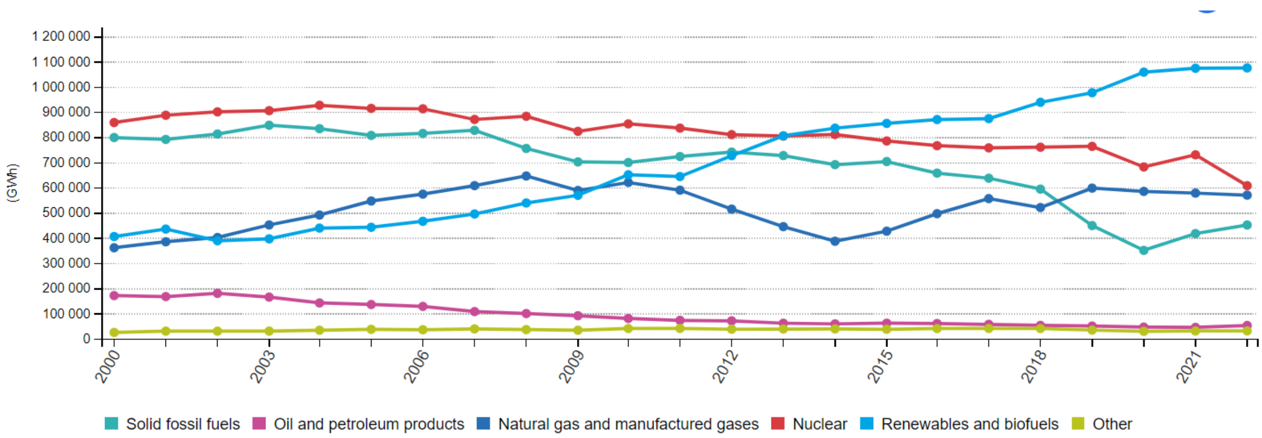

Figure 1: Gross electricity production (GWh) by fuel, EU, 2000-2022. From *Electricity and heat statistics,* by Eurostat, 2022.

As visible in Figure 1, the generation of electricity using renewables and biofuels has been steadily increasing since 2000. At the same time, electricity generation using non-renewables has been decreasing. Consequently, the total production of electricity has remained stable, fluctuating between roughly 2700 and 2800 terawatt hours (TWh) for the past 20 years. According to the yearly European Electricity Review published by EMBER, in 2023, a record 44 percent of the total electricity production was generated using renewable sources (Brown et al., 2024).

Renewable electricity from solar and wind power is intermittent energy. Unlike conventional power sources, the generation of intermittent renewable energy is not in full control of the facility owner or operator and cannot be stored. Though production can be stopped, production possibility is driven by the weather; solar power generation is contingent on sunlight availability, while wind power is contingent on wind speeds. Furthermore, there is no way to store the electricity generated. Hydropower is also intermittent to some degree; though water in hydropower reservoirs can be stored and employed upon desire, producers are still bound to the capacity of the reservoirs and weather conditions. For example, droughts in Europe in 2022 resulted in the lowest hydropower production since at least 2000 (Jones et al., 2023).

2.2 Renewable Energy Directives

Electricity Attribute Certificates (EACs) for electricity, as addressed in Hulshof et al. (2019), seek to alleviate the issue of information asymmetry prevalent in energy markets. Without an EAC system, consumers of electricity cannot distinguish between different types of electricity, regardless of its source. Furthermore, physical electricity cannot be traced back to its original source. Therefore, one is unable to purchase electricity according to their preferences. EACs then aim to solve this issue of information asymmetry inherent to the energy market (Hulshof et al., 2019).

The European Guarantee of Origin (GO) system is the most widely used EAC system. The GO system was established in 2001. The concept is simple; a GO is a certificate that documents the generation of 1 MWh of electricity. A producer may then request the issuance in their national registry of a GO for every MWh of renewable electricity they have fed into the grid. Such a GO may then be sold, traded, and claimed by the buyer. Upon such a claim, the GO is cancelled and removed from the national registry. This is called the "book and claim" system (Abad & Dodds, 2020).

In 2001, the directive on "the promotion of electricity produced from renewable energy sources in the internal electricity market" was published by the EU (European Parliament and the Council of the European Union, 2001, p.1). This directive is commonly known as the RES Directive and marks the first appearance of Guarantees of Origin. Per this directive, Member States were required to facilitate and recognize the issuance of GOs (European Parliament and the Council of the European Union, 2001). The RES directive was later superseded by the Renewable Energy Directive 2009/28/EC, commonly known as REDI. This directive broadened the scope to renewable energy, rather than only electricity, and set national binding targets. The overall target for the EU was set at 20 percent renewable energy production by 2020 (European Parliament and the Council of the European Union, 2009).

In 2002, the Association of Issuing Bodies (AIB) was founded. The AIB is responsible for the registry, issuing, trading, and cancellation of GOs. To harmonize the various national GO systems, the AIB created the "European Energy Certificate System" (EECS) standard and functions as a central hub for GO trading. As of March 2024, the AIB had 27 members, comprising both EU members and non-EU members (Association of Issuing Bodies, 2024b). Apart from Malta, Poland, and Romania, all EU countries are members of the AIB.

In 2018, REDI was substantially revised and REDII came into force, introducing new and more ambitious renewable energy targets for 2030, aiming for a binding renewable energy target of 32 percent in the EU (European Parliament and the Council of the European Union, 2018). It also required GOs to hold additional information and included provisions for the use of GOs for renewable fuels in the transport sector. As specified in REDII, GOs "have the sole function of showing to a final consumer that a given share or quantity of energy was produced from renewable sources" (European Parliament and the Council of the European Union, 2018, p. 328/90).

In November 2023, the renewable energy directive was revised yet again. In this revised version, commonly referred to as **REDIII**, energy targets were raised to 45 percent (42,5 percent binding) by 2030. In REDIII, a seemingly small, yet important shift is visible in the approach to GOs. It states that: "Guarantees of origin are a key tool for consumer information as well as for the further uptake of renewable energy purchase agreements" (European Parliament and the Council of the European Union, 2023, p. 13). Though the vision behind the GO system was always linked to promoting renewable energy, that was only explicitly entered into law in 2023. REDIII also introduced another objective: "To facilitate digital innovation…. Member States should, where appropriate, enable issuing guarantees of origin with a closer to real time timestamp." (European Parliament and the Council of the European Union, 2023, p.13). Not only does this new phrasing emphasize the importance of the GO system in the transition to renewables, but it also is a call for more granular sourcing of GOs, which would require more time-specific GO sourcing and thus improved transparency in the market.

2.3 The Guarantees of Origin Market

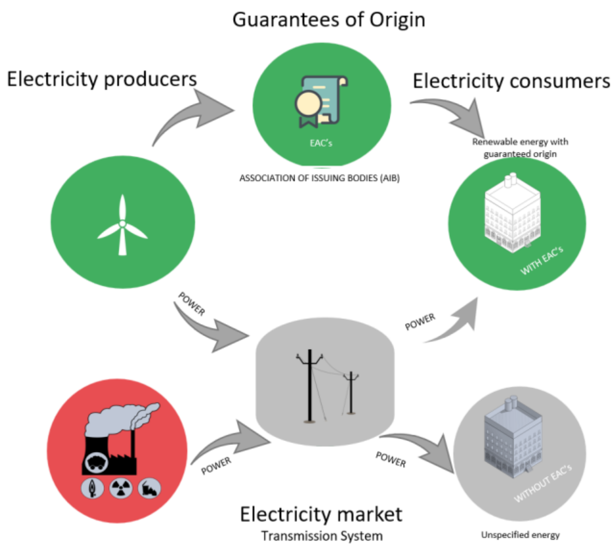

Figure 2: Illustration of the system for issuing and utilising guarantees of origin for electricity (Figure made by Becour AS).

There are multiple ways GOs can be sourced. There is a distinction between bundled and unbundled GOs (or EACs in general). When GOs are **bundled**, the GO is sold together with the physical electricity a consumer purchases. So, the electricity provider procures or produces GOs alongside physical electricity and includes the claim to renewable energy in the electricity contract. This often occurs in the form of Power Purchase Agreements (PPAs) and Green Tariffs. In the context of renewable electricity, a PPA is a direct contractual agreement between a renewable energy producer and a consumer. The consumer then agrees to purchase energy from the producer, which includes GOs. Green tariffs, on the other hand, are often offered by utility companies and include a program where consumers can choose to pay a premium on their electricity bill. The utility company acquires GOs accordingly.

When GOs are sold separately from the electricity, they are **unbundled** GOs. Unbundled GOs give the consumer more power to decide where to put their money, as they can choose to purchase from different providers, irrespective of their electricity supply. Though this can be used by companies that are simply looking for the cheapest GOs to purchase, it can also be used to support GOs from new power plants, local power plants, power plants with a larger societal benefit etcetera. Unbundled GOs are also easier to buy directly from the producer. Typically, then, transparency is higher when buying unbundled GOs.

2.2.1 GO demand and supply

Over the years, both GO demand and supply have increased. The most obvious factor contributing to changing GO supply lies in the **growth in renewable electricity production**, and thus potential GO supply. As visible in Figure 1, renewable electricity production grew steadily between 2000 and 2009 and started picking up in pace around 2010. Another foundational aspect of GO market development lies in the evolution of the **legislative framework** governing the GO market, primarily the various Renewable Energy Directives discussed previously. The initial RES Directive in 2001 marked the start of the GO market, but GOs were not yet formalised as a tradable certificate. Issuance of GOs was limited, with only eight countries having reported issuance in 2001 in the AIB statistics, compared to 27 in 2023. The legislative changes in REDI in 2009 marked a significant shift. REDI formalised the trade in GOs and mandated member states to recognise GOs issued by other member states. It marks a significant step in the integration of the European GO market. Such formalisation also put GOs higher on the agenda amongst consumers, encouraging demand.

Moreover, the gradual **broadening application** of GOs has played a role in growing supply and demand. Over time, regulations around the eligibility of renewable electricity for GOs have expanded. Increasingly more countries are issuing GOs for non-renewable electricity, though the market share is still low. A larger supply potential lies in the differing regulations around "supported" GOs. This includes GOs that have received some form of state support, such as a feed-in tariff. AIB members have different regulations around such GOs. According to a report from RECS international, around an estimated 300TWh of state-supported renewable electricity is not issued any GOs (David & Feng, 2019).

As environmental awareness and positive environmental attitudes grew in Europe, so did **demand for environmentally friendly goods and services**, including renewable electricity. Companies can use the purchase of GOs to reduce the emissions from their electricity purchases, which in turn can be used in for example Environmental Product Declarations (EPDs) and Corporate Sustainability Reporting (CSR). In a climate where stakeholders, consumers and investors care more about the environment, procuring GOs becomes more relevant to businesses. This interest shows in the emergence of initiatives such as RE100, which is a group of companies that have pledged to source 100% renewable energy at a chosen target year. Globally, the 420 RE100 members reported 224 TWh of renewable electricity consumption in 2022 (RE100, 2023). Regulations on GO procurement from RE100, which are stricter than "regular" EU regulation, are also often followed by many companies outside of RE100. For example, starting in 2024, RE100 criteria dictate that companies procure GOs from power plants built or recommissioned less than 15 years ago, thereby disqualifying old power plants (RE100, 2022). Ever since, market actors indicate that there has been more interest in power plants with a disclosed year of commissioning. The expansion of the RE100 network and its influence thus have been driving demand for GOs. Furthermore, green defaults, where renewable electricity is offered as a default option, have increased in popularity amongst electricity suppliers, increasing demand for GOs (Kaiser et al., 2020; Münzer, 2019).

Another relatively new development is the implementation of a "full disclosure" policy. The main goal of a full disclosure scheme is to create a level playing field for all electricity and enhance transparency. The Netherlands, Switzerland and Austria currently have a full disclosure system in place (Association of Issuing Bodies, 2023c). There are two main types of full disclosure. For one, there is "full production disclosure". Then, a certificate must be issued for every MWh produced, regardless of its production technology (RECS International, 2020). Austria and Switzerland have such a system in place at the moment. Those GOs can then be sold. But, as purchasing GOs from non-renewable sources is extremely unpopular, most expire after 12 months. Still, such a policy positively impacts GO supply. The alternative is a "full consumption disclosure" policy. Then, a certificate must be cancelled for every MWh consumed (RECS International 2020). This creates a level playing field for different types of electricity, as every MWh must be documented through the same system. Although a full consumption disclosure policy initially targets demand, such demand ultimately can be expected to encourage electricity producers to start issuing GOs. Currently, to my knowledge, this system has only been implemented in the Netherlands. According to RECS International, this is the preferred system (RECS International, 2020). An expansion of this system could have major implications on the European GO market; it would create a massive boost for GO demand, and thus also potentially push prices upwards.

2.2.2 Market size

The total amount of GOs issued for renewable electricity in the AIB in 2022 amounted to roughly 860TWh (Association of Issuing Bodies, 2024a). Roughly fifteen percent of those GOs are issued for nuclear power and fossil fuel generated power. In 2023, around 1200 TWh of renewable electricity was generated in the European region (EMBER, 2024). Based on this, around an estimated 60% of the renewable electricity generated in Europe was issued a GO through AIB. Historically, the supply of GOs has been higher than the demand, which can be seen by the fact that the amount of cancelled GOs is lower than the amount of issued GOs. The remainder, which does not get sold, expires typically 12 months after the production period. However, demand for GOs has been growing more rapidly than supply, such that the gap between issuance and cancellation has been steadily closing.

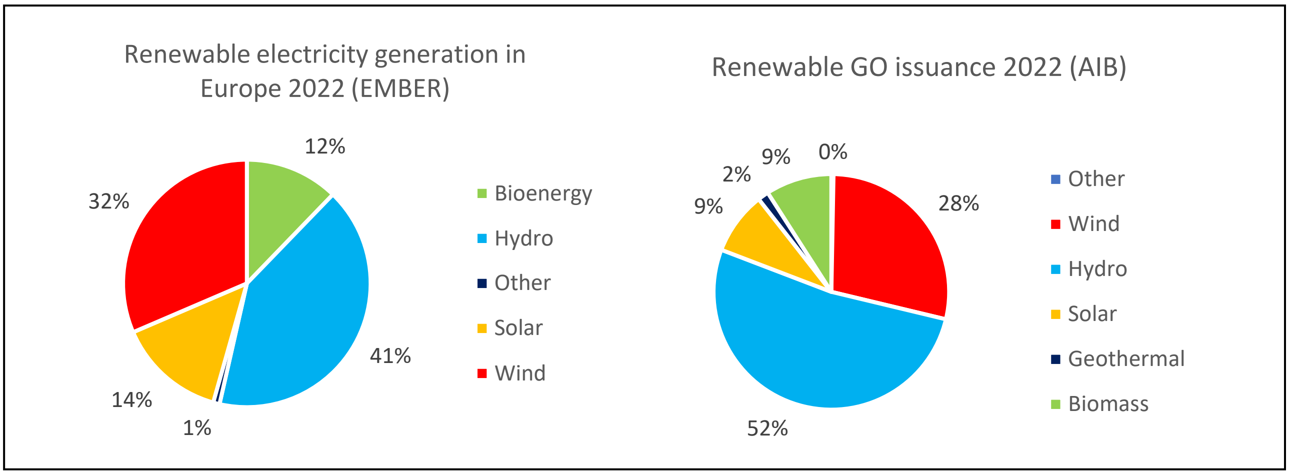

Figure 3: Renewable electricity generation in Europe 2022 (left) and issuance of GOs from renewable electricity production (right)

In Figure 3, the composition of the renewable electricity generation and GO issuance of 2022 is displayed. In 2022, 41% of the renewable electricity generated in Europe came from hydropower. In the same year, with 52%, over half of all GOs are issued for hydropower. Hydropower then is slightly overrepresented in the GO market. Solar power, on the other hand, is underrepresented in the GO market, with a volume of only 9%, despite being 14% of the electricity generation. The explanation of why GO issuance is not equal to renewable electricity supply comes from the fact that not every MWh of renewable electricity produced is and can be issued a GO. For one, producers may lack the knowledge, capacity or resources required to enter the GO market. For example, a survey conducted by "NLgroen" found that amongst Dutch farmers, only 16 percent of respondents knew what a GO was, despite 76 percent of respondents generating renewable energy (Kruisselbrink, 2023). Especially for small power plants, the registration fees and effort required may be too high to enter the market. A large part of the explanation also lies in the regulatory frameworks in various countries, particularly surrounding "supported" GOs. "Support" GOs refer to GOs of electricity that benefited from some form of a government support system, such as a Feed-in-tariff or a production related tax benefit. Some AIB members have no regulations on subsidies whatsoever, such as the Netherlands, Norway, Sweden, and Spain. However, in Germany for example, a producer that chooses to receive a feed-in tariff cannot receive a GO (Wimmers & Madlener, 2023). Historically, GO prices have been lower than the feed-in tariff, resulting in a low supply of German GOs. Other regulations on supported GOs include auctioning of the GOs, immediately cancelling the GOs, or obliging disclosure on subsidy reception on the GO.

2.2.3 Trading in the Market

Though the concept of a GO is rather straightforward, the workings of the market are complex. Typically, multiple intermediaries are involved in trading GOs before a GO reaches the final consumer. As a power producer, you have multiple options to sell your GOs. A frequently used figure from Oslo Economics (2018) illustrating how GOs are traded can be found in Figure 4.

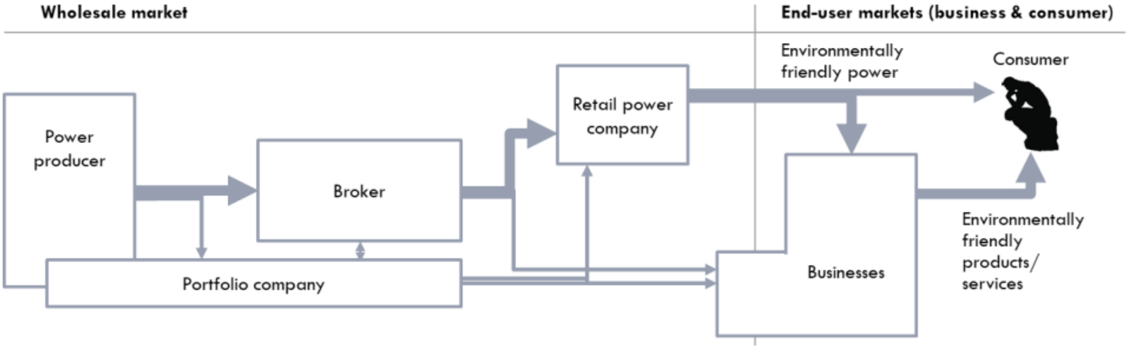

Figure 4: How GOs are traded: Buyers, sellers and intermediaries. From *Analysis of the trade in Guarantees of Origin* (p. 16), by Oslo Economics, 2018.

In this Figure, a distinction is made between the wholesale market and the end-user markets. The width of the arrows represents roughly the value of the GOs flowing through the parties in the market. Anything in between the power producer and the consumer of the power, albeit private or corporate, are intermediaries. Typically, a GO passes multiple parties before it reaches the consumer. Consequently, a large share of the final GO price the end-consumer pays, does not end up at the electricity producer.

Most power producers sell their GOs through brokers. A broker acts as an intermediary between the GO supplier and the retailer, a business, a power company, or another broker. According to Oslo Economics (2018), Statkraft reported selling an estimated 60 to 70 percent of their volumes through brokers (Oslo Economics 2018). Selling GOs through brokers limits risks for the energy producer, as brokers tend to possess high expertise and networks the producers may not possess themselves. Brokers earn fixed commissions for arranging the trade. Portfolio companies work similarly, but act as a counterparty for both the producer and the consumer, buying GOs from producers or managing the trade of GOs for the producer entirely. Portfolio companies also often assist in the documentation of renewable energy and offer GOs bundles with labels, certification, and promotional material (Oslo Economics, 2018).

GOs are often traded several times between brokers and/or portfolio companies before they reach the end-user market. It has even been reported that producers buy GOs from other producers, as a way of speculative trading (Snoeck, 2019). The prices in all these intermediated transactions are typically not publicly shared, and each time a transaction takes place, a fraction of the price is taken up. This way, usually only a small share of the total price paid by the consumer ends up at the power producer.

Another option is to engage in bilateral trade. Bilateral trade includes direct trade between the power producer and a retailer, business, or public organisation. If such a trade is established between the power producers and an electricity trader, the GO can be bundled with the physical power, often in the form of a Purchasing Power Agreement (PPA). Bilateral trade provides a more direct link between producer and consumer and therefore improves transparency of the trade and enhances the share of revenue taken by the producer (Oslo Economics, 2018). But, this type of trade can be time consuming and costly to facilitate, especially for small producers and consumers (Snoeck, 2019).

3. Literature review

The GO system has been under heavy debate ever since its implementation, both in academia and in the regular media. This Chapter contains an analysis of the existing body of literature on the GO market. Academic literature on GOs is quite scarce, so grey literature has occasionally been consulted as well, particularly concerning market developments. This literature review is divided into three Sections. First, it reviews the literature discussing the impact of the GO market on renewable energy production, the seemingly most common topic of review in academia. Next, it reviews what is available on the development of demand, supply, and market prices. In the last Section, the transparency in the GO market will be thoroughly analysed.

3.1 The impact of the GO market on renewable energy development

The main critique of the GO system relates to its questionable effects on renewable energy production. A large share of the available literature on the GO market has been dedicated to assessing the (potential) impact of the GO system on renewable energy production and investment decisions, with the overarching conclusion being that the GO system does not work sufficiently to enable additional renewable energy production.

In a panel data analysis on 30 European countries between 2009 and 2016, no significant relationship was found between the renewable energy supply development and the consumer market for products supported by GOs (Hamburger & Harangozó, 2018). Country-specific analyses have also been conducted. Mulder & Zomer (2016), upon analysing data from the Dutch electricity market, concluded that the GO system does not foster additional investments into renewable electricity, as consumers only pay a low premium for renewable electricity. Similar results were found in an analysis of the Greek market by Dagoumas & Koltsaklis (2017), who concluded that the GO prices were too low to be an incentive signal for investors. Similar results were also found in Herbes et al. (2020), who analysed the green electricity supply of electricity suppliers active in the United Kingdom, Italy, Germany, and France. They concluded that in those countries, the consumer demand for green electricity was not sufficient to drive the expansion of renewable electricity production independent from state support. Germany and France showed a strong dependence on Scandinavian certificates, which typically originate from decades-old power plants. Then, GO purchases arguably do not contribute to additional renewable electricity generation (Herbes et al., 2020). Additionality is also central in Brander et al. (2018), who critique the use of GOs in Scope 2 emission reporting. They argue that the system discourages mitigation of electricity consumption by companies, if companies can claim to be green by simply purchasing cheap GOs (Brander et al., 2018). Nordenstam et al. (2018) expand on this argument, claiming that if a GO does not lead to additional renewable electricity production, companies engaging in GO purchases rather than energy efficiency efforts may actually lead to higher overall CO2 emissions. Finally, Hustveit et al. (2017), aimed to assess the performance of a market of tradable green certificates, taking the Norwegian-Swedish electricity certificate market as a case study. They conclude that the uncertainty caused by the unpredictability and volatility of certificate prices discourages investments. Presumably, the same can be said for the GO market.

In conclusion, the literature discussed does not find a positive environmental impact of the GO system in Europe. The low GO prices and thus the low-income producers derive from the GO sales is the main driver for this, as they provide no incentive for investments in additional power supply. If such additionality does not exist, the system may even have negative effects on CO2 emissions, if it disincentivises electricity consumption mitigation.

3.2 GO Market dynamics: price, supply, and demand shocks

In Section 3.1, it became apparent that low GO prices are identified as a hindrance to the GO market having a positive impact on renewable electricity (RE) production. This raises a question: What is the price of a GO? And what impacts that price? Academic literature on GO prices is scarce. Therefore, in order to research this topic, grey literature had to be employed. First, the available literature on GO prices will be discussed. Then, an overview of the market developments will be presented, separated into structural developments and temporary developments/shocks.

3.2.1 Prices

Public information on GO prices is rare, let alone proper price data. Those active in the market, like brokers and traders typically have a good understanding of the market prices. However, to those outside the market, prices remain vague. Even the AIB, that registers the issuance and cancellations of GOs, does not obtain (price) details of the trade; such information remains between the market participants. In order to get an impression of the historic GO prices, literature tends to resort to price estimates based on market intel. Two recent articles discussing GO prices were published by Wimmers & Madlener (2023) and Petryk & Adamik (2023).

In Wimmers & Madlener (2023), a model to forecast GO prices was set up. They used data up to 2022 to calculate future prices, based primarily on historic GO prices, and private household Willingness to Pay (WTP) and Ability to Pay (ATP) for green electricity. The historic GO prices used in their research originated from a variety of sources, including GO auction data, price information from other academic research, and published market analyses. GO prices were forecasted to increase on average in the years to come, with prices ranging from 1,77 to 3,36 EUR/MWh. However, already in 2023, the GO market displayed how unpredictable it is, as average prices for 2023 already went way above their estimates. Though the volatility of the market was acknowledged in the research, the model did not provide insights into how such volatility could develop and impact the future prices. But most importantly, one could contest whether using private household WTP and ATP is suitable to capture GO demand, as it neglects corporate demand for GOs and regulatory frameworks impacting demand.

Another recent article analysing price trends in GOs in Poland by Petryk & Adamik (2023) tested the correlation between electricity prices and GO prices. They found a strong correlation with an R-squared of 0.85. The period they analysed was from Q1 2020 to Q2 2022, which was a period with a volatile price environment for both electricity and GOs. However, the article provides no explanation or argumentation for why such a (positive) correlation may exist. A potential explanation could be that GO supply and (renewable) electricity supply are linked, and thus share similar supply shocks. Therefore, a negative supply shock due to for example low hydro reservoirs would have an upward effect on both GO prices and electricity prices. However, renewable electricity is only a share of the total electricity production, so supply shocks will have different relative strengths. On the demand side, it is more complicated. For one, the demand for physical electricity cannot be equated with the demand for documentation of the origin of renewable electricity. Furthermore, high electricity prices may discourage GO purchases if the high prices make consumers reluctant to also purchase GOs on top of the high electricity prices. In that case, high electricity prices would imply lower GO demand and thus lower GO prices. That argument could also be flipped, as market actors have suggested that the high electricity prices actually increased GO demand, as consumers saw the GO price as only a marginal price addition. Notably, according to the GO and electricity price data collected and analysed for this research in Chapter 6, the relationship switches right after the research period in Petryk & Adamik (2023). Whereas electricity prices started decreasing around mid-2022, GO prices continued to increase (see Appendix Figure I). Based on this, I consider the correlation found in Petryk & Adamik (2023) as non-conclusive. Arguments for either a positive or a negative correlation can be made, so further research into this matter should be conducted before reaching a conclusion.

A relatively new trend in the GO market that may improve liquidity and access to market prices is the one of GO auctions. In a GO auction, GOs are auctioned off that have received public support such as a subsidy. The income of these auctions is then used to fund the national support scheme. The first auction took place in September 2013 in Italy. Since 2018, six other countries started GO auctions, being Luxembourg, France, Croatia, Slovakia, Portugal, and Hungary. The results of the auctions are published online by the corresponding issuing bodies. GOs obtained through auctions may be resold and do not represent the whole market, but their prices can still function as an indicator of market prices and trends (Wimmers & Madlener, 2023). Based on the public data published by the auctioning bodies, roughly 80 TWh of GOs were traded in such auctions in 2023, with roughly 47TWh being traded in the French auctions and 20TWh in the Portuguese auctions (see Appendix Figure II). The Italian auctions have been large in terms of offered volumes, but have been severely oversupplied, with only a third of the total offered volumes being sold. With an annual GO market size of around 900TWh, auctions still only make up a small share of the GO market. The prices at recent auctions indeed appear to follow the general trends. To my knowledge, no academic literature has discussed the (potential) effects of these GO auctions on market prices, liquidity, or volatility.

3.2.2 Supply and demand shocks

Through literature, several events have been identified as having had an impact on GO market prices. Such events are scattered throughout some academic literature, policy documents and blog posts.

First of all, weather conditions are continuously impacting the short-term supply on the GO market, due to the intermittent nature of most renewable energy sources. Therefore, periods of for example dryness, cloudiness, or a lack of wind can limit short term GO supply. Particularly hydropower reservoirs, given the large share of hydropower in the market, can create supply shocks in the electricity market (Mosquera-López et al., 2018). For example, in 2018, low Norwegian hydro reservoirs – because of a hot and dry summer – reportedly resulted in lower expected GO supply and thus increasing prices (Münzer, 2019). Around the same time, Swiss demand grew as a response to the implementation of the full disclosure policy. In September 2018, hydropower reservoirs recovered, and so did GO supply. Speculative trading further amplified these shifts in GO demand and supply (Münzer, 2019). Later, in 2021, drought led to low hydro reservoirs in the Nordics once more, causing a panic in the market, with market actors hoarding GOs

(Lakovlev, 2022). Later, at the end of 2023, on the contrary, the influx of Nordic hydro GO issuance was reported to create oversupply in a market already in a price decline (Lakovlev, 2023).

A frequently discussed event in the market is the response to the Fukushima nuclear power plant disaster in March 2011. Consumers and businesses started demanding nuclear free power contracts, reducing demand for nuclear GOs, and simultaneously boosting demand for documentation of nuclear-free electricity (Oslo Economics, 2018). It thus incentivised consumers to start procuring GOs, to demonstrate a lack of nuclear power consumption. Germany responded to the disaster by temporarily shutting down the oldest 6 of its 17 reactors (Grossi et al., 2017). However, in 2023, market actors report an increased interest in nuclear GOs, spurred by the higher prices for other renewable GOs, and a change in EU taxonomy regarding nuclear power (Malinen, 2023).

Regulatory changes have also triggered a price response. In 2016, a price surge occurred in response to a miscommunication by Ofgem, the regulatory body in the United Kingdom. In January 2016, they communicated that new regulation would allow unconstrained implicit trading of GOs (Ofgem, 2016a). This meant that consumers in the UK would be able to import foreign GOs without limit, therefore increasing demand for GOs. Consequently, prices went up (Oslo Economics, 2018). However, it was not clear when this new regulation would come into effect. Later, in April 2016, a clarification regarding the new regulation was published, which was still open to interpretation (Ofgem, 2016c). Only in June 2016, they finally clarified that the new regulation would apply for the scheme year 2016/17 onwards, and not for the 2015/16 scheme year (Ofgem, 2016b). Accordingly, GO demand adjusted back down.

2023 marked a historic year for the GO market, with prices reaching new records. The momentum towards rising prices started in 2021, when drought led to low hydro reservoirs in the Nordics once more (Lakovlev, 2022) The scarcity of supply triggered a market response and hoarding of GOs. In 2022, inflation in Europe was running high because of the fiscal stimuli during the COVID-19 crisis (Lakovlev, 2022). Moreover, the Russian invasion of Ukraine caused a spike in gas and electricity prices and heightened the urgency for energy independence and renewable energy solutions across Europe (Mills et al. 2023). Plus, 2022 turned out to be yet another dry year for Europe, further amplifying the shortages of hydropower. Interestingly, the high GO prices for renewables combined with a change in EU taxonomy around nuclear power, the demand for nuclear GOs is reported to have increased (Malinen, 2023).

Around August 2023, prices started decreasing. The hydro reservoirs balanced back to normal, and it was a windy year. Furthermore, in April 2023, the United Kingdom stopped recognising foreign GOs (Ofgem, 2023). The UK was a large net importer of mostly Norwegian GOs. Thus, their exit from the market reduced demand. And lastly, a temporary oversupply was created by the Italian auctions, after a large volume of GOs was left unsold due to the minimum auction prices being set too high. These factors combined contributed to GO prices decreasing.

In conclusion, the lack of literature available on GO prices and price dynamics reveals a research gap. While grey literature discussing supply and demand developments is available, literature on GO prices is very scarce. There is, to my knowledge, no literature discussing how GO prices have developed, and especially how these developments tie in with the demand and supply developments.

3.3 GOs as information carriers: the case of transparency

The absence of accessible price data points to a broader issue in the GO market. Transparency in this market is notoriously low. The issues with transparency in the GO market encompass more than just prices. Existing literature suggests that a lack of transparency may contribute to low prices of GOs. The upcoming Section delves into this literature discussing transparency in the GO market and evaluate to what extent these issues may influence pricing dynamics in the market. For the sake of clarity, the transparency related issues identified in the literature are categorised in three areas: those related to market-, product- and price transparency.

3.3.1 Market transparency

The GO market is complex and beyond the comprehension of many. This fosters a lack of trust in the market. Aasen et al. (2010) interviewed corporate consumers of renewable electricity tariffs in Norway and concluded that consumers mistrusted the system, because physical electricity cannot be tracked and a lack of understanding of the market. Mistrusting the system because physical electricity cannot be tracked is remarkable, because that is the core reason the GO system exists in the first place. Comparable results were found among households by Winther & Ericson (2013), who offered information to Norwegian households and led focus groups, found that participants found the presented information incomprehensible. This had negative effects on the participants' trust in the system.

The pervasive misunderstanding of the market recently became evident in the case against Budweiser. The Advertising Standards of Ireland (ASAI) called back Budweiser for its claim of 100 percent renewable electricity claim, based on their purchase of GOs (O'Doherty, 2024). However, under REDIII, Budweiser's claim was fully justified. The ruling of ASAI was based on a misconception of the GO market, wrongfully equating GOs to carbon offsets (Gunst et al. 2024).

The misunderstanding and misuse of the GO market also shows in the discussion surrounding double counting. Double counting, or double claiming as it is often referred to as, occurs when a MWh of renewable energy is claimed twice, by two separate parties. This can happen due to the existence and employment of different reporting methods. In a nutshell, companies following the Greenhouse Gas (GHG) protocol can choose between a "location-based" and a "market-based" method for reporting the emissions of their electricity consumption. The location-based method looks at the emissions of the physical electricity of the grid you are taking electricity from. The market-based method, on the other hand, bases the emissions on the purchasing decisions concerning electricity consumption. A company purchasing renewable GOs for their full electricity consumption would thus have zero market-based emissions, regardless of where this consumption takes place. Alternatively, a company located in a geographical area with only renewable energy production, would have zero location-based emissions. Having both location- and market-based leads to double counting. The renewable energy a party is claiming via location-based reporting can be claimed by another party by purchasing GOs and using market-based reporting. For example, in mid-2023, it became apparent that Iceland had exported GOs for approximately 15TWh, out of the 19TWh of renewable electricity produced in the country. The country hosts three large aluminium smelters, who combined claimed 12TWh of renewable energy through location-based reporting (Böck, 2023). This 12TWh of renewable energy produced in Iceland has thus been claimed twice. AIB has stated that location-based reporting in an area where a market mechanism (such as a GO system) exists, "undermines the credibility of the legislative guarantee of origin system" (AIBb, 2023, p. 5). However, despite the real problem that double claiming is in the market, double claiming has also been **misinterpreted**. For example, in Jansen (2017), the implementation of state-led GO auctions is discussed. The author proposes that auctioning GOs that have received state support leads to double counting. The double claim comes from the fact that the first "claim" to the renewable attribute is made by the producer in order to receive a subsidy and then by the consumer of the GO on the auction (Jansen, 2017). However, this is not double counting. The producer, upon receiving the subsidy, is not "claiming" the consumption of the renewable electricity they produced. Making a claim about the renewable nature of your production in order to receive a subsidy is independent of the GO system and does not invalidate the GO system.

The occurrence and accusations of double counting underscore the importance of transparency in the market. The confusion surrounding reporting methods and the subsequent double claiming reveals a lack of transparency in how energy attributes are tracked and documented, creating loopholes that allow for misrepresentation of renewable energy consumption. The misinterpretation by Jansen (2017) serves as an example of how deep the misunderstandings in this market go, as they are also visible in the literature. This lack of transparency in how the market operates and the consequent misuses and misunderstandings ultimately undermine the credibility of the GO system.

3.3.2 Price transparency

The next branch of transparency in GOs relates to price transparency. As discussed in Section 3.2, prices are generally not publicly available and price data or analysis in literature is also limited, often differing from source to source and including wide ranges.

There are two explanations for this lack of price transparency in the market. For one, GOs are often **bundled with other attributes and products**. For example, in a PPA, the purchase of the GO is bundled with the purchase of the physical electricity. As the interviews conducted by Snoeck (2019) revealed, the consumer typically does not see what share of the price is for the physical electricity, and what share is for the GO. This was found to be a strong deterrent for procuring renewable electricity (Snoeck, 2019). Furthermore, upon the evaluation of the GO market by Oslo Economics, it was found that this bundling of GOs with other products makes it hard to compare prices and capture the large variety in consumer preferences. This affects price transparency (Oslo Economics, 2018).

The second explanation relates to the **trading structure** in the market. Usually, it is unclear to consumers what share of the GO price they pay ends up going to the producer of renewable electricity. The number of intermediaries, and the prevalence of opportunistic trading behaviour create an environment where a lot of revenue is lost on the way (Snoeck, 2019; Syväri, 2022).

Interviews on the REC market in the United States conducted by Holt et al (2011) pointed out that a lack of price transparency affects confidence, risk perception, and inhibits producers from seeing renewable energy certificates as a potential source of revenue (Holt et al., 2011). Presumably, the same can be said for GOs.

3.3.3 Product transparency

The last aspect of transparency in the GO market relates to the transparency of a GO as a product. A large share of the information a GO contains never reaches the consumer. Whereas a GO represents a unique product based on its exact origin, GOs are often sold as generic products. One can divide the GOs end-users buy into three tiers, as proposed by Oslo Economics (2018). The first category is "generic" GOs. Most firms purchase such GOs, that are not differentiated in terms of location or technology (Oslo Economics, 2018). A GO is then usually nothing more than a tool to "tick off the box," enabling the consumer to claim renewable electricity without providing further transparency. According to Oslo Economics, Nordic Hydro is usually the cheapest GO available, due to large supply and low demand from the Nordics (Oslo Economics, 2018). The second category is what I will call "premium" GOs, with more information regarding geographical and/or technology, and other surface level information, such as the presence of ecolabels, year of commissioning and subsidy information. Lastly, there is the third tier, which is "tailored" GOs. These are GOs that are for example plant-specific, include some sort of reporting or marketing service, or include additionality clauses (Oslo Economics, 2018).

The practice of buying non-transparent, generic GOs does not come without risks. Interviews with German enterprises revealed that the incomplete and/or false information provided to consumers on green electricity is one of the most critical deterrents for electricity consumers to buy renewable electricity (Rahbauer et al., 2016). In 2012 for example, the extensive purchasing of primarily Norwegian hydropower GOs by Dutch companies led to uproar from environmental groups, who rebranded such GOs to 'sjoemelstroom' (cheat electricity) (Hufen, 2017). Consumers felt misled by their electricity suppliers, who had not been transparent about how the renewable electricity was sourced. Consequently, the demand for local Dutch GOs grew, and prices increased (Hufen, 2017). The recent case involving Budweiser and the ASAI, as briefly discussed in Section 3.2.2, also serves as an illustration of the risks associated with a lack of product transparency. Though Budweiser's claim to renewable energy using GOs was technically justified under REDIII, their claim could have been more credible and easier to defend, had Budweiser invested in sourcing high-quality, transparent GOs and documented them properly. Cases such as these also help explain why the transparency offered by premium and tailored GOs may come with a price premium.

3.4 Conclusion and research gaps to be addressed.

Based on the literature analysed for this literature review, several research gaps have emerged. Multiple articles point towards the impact of the GO system on renewable energy production, with the common conclusion being that it does not directly contribute to additional RE production. The main causes of this are the low GO prices, which are amplified by the low percentage of GO prices going to the producers caused by the large number of intermediaries in the market. Consequently, higher GO prices are a potential path for a more impactful GO market.

However, literature on what those GO prices are and what determines them is scarce. GO prices are not publicly available, and research tends to rely on estimates and market intel. A correlation between GO prices and electricity prices has been suggested, though a theoretical explanation for such a correlation was not provided. A GO forecasting model displayed the difficulties in predicting GO prices and did not account for the high volatility in the market. Developments of supply and demand are more available, primarily in grey literature. However, they are usually analysed in isolation and not put in a broader context with prices. That is, the link between these supply and demand changes with GO prices is not made.

Additionally, the literature review identified transparency as a persistent issue in the GO market. Market-, price- and product- transparency are all interrelated and point to various aspects of a lack of transparency in the market. Such a lack of transparency is a hindrance for consumers to purchasing GOs, ultimately affecting market prices through lower demand. However, existing assessments of the transparency in the GO market are primarily qualitative, and a quantitative analysis of its effects on pricing in the market is lacking.

In light of these findings, this study proposes two research questions. The first research question (RQ1) aims to gain insight into GO market price development. By leveraging historical data on demand, supply and GO prices, a picture of how GO prices have developed and to what extent demand and supply dynamics have played a role in that development. It is hypothesized that the price responses to demand and supply shocks have shown increasing volatility during the observed period.

The second research question (RQ2) takes a quantitative approach to the impact of product transparency on GO prices. Through data made available through Becour AS, it is possible to compare prices of “generic” GOs with “premium” GOs. The aim is to identify to what extent the price of a GO is influenced by the disclosing of attributes of the GO. In doing so, I also analyse market differentiation based on such attributes.

4. Conceptual framework

In this Chapter, the two conceptual frameworks that form the backbone of the research questions will be discussed. Section 4.1 discusses equilibrium theory and specify the core assumptions made with regard to supply and demand. It proposes that with increasing inelastic supply, the market becomes more volatile as it moves towards higher cancellation rates. This theory will be used for RQ1 in Chapter 5. Next, the framework for transparency and market differentiation will be discussed in Section 4.2. It proposes that information on GO attributes influences prices through two channels. For one, transparency improves credibility which creates a price premium. Furthermore, the information allows for market differentiation and thus price differentiation. Following these two frameworks, Section 4.3 pinpoints the expectations and hypotheses for the research questions.

4.1 Equilibrium theory

The statistics from the AIB combined with the market price data from Becour AS will be analysed through the lens of equilibrium theory in RQ1. The market equilibrium is determined by the interplay of demand, which decreases with increasing prices, and supply, which increases with increasing prices. At the point where supply equals demand, the market has obtained an equilibrium. In this model, structural growth/decline, and shocks in demand and supply impact equilibrium prices and quantities in the market. A negative (positive) supply shock pushes prices up (down) and quantities down (up). Demand shocks have the opposite effect on prices, as a negative (positive) demand shock pushes prices down (up). The simplest version of a market with a supply and demand curve is illustrated in Figure 5.

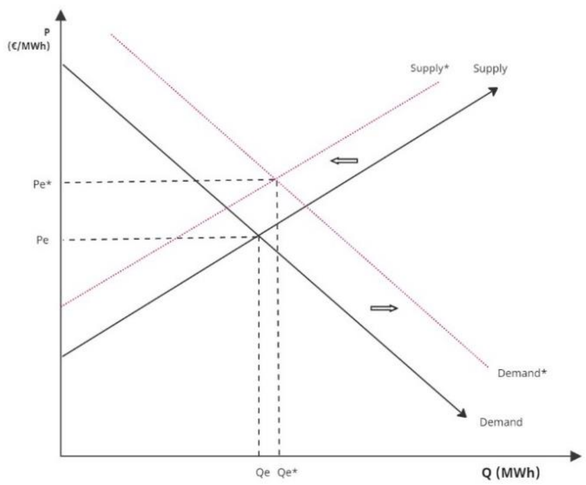

Figure 5: Basic supply-demand equilibrium.

While this simplified model provides a solid framework for understanding demand and supply dynamics, it does not capture the specific nuances of the GO market. Therefore, I build upon this standard model to represent the dynamics in the GO market more clearly. The model will represent a short-term supply and demand situation. Short-term is considered to be 12 months, the standard expiration period for a GO.

The assumptions I make regarding the supply curve are:

1) Engaging in a GO trade is not fully cost-free. Registration of a power plant, a transaction through AIB, and transferring of a GO etc induce costs. For simplicity, I assume these costs are fixed at FC. For prices below FC then, no GOs are issued or traded.
2) Once a GO has been issued, it expires after 12 months. Therefore, producers that have already issued a GO are willing to sell for any price at or above transaction costs at the end of the period.
3) Given assumptions 1) and 2) when market prices P equal FC, supply equals X.
4) As prices go up, new RE producers enter the market and issue GOs for their production.
5) There is a maximum amount of GOs (S_{max}) that can be issued for a given period, due to constraints in RE production, barriers to entry to the AIB market, national legislation etc. Weather conditions may impact S_{max} in the short term as well. When the market equilibrium is at S_{max}, the cancellation rate would be 100 percent.
6) Supply decreases in elasticity as prices go up until S_{max} is reached.

Considering these assumptions on supply, it is possible to illustrate different market stages to understand the effects of demand and supply shocks at varying demand levels. The conceptual framework is visualised in Figure 6.

Stage 1: Low demand. Demand curve $\mathrm{D_1}$ crosses at P=FC. However, at P=FC, supply is higher. The gap is the oversupply (XS) visible in the market. A shock in supply and demand is represented by the dotted lines. In this stage, shocks in supply and demand influence the size of XS, but do not change the market price, unless they are strong enough to fully remove XS. A market in Stage 1 then, will only see very minor price fluctuations.

Stage 2: Demand has grown to $\mathrm{D_2}$, to the point where the market is in equilibrium. Supply equals demand at the end of the flat part of the supply curve. Prices have thus remained unchanged from Stage 1. However, shocks now can impact market prices and quantities. A positive demand shock and a negative supply shock will push prices up. Negative demand shocks or positive supply shocks will create oversupply in the market but have a negligible impact on prices. A market in Stage 2 then will start showing more price volatility.

Stage 3: Demand has grown even more, to $\mathrm{D_3}$. Oversupply is no longer an immediate risk in the market. Demand and supply shocks will impact market prices and quantities no matter their direction.

Stage 4: Demand has grown yet again, to $\mathrm{D_4}$. As the equilibrium has moved up the supply curve, it is positioned at a place with weaker supply elasticity than in Stage 3. This implies that the impact of demand

and/or supply shocks on prices has increased, as illustrated in Graph 6. Therefore, the further along the supply curve the market is, the higher the volatility that can be expected in the market.

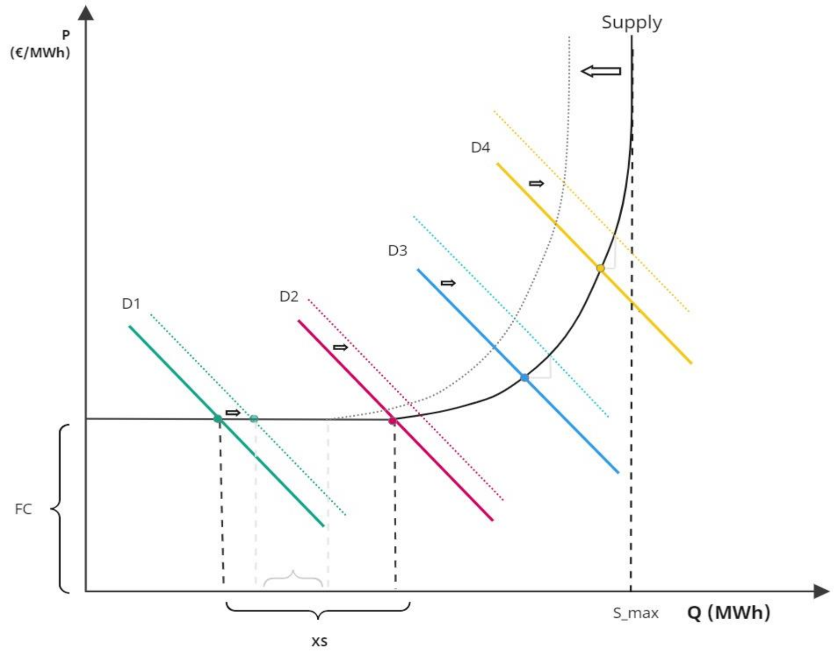

Figure 6: Conceptual supply-demand framework.

In the long term, both supply and demand can structurally move. An equal growth in supply and demand would keep the market prices unchanged, only moving along the x-axis with higher quantities. If demand grows faster relative to supply, the stages described above still hold. The growth in demand should then be interpreted as the growth in demand relative to supply. Alternatively, if supply sees growth stronger than demand, for example, due to a change in regulation, it will push the market "back" to a previous stage.

Overall, this model suggests that as supply and demand evolve over time, their respective growth/decline dictate at which stage the market is located, and thus how the market responds to shocks in supply and/or demand.

4.2 Transparency & Market differentiation

The conceptual framework relating to transparency and market differentiation can be summarized as follows: providing information on the individual characteristics of a GO results in product transparency. The framework posits that this impacts pricing dynamics through two channels. First, the product transparency has value to the consumer, as it enhances the trust and credibility of the system, the purchase, and the documentation process. This value to the consumer is represented by higher prices for the GO. Second, the information on the attributes of a GO enables consumers to make a purchasing decision tailored to their preferences. Consequently, different attributes will be associated with different prices, as product transparency allows for product- and price differentiation. Positive (negative) environmental attributes are then associated with higher (lower) prices. Figure 7 illustrates this theoretical framework.

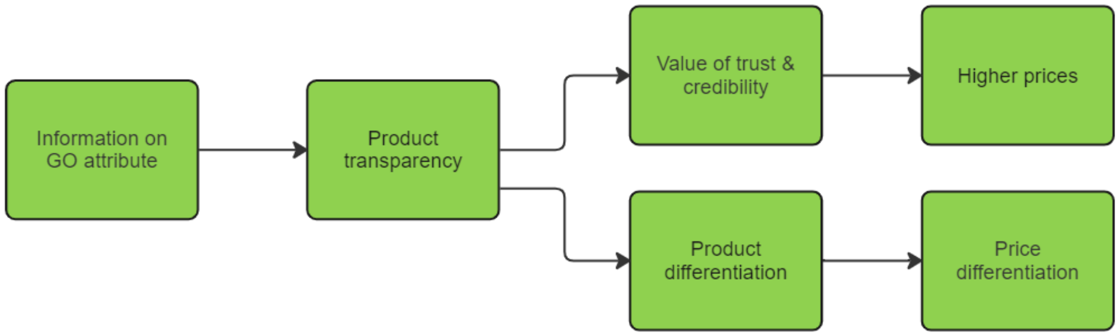

Figure 7: Conceptual framework for the effects of information disclosure.

Information on attributes of GO contributes to product transparency.

Providing information on the individual attributes of a GO contributes positively to product transparency. These attributes could include details about the renewable energy source, the year of commissioning, and other relevant characteristics. For example, the product transparency of a solar GO originating from France, produced in the first quarter of 2023, commissioned in 2019, with no ecolabel and no government support is clearly larger than that of a GO originating from any renewable energy source somewhere in Europe. Different levels of information provided thus represent different levels of product transparency. Such product transparency is hypothesised to have effects on prices through two channels: through product differentiation and through trust and credibility.

Product transparency creates value for the consumer.

Transparency is a factor influencing both trust-building and credibility to consumers. A lack of transparency fosters information asymmetry between the seller and the consumer of a GO. Information asymmetry is a well-established within economics, first coined by George Akerlof (1970) in his seminal "Lemons" article (Akerlof, 1970). The idea is as follows: suppose there is a market for a certain good, with low-quality and high-quality goods. If consumers cannot distinguish between low-quality and high-quality goods, sellers of low-quality goods can trade on the market for high-quality goods. The markets and prices of the goods merge into one. This harms both the high-quality sellers, as their income diminishes, and those who wish to purchase high-quality goods, as they cannot locate and purchase high-quality goods. Consequently, the high-quality goods may leave the market. Such a result is known as adverse selection. In the context of the GO market, information asymmetry created by intransparency would imply that the demand of those consumers looking for specific, high-quality GOs cannot be met, and the owners of said GOs do not receive the true value of the GO.

Later, Michael Spence (1973) posited the theory of "signalling" to counteract such adverse selection (Spence, 1973). Signalling theory is a framework used to understand how individuals or entities convey information to others in a way that impacts behaviour. Spence proposed that two parties could avoid the problem of adverse selection by having one party send out a signal that would reveal relevant information to the other party. The other party would interpret the signal and adjust their behaviour accordingly. Though Spence's paper was oriented around the labour market, positing that education serves as a signal for productivity to an employer, it is applied to many other cases as well. In the context of GOs, providing product transparency acts as a signal of the seller's commitment to providing accurate and reliable information about the GOs. Signalling theory then posits that such transparent disclosure can act as a signal of trustworthiness and commitment, which builds credibility. Buyers may then be willing to pay a premium for GOs with transparent attributes, viewing them as more valuable and credible.

Product transparency allows for price differentiation.

Market differentiation involves the process of distinguishing a product or service from others in the market to cater to specific consumer preferences. The GO market functions well to distinguish between non-renewable and renewable energy sources. However, differentiation between different types of renewable origins, requires that the GO contains (detailed) information on the origin. The product transparency provided by the information is hypothesized to lead to price differentiation.

In economics, product differentiation is the process of distinguishing a good or service from others to make it more attractive to a targeted market. The concept was first proposed by Edward Chamberlin in 1933, in "The Theory of Monopolistic Competition" (Chamberlin, 1933). He theorised a product is differentiated if "any significant basis exists for distinguishing the goods (or services) of one seller from those of another… buyers will be paired with selects, not by chance and at random (as under pure competition), but according to their preferences" (Chamberlin, 1933, p.56). Therefore, product differentiation allows consumers to make decisions based on their preferences. In Woo et al., (2014), product differentiation is analysed in the context of the electricity market. The literature revealed that product differentiation is a meaningful concept for the electricity market, as it can greatly contribute to meeting consumer demand more effectively and efficiently. The authors point out that especially in a world where environmental issues increasingly become more important, the provision of differentiated products is an important tool (Woo et al., 2014).

Though product differentiation is linked to signalling theory, in the sense that they are both concerned with providing a basis for differentiation and influencing consumer behaviour, they differ in their focus. In signal theory, the goal is to signal quality or reliability, whereas in monopolistic competition, the goal is to differentiate products to create uniqueness. Therefore, signal theory can be used to explain why prices may be higher for products deemed credible due to disclosure of attributes, whereas product differentiation explains why different attributes are associated with different prices.

In the context of the GO market, signalling theory reflects the difference between knowing the origin of a GO or not knowing anything, where knowing the origin provides trust and credibility. Product differentiation leads to a price difference between those origins.

4.3 Hypotheses

In line with the findings in the literature review and the conceptual frameworks established, the expectations with regard to the research questions are as follows:

For RQ1, given the conceptual framework established, I expect that the market has developed in the direction of moving up on the supply curve, if demand has been growing faster than supply. This would mean that the price volatility has increased. However, due to the exploratory nature of RQ1, no direct hypothesis is set up.

For RQ2, I expect that providing information on the attributes of a GO positively impacts the GO prices. The expectations with regard to market differentiation will be informed by the results of the first research question, where relative demand and supply for different technologies and countries will be collected. Technologies with high oversupply, or countries with high GO exports, will be expected to have lower prices than those who do not. The hypotheses that will be tested as thus as follows:

H2a: Disclosure of information on the GO attributes leads to higher GO prices.

H2b: Disclosure of information on the GO attributes leads to price differentiation among GOs based on their energy source and country of origin.

5. RQ1: Exploring historic market developments

In this Chapter, the methodology behind and results of RQ1 will be discussed. The research question is: "How have GO demand, supply and price dynamics developed over the past 15 years? And why?". This chapter contains the methodology (Section 5.1), the results (Section 5.2) and finally a summary (Section 5.3).

5.1 Methodology

This first Section will outline the methodology of RQ1. First, the various data sources and their content will be discussed. Finally, the assessment method will be explained.

5.1.1 Data sources

Data from Becour AS: Weekly closing prices

This data is a collection of "price curves", containing closing prices on various GO types. This dataset will be employed for RQ1. The GOs are differentiated primarily based on energy source. The data starts in 2008 with monthly price information on Hydro GOs. Later, Wind, Solar and Biomass are introduced, and data is available weekly. There is also very limited information on ecolabels and the year of commissioning. However, as those are not part of the objective of RQ1, they will not be part of the analysis.

AIB statistics

The AIB has published information on cancellation and issuing since 2001. There are two different datasets, as the reporting format changed in 2019. Furthermore, up until 2016, the data is split up in either technology or country of origin, but not both at the same time. So, for example, you can see how much Hydro GOs were issued, and how many GOs were issued in Norway, but not how many Norwegian Hydro GOs were issued. From 2016 onwards, this is possible. The AIB is also the source of information on relevant rules and regulations in the GO market in different AIB member countries.

A GO is associated with a list of attributes. However, the AIB only registers the country of origin and the energy source for all GOs. This is irrespective of how the GO has been sold or traded on the market. So, a generic "AIB", "Any RES" GO will still be issued and cancelled containing the technology and country of origin. How many times the GO has been traded, or whether a GO is linked to an ecolabel, the YOC of the associated power plant etc. is never part of the data.

5.1.2 Assessment method

The methodology of this Chapter is exploratory in nature. Exploratory research is often employed when the issue at hand is new or when data collection is challenging. Though the GO market is not "new", it is a relatively unexplored topic in literature. By assessing the data available, the aim is to discover trends, patterns and relationships within the supply, demand, and prices of GOs. GO issuance will represent the GO supply, whereas GO cancellation represents the GO demand. The analysis will not involve mathematical or statistical modelling and testing. Graphical representations and interpretations will discern overarching trends and temporal patterns. Temporal patterns will be contextualised by significant external events covered in Section 3.2. Furthermore, the data will be segmented based on technology and country of origin, to assess technology-specific or country-specific trends and expectations. This will further nuance the understanding of the market dynamics and inform our expectations for Chapter 6.

5.2 Results

This second Section delves into the results of the first research question. Using the AIB statistics and the price data from Becour AS, first the overall supply and demand development and corresponding GO price developments are analysed. The developments are contextualised with relevant events found in the literature review. Finally, the country and technology-specific supply and demand developments are analysed.

5.2.1 Overall supply and demand development

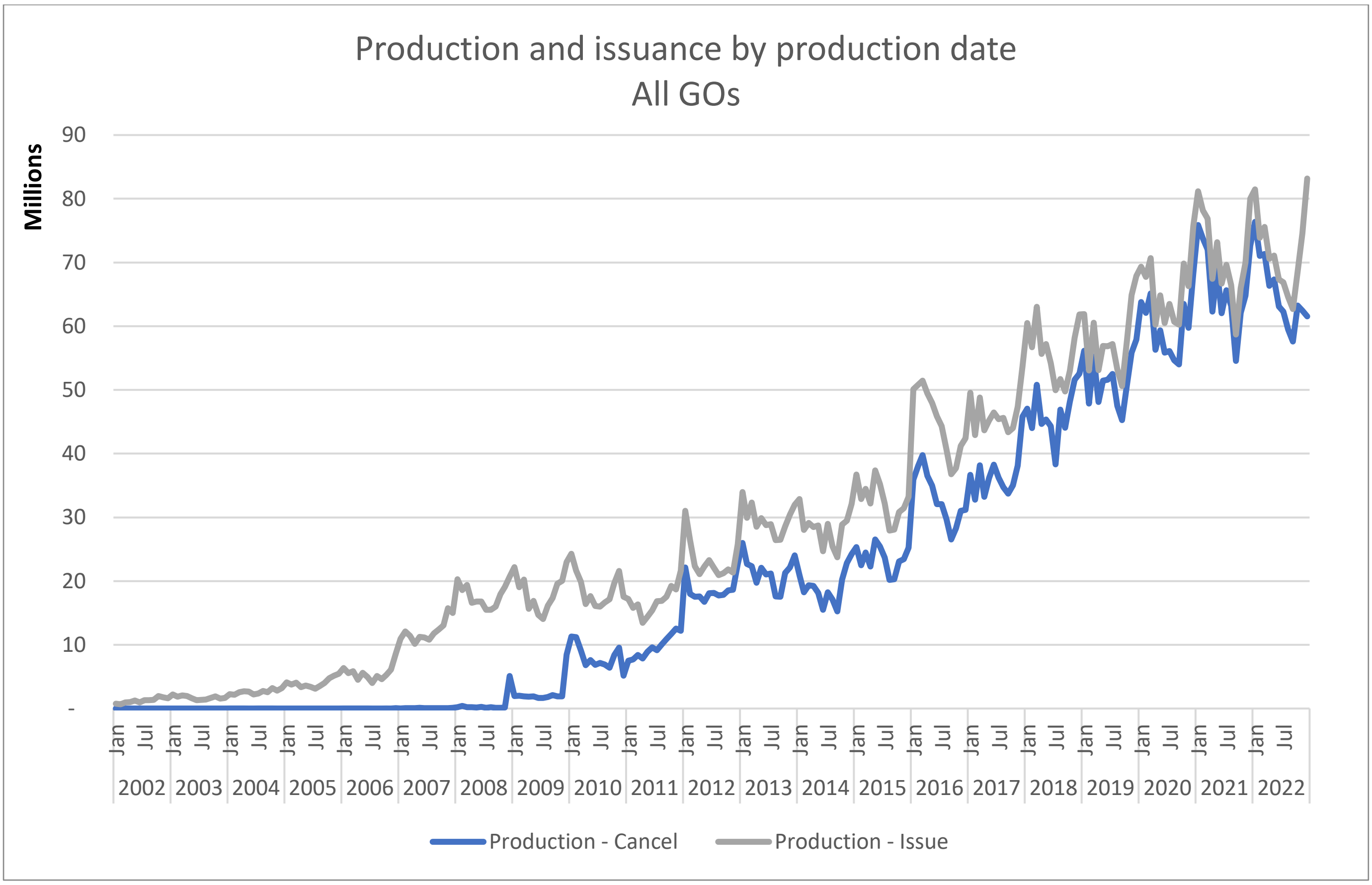

Figure 8: Production and issuance by production date for all GOs

In Figure 8 the issuance and cancellations are displayed from 2001 to the end of 2022. The interpretation of the AIB data and thus the figures resulting from it is complicated by the fact that the production, issuance, and cancellation of a GO can take place at different moments. For example, a MWh of renewable electricity can be produced in March 2018, but be issued a GO in September 2018, and cancelled later in December 2018. Rules on when issuing and cancellations can take place differ for AIB members. The time after production a GO can be issued ranges between 1 and 12 months, with monthly issuance the most common (Association of Issuing Bodies, 2023a). Except for Ireland and Lithuania, GOs expire 12 months after the production period (Association of Issuing Bodies, 2023a). The expiration deadline can then typically also be considered the cancellation deadline.

AIB reports the GO data in two ways; based on production date and based on transaction date. In Figure 8, the GO data is based on the production date. That is, the issuance and cancellation of the GO are both registered in the production month. With this production-based data, it is easier to interpret which GOs are left unsold than with transaction-based data. The data for 2023 is not yet complete, since GOs produced in 2023 are still valid and thus can still be issued and cancelled. Therefore, the figure ends in December 2022. As visible in the figure, both issuance and cancellations of GOs have seen a steady increase in the past 20 years. In the earlier years, there is a large gap between issuance (supply) and cancellations (demand). This implies that a large share of the GOs issued never got cancelled. This is the oversupply in the market. As the years progress, the oversupply declines. Especially in 2018, cancellations started catching up to issuance, and the gap is nearly closed. Accordingly, the "cancellation rate", as depicted in Figure 9, which is the rate of issued GOs that are cancelled, has been high the past few years. After a growth period from 2007 to 2012, cancellation rates dropped because of strongly increasing issuance in many countries, and only mildly growing cancellations. Cancellations picked up pace around 2014, with growing cancellation rates as a result. Around 2018, a gap emerged between the cancellation rate of GOs from all sources and GOs from only renewable sources. This is likely due to the uptake of non-renewable GO issuance as a response to the full disclosure policies implemented in Austria, the Netherlands and Switzerland.

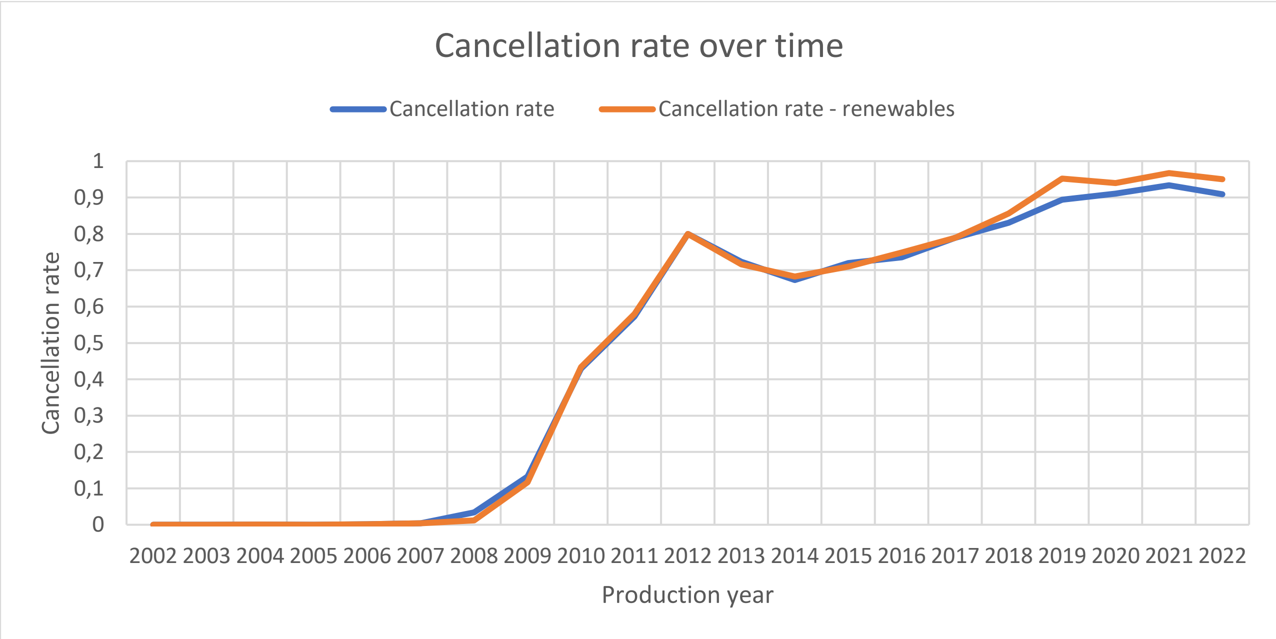

Figure 9: Cancellation rate of GOs over time

In the supply and demand framework established in Chapter 4, these supply and demand developments would suggest that from 2002 to 2018, the market was in Stage 1, characterised by low prices and oversupply. As cancellations and issuance slowly converged, the market moved towards Stage 2. In 2018, oversupply vanished, signalling that the market is in Stage 2, and higher demand can bring Stage 3 or 4. Consequently, it would be expected that before 2018, demand and supply shocks have little to no impact on prices. After 2018, price volatility would be much higher.

5.2.2 Price development and market shocks

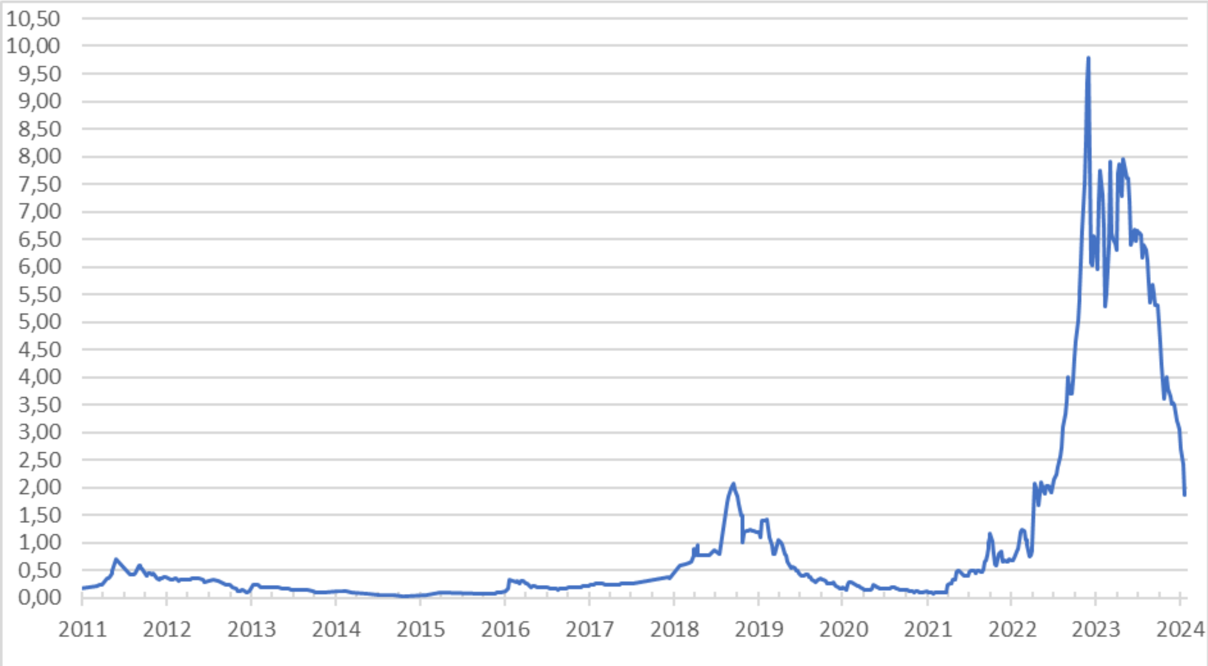

Figure 10: GO OTC Price development since 2011.

The price development of GOs since 2011 is displayed in Figure 10. Historically, prices of GOs have been low. To put the prices in perspective; the prices of a GO have ranged between one to five percent of the price of physical electricity. Ignoring the temporary price spikes in 2011, 2016 and 2018, prices of GOs have ranged between a few cents to 50 cents up until 2021. Afterwards, prices started increasing leading to a record of almost 10 euros per GO at the end of 2022. Then, prices fluctuated between 6 and 8 EUR per MWh until August 2023. Prices started dropping at the end of 2023, but market actors do not expect them to drop back to the level before the price peak.

There are 4 notable price spikes visible in the data. I will analyse them further while taking the demand and supply of GOs in the periods into account.

In March **2011**, a price spike was visible. This price spike can be attributed to the response to the Fukushima nuclear power plant disaster. As it became apparent in Chapter 3, this had two main consequences according to the literature. For one, the supply of nuclear GOs dropped, while the demand for nuclear-free

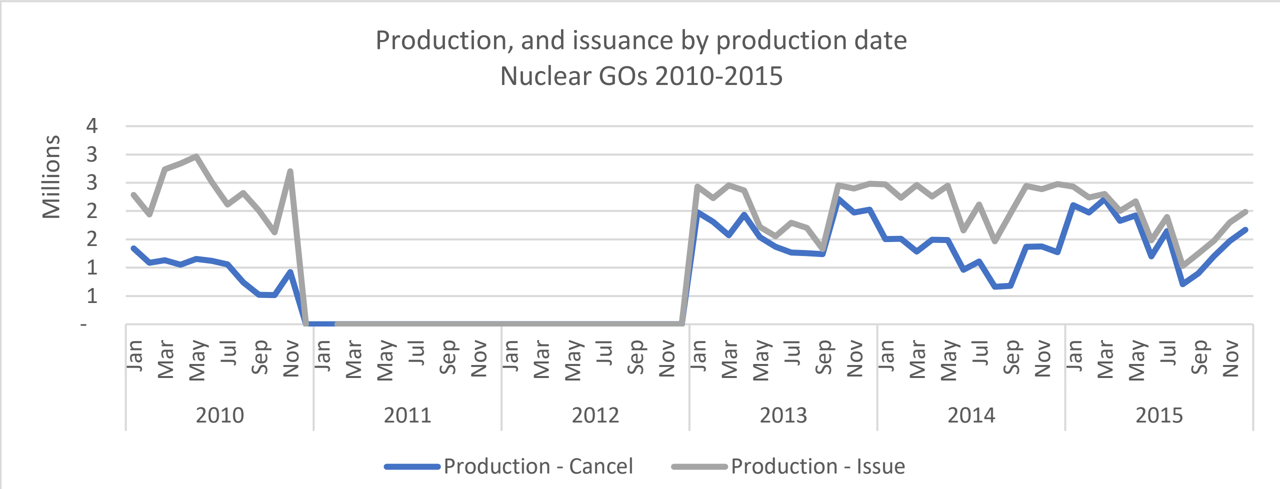

Figure 11: Production and issuance by production date for nuclear GOs from 2010-2015

electricity contracts increased. Theoretically, this would create an increase in prices. Figure 10 now shows that it did. The AIB data shows that in April 2011, right after the disaster, all production from 2010, amounting to 26TWh, was issued. Of those GOs, it appears that 15 million GOs ended up expiring. The remaining 11 million TWh of nuclear GOs were cancelled in June 2011, shortly after the issuance. After this, the market for nuclear GOs in AIB disappeared entirely, with the remaining production from 2011 and 2012 never being issued any GOs. The cancellations in June 2011 therefore seem like an attempt to quickly "get rid" of as many nuclear GOs as possible. Though nuclear GOs expiring is nothing out of the ordinary, the fact that more than half of the GOs issued for 2010 expired does show a demand response to the Fukushima disaster on nuclear power. Furthermore, the reported increase in demand for other GOs seems to be confirmed by the AIB data. Overall GO cancellations increased substantially in 2011, despite the lack of nuclear GOs. This could be at least partially attributed to the response to the Fukushima disaster. The growth however seems to be structural, as cancellations did not go back to the original level before 2011. This would indicate that the effect the Fukushima disaster had on the demand for (non-nuclear) renewable electricity was, at least to some extent, long-term. This is also confirmed by the price data. Though prices declined after the peak in May 2011, it was not until the end of 2013 that prices reached the levels of before the Fukushima disaster. Around this time, the cancellation rate had dropped to around 70 percent, indicating an increase in oversupply.

A second, small price spike occurred in **2016**, relating to the miscommunication by Ofgem in early 2016, as discussed in Section 3.2.2. This price spike hints at the impact of speculation in this market, as true GO demand and supply never really changed; it was the mere announcement of potentially increasing demand that led to actual increasing demand, as market actors started buying GOs in anticipation of the increasing demand. Later, when the miscommunication was corrected, prices went back down.

The third large price spike occurred in **2018**. Reasons for this according to the literature were the low wind and precipitation during the summer, coupled with an increasing underlying demand and sentiment trading. Improved hydro balances in the last quarter of 2018 provided a downward force to prices. Hydrology statistics from NVE confirm this, with hydro reservoirs in Norway being very well below the average in the summer of 2018, but returning to normal around week 40 (NVE, n.d.). The overall drought seems to have lasted roughly 15 weeks. Interestingly though, the same statistics reveal that the year 2010 was even dryer than 2018, including a dry autumn. Alternatively, the entire year of 2012 was relatively wet, with reservoirs being well above the average the whole year through (NVE, n.d.) As visible in Figure 8, 2018 is the first year the gap between issuance and cancellations of GOs closed at the end of the production year, after cancellation transactions saw a huge jump in 2017. This could explain why the weather conditions in 2010 and 2012 did not cause notable price shocks, while a similar event in 2018 did; the market was in a different stage in terms of demand and supply conditions (NVE, n.d.). Consequently, the market responded stronger in 2018.

Finally, there was a price spike in 2023 that superseded all earlier market developments. As discussed in Section 3.2, this was the result of many factors, such as drought in the Nordics, the Russian invasion of Ukraine, ever-increasing corporate demand, and a wave of inflation. As visible in Figure 10, the price spike that appeared was larger than any before. Price multiplied almost ten-fold in a matter of months. The NVE data revealed that the Norwegian weather of 2022 indeed was dryer than normal. Hydro reservoirs already returned to normal by the end of 2022, and the entirety of 2023 followed the median trajectory.

5.2.3 Supply and demand dynamics per technology and country

This Section delves into the supply and demand dynamics of GOs across different technologies and different countries. This will allow us to gather more insight into the price spikes and shocks observed. Furthermore, this will set the groundwork for the further analysis of GO price data in Section 6.2, by exploring whether there are differences between different technologies and different countries to be expected.

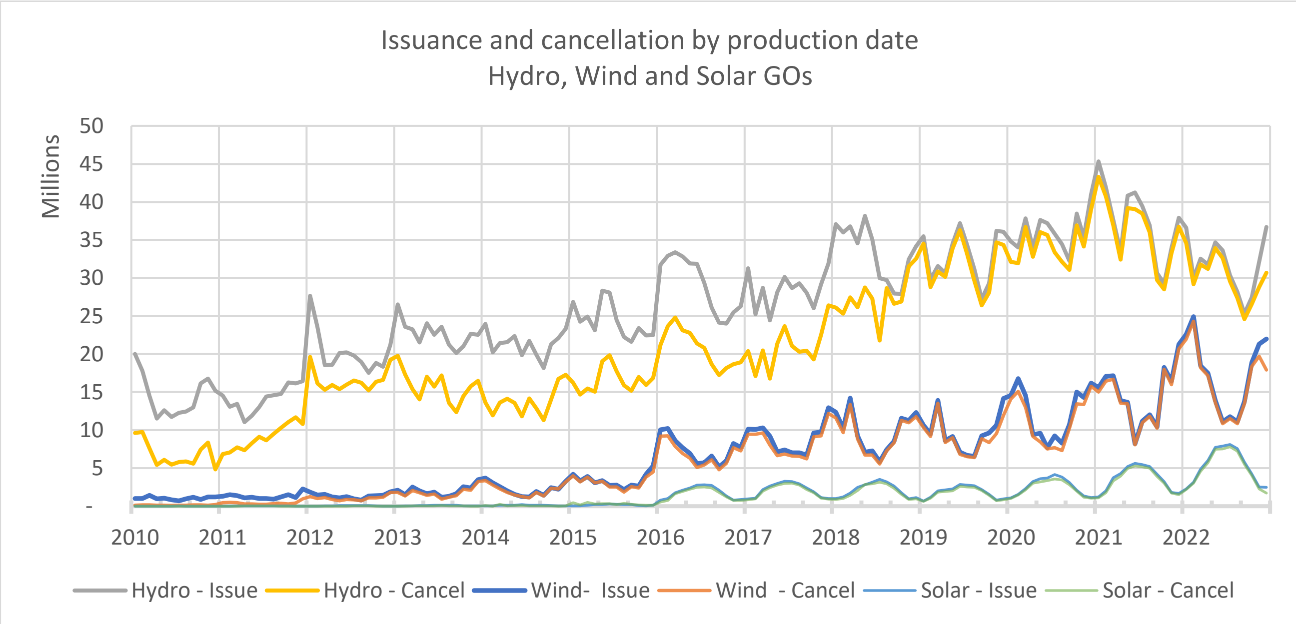

Figure 12: Issuance and cancellation of hydro, wind and solar GOs by production date

The three largest sources of GOs, being Hydro, Solar and Wind power, are all in (near) equilibrium as of date. Hydropower has a reputation for being oversupplied in the GO market. Up until around 2019, this appears to be true: there was a large gap between the issuance and cancellations of hydropower. Demand has steadily increased over the years, but the supply growth seems to have slowed down from 2018 onwards and has even displayed a downward trend since 2021. This disappearing oversupply of hydropower helps explain why the droughts of 2018, and later in 2022, had large impacts on the market. Wind and solar power both started growing quickly around 2016. The large jump between 2015 and 2016 is likely due to Spain joining AIB in 2016, which produces mostly solar and wind power. Historically, neither power source has displayed notable oversupply. Compared to Hydropower supply, Wind and Solar power both display strong seasonality, which was to be expected due to the intermittent nature of the technologies. The winters are the peak seasons for wind production, while solar production peaks in summer. Hydrology also seems to peak around wintertime, but less clearly and consistently.

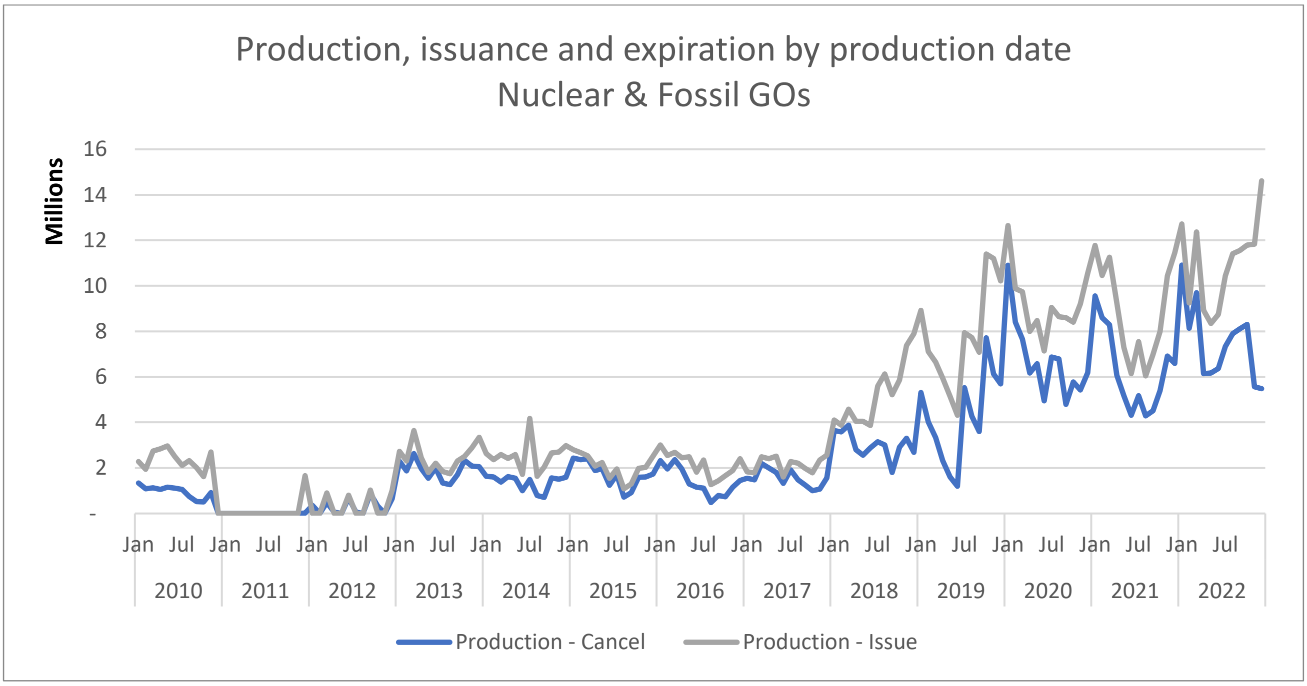

Figure 13: Issuance and cancellation of nuclear and fossil GOs by production date

In Figure 13, the issuance and cancellation of nuclear and fossil fuel GOs are depicted. GOs for fossil fuels and nuclear power have been limited, both in issuance and cancellations. Voluntary purchasing of non-renewable GOs is highly unpopular. After all, not many consumers are willing to purchase GOs to document the non-renewable nature of their electricity consumption. There is a strong uptake however in fossil fuel GOs after 2018. This can likely be attributed to the implementation of full disclosure policies in Austria, Switzerland, and the Netherlands. The full production disclosure policy in Austria and Switzerland implies that producers must issue GOs for fossil fuels, boosting primarily issuance. The Dutch policy of full consumption disclosure that went into effect in 2019 on the other hand mandates all consumers to purchase GOs, which boosts primarily demand and thus cancellations of all GOs, including fossil fuels. This would help explain why GO issuance and cancellations for fossil fuel GOs have increased. Overall, the fossil fuel GOs are still oversupplied by a large margin. Of the 67 million GOs issued in 2022, 64 percent were cancelled. Nuclear GOs display a similar oversupply, with 73 percent of 65 million GOs being cancelled in 2022. The reports of nuclear GO demand growing due to high GO prices and renewed EU taxonomy appear confirmed by the AIB data, with both issuance and supply showing a near doubling in 2022.

Biomass and Biogas, as depicted in Figure 14, both make up a small share of the GOs that are issued. In 2022, 66 million GOs for biomass were issued, of which around 14 million for biogas. The oversupply of biomass has become relatively small since 2020.

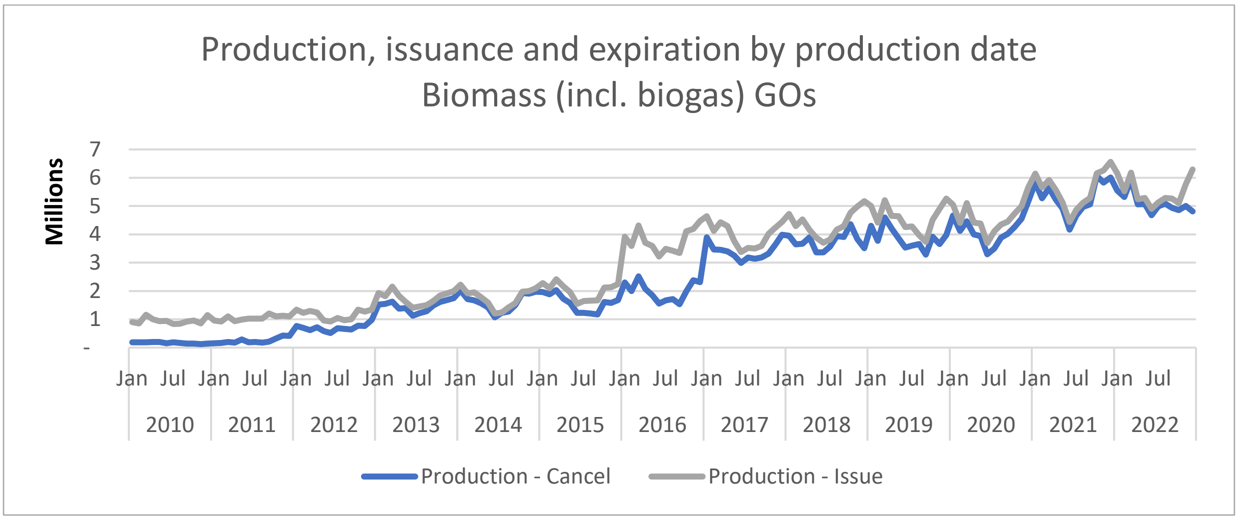

Figure 14: Production and issuance of biomass GOs by production date

To conclude, the data shows that around 2018/2019, the oversupply for hydro, solar, wind and biomass has virtually disappeared. Nuclear and fossil fuels are currently the main sources of oversupply in the GO market. Hereby it is valuable to consider that both power sources are distinct from the other sources, as fossil fuel is non-renewable and nuclear power is highly controversial. Still, the data suggests that the reputation of the GO market for renewable energy sources as a severely oversupplied market is unjustified. Taking the largest GO source, hydropower, as a baseline, the oversupply in nuclear power suggests lower prices for GOs from nuclear power. The fact that solar and wind were always practically in balance, indicates their popularity, so higher prices can be expected than for hydropower.

Country-specific dynamics

For production from 2022, Norway, Sweden, France, the Netherlands, and Italy were the largest issuers of GOs (see Appendix Figure III for GO issuance per country). Together, those five countries made up almost 60 percent of the total issued GOs. From the literature review, it appeared that GOs from the Nordics, and specifically Norwegian hydro GOs, are used as a reference point in the market. And, as observed in the price development, the state of Nordic hydro reservoirs has caused disruptions in the market on multiple occasions.

Countries can import and/or export GOs. Figure 15 displays whether a country was a net importer or a net exporter for production in 2022. Green countries are net exporters, whereas red countries are importing countries. Whether a country is a net importer or net exporter tells us something about the supply-demand dynamics within that country. It can be expected that countries with a strong preference for local GOs, such as the Netherlands, are associated with higher GO prices. So, in extension, a country that exports a lot of GOs, like Norway with a net export of 67 million GOs, indicates that that country has a local oversupply, caused by relatively high local supply and/or low local demand. Consequently, one can expect GOs from such a country to be priced lower than for example GOs from Germany, with a net import of 126 million GOs.

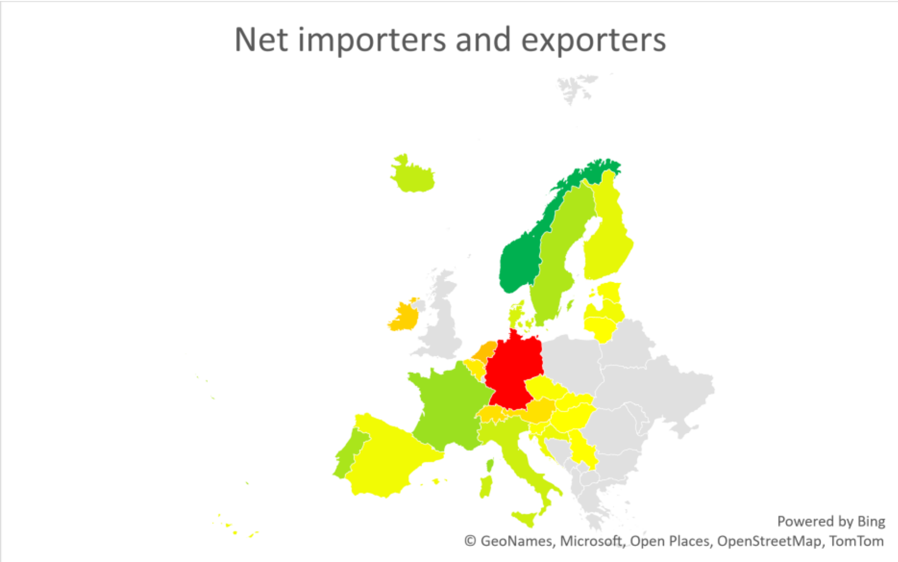

Figure 15: Net importing and net exporting countries for production year 2022 on a scale from red (importing) to green (exporting)

The diversification of the GO supply

By delving into the GO market per technology and country, an interesting trend appeared; the supply of GOs has become more diverse. Though hydropower is still the largest source of GOs, the uptake in other GO sources, most notably solar and wind, indicates a diversification of the GO supply. This may mean that shocks in the supply of one renewable energy source, will have a lesser impact on the overall market and thus potentially prices. The same holds for the diversification in the country of origin of GOs. For instance, when looking at the development of the GO issuance from Norway compared to the total market, it shows that that the share of Norwegian GOs has been decreasing since 2011 (see Appendix Figure IV). Between 2007 and 2011, Norwegian GOs made up around half of the total market. Then, it indeed is no surprise that Norwegian weather and market conditions largely determine the overall market. Since this period, however, the growth in Norwegian GO issuance has stalled, while other countries' issuance has grown. In 2022, while still being the largest issuer of GOs, only sixteen percent of total GO issuance originates from Norway. These trends indicate a diversification of the GOs on the market, with other sources than hydropower picking up and more countries joining the market and issuing GOs. This diversification could imply that the weather in the Nordics will have increasingly less impact on the market, as their supply relative to total supply decreases. Referring back to the conceptual framework, it implies that the supply shocks become relatively smaller. In extension, such a development could become a source of reduced volatility in the market.

5.3 Summary

The analysis of supply and demand in the market for Guarantees of Origins reveals significant trends over the past two decades. Demand, and supply, measured by cancellations and issuance of GOs respectively, have seen steady growth over the years. However, demand has grown quicker than supply. Since roughly 2019, the market oversupply has become marginal, and the market can be considered to be in equilibrium.

The notable price spikes in the market in 2011, 2018 and 2022 gained momentum, with each spike increasing in magnitude. This is in line with the expectations painted by the conceptual framework, given the increasing cancellation rate during this period. The market shifts along the supply curve, leading to increasing supply inelasticity and thus increasing price volatility. Consequently, price responses to market shocks increase. If the trend of demand growing faster than supply continues, it implies that the market will continue to be in a late stage in our framework, characterised by high price volatility. Accordingly, average prices can be expected to be higher.

The analysis of technology and country-specific issuance and cancellations provides insights into the expectations regarding market differentiation. Historically, wind and solar had limited oversupply. The oversupply of Hydro, the largest source of GOs, became limited around 2019. However, biomass, fossil, and nuclear power all three still display oversupply. Lower prices for those energy sources are then expected. There are differences into what extent different countries import and export GOs, with Germany standing out as a large importer, together with the Netherlands, Italy, and Switzerland. Norway and Sweden on the other hand stand out as large importers. Overall, these technology-specific and country-specific trends display a trend of diversification of GO supply. Potentially, this could function as a factor mitigating the volatility.

6. RQ 2: Transparency and market differentiation on prices

In this Chapter, the methodology behind and results of RQ2 will be discussed. The research question is: RQ2: What is the effect of disclosing information on GO attributes on the pricing of GOs? This Chapter contains the methodology (Section 6.1), the results (Section 6.2) and finally a summary (Section 6.3).

6.1 Methodology

6.1.1 Data sources

In order to assess the impact of transparency and market differentiation on prices, price data on GOs where the amount of disclosed information on the GO attributes varies is required. The data employed for RQ1 does not allow us to do that. The data utilised for RQ2 originates from GO detailed price data collected through Becour AS. Electricity price data from ENTSO-E will also be used.

Price data from Becour AS: Bid, offer and trading prices of individual GOs.

This dataset, obtained via Becour AS, has been comprised of intel from a variety of sources, some via brokers, portfolio companies, trading platforms, own trades, market reports and more. It contains detailed information on individual GO offers, trades or bids. The data employed ranges from January 2021 to February 2024. This data is much more detailed than the price data used in RQ1, where only general trends were observed.

The variables available in the data are as follows: Date, Time of entry/trade, Data source, Production year, Production quarters, Energy source, Origin, Year of Commissioning (YOC), Ecolabel, EAC, Close price, Bid price, Offer price, Volume, FX at the time, Price estimate. The price estimate is calculated based on the available offer, bid and/or close price. It is calculated as follows: if a closing price is available, it takes the closing price. Otherwise, it takes the average of the offer and bid prices. If only one of those is available, it takes that price.

A GO contains a list of attributes. Contrary to the AIB statistics in Chapter 5, where energy source and country of origin were always available, to what extent GO attributes are disclosed in this data differs. For example, a GO might only come with the information "Any RES, AIB", signifying that it is from any renewable energy source, originating from any AIB country. Other variables related to the attributes of a GO then have the value "NA". However, a GO can also contain information on all other variables. What one can do with those two GOs is the same; one can claim one MWh of renewable electricity consumption. However, the level of transparency provided by those GOs differs greatly. The GOs in the dataset are thus in the "bulk" or "premium" category. Tailored GOs are not part of this dataset.

Electricity price data from ENTSO-E

European wholesale electricity price data was obtained through EMBER (2024), who sourced and cleaned data from ENTSO-E (European Network of Transmission System Operators for Electricity). The data is publicly available. At the time of the data collection, the data spanned from 2015 until the end of 2023. It includes daily data for 29 countries, which includes all EU member states except for Malta and Cyprus, and additionally North Macedonia, Norway, Serbia, and Switzerland. This extensive dataset provides a good background to calculate average electricity prices in Europe. The electricity price data is not used for the primary regression analyses but will be included in a robustness check.

6.1.2 Data preparation

The price data was originally entered into MS Excel and went through a thorough cleaning process prior to the regression analysis. Much of the GO price data was originally entered manually, so the data had to be inspected for issues such as typing errors, trailing spaces, double entries, and faulty categorisations. Then, the data was transferred to Jupyter Notebook for further cleaning. Given the scope of this research, data entries of non-EECS GOs (I-RECS, REGOs, etc) entries were filtered out.

New variables were also created using the GO price data. New dummy "information" variables were created for Source, YOC, Ecolabel, and Origin. These variables have the value 1 if GO-specific information is available, and 0 if there is no information available. These variables then do not consider the actual content of the variable, only if information was provided. More details on the variables can be found in Section 6.1.4. The data on electricity prices and the weekly closing prices were also added to the data frame.

6.1.3 Descriptive statistics of the detailed data

The total amount of observations that will be used is 9507. Descriptive statistics were created for all variables, such as frequencies, means, standard deviations, and distributions. The most relevant of said descriptive statistics are summarized below.

Price

The average price in the dataset is 3,77 EUR/MWh. The standard deviation is high, with 2,40 EUR/MWh. As visible in Figure 16, the period of observation was one with large price fluctuations, aligning with the price trends found in RQ1. For our regression, this implies that the price of a GO will heavily depend on when the transaction took place. Therefore, the aspect of time needs to be included in the regression model. As mentioned, this will be in the form of the average closing price of the previous week.

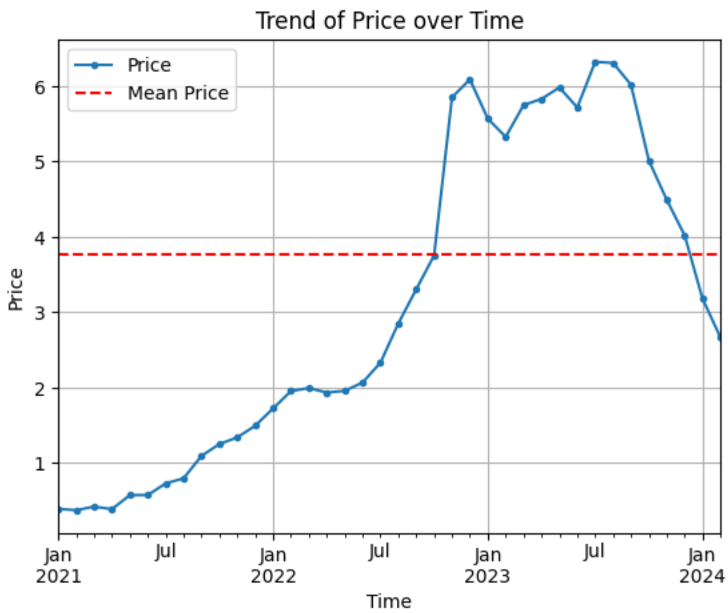

Figure 16: Price development and mean price in dataset

Origin

Table 1: Distribution of "Origin" variable

Country/Region	Count (per country (group))
AIB	6435
Nordic	1442
Norway	1181
Germany	89
Denmark	73
Austria, Spain, Netherlands, Sweden, Switzerland	32-42
Italy, Finland, France, Iceland	18-25
Iceland	17
Others	<10

Two-thirds of the observations have the generic "AIB" origin. If this dataset was fully representative of the GO market, that would imply that only a third of the GOs is traded with some information on where they were produced. And even then, more than half of those GOs with origin information have the origin "Nordic", which can be either Norway, Sweden, Finland, or Denmark. However, it should be noted that the data obtained originated from a company located in Norway, and also has a large share of its business activity in Norway. This could exacerbate the dominance of Norway and Nordics in this dataset.

Ecolabels

9 different ecolabels are present in the dataset. Together, they make up 52 observations. Out of the total dataset, this is quite few. But, they may have a large effect on prices, so cannot be ignored.

Year of Commissioning

The total number of observations with a specified Year of Commissioning (YOC) is 88. They lie in the range 2009-2021. This implies that for those GOs that have a specified YOC, the power plants are relatively young. 15 years is the benchmark that RE100 for example uses for a power plant to be eligible towards renewable electricity commitments.

Support

Out of all the observations, 2310 observations have specified "No support". Only 7 observations have "Support". Receiving support can be regarded as a negative attribute, as seen by the banning of supported GOs by some member states. Consumers of GOs may feel like GOs that have received support already do not "deserve" extra income and prefer unsupported GOs. The remaining is unspecified. In light of this distribution, information on "Support" can virtually be considered as a specification of the GO not having received any support.

Production year and Advance

Most observations are from the production year 2023. The further removed from 2023, the fewer observations available. This is likely because GOs can be purchased 5 years in advance and have a validity of 12 months. So, for example, in 2020, no more observations of production year 2018 will be found, and neither will observations for production year 2027. Given the period of the data then, the distribution of the production year categories in the dataset follows expectations.

The majority of the transactions were made either in the same year as the production or one year ahead. The average value for Advance is 1,2. This means that on average, GOs are bought for the upcoming year.

Energy source

Table 2: Distribution of "Source" variable

Energy source	Count
Hydro (H)	4137
Wind (W)	1669
Any RES	1266
H/S/W	1043
Solar (S)	903
Biomass (B)	210
Nuclear (NUK)	99
S/W	48
H/W	28
Biogas (G)	29
Other combinations	4

A large majority of the GOs concern hydropower. This can be expected due to the dominance of hydropower in the GO market, representing about half of all GOs. Wind, Solar and Biomass are also well represented. Nuclear and Biogas have few observations. But, this is not surprising given their small market share. When a GO is labelled with "Any RES", it may include (a combination of) Hydro, Solar, Wind, Biomass and Geothermal power. So, Nuclear and Biogas are not part of Any RES. There are no observations for specified geothermal power present in the dataset. The observations in the category "Other" have been removed prior to the regression analysis, so as to not include categories with only one observation.

6.1.4 Estimation procedure

The estimation procedure employs an Ordinary Least Squares (OLS) model to analyse the relationship between various predictors relating to GO attributes and the logarithm of price.

Table 3: Independent variables for equation (1)

Variable name	Description	Type of variable
Origin_info	Whether country or region of production has been specified (1) or not (0)	Dummy variable
Some_RES	The energy source has been specified down to multiple energy sources (1)	Dummy variable
One_RES	The energy source has been specified to one energy source (1)	Dummy variable
Support_info	Whether state support or lack thereof has been specified (1) or not (0)	Dummy variable
YOC_info	Whether the year of commissioning has been specified (1) or not (0)	Dummy variable
Label_info	Whether or not an ecolabel has been specified (1) or not (0)	Dummy variable
Weekly_log	Log-transformed weekly median market closing price of the preceding week	Continuous
Prod_year	Production year of the GO	Nominal
Advance	How far in advance the transaction takes place before the production year.	Discrete

All the independent variables that will be employed for the first regression are included in Table 3. The independent variables of interest are "Origin_info", "Some_RES" and "One_RES", "Support_info", "YOC_info" and finally "Label_info". These are all dummy variables, depicting whether a specific part of information is available on the GO or not. For energy source, two dummy variables are created, to reflect different degrees of information disclosure. That is, whether it is specified to some energy sources, or to one specific one.

Furthermore, the regression includes three control variables. The first control variable functions to take time trends into account. For that goal, weekly "closing price" data is employed. These are closing prices Becour AS receives every Friday from a trading firm. It contains closing prices for all production years traded in that week. The median of this weekly data is added as a control variable (Weekly_log). This way, the effect of the time trends in the market is captured. The median is chosen over the average to reduce the sensitivity to outliers. Alternative methods could be to include a moving average or a lagged variable for prices. However, these options are not preferred because the calculation of them depends on the availability of the data points preceding an observation. For example, if there is a gap in data collection, the calculation needs to go further back in time. Plus, the preceding data points may not accurately represent the average market prices, if certain attributes are under- or overrepresented in a certain period. For example, if a lot of data from expensive Dutch GOs was collected, the weekly average might inaccurately be inflated. This impacts the accuracy and relevance of a lagged price or moving average. Therefore, the weekly closing prices have been chosen as a method to deal with time. To ensure the exogeneity of the calculated weekly price average, I specifically set the price from the Friday preceding the observation. Then, the observed price (our dependent variable) is certain to not impact the associated weekly average price.

The other control variables are "Prod_year" and "Advance". Different production years typically are associated with different prices. For example, production from 2023 was amongst the most expensive for an extended period. As the Weekly_log is the median of all production years, Weekly_log does not capture this effect. Prod_year then will control for such differences. Advance further nuances this relationship, as it considers how much time is in between the production year and the year the transaction took place. This is because typically, production years in the future contain a price premium. So, if a GO is offered in 2023 for the production year 2028, "Advance" would be 5. Including both Prod_year and Advance may introduce collinearity to the model, considering Advance is calculated using Prod_year. However, both will be included due to their distinct focus. Whereas Prod_year reflects price difference for different production years, Advance reflects the effect of future purchasing. Plus, collinearity generally is a smaller problem when it concerns control variables, considering their collinearity does not impact the coefficients of the explanatory variables.

For both the price variables, a log transformation is chosen, because the relationship between price and other variables is better represented as a proportional one than an additive one. As prices increase, the price differences between different GO attributes likely also increase. For example, a 5-cent difference when GO prices are 20 cents is not comparable to a 5-cent difference when prices are 7 euros. A log transformation of price can better take this into account.

Based on this, the final estimation equation is:

$$(1) \quad log(P) = \alpha + \beta_1 Prod\_year + \beta_2 Advance + \beta_3 Some\_RES + \beta_4 One\_RES + \beta_5 Origin\_info + \beta_6 YOC\_info + \beta_7 Support\_info + \beta_8 Label\_info + \beta_9 Weekly\_log + u$$

To examine the joint significance of the information variables, an F-test will be conducted. The null hypothesis of this test states that the coefficients associated with transparency are all equal to zero. The coefficients and significance of the individual variables will also be tested. The coefficients will indicate the overall effect of providing information on GO prices.

Next, I run a regression to test for differentiation based on country of origin and energy source. In this regression, I use the original variables for "Origin" and "Source" rather than the associated dummy variables. The change in variables is summarised in Table 4.

Table 4: Change in variables for equation (2)

Variable name	Description	Type of variable	Replaces
Origin	The origin of production. Treatment is "AIB"	Nominal	Origin_info
Source	The energy source of the GO. Treatment is "Any RES"	Nominal	Some_RES & One_RES

The estimation equation for this test is as follows:

$$(2) \quad log(P) = \alpha + \beta_1 Prod\_year + \beta_2 Advance + \beta_3 Source + \beta_4 Origin + \beta_5 YOC_{info} + \beta_6 Support\_info + \beta_7 Label\_info + \beta_8 Weekly\_log + u$$

For this regression then, instead of the information variables for energy source and origin, the original variables, "Source" and "Origin", are used. Again, the joint significance will be tested, and individual coefficients will be analysed. So, while the first regression only tests the average effect of the **presence of information** on Origin and Energy Source, the second regression will tell us more about to what extent this effect is **differentiated** for different countries and energy sources.

The assumptions made related to OLS are:

1. Zero mean of residuals: $E(u) = \mathbf{0}$. The expected value of the residuals is zero, indicating that on average, the model predicts the outcome accurately.
2. There is no correlation between the residuals and the explanatory variables: $cov(u, xj) = 0 \; where \; j = 1,2, \ldots .k$.
3. Zero conditional mean: $E(u|x_1, x_2, \ldots, X_j) = 0$. The expected value of the residuals, given the values of the explanatory variables, is zero.

To check the robustness of the models and the results, a selection of tests will be performed. The residuals will be tested for normality and heteroskedasticity. A leverage plot will help identify and possibly eliminate any outliers and incorrect data entries. A Ramsey RESET test will be performed to test the functional form of the model. Furthermore, multicollinearity will be evaluated. Finally, 10-fold cross-validation tests will assess the performance of the model on unseen data and test for overfitting.

6.2 Results

This Section presents the results from the regression analyses. Section 6.2.1 will discuss the results for equation (1), followed by a discussion of equation (2) in Section 6.2.2

6.2.1 Impact of information on GO prices

The results from the first regression indicate that providing information on the origin of a GO, as represented by the "info" variables, has a positive impact on prices. By taking the information dummy variables, the actual content of the information is disregarded.

Table 5: Regression results for equation (1)

	All observations	Excl. NUK and G
Adj. R-squared	0,858	0,920
No. observations	9507	9385
F-statistic; Prob(F-statistic)	5886; 0,00	6994; 0,00
	Coefficient (std error)	
Intercept	-0,6065*** (0,031)	-0,6652*** (0,029)
Prod_year[T.21]	0,2942*** (0,032)	0,2901*** (0,030)
Prod_year[T.22]	0,6432*** (0,035)	0,6841*** (0,032)
Prod_year[T.23]	0,4049*** (0,041)	0,4551*** (0,037)
Prod_year[T.24]	0,3377*** (0,046)	0,4063*** (0,040)
Prod_year[T.25]	0,1371*** (0,054)	-0,1970*** (0,047)
Prod_year[T.26]	-0,1002 (0,063)	-0,0301 (0,054)
Prod_year[T.27]	-0,3670*** (0,072)	-0,3024*** (0,062)
Prod_year[T.28]	-0,5668*** (0,081)	-0,5109*** (0,071)
Weekly_log	1,0475*** (0,009)	1,0703*** (0,008)
Advance	0,1884*** (0,010)	0,1699*** (0,008)
Some_RES	0,0475*** (0,010)	0,0439*** (0,010)
One_RES	-0,0460*** (0,011)	0,0296** (0,009)
Origin_info	0,0633*** (0,011)	0,0315*** (0,008)
YOC_info	0,0612 (0,040)	0,0739* (0,038)
Support_info	0,0870*** (0,009)	0,0445*** (0,007)
Label_info	0,1702** (0,056)	0,1291** (0,057)

*** P-value < 0.001
** P-value < 0.05
* P-value < 0.1

The results of the regression are displayed in the second column of the table. The individual coefficients show that Some_RES and One_RES, representing the disclosing of a group of energy sources and a specific energy source respectively, both have significant coefficients. Furthermore, the presence of an ecolabel (Label_info) and information on whether a GO has received support (Support_info) all have significant positive coefficients. However, it should be kept in mind that Support_info almost exclusively represents information that the GO has not received any support. The positive coefficient for YOC_info is not significant with a P-value of 0,125. Origin_info is found to be positively significant. This would indicate that overall, information on the country of origin of a GO impacts its price. With a coefficient of 0,0315, it would imply a 3,2 percent price premium.

The three control variables included, Weekly_log, Prod_year and Advance, are all significant. They control for the time trends present in the market, the fact that different production years have different price trends, and that buying GOs further in advance contains a premium.

The negative coefficient for One_RES stands out in the results. It seems counterintuitive that providing specific information on the energy source of the GO has a negative effect on the value of the GO. This could be explained by the presence of Nuclear and Biogas GOs. A residual plot where the source categories are labelled confirms this, with residuals for Nuclear and Biogas GOs being structurally low (see Appendix Figure V). Those outliers may also explain the very heavy lower tail of the QQ-plot.

To improve the interpretability of the model, and improve the normality of the residuals, the model was tested again excluding observations on Nuclear and Biogas GOs, given the reported low prices of those GOs. By grouping them together in "One_RES", the effects of specifying down to one type of energy source compared to Any RES might be underestimated. Furthermore, "Any RES" does not include nuclear and biogas power, so in order to fully capture the difference between Any RES and Some/One_RES it is useful to only look at the energy sources that are actually part of Any RES. The results of this regression, which excludes biogas and nuclear power, are in the third column of Table 5. As visible in the QQ-plots in Figure 17, the heavy lower tail of the QQ plot greatly reduced after the exclusion.

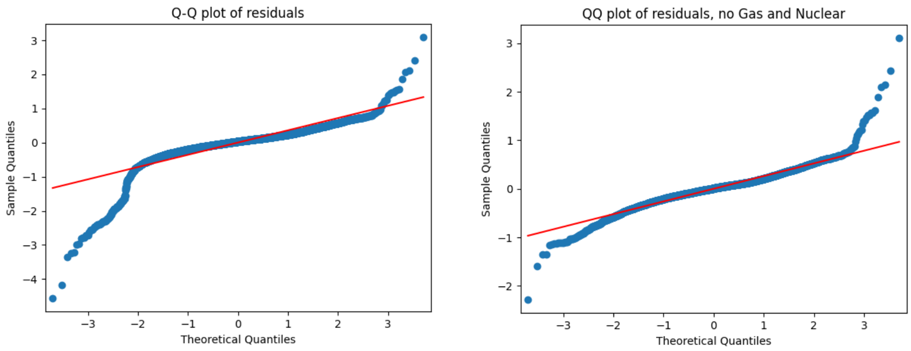

Figure 17: QQ-plots of regression including (left) and excluding (right) nuclear and biogas GOs

Running the regression without Nuclear and Biogas, had minimal effects on the coefficients and significance of all variables, except for "One_RES" and "YOC_info". One_RES is now positive, aligning with our initial hypothesis. Surprisingly, combinations of Hydro, Solar and Wind in Some_RES have a higher positive coefficient than One_RES. However, their confidence intervals overlap. A two-tailed t-test comparing Some_RES with One_RES reveals that their coefficients are not significantly different. Given that Some_RES represents nearly exclusively H/S/W, this result suggests that excluding biomass and geothermal power by purchasing H/S/W is valuable to a GO, but further specifications are not relevant. YOC_info is now weakly significant.

6.2.2 Market differentiation based on energy source and origin

The results of the second regression provide a more detailed insight into the GO prices with regard to the provided information. Instead of only looking at the presence of information, the regression now considers the content of the information. It allows us to analyse whether there are differences within different energy sources and/or different countries of origin.

The regression results are displayed in Table 6. Just like in the first regression, YOC_info, Support_info and Label_info have positive coefficients. Their coefficients did not change much with the new model specification. However, Label_info is now only weakly significant and YOC_info is not significant anymore.

The results show evidence of market differentiation based on the energy source, with an F-statistic of 282,51 and a corresponding P-value of 0,000 for the joint variable "Source". Negative significant coefficients were found for the categories Biomass, Biogas and Nuclear GOs. Hydro (H), Wind (W) and the Hydro/Solar/Wind (H/S/W) combination had positive significant coefficients. The negative coefficients for Biogas (G) and Nuclear (N), which suspected in the previous model, are high. For example, the coefficient of -2,64 for Biogas implies that prices for Biogas are more than 90 percent lower than for Any RES. The negative significant coefficient stands out. It implies that disclosing that a GO is produced from Biomass has a negative impact on the prices. So, there is an incentive to "hide" behind the Any RES label, and punishes the transparency provided by the information disclosure. The positive coefficients for Hydro, Wind, and the H/S/W combination indicate that they have a higher value than GOs labelled with Any RES. They show a price premium between 3 and 5 percent. These results do not fully align with our expectations, as Solar was expected to also have a price premium. Notably, the results provide evidence against the common perception that GOs from hydropower are cheaper than Wind and Solar. Overall, then, market differentiation is present for differentiation between H, S, W, and other power sources. Within H, S and W, differences are minimal, though there is no premium found for Solar energy.

Table 6: Regression results for equation (2)

Dependent Variable	Price_log		
No. Observations	9479		
Df. Model	35		
R-squared	0,923		
Adj. R-squared	0,922		
F-statistic; Prob(F-statistic)	3841; 0,000		
	Coefficient	Std error	P-value
Intercept	-0,645	0,029	0,000
Prod_year [T. 20]			
Prod_year [T. 21]	0,281	0,030	0,000
Prod_year [T. 22]	0,673	0,032	0,000
Prod_year [T. 23]	0,451	0,037	0,000
Prod_year [T. 24]	0,399	0,041	0,000
Prod_year [T. 25]	0,188	0,048	0,000
Prod_year [T. 26]	-0,035	0,055	0,519
Prod_year [T. 27]	-0,307	0,063	0,000
Prod_year [T. 28]	-0,524	0,072	0,000
Source [T. Any RES]			
Source [T. B]	-0,107	0,019	0,000
Source [T. G]	-2,645	0,134	0,000
Source [T. H]	0,055	0,009	0,000
Source [T.H/S/W]	0,054	0,010	0,000
Source [T.H/W]	-0,029	0,057	0,612
Source [T.NUK]	-2,017	0,046	0,000
Source [T.S]	-0,014	0,013	0,274
Source [T.S/W]	-0,090	0,057	0,117
Source [T.W]	0,029	0,010	0,005
Origin [T.AIB]			

Origin [T. Austria]	0,066	0,083	0,427
Origin [T. Denmark]	0,107	0,030	0,000
Origin [T. Finland]	-0,060	0,033	0,066
Origin [T. France]	-0,159	0,096	0,097
Origin [T. Germany]	0,099	0,045	0,027
Origin [T. Iceland]	-0,054	0,067	0,420
Origin [T. Italy]	0,064	0,063	0,312
Origin [T. Netherlands]	0,235	0,072	0,001
Origin [T. Nordic]	-0,012	0,009	0,188
Origin [T. Norway]	0,021	0,013	0,099
Origin [T. Spain]	0,157	0,065	0,016
Origin [T. Sweden]	0,050	0,029	0,086
Origin [T. Switzerland]	0,237	0,142	0,096
Advance	0,169	0,008	0,000
Weekly_log	1,063	0,008	0,000
YOC_info	0,054	0,045	0,229
Support_info	0,041	0,008	0,000
Label_info	0,120	0,070	0,088

The results also show evidence of market differentiation based on origin, with an F-statistic of 4,151 and a corresponding P-value of 6,462E-7 for the joint variable "Origin". For the individual countries, the results only found positive significant coefficients for Denmark, Germany, Netherlands, and Spain. The Netherlands, Spain, and Switzerland stand out in terms of their coefficients, indicating a price premium between 20 and 25 percent for GOs originating from those countries. However, it should be noted that Switzerland was only weakly significant at the 10 percent level. I had expected there to be no significant negative coefficients for Origin. Negative coefficients for GOs from Finland and France were present, but they were only weakly significant. The remaining countries were not significant. This would indicate that for the majority of countries in this dataset, providing information on the exact origin does not impact the price of the GO. However, this may have been due to the limited data on individual countries. In fact, the individual coefficients of all countries, except for Nordic and Norway, should likely be approached with a grain of salt due to the relatively limited data.

Robustness tests

Normality of residuals

Visual inspection of the normality of the residuals reveals no serious issues with the normality assumption, though the heavy tails of the QQ-plot suggest that there are more outliers than would be expected in a normal distribution (see Appendix Figure VI).

Analysing leverage and outliers

A leverage plot was created in order to identify influential observations that may disproportionately affect the estimated coefficients. How problematic an observation with high leverage is, also depends on its corresponding residuals. Observations with high leverage but low residuals indicate that though they are observations with high influence on the regression, they fit the trends of the overall data well. If an observation with high leverage also has high residuals, may create issues with biasedness.

The leverage plot below shows that there are a lot of observations with relatively high leverage. Observations with both high leverage and high residuals could be problematic. Upon suspicion that "Origin" was the cause of this, as some countries have relatively few observations and can be expected to have high leverage, the observations in the leverage plot were labelled with their category of origin (see Appendix Figure VII). This confirms the suspicion, with distinct origin categories being associated with high leverages, compared to observations from AIB.

Outliers were also analysed using Cook's distance. However, upon further inspection of those variables deemed outliers, the observations appeared legitimate. Therefore, it was not considered an argument to remove them.

Heteroskedasticity tests

Heteroskedasticity refers to a situation where the variance of the residuals is not constant for all price levels. I tested for heteroskedasticity using the Breusch-Pagan LM-test and the White test. Both showed evidence of heteroskedasticity. Therefore, heteroskedasticity robust residuals must be and have been employed.

Ramsey RESET for functional form.

A Ramsey RESET test was performed to evaluate the functional form of the model. Fitted values from the regression were obtained, and their squared and cubed values were added to the model. The results from the test reveal an F-statistic of -40,174, with a corresponding P-value of 1,0. Therefore, the conclusion is that the Ramsey RESET test indicates that the model is not misspecified as a linear regression model.

Multicollinearity

Multicollinearity was assessed by calculating the Variance Inflation Factor (VIF). The VIF estimates how much the variance of a coefficient is inflated because of linear dependence with other coefficients (Allison, 2012). Multicollinearity only impacts the variables that are linearly dependent on one another. Typically, VIF values above 5 would be considered problematic, especially those above 10. There are some VIF values above 10 for some categories within Prod_year, but that can be expected for categorical variables with multiple levels. More concerning perhaps is the VIF value of 11,96 for "Advance". However, this was also expected, as it is calculated using Prod_year. And indeed, Prod_year and Advance share a high correlation of 80 percent. However, considering Prod_year and Advance were both included as control variables, and their multicollinearity will not impact the variables of interest related to GO attribute information, I believe I can safely ignore the multicollinearity. Furthermore, later tests will reveal that the inclusion of "Advance" as a control variable is relevant to the accuracy of the model. Advance will thus not be removed.

Cross-validation

K-fold cross-validation was employed to assess the generalisation capability of the regression model. This is especially relevant considering the large size of the dataset, and the associated risk of overfitting. Overfitting refers to the situation where the model is capturing "noise" that is present in the dataset. Then, the model does not perform well on new, unseen data. K-fold cross-validation can help test for this.

The dataset was divided into 20 folds (k=20). The model was then trained on k-1 folds of the data. Then it assesses the performance of the trained model on the remaining fold of testing data. The average R-squared on the training data was 0,9228. For the testing data, it was only marginally lower with 0.9214. This latter value represents the predictive power of the trained model on unseen data. The high R-squared values indicate that the model has high predictive power and performs well on unseen data. The process was also repeated with different values of k, with comparable results.

Adding/removing variables

Finally, as part of the robustness checks, I experiment with some different model specifications by removing control variables and adding a new variable to the model. This will give further insight into the stability of the model.

First, the main control variable, Weekly_log, was left out. The purpose of this variable was to take the strong time trends into account. As expected, leaving out this variable had substantial effects on the predictive power of the model, with the adjusted R-squared dropping to 0,485. The relevance of Weekly_log is interesting, as it confirms that the overall market prices are crucial in predicting the price of a GO. Furthermore, the coefficients and significance of the variables change substantially. Similar findings were found upon leaving out Advance and Prod_year, both in isolation and jointly, with previously significant explanatory variables no longer being significant and R-squared values dropping. This suggests that the control variables are important for the model specification and estimation.

Lastly, electricity prices were included as an added variable. In Petryk & Adamik (2023) electricity prices were found to be positively correlated with GO prices in Poland. Upon including the average European electricity price in the model, the model changed little in terms of coefficients and standard errors. The coefficient for electricity prices was found to be positive, but non-significant with a P-value of 0,497. However, as discussed in the literature review, I must note that I considered there to be no foundation for including electricity prices in our model, and the purpose of this addition was solely to assess the robustness of our model. The correlation found in the time frame analysed by Petryk & Adamic (2023) may be coincidental, as is the coefficient found in our model. Importantly, the inclusion of electricity prices did not substantially alter the significance of the other variables in our model.

Overall, the robustness tests ensured and confirmed the reliability and validity of our regression model. Though outliers and evidence of heteroskedasticity were found, our model remained robust overall. Furthermore, the inclusion of control variables proved to be relevant to the model specification. The inclusion of electricity price provided insights into the stability of our model, as it did not alter the significance of our variables of interest.

6.3 Summary

In the first regression in Section 6.2.1, information variables related to GO attributes were found to have a positive impact on GO prices. This indicates that transparency regarding the country of origin, energy source, ecolabels and government support contribute to higher GO prices. Year of commissioning was, contrary to expectations, not found to be significant. Potentially this will change soon, as the new RE100 regulation regarding requiring an earliest year of commissioning has made this attribute much more relevant. In this first analysis, only the presence of information was considered, not their content. The control variables functioned to take time trends and premiums for future production into account and were all significant. The results showed that GOs from nuclear power and biogas had strong negative residuals and were responsible for the negative coefficient for One_RES that was found. Upon excluding observations from nuclear power and biogas, the coefficient for One_RES became positive.

That brings us to the second regression, where the impact of market differentiation was tested. For energy source, negative coefficients were observed for Biogas, Nuclear and Biomass, while positive coefficients were found for Hydro, Wind, and the combination of Hydro, Solar and Wind compared to “Any Renewable Energy Source”. The price premium for Hydro, Wind and H/S/W ranged between 3 to 5 percent. Solar power was not found to be different from Any RES. Overall, this confirms that while the exclusion of Biomass and Geothermal energy increases the price of a GO, further specifications only have minor impacts on GO prices. For country of origin, significant positive coefficients were found only for GOs originating from Spain, Denmark, Germany, and the Netherlands. Significant negative coefficients were not found for any countries, though Finland and France were weakly negatively significant. For the remaining countries in the dataset, no significant coefficients were found. This indicates that for most countries, there is no significant price premium for specifying the country of origin. But, also that transparency on the origin of the country does not lead to lower prices of the GO. Differentiation on the basis of YOC, Support and Ecolabels was not tested due to the limited availability of data on those variables.

H2a: Disclosure of information on the GO attributes leads to higher GO prices.

Upon excluding nuclear and biogas power, the information variables relating to Origin, Support, Label, and Energy source were positively significant. Year of commissioning was also positive, but was only weakly significant at the 10 percent level. Therefore, the data showed evidence to support the hypothesis that disclosure of information on the GO attributes leads to higher GO prices. However, it should be noted that no significant difference was found between Some_RES and One_RES.

H2b: Disclosure of information on the GO attributes leads to price differentiation among GOs based on their energy source and country of origin.

The F-tests for energy source and origin were both significant. Therefore, there is evidence for market differentiation based on energy source and origin. Hydro, Wind, and the combination of Hydro, Solar and Wind (H/S/W) were shown to have a positive price premium, whereas Biogas, Nuclear and Biomass had negative price premiums. On an individual country level, Germany, Spain, the Netherlands, and Austria were the only countries with significant price premiums within Origin. No countries had significant price reductions.

7. Discussion

The main objectives of this research were to 1) analyse the historic GO market trends concerning supply, demand, and prices, and how prices have responded to market shocks and to 2) analyse whether enhancing product transparency by providing information on GO attributes impacts GO prices.

The results of **RQ1** provide a comprehensive overview of the market developments over the last 20 years. Such an overview aids the general understanding of the GO market and provides a relevant background for future research into the market. The results support the conceptual framework proposed in Chapter 4. That is, as the market grew over the years, and demand came closer to supply, the market responded stronger to shocks in demand and supply. Following this, if expectations of demand growing faster than supply are correct, I expect **high price volatility and higher overall price levels** in the years to come. Given that low GO prices were identified in the literature review as a leading cause of why the GO market fails to positively impact renewable energy production, such higher prices are beneficial. However, increasing volatility could have the opposite effect, as it fosters extra uncertainty in the market.

Given the exploratory nature of **RQ1**, the research **did not test the hypothesis** of increasing volatility quantitatively. Neither did it attempt to forecast prices. Therefore, I cannot consider these findings conclusive. Still, this research and its results can function as a foundation upon which to build future research regarding these topics. For example, given what is available on how demand and supply have developed, one could attempt to develop a demand and supply curve. The uptake of GO auctions poses a potential source of volatility in the market. Relatively large volumes of GOs are offloaded into the market on a specific day, possibly functioning as a short-term positive supply shock. Research could attempt to analyse the auction data and compare market responses before and after auction events, in order to assess how such auctions affect the market. Furthermore, the (expected) increasing volatility raises the question of how this may impact the future GO market. Previous research has suggested that price volatility in the GO market creates uncertainty and discourages investments (Hustveit et al., 2017). Therefore, **future research** into how this volatility may be mitigated in the market could be valuable.

Three main factors should be taken into consideration in the interpretation of our results. For one, there is substantial **speculative trading** in the market. This may not be reflected in the issuance and cancellation statistics from AIB, but it does play a role in GO prices, as was found in the literature review. The speculative trading in the market then may contribute to the price volatility observed. The increasing volatility found would then also be (partially) attributed to the increasing activity of speculative trading. So, future research could focus on the role and impact of speculative trading in the GO market. Furthermore, in this research, it is assumed that the issuance and cancellations of GOs in the **AIB statistics** represented supply and demand, respectively. However, these statistics do not capture the true supply and demand as they exist on the market for the end-consumer. For example, a GO can be sold on the end-consumer market as a generic GO, not specified in origin or technology. However, in the AIB statistics, it will still be issued and cancelled as a GO with a specified country of origin and technology. So, in other words, the fact that for example a Norwegian Hydro GO is cancelled in the AIB statistics, does not mean it was sold to the end-consumer as such. In fact, in the data analysed for RQ2, two-thirds of all observations had the generic origin “AIB”. This implies that the AIB statistics, though functioning well for analysing overall market trends, cannot be viewed as an accurate representation of the true supply and demand on the market for consumers.

Furthermore, upon analysing the AIB data, some data was found that did not seem fully correct. That is, in the early years of the statistics on the GO market, the number of GO cancellations and expirations did not add up to the number of GOs issued, which should be the case. After all, a GO that is issued but not cancelled can only end up expiring. Upon email correspondence, the AIB confirmed that this could be due to some member countries not reporting to the AIB properly, especially in the earlier years. If cancellations and/or expirations were underreported, this would imply that the increasing cancellation rate can also be partially attributed to an improving reporting quality.

For RQ2, a positive effect of product transparency, as measured by the disclosure of GO attributes, on GO prices was found. That is, the disclosing of information had a positive effect on the GO price. Furthermore, the results also provided evidence for market differentiation, as indicated by differing price effects of different energy sources and/or country of origins. These higher price levels imply that providing transparency could help boost income from GOs. Such disclosure and the consequent market differentiation can then further facilitate this by creating price differentials more accurately representing supply and demand dynamics for different attributes. If the data obtained is representative of the end-user market, the positive coefficients for the information variables then indicate an incentive to transparently disclose GO attributes. The market price trends were included in the regression, showing a highly significant coefficient close to one. Putting this in perspective, this suggests that while market differentiation and information disclosure are relevant in determining GO price, the market trend exerts a dominant influence on pricing dynamics.

Upon analysing market differentiation, the regression results indicate that it is possible for certain GOs to "hide" behind generic labels. Biomass was found to have a strong negative coefficient. This implies that those trading biomass GOs could profit by labelling it as "Any RES". Though a significant negative coefficient was only found for biomass, this is likely the case for more attributes. Attributes with potentially negative effects on prices may be underrepresented in the extent to which they are disclosed. That is, if a market actor suspects that a specific attribute would have a negative impact on the GO price, they could choose to hide it. For example, an old power plant could choose not to disclose the Year of Commissioning (YOC), expecting that consumers prefer newer power plants. If this happens structurally, old power plants are underrepresented in our sample with a specified YOC. If disclosing were made mandatory for example, perhaps more "negative" information would be disclosed, altering the overall effect of information disclosure. However, GOs with "negative" information may still possibly benefit from higher prices through increased trust in and credibility of the transaction and the overall market. If the sample of GOs with disclosed information contains relatively much "positive" information, this cannot be ensured.

Knowing this, this research does not enable us to fully isolate the effects of transparency and market differentiation. In a way, they are two sides of the same coin. For example, are you willing to pay extra for Dutch GOs because you want the GOs to be transparent in their origin, or because you specifically want GOs from the Netherlands? Or a combination of the two? Given the nature of the data, this research cannot fully isolate this. Keeping this in mind, a future experimental study could help clarify the relationship between transparency and market differentiation, enhancing the robustness and generalizability of our findings. In such a design, one could manipulate the level of transparency randomly without disclosing the actual information, to isolate the true effect of product transparency.

8. Conclusion

In this study, I have analysed the historic development of Guarantee of Origin (GO) market prices with respect to supply and demand shocks, and to what extent information disclosure impacts the price of a GO. Literature suggests that low GO prices are a significant barrier to the GO market's positive impact on renewable electricity production. However, there is limited research on the specific determinants of GO prices.

Firstly, I conducted an exploratory analysis of GO issuance, cancellation, and prices. The results revealed that the GO market has shown increasing volatility, as demand is getting closer to supply. Shocks in the market have gained momentum, and with growing demand, the expectations are that this trend continues. Demand and supply shocks would then have greater impacts on the market prices. Plus, a closing gap between demand and supply would imply higher average prices in the long term. Contrarily, the growing diversification of GO supply, with more countries joining AIB, and growing issuance from wind and solar energy, might mitigate price volatility.

Secondly, using a linear regression model, I analysed to what extent information disclosure impacts the price of a GO. The regression results showed evidence for price premiums based on attribute disclosure. GOs from hydropower, wind power, or a combination of hydro, solar and wind were priced higher than those without any renewable energy source specification. On the other hand, biogas, biomass, and nuclear power all were associated with lower prices. Especially the negative coefficient for biomass stands out, as it implies that it is possible to increase profits from biomass GOs by “hiding” behind a label of “Any RES”. Price premiums were also observed for GOs from Denmark, Germany, Spain, and the Netherlands, indicating strong local demand. A specification that a GO has not benefited from a government support scheme also contained a price premium. Our results suggest that producers can benefit from more transparently disclosing GO attributes. However, there is a risk of a selection bias in our data, as GOs with “negative” attributes may be hidden by generic labels. Nonetheless, I expect that such GOs could still benefit from the increased trust and credibility that comes with higher product transparency. Further research is required to confirm this.

In conclusion, our study reveals two main insights regarding GO market prices. Firstly, market price volatility has been increasing, and higher, more volatile prices are to be expected in the future. Secondly, the price of an individual GO appears to depend on the degree of product transparency provided by the transaction, and what those attributes are. Product transparency can thus increase the price of a GO. However, further research is needed to investigate whether “negative” attributes can also benefit from greater transparency through the benefits associated with product transparency, such as trust and credibility.

Given that low GO prices limit the GO market's ability to positively impact renewable electricity production, these avenues for higher prices may aid the GO market in fostering sustainability. However, it is important to note that the product transparency provided by information disclosure is only a small part of the total picture of “transparency”. If the majority of the price premium ends up at intermediaries, and not at the producers, they will not contribute to additional production. Moreover, market volatility suggests sensitivity to even small shocks in demand and supply, potentially resulting in temporarily low prices. Therefore, exploring ways to mitigate this volatility is crucial.

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Appendix A: Additional figures

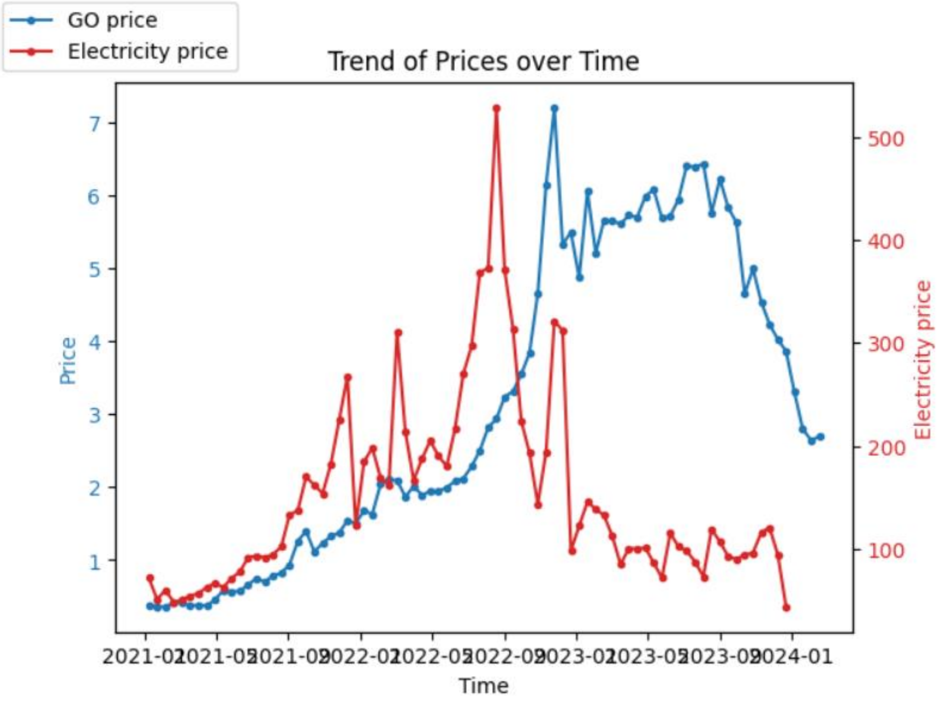

Figure I: Trend of GO prices and electricity prices from Q1 2021 to Q4 2023

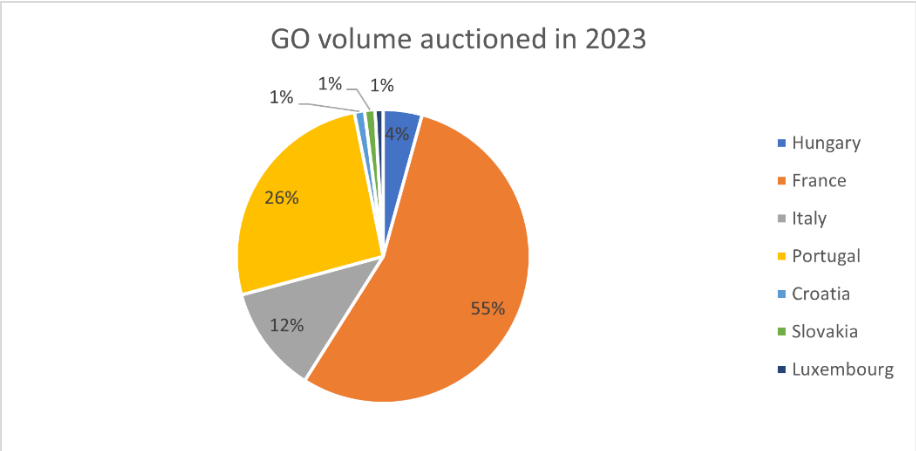

Figure II: Distribution of GO volumes auctioned in 2023

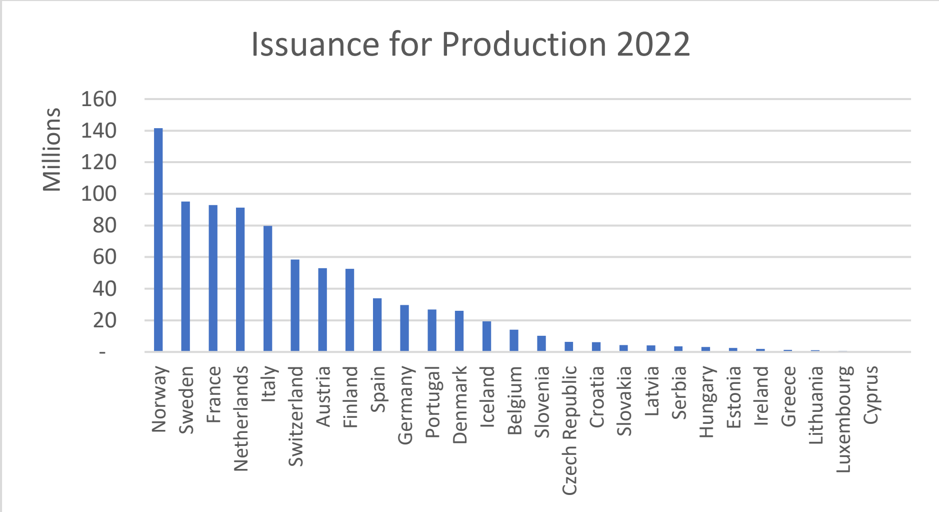

Figure III: Aggregate issuance from Hydro, Solar and Wind GOs for ten countries in 2022

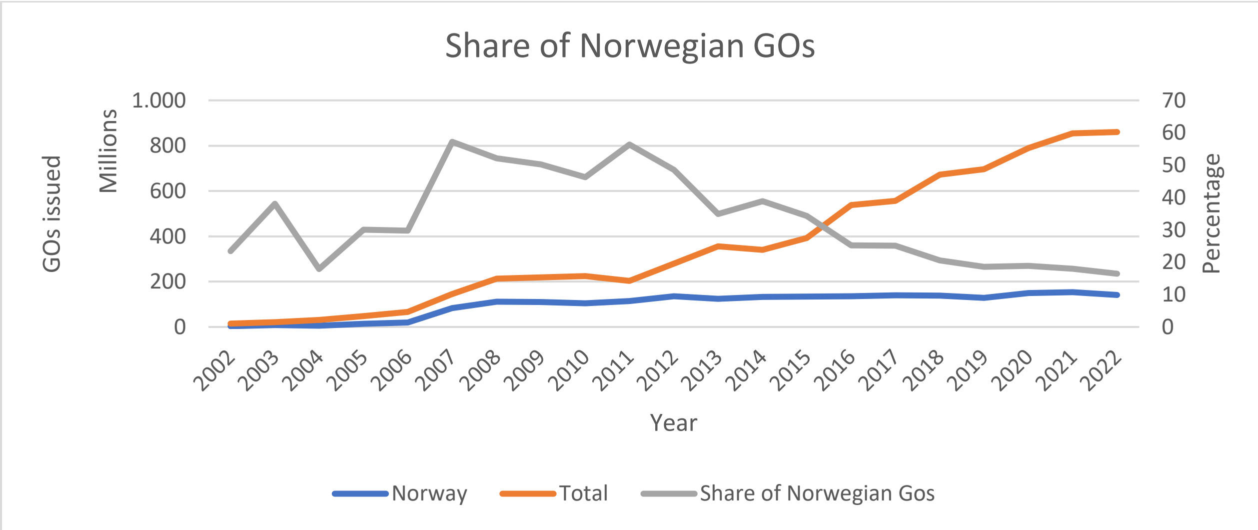

Figure IV: Development of the volume of Norwegian GOs of the total GO market from 2002 to 2022

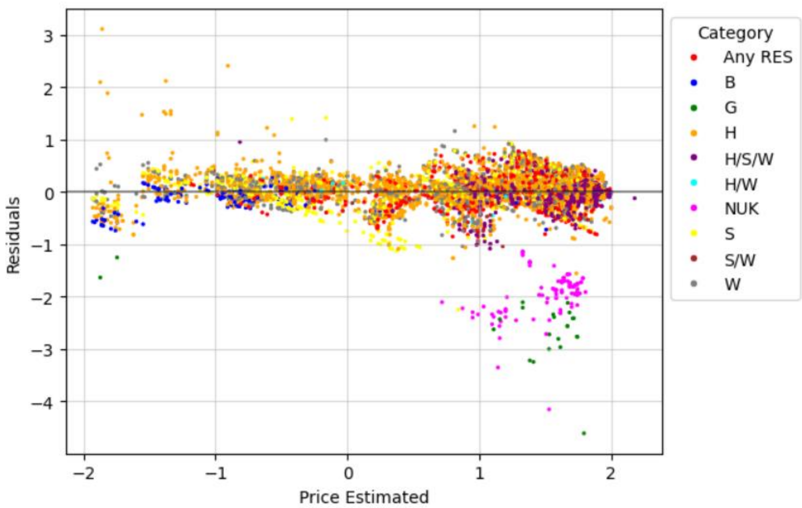

Figure VI: Residual plot for regression (1) including all observations

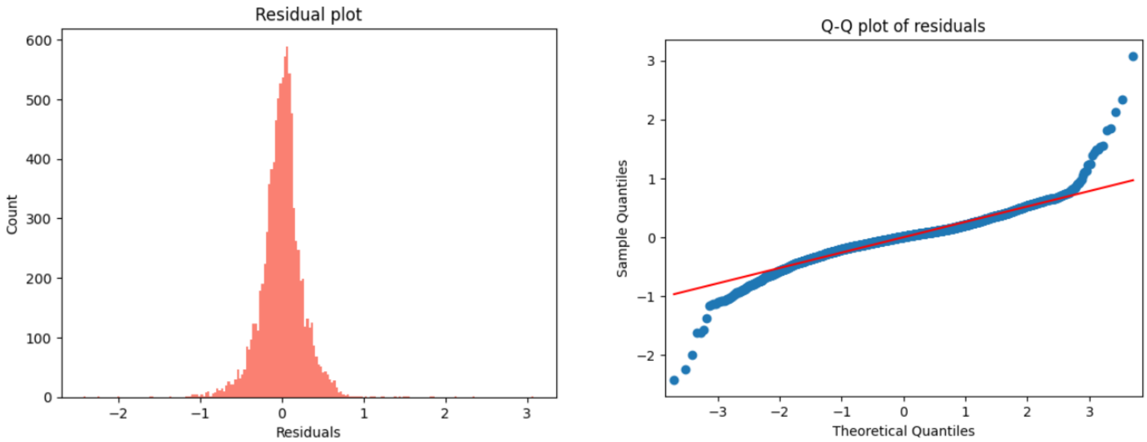

Figure VII: Residual plot and QQ-plot of residuals for regression (1) excluding NUK and G

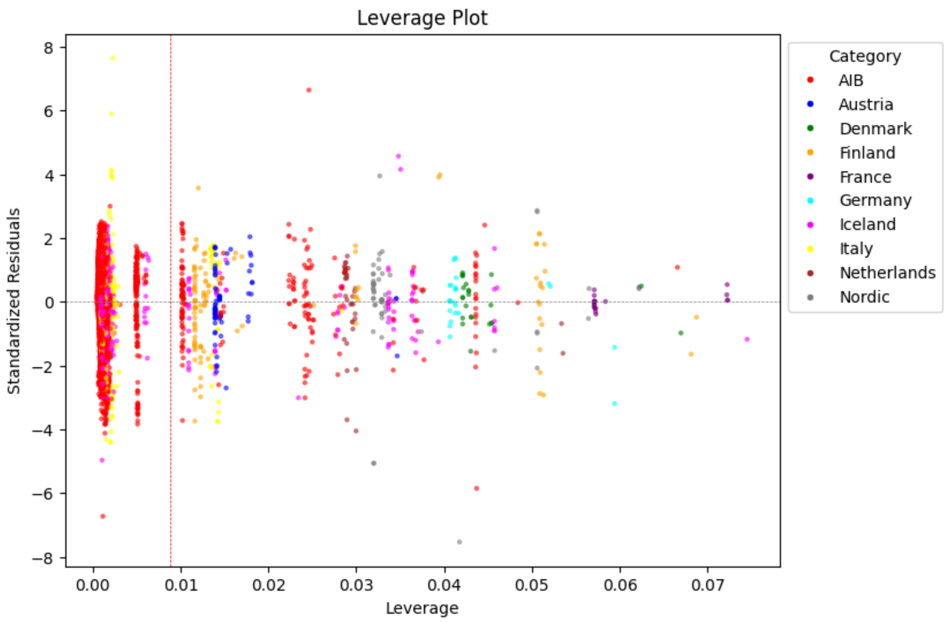

Figure VIII: Leverage plot for regression (2)

Appendix B: Regression results

Table I: Results for equation (1), including NUK and G

```
                            OLS Regression Results
==============================================================================
Dep. Variable:              Price_log   R-squared:                       0.858
Model:                            OLS   Adj. R-squared:                  0.858
Method:                 Least Squares   F-statistic:                     5886.
Date:                Tue, 16 Apr 2024   Prob (F-statistic):               0.00
Time:                        10:51:22   Log-Likelihood:                -3874.3
No. Observations:                9507   AIC:                             7783.
Df Residuals:                    9490   BIC:                             7904.
Df Model:                          16
Covariance Type:                  HC3
==================================================================================
                     coef    std err          z      P>|z|      [0.025      0.975]
----------------------------------------------------------------------------------
Intercept         -0.6065      0.031    -19.353      0.000      -0.668      -0.545
Prod_year[T.21]    0.2942      0.032      9.307      0.000       0.232       0.356
Prod_year[T.22]    0.6432      0.035     18.571      0.000       0.575       0.711
Prod_year[T.23]    0.4049      0.041      9.990      0.000       0.325       0.484
Prod_year[T.24]    0.3377      0.046      7.275      0.000       0.247       0.429
Prod_year[T.25]    0.1371      0.054      2.546      0.011       0.032       0.243
Prod_year[T.26]   -0.1002      0.063     -1.597      0.110      -0.223       0.023
Prod_year[T.27]   -0.3670      0.072     -5.124      0.000      -0.507      -0.227
Prod_year[T.28]   -0.5668      0.081     -6.958      0.000      -0.726      -0.407
Weekly_log         1.0475      0.009    111.627      0.000       1.029       1.066
Advance            0.1884      0.010     19.102      0.000       0.169       0.208
Some_RES           0.0475      0.010      4.577      0.000       0.027       0.068
One_RES           -0.0460      0.011     -4.117      0.000      -0.068      -0.024
Origin_info        0.0633      0.011      5.701      0.000       0.042       0.085
YOC_info           0.0612      0.040      1.536      0.125      -0.017       0.139
Support_info       0.0870      0.009      9.574      0.000       0.069       0.105
Label_info         0.1702      0.056      3.045      0.002       0.061       0.280
==============================================================================
Omnibus:                     6210.924   Durbin-Watson:                   1.250
Prob(Omnibus):                  0.000   Jarque-Bera (JB):           175300.746
Skew:                          -2.701   Prob(JB):                         0.00
Kurtosis:                      23.331   Cond. No.                         82.9
==============================================================================

Notes:
[1] Standard Errors are heteroscedasticity robust (HC3)
```

Table II: Results for equation (1), excluding NUK and G

```
                            OLS Regression Results
==============================================================================
Dep. Variable:              Price_log   R-squared:                       0.920
Model:                            OLS   Adj. R-squared:                  0.920
Method:                 Least Squares   F-statistic:                     6994.
Date:                Tue, 16 Apr 2024   Prob (F-statistic):               0.00
Time:                        10:51:23   Log-Likelihood:                -966.14
No. Observations:                9385   AIC:                             1966.
Df Residuals:                    9368   BIC:                             2088.
Df Model:                          16
Covariance Type:                  HC3
==================================================================================
                     coef    std err          z      P>|z|      [0.025      0.975]
----------------------------------------------------------------------------------
Intercept         -0.6652      0.029    -22.797      0.000      -0.722      -0.608
Prod_year[T.21]    0.2901      0.030      9.539      0.000       0.230       0.350
Prod_year[T.22]    0.6841      0.032     21.605      0.000       0.622       0.746
Prod_year[T.23]    0.4551      0.037     12.430      0.000       0.383       0.527
Prod_year[T.24]    0.4063      0.040     10.039      0.000       0.327       0.486
Prod_year[T.25]    0.1970      0.047      4.190      0.000       0.105       0.289
Prod_year[T.26]   -0.0301      0.054     -0.553      0.580      -0.137       0.077
Prod_year[T.27]   -0.3024      0.062     -4.859      0.000      -0.424      -0.180
Prod_year[T.28]   -0.5109      0.071     -7.176      0.000      -0.650      -0.371
Advance            0.1699      0.008     20.221      0.000       0.153       0.186
Weekly_log         1.0703      0.008    133.649      0.000       1.055       1.086
Some_RES           0.0439      0.010      4.340      0.000       0.024       0.064
One_RES            0.0296      0.009      3.465      0.001       0.013       0.046
Origin_info        0.0315      0.008      3.747      0.000       0.015       0.048
YOC_info           0.0739      0.042      1.765      0.078      -0.008       0.156
Support_info       0.0445      0.007      5.971      0.000       0.030       0.059
Label_info         0.1291      0.057      2.281      0.023       0.018       0.240
==============================================================================
Omnibus:                     1294.175   Durbin-Watson:                   1.048
Prob(Omnibus):                  0.000   Jarque-Bera (JB):            16424.410
Skew:                           0.170   Prob(JB):                         0.00
Kurtosis:                       9.472   Cond. No.                         82.9
==============================================================================

Notes:
[1] Standard Errors are heteroscedasticity robust (HC3)
```

Table III: Results for equation (2)

OLS Regression Results

Dep. Variable:	Price_log	R-squared:	0.923
Model:	OLS	Adj. R-squared:	0.922
Method:	Least Squares	F-statistic:	3841.
Date:	Tue, 16 Apr 2024	Prob (F-statistic):	0.00
Time:	11:06:22	Log-Likelihood:	-981.24
No. Observations:	9479	AIC:	2034.
Df Residuals:	9443	BIC:	2292.
Df Model:	35		
Covariance Type:	HC3		

	coef	std err	z	P>|z|	[0.025	0.975]
Intercept	-0.6454	0.029	-22.006	0.000	-0.703	-0.588
Prod_year[T.21]	0.2812	0.030	9.274	0.000	0.222	0.341
Prod_year[T.22]	0.6732	0.032	21.169	0.000	0.611	0.736
Prod_year[T.23]	0.4507	0.037	12.269	0.000	0.379	0.523
Prod_year[T.24]	0.3991	0.041	9.735	0.000	0.319	0.479
Prod_year[T.25]	0.1883	0.048	3.960	0.000	0.095	0.282
Prod_year[T.26]	-0.0354	0.055	-0.644	0.519	-0.143	0.072
Prod_year[T.27]	-0.3072	0.063	-4.902	0.000	-0.430	-0.184
Prod_year[T.28]	-0.5238	0.072	-7.303	0.000	-0.664	-0.383
C(Source, Treatment("Any RES"))[T.B]	-0.1066	0.019	-5.633	0.000	-0.144	-0.070
C(Source, Treatment("Any RES"))[T.G]	-2.6451	0.134	-19.799	0.000	-2.907	-2.383
C(Source, Treatment("Any RES"))[T.H]	0.0546	0.009	5.856	0.000	0.036	0.073
C(Source, Treatment("Any RES"))[T.H/S/W]	0.0536	0.010	5.339	0.000	0.034	0.073
C(Source, Treatment("Any RES"))[T.H/W]	-0.0290	0.057	-0.507	0.612	-0.141	0.083
C(Source, Treatment("Any RES"))[T.NUK]	-2.0169	0.046	-43.975	0.000	-2.107	-1.927
C(Source, Treatment("Any RES"))[T.S]	-0.0137	0.013	-1.094	0.274	-0.038	0.011
C(Source, Treatment("Any RES"))[T.S/W]	-0.0899	0.057	-1.566	0.117	-0.202	0.023
C(Source, Treatment("Any RES"))[T.W]	0.0288	0.010	2.806	0.005	0.009	0.049
C(Origin, Treatment("AIB"))[T.Austria]	0.0658	0.083	0.795	0.427	-0.096	0.228
C(Origin, Treatment("AIB"))[T.Denmark]	0.1071	0.030	3.566	0.000	0.048	0.166
C(Origin, Treatment("AIB"))[T.Finland]	-0.0604	0.033	-1.841	0.066	-0.125	0.004
C(Origin, Treatment("AIB"))[T.France]	-0.1591	0.096	-1.660	0.097	-0.347	0.029
C(Origin, Treatment("AIB"))[T.Germany]	0.0994	0.045	2.209	0.027	0.011	0.188
C(Origin, Treatment("AIB"))[T.Iceland]	-0.0543	0.067	-0.806	0.420	-0.186	0.078
C(Origin, Treatment("AIB"))[T.Italy]	0.0637	0.063	1.011	0.312	-0.060	0.187
C(Origin, Treatment("AIB"))[T.Netherlands]	0.2352	0.072	3.265	0.001	0.094	0.376
C(Origin, Treatment("AIB"))[T.Nordic]	-0.0120	0.009	-1.317	0.188	-0.030	0.006
C(Origin, Treatment("AIB"))[T.Norway]	0.0210	0.013	1.649	0.099	-0.004	0.046
C(Origin, Treatment("AIB"))[T.Spain]	0.1572	0.065	2.420	0.016	0.030	0.284
C(Origin, Treatment("AIB"))[T.Sweden]	0.0503	0.029	1.716	0.086	-0.007	0.108
C(Origin, Treatment("AIB"))[T.Switzerland]	0.2366	0.142	1.663	0.096	-0.042	0.515
Advance	0.1687	0.008	19.907	0.000	0.152	0.185
Weekly_log	1.0628	0.008	130.553	0.000	1.047	1.079
YOC_info	0.0539	0.045	1.202	0.229	-0.034	0.142
Support_info	0.0413	0.008	5.069	0.000	0.025	0.057
Label_info	0.1197	0.070	1.705	0.088	-0.018	0.257

Omnibus:	1326.633	Durbin-Watson:	1.067
Prob(Omnibus):	0.000	Jarque-Bera (JB):	19165.866
Skew:	-0.010	Prob(JB):	0.00
Kurtosis:	9.966	Cond. No.	82.5

Notes:
[1] Standard Errors are heteroscedasticity robust (HC3)

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway