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The European Market for Guarantees of Origin for Green Electricity: A Scenario-Based Evaluation of Trading under Uncertainty

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Abstract

Guarantees of Origin (GO) were introduced in order to enhance transparency about the origin of production of green electricity in Europe. The separation of electricity and GO trade has resulted in a prosperous GO market that is, however, characterized by non-transparency and opportunistic behavior. Historic price development occurs seemingly erratically and can therefore not be used to forecast future GO prices. This paper firstly provides an overview of the European GO market and an analysis of the historic price development; secondly, it proposes a model for determining future price developments of European GOs for different renewable energy technologies in different countries up to 2040. For non-household consumers, the model introduces a novel approach to determine the willingness-to-pay for green electricity. Four different scenarios are considered (*Status Quo*, *Sustainable Development*, *Full Harmonization*, *Ideal Development*). It is found that GO prices can be expected to increase on average in the next years, with prices ranging from 1.77 to 3.36 €/MWh in 2040. Coupled with rising demand for green electricity and further standardization of issuance procedures as well as the projected price developments, GOs could become a useful additional policy instrument for the promotion of green electricity in the EU.

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Keywords: renewable energy; green electricity; policy; willingness to pay; power purchase agreement; Europe; guarantees of origin

Highlights:

- Provides an overview of the European GO market and historic price developments
- The European GO market is found to be non-transparent, volatile and characterized by opportunistic behavior of participants
- Scenario- and model-based evaluation of GO price developments in Europe until 2040
- Average GO prices (by country and technology) are expected to increase until 2040
- Standardized GO issuance and expected price rises will raise GO market relevance

List of Abbreviations Used:

AIB	Association of Issuing Bodies
ATP	Ability-to-pay
CAGR	Compound annual growth rate
EECS	European Energy Certificate System
EEX	European Energy Exchange
EPEX	European Power Exchange
EU	European Union
GHG	Greenhouse gases
GO	Guarantees of Origin
IEA	International Energy Agency
LCOE	Levelized cost of electricity
MWh	Megawatt-hour
NACE	Statistical Classification of Economic Activities in the European Community (*nomenclature statistique des activités économiques dans la Communauté européenne*)
OECD	Organisation for Economic Co-operation and Development
PPA	Power purchase agreement
RED	Renewable Energy Directive
RES	Renewable energy sources
WAVG	Weighted average
WTP	Willingness-to-pay

1 Introduction

Since the European energy market liberalization starting in 1996 [1], consumers can freely choose their electricity supplier and may actively select one that provides so-called “green” electricity, i.e., electricity generated from renewable sources such as wind, solar, hydro, or biomass [2]. As electricity is a homogeneous good, the origin of a specific Megawatt-hour (MWh) of green electricity from the grid cannot *per se* be determined [3]. Consumers who are nonetheless willing to purchase green electricity have four general options. Presented in the order of their increasing positive impact on green electricity production and additional organizational effort and costs, these are: *unbundled energy attribute certificates* (EAC), p*ower purchase agreements* (PPA), *renewable energy offerings,* and *direct investments for self-consumption* (on-site and off-site) [4]. Amongst commercial and industrial consumers, EACs are the most frequently used option for green electricity acquisition [5].

These EACs allow energy providers to label electricity sold to consumers as “green” [6]; Guarantees of Origin (GO) were introduced in the European Union (EU) in 2001 [7] and are the most commonly used type of EACs in the EU [8]. GOs are freely tradable across most European countries, and since their implementation, a market for GO trade has emerged [10].

This European GO market functions as follows: for every MWh of green electricity that is fed into the grid by a producer, that producer may request the issuance of one GO in the respective national registry. During its lifetime, this GO may be traded internationally between traders, utilities, and suppliers until it is canceled upon request when the corresponding MWh of green electricity has been sold and must be disclosed to a consumer. If the GO is not cancelled after 12 months, it expires and is removed from the registry. The corresponding MWh of green electricity is still fed into the grid – the “greenness” of the electricity, however, has not been sold [11, 12].

As this trade can also be conducted on an international basis in the European Energy Certificate System (EECS), an acknowledged independent institution is required to ensure the correct processing of GOs because of different systems diverging from one another in terms of regulations [3, 11]. The Association of Issuing Bodies (AIB) initially defined, and continues to refine, a regulatory framework that is in compliance with related EU and national laws [9]. As of January 2023, 27 European countries were members of the EECS, including the non-EU member states Norway, Iceland, and Switzerland [13].

It is important to note that the GO scheme differs from other green certificate schemes, such as the Norwegian-Swedish green certificate scheme that was introduced 2003 in Sweden and

2012 in Norway. As a market-based support system, this scheme aims at promoting renewable electricity generation and is separate from the European GO system [14, 15].

The GO market is fully independent of the electricity market, as with GOs only the "greenness" of electricity is traded [10]. The market is characterized by non-transparent bilateral trading that is mostly conducted on private trading platforms, although an attempt to establish an open auctioning platform is currently being made [16]. Such exchange platforms might help increase transparency and liquidity in the market [17]. Despite these efforts, only limited information on GO prices is publicly available. Further, prices are subject to volatility and, as discussed in literature, subject to opportunistic behavior. These issues can lead to significant information asymmetry in the market [18]. This assessment is supported by recent market developments observed in the second half of 2022, as the market saw unprecedented price increases over all commonly traded types of GOs, as electricity suppliers rushed to purchase supposedly shortened GO volumes, when fears of an energy crisis in Europe grew [19–21]. Similar price developments were observed in 2018 as the prospects of low Norwegian hydro reservoir levels resulted in expectations of reduced GO supply. Once it had become clear that production would remain stable, prices returned to pre-2018 levels [10, 22]. This price volatility, non-transparency, and other issues, such as incomplete information of consumers, are reasons that the GO scheme is criticized as being no more than a marketing vehicle rather than a useful complementary policy tool to promote the production of green electricity [2, 18, 23–25].

This paper aims at reducing this non-transparency by first providing a detailed overview of the European GO market and historic price developments. A literature review sheds light on the criticism that is brought up against the GO scheme. Our main contribution, however, is a novel model-based approach to forecast GO prices under non-transparent market conditions as they prevail in the GO market. Firstly, to our knowledge, no such model exists yet in the scientific literature. While some commercial providers[1] provide GO price projections, they give no insight into their models. We thus add transparency and new insights about the actual market mechanisms that seem to be at work by explicitly modeling GO supply and demand. Secondly, our analysis can be used by regulators to determine whether, and in what respect, the existing GO market might need reform. Other stakeholders, such as project developers of and investors

[1] For example, enervis energy advisors, Berlin, Germany (https://enervis.de/en/product/price-forecast-for-european-guarantees-of-origin-for-green-electricity-goo/, last accessed June 17, 2023) or Thema, Oslo, Norway (https://thema.no/en/energy-markets/guarantees-of-origin/, last accessed June 17, 2023).

in renewable energy production plants, can use the model-based price projections provided to better assess the expected profitability of their intended projects.

The remainder of this paper is structured as follows. Section 2 discusses relevant literature on the GO market and price development as well as willingness-to-pay for green electricity. In Section 3, we introduce relevant theoretical background to our model approach. This approach is explained in Section 4, where we also introduce our four scenarios. Section 5 gives an overview of the data that was used to model possible future scenario-based GO price developments, which are then discussed in Section 6. The final section closes with a conclusion and implications of our results for policy makers.

2 Literature Review

Most of the existing literature on the topic of European GOs focuses on the effectiveness of the system in terms of green electricity production promotion, and much less on historical GO prices. In this section, we will show that currently no literature exists that has attempted to design a price forecasting model for GOs, and that we are thus the first to apply such a model to the European GO market. We further provide an assessment of historic price developments of GOs and an overview of literature on willingness-to-pay for green electricity.

2.1 Critical Evaluation of GOs

Firstly, the impression of energy production, use, and disclosure that is created by the EECS differs significantly from the actual trading of green electricity [24]. For example, Icelandic GOs can be traded and used for disclosure in mainland Europe although no physical grid connection exists [28]. Thus, when consumers purchase green electricity that is certified by GOs, they might assume to be supporting the production of local, additional renewable energy, when this electricity might not even be fed into the European electricity grid [29].

Secondly, the issue of (perceived) double counting must be addressed. This occurs when the perception arises that an amount of green electricity has been certified or traded twice, and it can result in further distrust in the system [30]. For example, Norwegian GOs can be exported to other European countries and be used to disclose the production of green electricity. In theory, these redistributions of disclosed green electricity are calculated in the so-called "residual mixes". However, consumers are seldom made aware of these, as, e.g., Norway's residual mix consists of a large proportion of electricity generated from fossil fuels due to the fact that actors in Germany are purchasing many Norwegian GOs and disclosing this as green electricity [32], while Norwegian consumers assume that their electricity is implicitly "green" due to the mostly renewable domestic electricity mix [33, 34]. It was observed, however, that once consumers were better informed, some positive willingness-to-pay (WTP) for GOs emerged [31]. Nonetheless, the impression arises that green electricity is marketed twice, which is further strengthened when the heterogeneous regulations of AIB member states on the issuance of GOs for supported green electricity are considered, see Section 5.1.

Finally, the mostly low price levels are mentioned as the third negative aspect of the EECS. Although official information on GO prices is not publicly available, it is known that prices for hydro GOs have usually ranged from 0.05 to 0.5 € per MWh in the last few years [10] and peaked at around 5 € per MWh in fall of 2022 [20]. These prices provide an additional revenue stream for power producers, but are too low to trigger significant investments in renewable energy production [2, 9, 35]. Furthermore, the price volatility, as discussed in Section 2.2, increases information symmetry effects in the GO system [18].

To rebalance these critical remarks, it is important to note that the GO system was never designed with the intention to promote green electricity production, as its goal is electricity information disclosure [26]. This purpose is generally fulfilled [10]. In a special form of disclosure, GOs can also be used in greenhouse gas (GHG) protocols and might therefore be useful in improving GHG inventories and monitor the carbon footprints of companies and households [25, 36].

GOs are also necessary because the acceptance of renewable electricity production and the transition to carbon-neutral economies is based mainly on information and trust [28, 37].

Furthermore, despite of historically very low price levels, GOs can generate additional income for producers. In countries that allow the issuance of GOs in addition to the reception of financial support for RES (renewable energy source) production, revenue generated from trading GOs is a highly welcomed source of income, provided that the registry fees are sufficiently low[2] [9, 25]. Once GO prices reach levels that exceed governmental support schemes, they may well become decision-relevant revenue components for project developers and RES producers.

The above-mentioned lack of increased incentive for green electricity production through GOs can be addressed when GO prices are analyzed closely. Once it becomes more economically viable to issue GOs than to use national subsidies for RES production, GOs will have a positive impact on the production of renewable electricity [2, 39]. GO prices are influenced by the age, technology and location of a power plant [40]. The most influential force,

[2] For details of current fees in the national registries, see [38].

however, is the fundamental concept of supply and demand [27], but which works differently for different types of GOs. For example, Dutch GOs that are in limited supply, are demanded by many consumers with a high WTP. Thus, Dutch GO prices are typically much higher than most others (see Section2.2) and the GO system seems to have an effect on green electricity promotion [24]. In contrast, GOs from Norway, mainly generated from hydropower, are used as a cheap source for green electricity labeling, as supply greatly exceeds demand and Norwegian consumers are less interested in purchasing green electricity. Over the last years, the European demand for green electricity has been lower than supply, as can be seen by the expiry of GOs in the EECS, and this has resulted in low prices [28]. Thus, in theory, once demand for GOs increases, prices will rise and therefore result in GOs becoming a potentially effective tool for the promotion of renewable energy production [41].

This necessary demand could be generated if European policy-makers were to pave the way. Reasons for this are increased demand levels from interested household consumers who are willing to pay higher electricity prices in exchange for higher amounts of renewable energy in their supply mixes. Additional demand is generated by increased corporate awareness and a more active approach in terms of energy acquisition [4, 8, 33, 42].

2.2 Price Information and Evaluation

As this paper proposes a model to forecast GO prices, an analysis of historic GO prices was conducted, with a summary being provided in this subsection. This analysis was based on information from the literature and from commercial providers of price information about European GOs. Some countries auction GOs to bidders, such as Italy, France, or Luxembourg.[3] These auction results are published online and can be used as an indication of current GO prices, although they can then be resold on the international GO market, where prices might differ. Table 1 provides an overview of some GO prices; a more detailed description of these prices can be found in Table A-1 in the Appendix.

[3] See https://www.aib-net.org/facts/market-information/auctioning-gos-aib-members, last accessed January 21, 2023.

Table 1: Overview of historic GO price ranges

GO type	Period	Price / price range [€/MWh]
Nordic Hydro	2015-2018	0.05 – 3.40
German (Unspecified)	2018	0.8 – 1.6
Austrian (Unspecified)	2018-2019	0.9 – 1.45
Dutch Wind	09/2018	8
EU Hydro	2018-2020	0.15 – 1.98
EU (Average), 2022 Futures	September 2021	1.25
EU (All)	Spring 2022	1.7 – 2.3
Italy (Weighted average auction price for all technologies)	January – December 2022	1.03 – 6.46

Abbreviations used: GO = Guarantee of origin; EU = Generic European (Origin Unspecified)

GOs issued for Nordic Hydro, i.e. for green electricity generated in Denmark, Finland, Iceland, Sweden, or Norway, are the most numerous ones and considered as a bottom benchmark for prices [10, 43]. Therefore, most price analyses and information available focus solely on Nordic Hydro prices. As prices depend mainly on the location, technology, and age of the power plant concerned, prices for different types of GOs can vary. Note that since the introduction of the EECS, prices have been relatively stable, ranging around 0.5 to 1.5 €/MWh for most GO types. In the last few years, however, it could be observed that GO prices are in fact highly volatile and apparently subject to demand-driven opportunistic behavior of market participants: price increases in 2011 probably resulted in speculations regarding the increase of renewable energy production in the wake of the Fukushima nuclear plant disaster [22]. Another rise in prices was noted in the wake of miscommunications concerning the United Kingdom’s unconstrained trade of GOs circulated [44]. In 2018, the highest price increase for certain GOs occurred, with Dutch Wind GOs reaching levels of up to 8 €/MWh, see Table 1 and Table A-1 in the Appendix. This probably resulted from the drought situation in Europe and the perceived lack of available hydropower and thus Nordic Hydro GOs, driving up all other prices [10]. Dutch GO prices rose to such high levels due to high local demand [24]. In 2021, prices increased again due to expectations of reduced availability of Nordic Hydro GOs in the winter of 2021/2022 because of low hydro reservoir levels in Norway caused by a lack of rainfall in 2021 [45]. Another drastic price increase was observed after the Russian attack on Ukraine in February 2022. As shown in Fig. 1, prices for different types of GOs abruptly jumped by about 1 €/MWh and have been steadily increasing to around 5 €/MWh – unprecedented price levels for most GO types [19, 20]. Italian GO auction results showed a similar development in 2022 [21]. This demonstrates the volatile nature of the European GO market, fuelled by opportunistic market behavior.

It was found that the GO market also contains some trading activities that include futures contracts (i.e. derivatives). It is possible to trade GOs up to three years in advance, i.e., in 2022, 2025 futures can be purchased. Future prices seem to follow the current-year price level, but include a slight premium, as depicted in Fig. 1. Past-year GOs can still be traded to some extent due to the lifetime of 12 months.

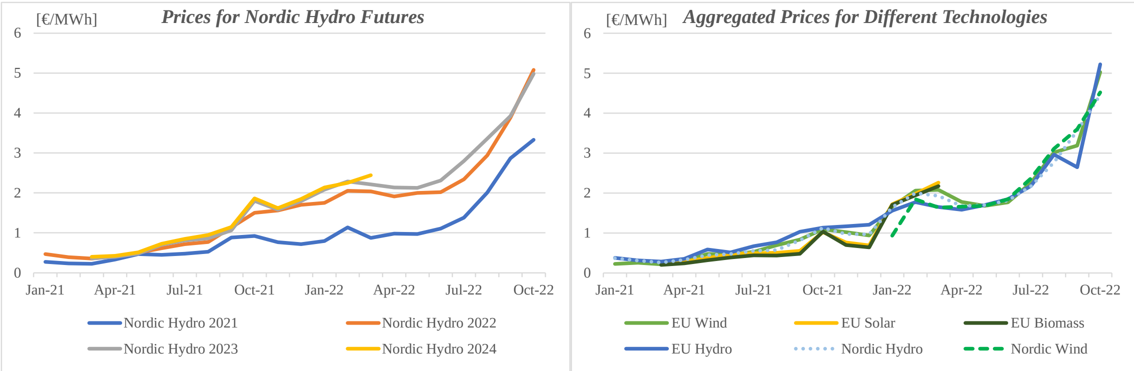

Fig. 1. GO Prices for Nordic Hydro Futures in 2021 and 2022 (left plot), Aggregated Prices for Different Technologies (right plot). Source: Own illustration, based on Argus Media [20] and Robert [19].

In 2022, the European Energy Exchange (EEX), launched a European-wide marketplace to trade GOs in an auction format through its subsidiary EPEX Spot. This plan had been announced in November 2021 [16]. Earlier attempts to establish such a market in 2012 had failed around 2018, as interest in GOs remained low and traded volumes were close to zero at that time [10]. This renewed attempt in 2022 allows for the trade of four different types of GOs, European Hydro, Solar and Wind, as well as Nordic Hydro, and has apparently garnered some interest. Results of the first auction achieved prices at around 4-6 €/MWh[4], which reflects current market prices. Traded volumes are not publicly accessible and information on the location and age of producing plants as well as the time of production are not disclosed. These prices might have therefore resulted from a high demand with limited supply. With high prices and demand seemingly increasing, this second attempt might succeed in adding transparency to the GO market.

[4] Auction results can be found at https://www.epexspot.com/en, last accessed February 28, 2023.

2.3 Willingness-To-Pay for Green Electricity

The determination of WTP is a central part of the proposed model as it plays an essential role in predicting the success of environmental policies and generation schemes such as GOs [46]. Here, we refer to WTP as the maximum price that a consumer is willing to pay for a certain good [47]. Literature typically focuses on the assessment of WTP for green electricity itself, not EACs, and here mostly on that of household consumers.

Calikoglu & Aydinalp Koksal [48] are an exception to this rule. They surveyed 200 Turkish industrial consumers and found that 20% of them were willing to pay extra for green electricity. They also found that WTP depends on the generation technology and point at heterogeneous WTP ranges and trends in different countries, impacted by various factors.

In a study conducted by the OECD [49], over 60% of consumers stated that they were willing to pay more for electricity from renewable sources than for electricity from conventional sources. This is supported by Yang et al. [50] and Sundt & Rehdanz [37], who found that, in general, people are willing to pay higher prices for green electricity.

Soon & Ahmed [51] found that WTP for green electricity varies depending on knowledge, information, awareness and exposure to renewable energies and green electricity production, which is supported by Rowlands et al. [52], Roe et al. [46], Bollino [53], Diaz-Rainey & Ashton [54] and Knapp et al. [55]. It is therefore evident that the WTP for green electricity depends on socio-economic factors and varies between different types of consumers [48, 51, 53].

The energy source from which green electricity is generated also has an influence on the WTP [48]. Table 2 shows different WTP values in US-$ per month for varying green electricity sources as found by Knapp et al. [55], Grilli [56] and Borchers et al. [57].

Table 2. Varying WTP values depending on green electricity sources

Technology / green electricity source	WTP [US-$ per month]	Reference/s
Mixed source / “green”	13.10	[56]
Mixed source / “green”	8.44 – 17.00 (Mean)	[57]
Mixed source / “green”	5.10 (Low) – 7.38 (High)	[55]
Solar	14.40	[56]
Solar	14.68 – 21.54 (Mean)	[57]
Wind	14.14	[56]
Wind	6.14 – 15.47 (Mean)	[57]
Biomass	11.02	[56]
Biomass	-2.22 – 10.59 (Mean)	[57]
Hydropower	9.57	[56]
Geothermal	36.90	[56]

Abbreviation used: WTP = Willingess-to-pay

However, it should be noted that the WTP for green electricity is limited [24]. In their study, Andor et al. [58] compared several WTP data sets from Germany and conclude that the WTP for green electricity is modest at best and has in fact been declining. This is corroborated by Winther & Ericson [33] at the European scale, who note that Europe as a whole is failing to significantly increase consumer WTP for green electricity. In contrast to that, for North America, Yevdomikov et al. [59] estimated the development of the WTP of urban residential electricity consumers in Canada from 1991 to 2013, finding that the WTP for green electricity has been steadily increasing since 2005. The same can be said for Italian consumers who are, in general, willing to support Italian efforts to increase the production of green electricity through higher prices [60]. In their meta-analysis, Soon & Ahmad [51] conclude that, on a global average, the WTP for green electricity is in fact increasing. Finally, Hast et al. [29] find that “green electricity” products have price premiums of up to 5% compared to “standard” electricity.

3 Theoretical Background

The proposed model relies on certain economic theories and concepts that are discussed in the following.

3.1 Monopolistic Competition

The GO market can be interpreted as a market with monopolistic competition [61], a concept which has been used to model many different kinds of industries, but which is less well known than perfect competition. It describes a market situation where many producers compete against each other, selling products that are not perfect substitutes (i.e. that differ in branding or quality). Firms take the prices offered by the competitors as given and ignore the impact of the own prices on the prices of the other firms. Unlike in the case of perfect competition, firms maintain spare capacity. A monopolistically competitive market differs from perfectly competitive ones in two main respects: it produces heterogeneous products, and it involves a great deal of non-price competition (e.g. based on subtle product differentiation). Because of brand loyalty (or in the case of GO, preference for specific types of GO from specific countries, such as Dutch Wind or Nordic Hydro, see Section 2), a firm in a monopolistic competition market can raise the price of its product/s without losing all of its customers, implying that the firm's demand curve has a negative slope (in contrast to perfect competition, which has a perfectly price-elastic demand schedule). This theory of monopolistic competition characterizes the GO market quite well, and was thus used as a guidance in the model development (e.g., regarding the slopes and shapes of the demand and supply curves, role of transaction costs, and the modeling of technology- and country-specific GO prices).

As is the case with most other markets, the GO market is determined by the interaction of supply and demand. Normally, where supply and demand curves intersect, the market equilibrium price is found [62]. The GO market, however, has been characterized by an oversupply of GOs, as supply exceeds demand for most GO types [63]. Thus, prices in this market generally do not necessarily follow standard market-based principles, but might be influenced strongly by opportunistic behavior and transaction costs [22, 44, 45]. For the sake of our model, see Section 4, we argue that the GO market is characterized by a perfectly inelastic supply [64]. Here, no matter how high or low prices are, supply does not change. The historical over-supply situation mentioned above demonstrates that current GO price levels are not yet perceived as a reason to invest in new renewable energy capacity. Rather, GOs are produced more as a by-product, and income from GO sales is perceived as "nice-to-have", especially due to low transaction costs for GO issuance [38]. The case of a change in price elasticity of supply beyond a certain boundary price could theoretically apply to the GO market, if prices were higher than mark-ups explained, e.g., through guaranteed feed-in-tariffs or feed-in premia [65].

3.2 Willingness- and Ability to Pay and Environmental Concern

Although some of the findings addressed in Section 2.3might not be directly transferable to Europe and GOs, they do indicate that environmental concern, reflected in WTP, is growing amongst the population. Research mainly focuses on household consumers, which is why studies on the WTP of industrial and commercial consumers is still scarce. The WTP for non-household consumers is estimated in our proposed model, enabling to determine expected future GO prices reasonably well by realistically modeling the supply of GOs as well as private household and non-household sector GO demand. The WTP for household consumers is based on assumptions from literature, see Section 5.

Our approach builds upon three general concepts, WTP, already introduced in Section 2.3, and the ability-to-pay (ATP) that is often referred to in public health concepts [66] and taxation [67]. ATP differs from WTP in the sense that people must have (monetary) resources that can be allocated towards a certain good or service in order to express their preferences [66], in our study for the technology type and origin of GOs. The concept of ATP has been subject to some research in energy economics that focuses mainly on household consumers, e.g., Pederizini [68], Fankhauser & Tepic [69] and Bose & Shukla [70], while our paper, for ATP, focuses on non-household consumers. Thirdly, we rely on a measure that we refer to as *environmental concern*, following Rowlands et al. [52] who determined that consumers who had a high “ecological concern” were willing to pay a large premium for green electricity. Due to the lack of WTP data for non-household consumers, we introduce the parameter *environmental concern* as the non-household consumers’ willingness to position themselves as “green”, possibly for marketing reasons or due to supply chain regulations [71]. ATP and environmental concern determine a consumer’s WTP, as shown in the following section.

4 Model Specification

According to Velazquez Abad & Dodds [40], the value of a GO depends on the size of the market, the demand for green electricity or tariffs, and the question of whether disclosure is mandatory and, if so, whether the disclosure scheme is also mandatory for complementary subsidy schemes. All this information is accounted for in our model-based approach. The model calculates average yearly prices for all types of GOs. In this set-up, depending on the observed GO type and year, situations of over-supply, as could be observed for certain types of GO in the past, such as those from Nordic Hydro, are sometimes created. For other GO types that are more desirable to consumers, such as Dutch GOs, higher prices are formed due to high demand

and WTPs. Thus, in this model, if consumers have the possibility, they will always choose the type of GO that corresponds to their highest WTP. An optimization of prices does not occur.

4.1 Modeling of GO Supply

The GO market's supply structure, characterized by monopolistic competition, must be modeled in our approach. For this, the model determines the supply of a certain type of GO for a certain point in time. GO supply is inelastic. GOs are only differentiated according to their origin *o* and production technology *t*, e.g., Spanish Solar. The amount of GOs issued in a given period *p* is calculated as the issuance rate of a certain country of origin *o* for the technology *t*. The issuance rate is the number of GOs issued for a technology *t* in relation to the produced electricity from this technology, a parameter that we assume from past data, see Section 5.1. $Supply_{o,t,p}$ of a GO is then determined by multiplying the corresponding issuance rate $IR_{o,t,p}$ with the produced electricity $El_{o,t,p}$ of technology *t* in period *p*, see Eq. (1):

$$Supply_{o,t,p} = IR_{o,t,p} * El_{o,t,p} \tag{1}$$

4.2 Modeling of GO Demand

Literature suggests that not all non-household consumers are willing to pay for green electricity [72], which our model approach addresses through the determination of the non-household consumers' WTPs by an exogeneous parameter that we earlier introduced as *environmental concern*, and their ATP. The ATP of a non-household consumer *k* is calculated at the ratio of their profits and their electricity cost (see Eq. (2)) and reflects how much additional money could be spent on acquiring GOs. The values of both ATP and environmental concern range from 0 to 1.

$$ATP_k = \frac{Profits_k}{Electricity\ cost_k}, \in [0,1] \tag{2}$$

Next, determination of the WTP from the ATP and the environmental concern is shown for three fictional non-household consumers A, B, and C in Fig. 2. WTP is expressed as a share of electricity costs that will be paid extra for green electricity, referred to as the relative maximum willingness-to-pay $WTP_{max,rel,k}$ of a consumer *k*. In this example, A's environmental concern value is low, but ATP is high. A is therefore willing to pay a limited surplus for green electricity, but not as much as C who has higher values for both factors and thus the higher $WTP_{max,rel,k}$. $WTP_{max,rel,k}$ can range from 0 to 1. In contrast, a household consumer is given a fixed parameter value based on assumptions from residential WTP literature on green electricity. Thus, from here on, the approach adopted for non-household consumers is used analogously for household consumers, see Fig. 2. Obtained values for $WTP_{max,rel,k}$ are then multiplied with the corresponding electricity prices $P_{El,k}$ in €/MWh to determine specific maximum $WTP_{max,k}$, see Eq. (3).

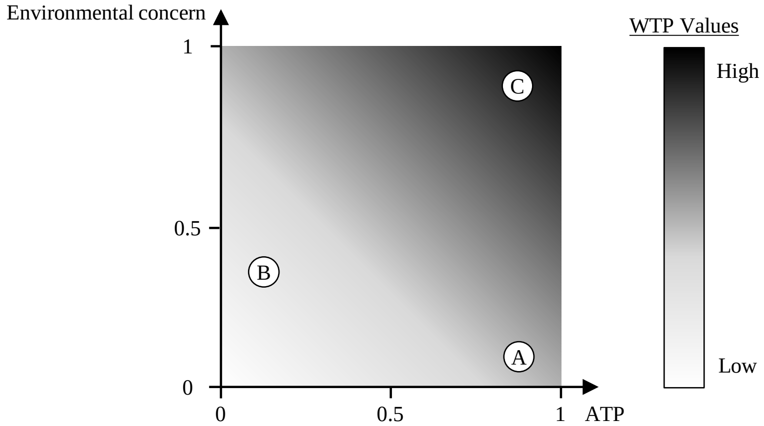

Fig. 2. Estimation of relative maximum willingness-to-pay $WTP_{max,rel}$ for exemplary non-household consumers A, B, and C

Abbreviations used: ATP = Ability-to-pay, WTP = willingness-to-pay

$$WTP_{max,k}\left[\frac{€}{MWh}\right] = WTP_{max,rel,k}[\%] * P_{El,k}\left[\frac{€}{MWh}\right] \tag{3}$$

Putting illustrative values to this, consumer C might be willing to pay an additional 30% of the electricity costs for the acquisition of green electricity, while A will pay 15% extra, B 10% and the household sector consumer D, say, 35%. Assuming universal electricity prices of 10 €/MWh, A will pay additional 1.5 €/MWh for green electricity, B 1 €/MWh, and so on. This is $WTP_{max,k}$ that is then reduced by derating factors to mirror individual consumer preferences based on consumer *k*'s country *c* for GOs of origin *o*, $DF_{c,o}$, and technology *t*, $DF_{c,t}$, as GO prices depend on origin and technology [40]. The calculation is shown in Eq. (4).

$$WTP_{k,o,t} = WTP_{max,k} * DF_{c,o} * DF_{c,t};\ DF_{c,o}, DF_{c,t}\ \in\ [0,1] \tag{4}$$

Next, the calculated WTPs are sorted in descending order. The demand of the consumer with the highest WTP for a GO of origin *o* and technology *t* is satisfied first. GO demand is assumed as being exogeneous. Once this demand is satisfied, demand corresponding to the second-highest WTP, in this case consumer C, is satisfied next. This is repeated until the supply of this type of GO has been used up. The equilibrium price $P^{*}_{o,t,p}$ of a GO of origin *o* and technology *t* in a period *p* is the smallest WTP that corresponds to the consumer who was able to satisfy at least one MWh of their demand, in this case consumer A. Demand $D_{A,p}$ is then decreased by the amount of acquired GOs of this type and satisfied by GOs corresponding to the next-lowest WTP of this specific consumer A. This procedure is repeated for every type of $GO_{o,t}$. Thus, the demand curve follows a declining step function characteristic and has a negative slope (see Fig. 3).

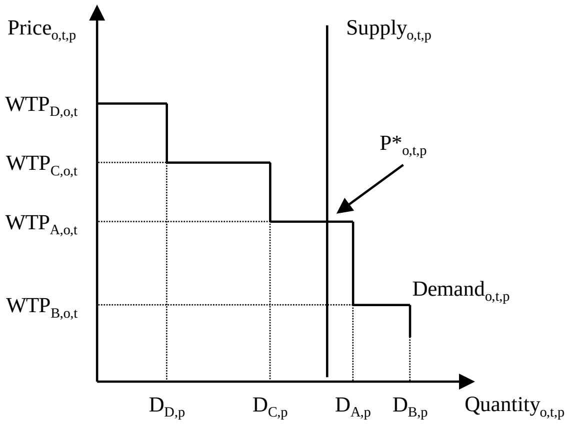

Fig. 3. Determination of the equilibrium price *P*o,t,p*

4.3 Model Assumptions and Limitations

The assumptions provided in the section focus on limiting the model's scope and apply to all four scenarios considered. Assumptions regarding the data and scenarios will be provided in the corresponding sections.

Considering the consistent amount of expiring GOs, producers issue GOs irrespective of whether they will be able to sell them [63]. This leads to the assumption that transaction costs are negligible, although some registries do charge modest fees for the issuance and trade of GOs [38]. This behavior of GO issuance regardless of the possibility of trading is implemented into the model by applying perfect inelasticity to the supply curve, as discussed in Section 3.1. Thus, the amount of GOs issued per type of GO depends on RES production and estimated GO issuance rates only.

An analysis of GO issuance shows that seasonality exists in supply and demand. However, from AIB data it is not possible to determine whether transactions and cancellations of GOs depend on which month they were issued; one can only determine that GOs were cancelled in a given country in a given month [63]. Adding to this, the lifetime of GOs is limited to 12 months. We thus argue that opting for a yearly approach is more appropriate.

For certain types of GOs, the inelastic supply curve will not be met by the remaining demand for green electricity. Thus, for some GO types, the equilibrium price will not be found, and thus results in a price of 0 €/MWh. Therefore, we assume that demand exceeds supply from a certain year onwards. This depends on the expected development of demand.

Historically, prices for the least-desired GOs, Nordic Hydro, are at a minimum of 0.05 €/MWh (see Table A-1 in the Appendix). In our model, prices are determined by the lowest WTP that may lie below past minimum prices. Thus, the fact that GOs seem to have a lower price boundary is neglected.

The upper price boundary is assumed to be limited by the lowest levelized cost of electricity (LCOE) for green electricity in a given year. As GOs only represent the "greenness" of electricity but do not include the physical delivery of the electricity itself, consumers will not pay a GO price that exceeds the LCOE of green electricity, as they would have to additionally purchase the physical electricity to be as well off as when buying green electricity. These LCOE values are determined by the LCOE for wind or solar photovoltaics, as these renewable technologies are expected to have the lowest LCOE [73, 74].

Due to limited insight into the GO market and the lack of knowledge regarding the age of the issuing power plants, GOs are only differentiated from one another by their country of origin and technology.

The WTP values that ultimately determine the prices of future GOs are determined through an analysis of past data. Calculations and assumptions regarding the future change of WTP for GOs would add further uncertainty to the model. Therefore, calculated WTPs for GOs of certain consumers remain constant over the complete timeframe considered.

Similarly, sectoral socio-demographics also do not change over time. However, their future electricity consumption will be changing according to the literature; some recent developments are discussed Section 5.

5 Data and Scenarios

In total, the market for GOs has been growing since its introduction in 2001 and is expected to continue to do so in the future [16, 19, 27, 78]. All GO data that were used are publicly available on the AIB website. Note that the data provided to the AIB by its member states is inconsistent, because some countries report fully on cancelation but neglect reporting on issuance [63]. Due to these limitations, data about individual countries' issuance, trade, cancellation were available on a monthly basis from 2016 onwards. Fig. 4 shows the data flow diagram for our proposed model. Along the left branch, we show how data for the supply side is gathered, as described in Section 5.1, while the right branch focuses on consumer demand and WTP, for which a data overview is given in Section 5.2.

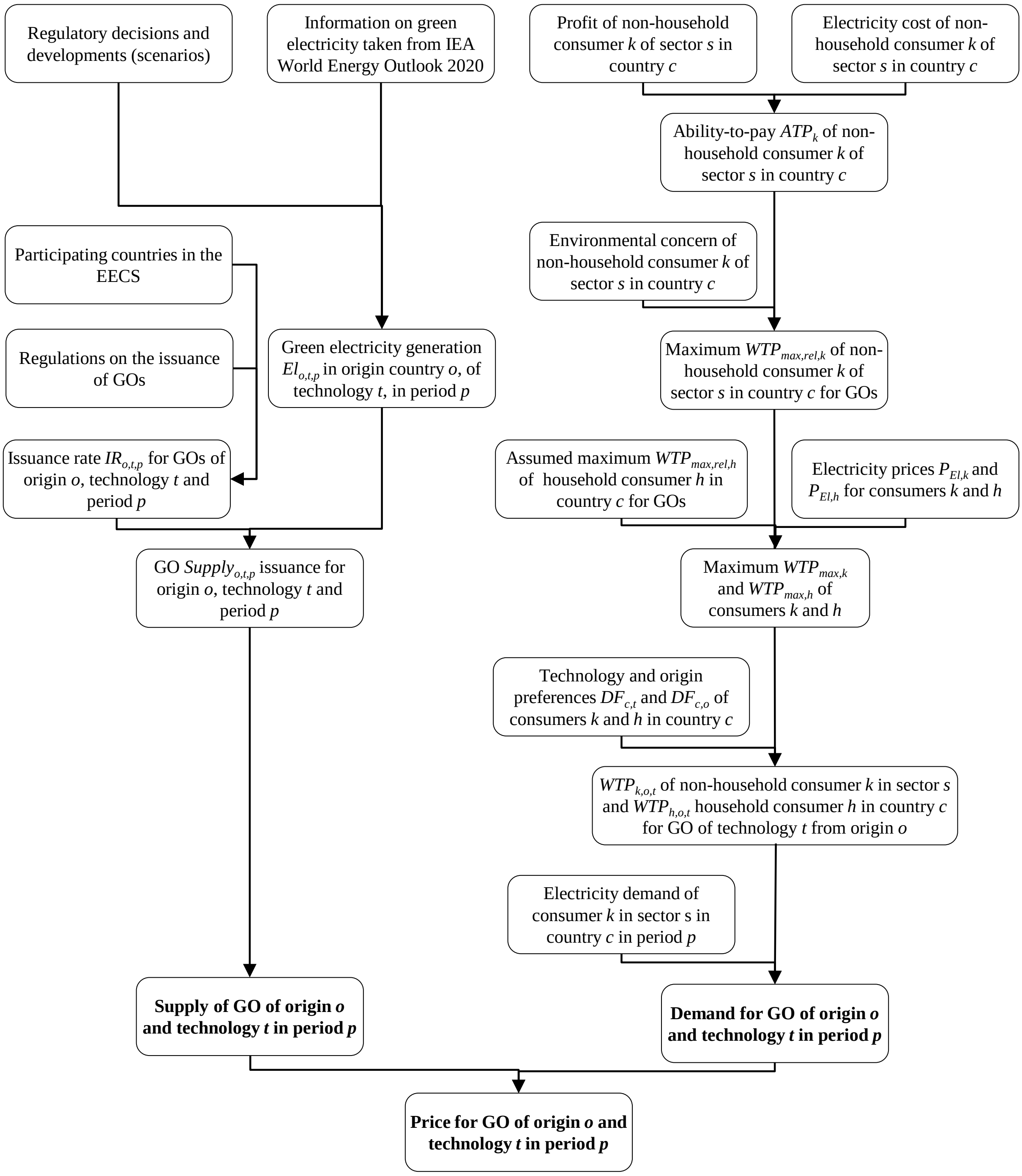

Fig. 4. Data and work flow diagram

Abbreviations used: EECS = European Energy Certificate System; GO = Guarantee of Origin; ATP = Ability-to-pay; WTP = Willingess-to-pay

5.1 GO Data

GO data are provided in two different ways. The first – so-called production statistics – refer to the month and year when the electricity was produced. The second type of data – transaction statistics – refer to the month and year when the transaction of the GO took place. For this model, the amount of GOs currently existent in the registries connected to the AIB Hub was relevant. Thus, all analyses were conducted with transaction data [63]. Following Kuronen & Lehtovaara [79], a shifted calculation approach was used for the cancelation data. For this paper, the EECS member countries (as of end-2020) were divided into six categories, depending on their regulations regarding the issuance of GOs, see Table 3. This gives an indication of the level of regulation and harmonization in and amongst AIB member states. Issue rates, i.e., the share of issued GOs in green electricity production, vary between technologies and categories, as shown in Table 4.

Table 3. Categorization of EECS member countries and GO systems introduced

Category	Description	Countries
1	Issuance of subsidized electricity, but disclosure on GO	Austria, Denmark, Estonia, Finland, Italy, Portugal, Switzerland
2	Subsidized GOs are auctioned	France, Luxembourg, Slovenia, the Slovak Republic
3	Subsidized GOs are immediately canceled	Cyprus, Lithuania
4	No regulations on subsidies	Belgium, Croatia, the Czech Republic, Greece, the Netherlands, Norway, Spain, Sweden
5	No issuance of supported GOs	Germany, Ireland, Serbia
6	No subsidy system in place	Iceland

Abbreviations used: GO = Guarantees of origin

Table 4. Share of GOs issued relative to green power production, by category and technology

Category	1	2	3	4	5	6
Biomass	0.64	0.26	0.08	0.49	0.21	No GO issuance
Geothermal	0.52	0.03	No GO issuance	No GO issuance	No GO issuance	0.92
Hydro	0.78	0.49	0.35	0.6	0.63	0.98
Solar	0.53	0.05	No GO issuance	0.37	0.02	No GO issuance
Wind	0.68	0.28	0.5	0.73	0.09	No GO issuance

Abbreviations used: GO = Guarantee of Origin

Sources: Own calculations, based on data from [63] and [80]

The results of a more detailed analysis of the GO market in terms of issuance, cancelation, trade behavior (i.e., whether the country acts as a trade hub due to low transaction fees), and further parameters can be found in Table A-4. Note that for the determination of the input data for the model, the assumed amount of future GO volumes per country and technology must be calculated first. For this, data for electricity production is taken from the IAE World Energy Outlook [81]. Future GO volumes are based on the aforementioned issuance rates and assumed to increase by 5% annually from 2025 onwards. Countries can begin issuing GOs starting in 2025 for technologies for which they had not issued GOs previously. Development of electricity production from technologies depends on the scenario considered, see Section 5.3.

5.2 ATP-WTP Data

To calculate the ATP and eventually the WTP for GOs, Eurostat was chosen as the main data source. The data sets used for the calculation of the relevant parameters of the model are listed in Table 5. First, sector categories had to be matched between tables “nrg_cb_e” and “sbs_sc_ind_r2” in order to be able to compare revenues and the number of companies with the respective electricity consumption by following Eurostat [82]. For this study, sectors corresponding to Level 2 of the Classification of European Economic Statistics (NACE) sectors were chosen. Refer to Table A-3 in the Appendix for more details.

Table 5. Data sets used for ATP/WTP, demand and profit calculations

Data set	Contents	Used for…	Source
Household characteristics	Household distributions	WTP, demand	[83]
Nrg_cb_e	Electricity consumption	ATP, demand	[84]
Nrg_pc_205	Electricity prices	ATP, WTP	[85]
Sbs_sc_ind_r2	Structural data on European industry, i.e., average revenue and number of companies per NACE sector & size	Profit, demand, ATP	[86]
Swiss Electricity Statistics	Electricity consumption & prices in Switzerland	ATP, demand, WTP	[87]

Abbreviations used: ATP = ability to pay, WTP = willingness to pay

Next, the average electricity consumption per NACE sector was calculated on the country level by weighting the consumption provided in the energy balance with the respective revenues. Then, the consumption per NACE sector was divided amongst the different size categories according to the respective proportions of total sector revenues. By dividing the resulting values by the number of companies of a specific NACE sector of a specific size in a specific country, the average electricity consumption of the company in question was determined.

Then, price data, taken from the data sets shown in Table 5, were matched to the afore-calculated average electricity consumption per sector, size, and country for determining the average electricity costs. These calculations provided the model with values for the average electricity demand of industrial and private consumers in Europe until 2017.

Expected future electricity demand is based on assumptions in the "Stated Policy Scenario" of the IEA World Energy Outlook [81]. Thus, this model only covers the timeframe from 2020 to 2040. The assumed demand for green electricity matching the Gos is assumed at 558.63 TWh (21.57% of total demand) because an overestimated demand would result in unrealistically high prices. By 2040, it is assumed that 50% of total electricity demand would be covered by Gos, resulting in a compound annual growth rate (CAGR) of 9% for the initial green electricity demand.

The environmental concern, a vital part of this model's WTP calculation, was estimated based on assumptions of the different NACE sectors' exposure to environmentally concerned consumers, private or commercial. For example, companies belonging to the sector "Manufacturing of basic metals" (C24) are likely to have less concern for environmental issues than companies in the sector "Manufacture of food products" (C10), as the latter are more involved with consumers who are conscious about the environmental impact of their purchases. Sectors that had representatives in the RE100-iniative were assumed to have a higher environmental concern, depending on their respective goals [88]. The values used for this analysis are reported in Table A-3 in the Appendix.

As shown in Section 4.2, the $WTP_{max,rel}$ for non-household consumers is assumed as a value dependent on ATP and environmental concern, see Table 6, expressed as a discrete percentage value that was then multiplied with the corresponding electricity price. The $WTP_{max,rel}$ for European households was taken from OECD [49]. Derating factors to determine consumers $WTP_{k,o,t}$ depending on the origin o, the technology t of the GO and, for the former, the country c of the consumer are listed in Table A-5 and Table A-6 in the Appendix. Note that in this case, we did not differentiate technology preferences by country.

Correction factors were applied to the WTP values obtained. As prices for Gos must be paid on top of electricity prices and Gos are the least attractive form of green electricity acquisition, these $WTP_{max,rel}$ values are reduced for households, see Table A-2, , and a correction factor of 0.15 is applied to all $WTP_{k,o,t}$ after multiple test runs had exceeded upper price boundaries.

Table 6. $WTP_{max,rel}$ values for non-household consumers (depending on ATP levels)

Environmental concern	ATP				
	$x \leq 20\%$	$20\% < x \leq 40\%$	$40\% < x \leq 60\%$	$60\% < x \leq 80\%$	$80\% < x \leq 100\%$
$y \leq 20\%$	0	0.025	0.05	0.075	0.1
$20\% < y \leq 40\%$	0.025	0.05625	0.0875	0.11875	0.15
$40\% < y \leq 60\%$	0.075	0.11875	0.1625	0.20625	0.2
$60\% < y \leq 80\%$	0.15	0.2125	0.275	0.3375	0.25
$80\% < y \leq 100\%$	0.1	0.15	0.2	0.25	0.3

Abbreviations used: ATP = Ability-To-Pay, *x* and *y* refer to the coordinates in Fig. 2

5.3 Scenario Description

Given the model's scope to 2040, and the uncertainty regarding the future development of the GO market, we calculate GO prices for four different scenarios that differ mainly regarding demand and supply development. The scenarios offer the extreme cases that could occur in terms of renewable energy production and regulatory harmonization amongst AIB members, thus providing bounds for expectable GO price developments.

Scenario 1 ("Status Quo"): In the first scenario, it is assumed that regulations in the AIB regarding harmonization of regulations amongst members were not put in place. Additionally, countries would not increase their RES production by introducing new technologies if they had not used that certain technology before. Industry demand and electricity supply would follow the Stated Policy Scenario of the IAE World Energy Outlook [81].

Scenario 2 ("Sustainable Development"): Scenario 2 assumes a more sustainable development of industry and household demands in alignment to the IEA's "Sustainable Development Scenario" [81], reflected by increased demand for electricity. The production of electricity from RES is assumed to be greater than in the status quo.

Scenario 3 ("Full Harmonization"): The third scenario is characterized by full harmonization of regulations amongst AIB members concerning the issuance of GOs in the EECS, creating a level playing field for GO branding in Europe. Here, all AIB member countries are given issue rates corresponding to the average issue rates of category 5, effectively banning the issuance of GOs for subsidized electricity production. This could be perceived as one possible measure against perceived double counting.

Scenario 4 ("Ideal Development"): The fourth scenario combines assumptions made in Scenarios 2 and 3. While the development of supply, i.e., green electricity production, and demand are determined by the assumptions made in Scenario 2, GO issue rates correspond to those estimated in Scenario 3. Therefore, this scenario represents a green transition paired with full harmonization amongst AIB members.

6 Results and Discussion

In the model application runs, four scenarios were considered. Each scenario had different assumptions regarding future RES generation and the regulations of the various European GO markets. The scenarios were briefly described in Section 5.3, while the results are compared in the following. All prices are shown as weighted averages (WAVG), i.e., average prices are calculated based on the proportion of respective GO types in the total amount of issued GOs. Additionally, annual growth rates (CAGR) are calculated.

6.1 Scenario Comparison

When directly comparing the amount of GOs issued amongst the different scenarios, as shown in Fig. 5, these volumes vary greatly between the scenarios. The highest GO volumes were found in Scenario 2. That result is plausible, as this scenario assumes an increased production of green electricity, compared to Scenarios 1 and 3, and has no further regulations concerning the limitation of GO issuance for subsidized electricity in place. This means that countries that had high issue rates in Scenario 1 issue more GOs in Scenario 2 because their electricity production from RES increased. In Scenario 3, however, green electricity generation is at the same level as the status quo, but regulations concerning the issuance of GOs for subsidized electricity are in place. This results in a reduction of the supply of GOs, as countries would produce the same amount of green electricity as in Scenario 1, but issue rates would be substantially lower than before. Scenario 4 combines the assumptions made in Scenarios 2 and 3. Initial GO volumes are at a similar level as in Scenario 3 but increase rapidly to exceed volumes seen in Scenario 1 by 2040. This is supported by the average CAGR for Scenario 4 that, with a value of 8.85%, shows the highest value amongst all scenarios. In all scenarios, hydro GOs are the most abundant ones, followed by wind GOs.

To make prices comparable, the WAVG is calculated over all technologies and countries per scenario. Across all four scenarios, the price corridor ranges from 1.22 to 1.61 €/MWh in 2020 and 1.77 to 3.36 €/MWh in 2040. This results in the price developments shown in Fig. 6. Here, on average, GO prices in Scenario 3 are highest throughout the complete regarded timeframe. In this model, prices are determined mainly by the interaction of demand and supply. Therefore, it makes sense for the highest prices to occur in the scenario with the lowest supply, i.e. Scenario

3 (see Fig. 5). Consequently, the lowest prices are found in the scenario with the highest supply (Scenario 2). As the initial GO supply, in 2020, was lower in Scenario 4 than in Scenario 1, it is no surprise that average prices in Scenario 4 are slightly higher than in Scenario 1. With supply having increased over the years, a fall in prices is to be expected.

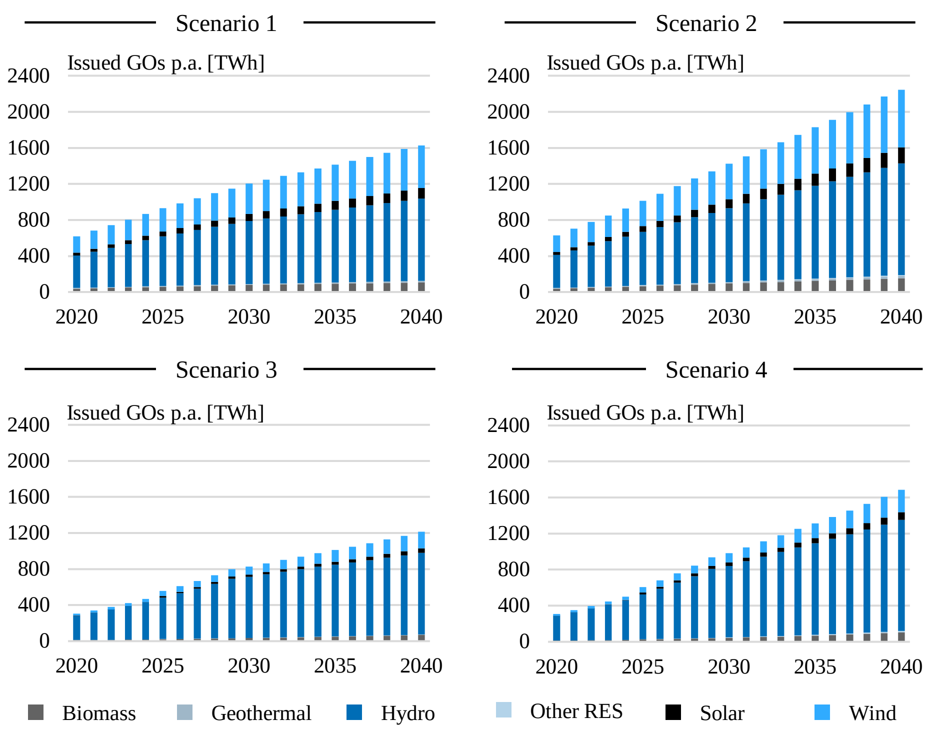

Fig. 5. Comparison of issued GO volumes, by scenario, 2020-2040

Abbreviations used: GO = Guarantees of origin; p.a. = per year; RES = renewable energy sources

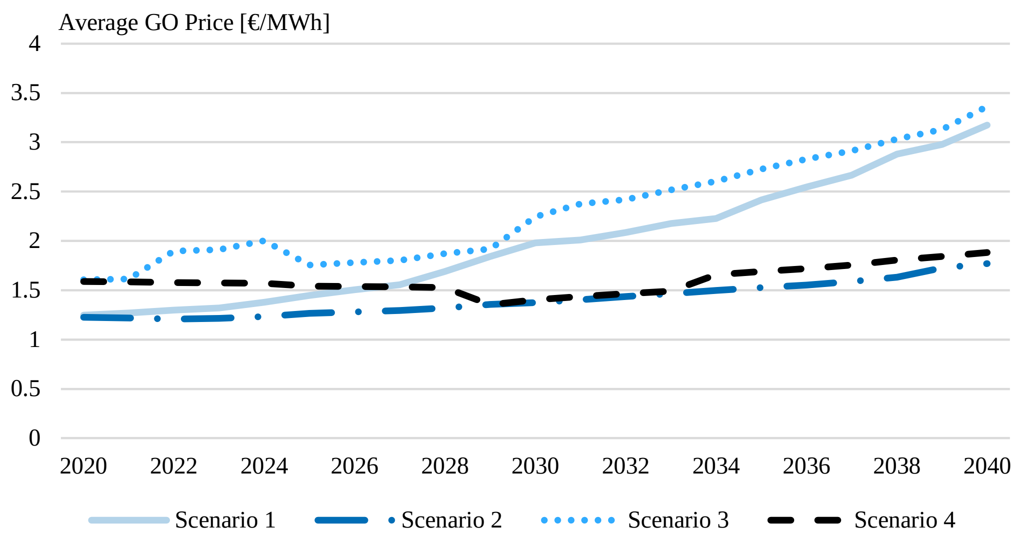

Fig. 6. Development of average prices over all technologies and all countries for GOs, by scenario, 2020-2040

Abbreviations used: GO = Guarantees of origin

When comparing average GO prices for the different technologies, the same pattern arises amongst all four scenarios. While in Scenarios 3 and 4, in the beginning, geothermal GO prices are lower than other GO prices, they eventually surpass all other technologies and continuously fetch the highest prices from 2025 to 2040. For all scenarios considered, the next highest prices in descending order are for solar GOs, other RES, wind, biomass, and hydro GOs. In Scenario 3, however, prices for geothermal and solar GOs in 2040 are close to each other, with average prices of 12.82 and 12.57 €/MWh, respectively. The development of these prices for each scenario is depicted in Fig. 7. Additionally, Table 7 provides an overview of prices per technology for each scenario for the years 2020, 2030 and 2040.

When closely examining Fig. 7, it can be noticed that around 2025, GOs of the type "other RES", and in Scenarios 3 and 4, also those of the types "geothermal" and "solar", experience sudden jumps in GO price levels. For GOs of the type "other RES", this is explained by the issuance of this type at the beginning (i.e., in 2025). The drop of solar GOs in the last two scenarios can be explained by the increase of GO supply that occurs from 2025 onwards. In these scenarios, issue rates, and thus GOs on the market, are limited by assumed harmonization measures amongst AIB members. In 2025, when countries begin issuing GOs for technologies that had previously not received any GOs, supply increases and, as the market is demand-driven, prices are reduced. However, for geothermal GOs, the opposite price development occurs. Here, when supply increases in 2025, prices also increase. This is caused by the sudden appearance of more desired geothermal GOs on the market. From 2020 to 2024, the only geothermal GOs on the market that are available in sufficiently high quantities to affect GO market prices, are from Iceland. The WTP for Icelandic GOs is low, however, compared to other countries, because of the geographical derating factors that were applied to the WTP values, see Table A-5.

Consequently, when geothermal GOs from other countries enter the market, the overall price will increase because consumers have higher WTPs for these GOs. Additionally, in reality, such jumps would probably not occur. Instead, these price changes would likely follow a less steep curve, as technology portfolio diversification and increased GO issuance would happen more gradually.

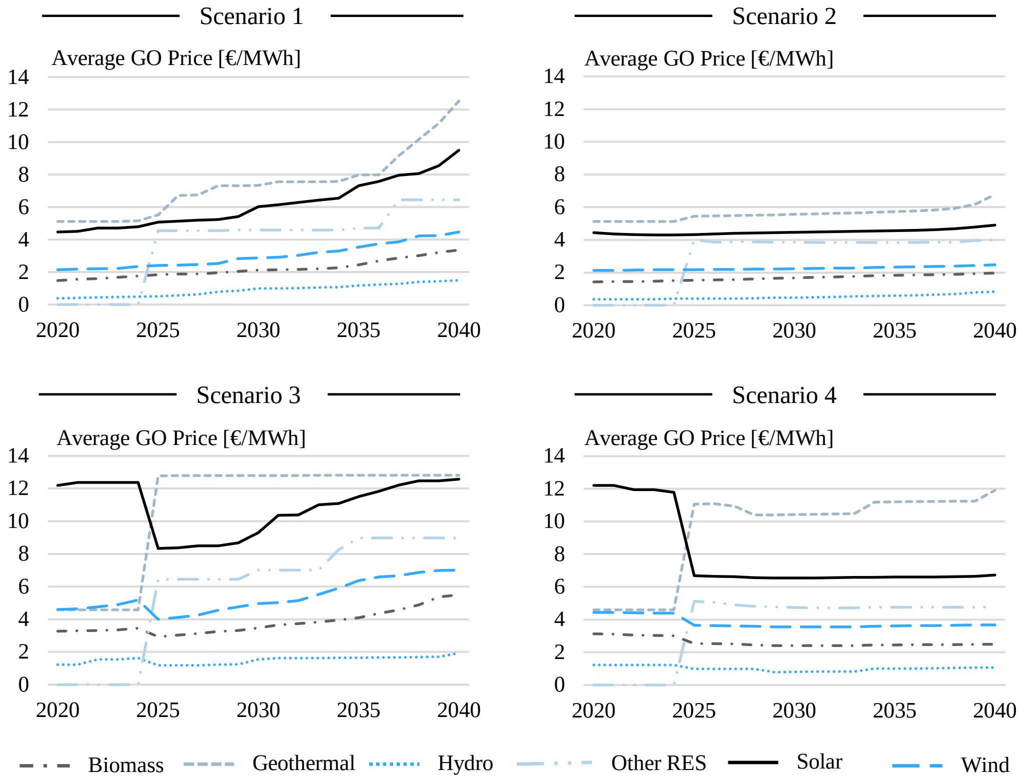

Fig. 7. Comparison of price developments per technology for all four scenarios

Abbreviations used: GO = Guarantee of Origin; RES = Renewable energy sources

Table 7. Average GO prices in €/MWh per technology for all four scenarios, in the years 2020, 2030, and 2040

	Scenario 1			Scenario 2		
Technology	2020	2030	2040	2020	2030	2040
Biomass	1.47	2.12	3.36	1.44	1.67	1.98
Geothermal	5.13	7.33	12.54	5.13	5.56	6.77
Hydro	0.4	0.99	1.51	0.37	0.47	0.82
Other RES	0	4.59	6.45	0	3.86	3.98
Solar	4.46	6.03	9.5	4.43	4.46	4.91
Wind	2.15	2.88	4.47	2.14	2.22	2.47
	Scenario 3			Scenario 4		
Technology	2020	2030	2040	2020	2030	2040
Biomass	3.26	3.46	5.51	3.13	2.41	2.49
Geothermal	4.59	12.8	12.82	4.59	10.41	11.91
Hydro	1.23	1.55	1.93	1.23	0.8	1.06
Other RES	0	7	8.97	0	4.73	4.77
Solar	12.19	9.3	12.57	12.19	6.53	6.72
Wind	4.59	4.96	7	4.44	3.54	3.66

Abbreviations used: GO = Guarantee of Origin; RES = Renewable energy source

On average, over all scenarios, geothermal GOs are the most expensive ones. This finding changes when looking at different countries in the scenarios. In the scenarios that assume an increase in green electricity production by adding previously unused technologies to their technology portfolio, i.e. Scenarios 2 and 4, the highest prices are ultimately determined by geothermal GOs, as the WTP for these is the highest and a scarcity of such GOs exists in all countries. However, in Scenario 1, solar GOs are the most expensive ones in Belgium, Denmark, Switzerland, Spain, and the Czech Republic, amongst others. In other countries, e.g., Ireland, wind GOs are the most expensive ones over the complete timeframe. Changes regarding technology-wise price ranking occurred in ten countries. In Germany, prices for geothermal GOs exceed those of solar GOs from 2025. In 2025, Slovenian solar GOs become more expensive than Slovenian hydro. In Scenario 3, nine countries experience a change in the most expensive GO by technology. Here, in most countries, solar GOs experience the highest prices. By 2040, only six countries feature geothermal GOs achieving higher price levels, and only four countries experience wind prices that exceed solar GO prices.

When minimum prices are regarded, a similar pattern to that in the prior maximum price analysis arises. In general, one technology is dominant: for all four scenarios, hydro GOs reach the lowest prices in most countries. Hydro GOs are currently by far the most abundant type of GO in the EECS. Therefore, when keeping the model's design in mind, these results are to be expected. Only a few exceptions occur: the most notable in each scenario is Cyprus, where the lowest prices are for wind GOs up until 2025. Then, in Scenarios 1 and 3, biomass becomes the cheapest technology. In Scenarios 2 and 4, from 2025 onwards, hydro GOs were even cheaper.

Note that one of the assumptions in the model is that no lower price boundary exists. This becomes important when considering prices for Norwegian hydro GOs in Scenarios 1 and 2. Here, up until 2022 and 2027, respectively, prices of 0 €/MWh are calculated. This results from the still occurring over-supply of GOs in these two scenarios, explained by Norwegian hydro being one of the most abundant types of GO and consumers having the lowest WTP. In Scenario 2, where the number of issued GOs is highest, the same occurs for Swedish hydro GOs up until 2023.

6.2 Validation of Results

As the model addresses future price predictions, a validation of results will only be possible in the future (ex post evaluation). However, the GO market offers futures (derivatives) contracts, sometimes for up to several years into the future. Thus, these futures prices can be used as an indication of the model performance but must be treated with caution due to the aforementioned opportunistic behavior of GO market participants. Price developments are discussed in Section2.2.

As an additional indication of the plausibility of the model-based results obtained in our study, two surveys from the literature that had asked participants to estimate the development of future GO prices were scrutinized. In the results of the first survey, conducted by Greenfact [89], expected prices for 2021 were between 0.2 and 0.3 €/MWh for hydro and between 0.3 and 0.4 €/MWh for wind GOs. In the other survey, participants were asked to state their price expectations for German GOs, independently of the respective technology. For 2025, the average price was expected to be approximately 1.6 €/MWh. Prices were anticipated to increase to just over 2 €/MWh by 2030 [90]. These surveys were conducted amongst market participants and experts but can only give an indication of possible price developments, as GO prices are subject to speculation and regulatory changes, and are likely influenced by external events (incl. shocks), too.

When examining prices for wind GOs in 2021, the results obtained in the scenarios greatly exceed the estimations expressed in the first survey. In Scenarios 1 and 2, average prices for wind GOs are expected to lie at 2.19 and 2.14 €/MWh, respectively. In Scenarios 3 and 4, price levels practically double. Here, they reach levels of 4.64 and 4.43 €/MWh, respectively. The lowest prices for wind GOs, and thus closest to the given estimation in the survey, are those calculated for GOs from Norway in Scenario 1. These prices are estimated at 0.97 €/MWh in 2021 and thus still exceed the price expectations of the market participants by more than 100%, but are in the range of the prices of the future products in 2022 and 2023, and prices observed in early 2022 (but less so end of 2022).

On average, hydro GO prices are closer to the estimate than wind GO prices. In Scenarios 1 and 2, prices for GOs from hydropower in 2021 are calculated at 0.41 and 0.37 €/MWh, respectively. This is very close to the average GO price from the first survey. In both scenarios, prices for hydro GOs in Norway and Sweden reach zero. This means that the demand for these two GO types exceeds supply. In the other two scenarios, average hydro GO prices are expected to reach 1.23 and 1.22 €/MWh, respectively. Due to these scenarios' assumptions regarding the harmonization of regulations, and the resulting reduction of GO issue rates amongst AIB member states, a situation of oversupply does not occur for any type of GO. However, once again, prices for Norwegian Hydro GOs are the closest to the survey results. These prices were calculated at 0.24 €/MWh in 2021. Swedish GOs are the ones with the next lowest price at 0.6 €/MWh.

In general, in the model results, prices for GOs from Germany are slightly below the European average. As can be seen in Table 8, prices calculated in the first scenario are closest to the survey results. In Scenario 2, the supply of GOs is raised by an increased production of green electricity and the diversification of technology portfolios in all countries. Consequently, GO prices are lower. The opposite occurs in Scenarios 3 and 4. Here, prices are far higher and exceed by far the survey's results in 2025 and 2030, caused by the limitation of the supply of GOs in the EECS.

Table 8. GO prices in Germany obtained from a survey amongst market participants compared to the results obtained from the model calculations [€/MWh]

Observed year	2025	2030
Survey	1.6	2.02
Scenario 1	1.03	1.73
Scenario 2	0.81	0.83
Scenario 3	3.32	3.8
Scenario 4	3.18	3.17

Source: Köpke (2020), own calculations

An additional validation tool is the comparison of the model results with historic prices. Prices ranging up to 8 €/MWh for certain types of GOs, in this case Dutch GOs, have been observed in the past. Additionally, when demand is high enough, a situation which has in the past been artificially stimulated through opportunistic behavior on the market, prices greatly exceed current levels and even surpass average prices calculated in the model presented here. When regarding prices paid for GOs issued by new power plants, i.e., those that are not older than six years, a similar observation can be made, as these prices are found to reach levels of up to 3.4 €/MWh. Swiss GOs even reached prices ranging up to 4 €/MWh, which is higher than any average result for this type of GO in any scenario of our study (see historic prices in Table A-1 for a further comparison). Price levels of around 5 €/MWh, seen in late 2022, might give reason to assume further price increases – although the market will likely cool down, and thus prices will decrease again, as it has been observed in the past.

Therefore, following the reflections in this section, we find that the GO prices obtained from the model calculations are, in general, in the range of previously seen and currently future traded prices. For some scenarios and certain GO types, prices resemble the estimations made by market participants and experts. Some anomalies occur, such as high prices for geothermal GOs or for solar GOs (in Scenarios 3 and 4). However, while geothermal GO prices cannot easily be verified or falsified due to a lack of historic price information, the solar GO prices can be explained by the scenarios' drastic reduction of supply and consequential creation of higher prices through the limitation of GO issue rates and increased harmonization amongst AIB member states.

6.3 Sensitivity Analysis

A sensitivity analysis reveals the model's dependence on different input variables. The results are shown in Fig. 8. Six variations were conducted for each selected parameter or variable. The first three reduced the selected parameters' values by factors of 0.1, 0.2, and 0.5, respectively. The other three calculations increased the same values by factors of 2, 5, and 10. The variable "WTP percentages", setting values for $WTP_{max,rel}$, had the highest influence on GO prices, while the LCOE cap had almost no influence. This gives an indication of the robustness of the model-based results. The logarithmic scale was chosen to adequately show the price variations (it was applicable since no negative values occurred).

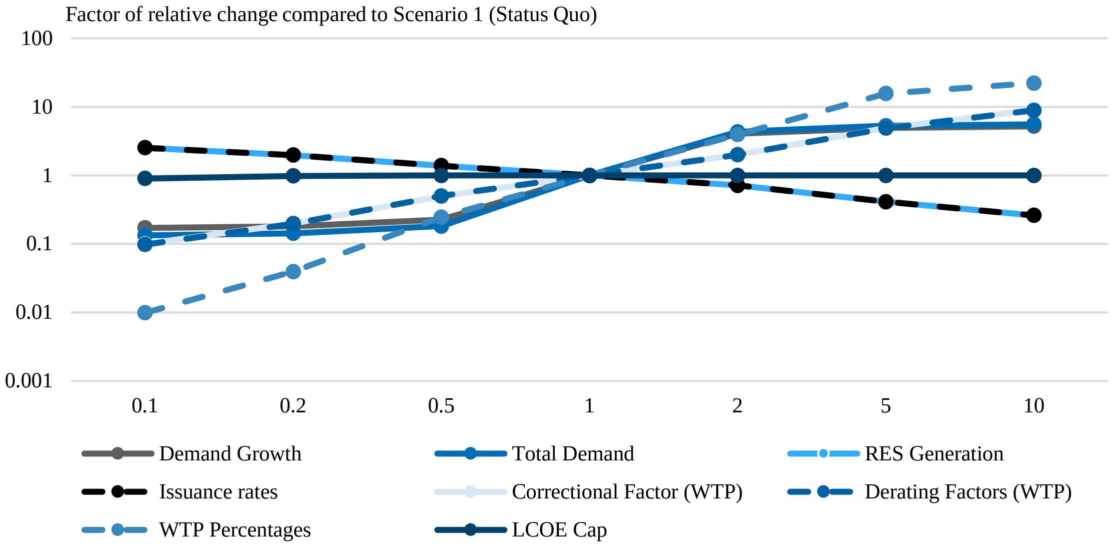

Fig. 8. Results from the sensitivity analysis

Abbreviations used: RES = Renewable Energy Source; WTP = Willingness-to-pay; LCOE = Levelized Cost of Electricity

7 Conclusions and Policy Implications

The aim of the present study was to increase transparency on the GO market. This was done by first analyzing developments and shortcomings of the EECS, and then by introducing a model to estimate future GO prices. Our goal was achieved by first providing an overview of the situation in the 26 AIB member states. On the basis of extended analyses of European energy demand and supply, structural statistics, as well as publicly available GO data, our model-based analysis was then able to provide new insights into possible future price and volume developments of GOs for different technologies and origins on a yearly basis up until 2040. When examining the prices that were obtained from the model calculations, it is found that most GO types reach levels that had previously occurred in the market. Comparing these prices to expert expectations from surveys, we can conclude that these results are quite realistic when taking the uncertainty of the used data and the mentioned opportunistic behavior of market participants into account. External events, such as Europe's energy crisis in 2022, influenced market behavior and were not foreseen by the model.

Although GOs were originally introduced to disclose the production of green electricity to European consumers – a purpose that they generally fulfil – the public opinion of this system is negative, as GOs currently provide little or no incentive to increase the production of green electricity. For GOs to become relevant in green electricity producers' investment decisions, prices must increase to levels exceeding current governmental support schemes and subsidies for RES. For wind GOs, these prices range between 15 to 25 €/MWh, for solar GOs from 17 to 22 €/MWh, and for biomass GOs up to 89 €/MWh [35]. However, even in Scenario 3, where full harmonization amongst participating AIB member states is assumed – and thus a substantial reduction of the supply of GOs on the market – prices are on average far off these targets, with geothermal and solar Gos achieving average prices of just over 12.5 €/MWh in 2040.

With increasing numbers of renewable energy plants falling out of support schemes, e.g., old wind turbines in Germany having reached the end of the 20-year subsidy period, Gos might become a possible revenue stream in addition to wholesale electricity sale. These plants are usually fully written off and do not require further subsidization to be operated profitably, and if repowering is not an option, they might continue to run, and generate Gos outside of the German *Doppelvermarktungsverbot* [91].

Therefore, we can conclude that under the current market regime, Gos are not likely to become a dedicated policy category for the promotion of green electricity production in Europe. If policy-makers, however, were to further increase harmonization amongst issuing AIB member states, as it is currently being done in the *FaStGO* project [92], Gos could lose their negative image, and the often stated arguments of (perceived) double counting and "greenwashing" could be refuted [92]. In July 2021, the European Commission introduced a proposal for an amendment of the Renewable Energy Directive (RED) that would effectively lead to the elimination of the German *Doppelvermarktungsverbot*. On the one hand, this would address the issue of heterogeneous regulations (and perceived double counting) but, on the other hand, would likely cause a drastic increase of the GO supply which would then result in price decreases [93].

However, if prices for GOs increased as forecast by the model, consumers willing to purchase green electricity at low costs might switch to other alternatives for green power acquisition, such as PPAs, that have a more direct impact on the increase of green electricity production. With corporate awareness on the rise, and companies pursuing to create a “greener” image of themselves, GO prices will likely increase further in the medium- to long-term. The aspects of local green electricity generation and additionality, i.e., the establishment of additional renewable power plants, are gaining importance, and can only be addressed by issuing and canceling the corresponding GOs on a regular basis.

Finally, it can be said that in the wake of European efforts to decarbonize the economy and to significantly increase the amount of RES in electricity production, the GO market volume will increase in the coming years. As both household and corporate consumers are expected to become more aware of the necessity to purchase green electricity, demand will increase and drive GO prices to higher levels.

With current policies and the actual state of harmonization in the market, however, the GO system will not be able to overcome the trust issues that it is currently experiencing. Additionally, prices will remain at levels that will have only marginal effects on the increase of green electricity production. Therefore, harmonization amongst AIB member states concerning the issuance of GOs, the provision of GO data without discrepancies, the promotion of the GO system as a provider of viable and trustworthy disclosure, and the creation of a possible further RES production incentive system based on GOs must receive higher priorities by European policy-makers. These steps would allow the GO system to become a market-driven incentive model and would free up governmental funds that could be invested in other projects concerning the decarbonization of European economies.

Consequently, future research should focus on reducing the limitations of our proposed model and increasing its accuracy. This should include the adaptation of price elasticity. Additionally, by analyzing GO data on a monthly basis, seasonal factors in the production of green electricity could be included and thus provide a more accurate depiction of the real market situation. A major factor of uncertainty was the determination of the WTP for green electricity – and thus also for GOs – for industrial and commercial consumers. A survey-based determination of this WTP would not only improve future GO price models’ results but could also be applied to other research focusing on alternative acquisition possibilities for green electricity, and thus providing valuable new insights potentially useful in other research focusing on the promotion of RES in electricity production.

Model and Data Accessibility

All data described in Section 5 and the model documentation and code can be accessed at Github: https://github.com/alexwimmers/GO-Price-Forecast-Model/tree/GO-model.

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Appendix

Table A-1. Overview of historic GO prices

Type of GO	Period	Price / price range	Source
Alpine Hydro Power	2017	0.2 €/MWh	[35]
Austrian (unspecif.)	2018	0.9 – 1.45 €/MWh	[10]
Austrian Hydro (age unspecif.)	2019	1.32 €/MWh	[94]
Dutch Wind	Sep 2018	8 €/MWh	[22]
EU Biomass (unspecif.)	2018	1.62 €/MWh	[94]
EU Hydro (age unspecif.)	2018	1.24 – 1.25 €/MWh	[10]
EU Hydro (unspecif.)	2020	0.15 – 0.21 €/MWh	[95]
EU Hydro (unspecif.)	2018-2020	0.49 - 1.98 €/MWh	[94]
EU (average 2021)	Sep 2021	0.75 €/MWh	[45]
EU (average 2022)	Sep 2021	1.25 €/MWh	[45]
German (unspecif.)	2018	0.8 – 1.6 €/MWh	[10]
Italian Wind Auction (weighted average)	Jan 2022 / Mar 2022 / Jun 2022 / Oct 2022 / Dec 2022	1 €/MWh / 1.32 €/MWh / 1.88 €/MWh / 5.01 €/MWh / 5.93 €/MWh	[21]
Italian Unspecified Technology Auction (weighted average)	Jan 2022 / Mar 2022 / Jun 2022 / Oct 2022 / Dec 2022	1.03 €/MWh / 1.65 €/MWh / 1.93 €/MWh / 5.28 €/MWh / 6.42 €/MWh	[21]
Italian Solar Auction (weighted average)	Jan 2022 / Mar 2022 / Jun 2022 / Oct 2022 / Dec 2022	1.11 €/MWh / 2.01 €/MWh / 2.22 €/MWh / 5.32 €/MWh / 6.52 €/MWh	[21]
Italian Hydro Auction (weighted average)	Jan 2022 / Mar 2022 / Jun 2022 / Oct 2022 / Dec 2022	0.89 €/MWh / 1.46 €/MWh / 1.99 €/MWh / 5.60 €/MWh / 6.28 €/MWh	[21]
Large Nordic Hydro	2007–2015	0.05 – 0.6 €/MWh	[44]
Nordic (unspecif.), new	2018	2 – 2.7 €/MWh	[10]
Nordic (unspecif.), new	2018	2.34 – 3.4 €/MWh	[10]
Nordic (unspecif.), old	2018	0.55 €/MWh	[10]
Nordic (unspecif.), retrofitted	2018	1 – 1.9 €/MWh	[10]
Nordic Hydro (age unspecif.)	2015	0.05 – 0.5 €/MWh	[75]
Nordic Hydro (age unspecif.)	2017	0.22 – 0.38 €/MWh	[10]
Nordic Hydro (age unspecif.)	Sep 2018–Dec 2018	1.24 – 2 €/MWh	[22]
Nordic Hydro	2017	0.31 €/MWh	[35]
Northern Continental Europe Wind Power	2017	0.45 €/MWh	[35]
Swiss (unspecif.)	2018	1.5 – 4 €/MWh	[10]
Swiss Hydro	2017–2018	1 – 4 CHF/MWh*	[22]
Swiss PV (unspecif.)	2018	14.30 €/MWh	[94]

Abbreviations used and explanations: EU = European (in general); GO = Guarantee of Origin; *Hydro* refers to GOs from hydropower generation; *Nordic* refers to GOs from Denmark, Finland, Norway, or Sweden; *PV* refers to GOs from solar (photovoltaic) generation; unspecif. = unspecified. 1 CHF ~ 1.03 €.

Table A-2. Overview of household WTPs

	WTPs for green electricity				
	0%	> 0%	> 25%	> 50%	> 75%
France	28.5	56	10.5	4.5	0.5
Netherlands	32	56	8.5	3	0.5
Spain	28	56	11	4	1
Sweden	23	62	10	4	1
Switzerland	8.5	72	15	4	0.5
EU Average	24	60.4	11	3.9	0.7
Reduced WTP for GOs (% of total electr. price)	0	3.75	11.25	18.75	24

Abbreviations used: GO = Guarantee of Origin; WTP = Willingness-to-pay

Source: OECD (2014): pp.102-103, own estimation

Table A-3. Values for *environmental concern* for WTP calculation

Sector Description	NACE Code	Environmental concern	Source
Mining of coal and lignite	B05	0.1	Own estimation
Extraction of crude petroleum and natural gas	B06	0.1	Own estimation
Mining of metal ores	B07	0.2	Own estimation
Other mining and quarrying	B08	0.15	Own estimation
Mining support service activities	B09	0.2	Own estimation
Manufacture of food products	C10	0.65	[88]
Manufacture of beverages	C11	0.75	[88]
Manufacture of tobacco products	C12	0.4	Own estimation
Manufacture of textiles	C13	0.7	[88]
Manufacture of wearing apparel	C14	0.55	Own estimation
Manufacture of leather and related products	C15	0.6	Own estimation
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	C16	0.65	Own estimation
Manufacture of paper and paper products	C17	0.4	[88]
Printing and reproduction of recorded media	C18	0.4	Own estimation
Manufacture of coke and refined petroleum products	C19	0.1	Own estimation
Manufacture of chemicals and chemical products	C20	0.5	[88]
Manufacture of basic pharmaceutical products and pharmaceutical preparations	C21	0.4	[88]
Manufacture of rubber and plastic products	C22	0.3	Own estimation
Manufacture of other non-metallic mineral products	C23	0.35	Own estimation
Manufacture of basic metals	C24	0.4	Own estimation
Manufacture of fabricated metal products, except machinery and equipment	C25	0.5	Own estimation
Manufacture of computer, electronic and optical products	C26	0.3	[88]
Manufacture of electrical equipment	C27	0.4	Own estimation
Manufacture of machinery and equipment n.e.c.	C28	0.4	[88]
Manufacture of motor vehicles, trailers and semi-trailers	C29	0.45	[88]
Manufacture of other transport equipment	C30	0.35	Own estimation
Manufacture of furniture	C31	0.7	Own estimation

Sector Description	NACE Code	Environmental concern	Source
Other manufacturing	C32	0.5	Own estimation
Repair and installation of machinery and equipment	C33	0.4	Own estimation
Water collection, treatment and supply	E36	0.7	Own estimation
Sewerage	E37	0.5	[88]
Waste collection, treatment and disposal activities; materials recovery	E38	0.7	Own estimation
Remediation activities and other waste management services	E39	0.6	[88]
Wholesale and retail trade and repair of motor vehicles and motorcycles	G45	0.4	Own estimation
Wholesale trade, except of motor vehicles and motorcycles	G46	0.6	[88]
Retail trade, except of motor vehicles and motorcycles	G47	0.7	[88]
Accommodation	I55	0.5	[88]
Food and beverage service activities	I56	0.5	Own estimation
Publishing activities	J58	0.5	Own estimation
Motion picture, video and television programme production, sound recording and music publishing activities	J59	0.6	Own estimation
Programming and broadcasting activities	J60	0.4	Own estimation
Telecommunications	J61	0.8	[88]
Computer programming, consultancy and related activities	J62	0.8	[88]
Information service activities	J63	0.75	[88]
Legal and accounting activities	M69	0.3	[88]
Activities of head offices; management consultancy activities	M70	0.65	[88]
Architectural and engineering activities; technical testing and analysis	M71	0.45	[88]
Scientific research and development	M72	0.65	Own estimation
Advertising and market research	M73	0.8	[88]
Other professional, scientific and technical activities	M74	0.6	Own estimation
Veterinary activities	M75	0.4	Own estimation
Rental and leasing activities	N77	0.6	Own estimation
Employment activities	N78	0.4	Own estimation
Travel agency, tour operator and other reservation service and related activities	N79	0.5	Own estimation
Security and investigation activities	N80	0.2	Own estimation
Services to buildings and landscape activities	N81	0.6	Own estimation
Office administrative, office support and other business support activities	N82	0.6	Own estimation
Repair of computers and personal and household goods	S95	0.4	Own estimation

Abbreviations used: NACE = Nomenclature générale des activités économiques dans les Communautés Européenne (Classification of European Economic Statistics)

Source:[88], own estimations

Table A-4. Overview and categorization of EECS member countries as of mid-2019

Country (Or Country area)	Competent body	Subsidy category	Fees	National certificate system	International trade	Own domestic platform
Austria	E-Control	Cat. 1	No	No	Yes	Yes
Belgium (Federal)	CREG	Cat. 4	No	No	Yes	Yes
Belgium Brussels	Brugel	Cat. 4	No	No	Yes	Yes
Belgium Flanders	VREG	Cat. 4	Yes	Yes	Yes	Yes
Belgium Wallonia	SPW Energie / CWaPE	Cat. 4	No	Yes	Yes	Yes
Switzerland	Pronovo	Cat. 1	Yes	No	Yes	Yes
Cyprus	TSOC	Cat. 3	Yes	Yes	Yes	Yes
Czech Republic	OTE	Cat. 4	Yes	No	Yes	Yes
Germany	UBA	Cat. 5	Yes	Yes	Yes	Yes
Denmark	Energinet	Cat. 1	Yes	No	Yes	No (CMO.grexel)
Estonia	Elering	Cat. 1	Yes	No	Yes	Yes
Spain	CNMC	Cat. 4	No	Yes	Separation of GOs intended for import and export	Yes
Finland	Finextra	Cat. 1	Yes	Yes	Yes	Yes
France	EEX	Cat. 2	Yes	No	Yes	Yes
Greece	DAPEEP / HEDNO / CRES	Cat. 4	No	Yes	Yes	Yes
Croatia	HROTE	Cat. 4	Yes	No	Yes	No (CMO.grexel)
Ireland	SEMO	Cat. 5	No	No	Yes	No (CMO.grexel)
Iceland	Landsnet	Cat. 6	Yes	No	Yes	No (CMO.grexel)
Italy	GSE	Cat. 1	Yes	No	Yes	Yes
Lithuania	Litgrid AB	Cat. 3	Yes	Yes	Only import	No (CMO.grexel)
Luxembourg	ILR	Cat. 2	Yes	No	Yes	No (CMO.grexel)
Netherlands	CertiQ	Cat. 4	Yes	No	Yes	Yes
Norway	Statnett	Cat. 4	Yes	No	Yes	Yes
Portugal	Rede Eléctrica Nacional, S.A. (REN)	Cat. 1	Yes	Yes	Yes	Yes
Serbia	EMS	Cat. 5	Yes	No	Yes	Yes
Sweden	Energimyndigheten	Cat. 4	Yes	Yes	Yes	Yes
Slovenia	Energy Agency / Borzen	Cat. 2	Yes	Yes	Yes	Yes
Slovakia	OKTE	Cat. 2	Yes	No	Yes	Yes

Country (Or Country area)	Trade balance (2015-2019)	Trade hub (2015-2019)	Consumption (2015-2019)	Proportion of issuance (2019)	Proportion of cancel. (2019)	Shifted prop. of cancel. (2019)
Austria	Negative	Yes	Consumer	0.021424047	0.037883179	0.032454632
Belgium (Federal)	Negative	Yes	Consumer	0.016463224	0.039611106	0.035522748
Belgium Brussels	Lack of data	Lack of data	Lack of data	0	0	0
Belgium Flanders	Lack of data	Lack of data	Lack of data	0	0	0
Belgium Wallonia	Lack of data	Lack of data	Lack of data	0	0	0
Switzerland	Negative	No	Consumer	0.095128656	0.088430042	0.083808439
Cyprus	Lack of data	Lack of data	Producer	0.000337672	0	0
Czech Republic	Positive	No	Producer	0.008335271	0.000983337	0.001864038
Germany	Negative	No	Consumer	0.022031789	0.173304752	0.158670194
Denmark	Positive	No	Producer	0.028931447	0.014841155	0.013331771
Estonia	Positive	Yes	Producer	0.004086356	0.000471532	0.000578586
Spain	Positive	No	Producer	0.143756032	0.125417968	0.120358496
Finland	Positive	No	Producer	0.040907033	0.04149955	0.037288875
France	Positive	No	Producer	0.079916686	0.067765929	0.075425313
Greece	Lack of data	Lack of data	Lack of data	0	0	0
Croatia	Positive	No	Producer	0.007435576	0.002644953	0.003194225
Ireland	Negative	No	Consumer	0.003198566	0.011490545	0.011640314
Iceland	Positive	No	Producer	0.023687093	0.006319384	0.004605022
Italy	Positive	No	Producer	0.129264574	0.077423193	0.080583479
Lithuania	Negative	No	Consumer	0.000415937	0.002066573	0.002100529

Country (Or Country area)	Trade balance (2015-2019)	Trade hub (2015-2019)	Consumption (2015-2019)	Proportion of issuance (2019)	Proportion of cancel. (2019)	Shifted prop. of cancel. (2019)
Luxembourg	Negative	Yes	Consumer	0.000665903	0.005062893	0.006328675
Netherlands	Negative	No	Consumer	0.081629158	0.087323332	0.092680187
Norway	Positive	Yes	Producer	0.188048895	0.109938713	0.105441595
Portugal	Negative	Yes	Consumer	0	0	0
Serbia	Lack of data	Lack of data	Producer	9.94E-06	1.10E-05	6.34E-05
Sweden	Negative	No	Producer	0.099308569	0.106162988	0.09557441
Slovenia	Positive	No	Producer	0.005017581	0.001347882	0.001196152
Slovakia	Lack of data	Lack of data	Lack of data	0	0	0

Notes: Belgium (Federal) refers to Belgian offshore territories in the North Sea & English Channel. // Trade balance = export – import. // Trade hub = Import / Cancellation. If > 1, Trade Hub, i.e. import of GOs to trade for export and foreign consumption. // Consumption = Issuance - Cancellation

Sources: Own calculations based on 38, 63, 96–122)

Table A-5. Derating factors $DF_{c,o}$ of a GO of origin *o* applied to consumer *k*'s $WTP_{max,k}$ depending on *k*'s country *c*

	AT	BE	DK	FI	FR	DE	UK	IT	IE	NL	NO	PO	ES	SW	CH	HR	CY	CZ	ET	GR	IC	LI	LU	SE	SK	SL
AT	1	0.7	0.6	0.6	0.7	0.9	0.4	0.9	0.2	0.6	0.2	0.4	0.4	0.6	0.9	0.7	0.4	0.9	0.7	0.6	0.3	0.4	0.5	0.6	0.9	0.9
BE	0.7	1	0.8	0.7	0.9	0.9	0.7	0.5	0.5	0.9	0.3	0.5	0.5	0.6	0.7	0.5	0.3	0.6	0.5	0.3	0.3	0.5	0.9	0.5	0.6	0.6
DK	0.6	0.8	1	0.8	0.6	0.9	0.6	0.5	0.5	0.7	0.3	0.4	0.4	0.8	0.6	0.4	0.3	0.6	0.7	0.3	0.4	0.7	0.7	0.4	0.5	0.5
FI	0.6	0.7	0.8	1	0.5	0.7	0.5	0.5	0.4	0.7	0.4	0.3	0.4	0.9	0.6	0.4	0.2	0.5	0.9	0.3	0.5	0.9	0.6	0.3	0.5	0.5
FR	0.7	0.9	0.6	0.5	1	0.9	0.8	0.9	0.5	0.6	0.2	0.6	0.7	0.4	0.8	0.6	0.4	0.5	0.4	0.6	0.4	0.5	0.9	0.4	0.5	0.6
GER	0.9	0.9	0.9	0.7	0.9	1	0.7	0.7	0.5	0.9	0.2	0.4	0.4	0.5	0.9	0.6	0.4	0.9	0.6	0.5	0.4	0.6	0.9	0.5	0.6	0.6
UK	0.4	0.7	0.6	0.5	0.8	0.7	1	0.6	0.9	0.8	0.3	0.5	0.5	0.4	0.8	0.4	0.3	0.5	0.3	0.2	0.6	0.3	0.6	0.4	0.5	0.5
IT	0.9	0.5	0.5	0.5	0.9	0.7	0.6	1	0.5	0.6	0.2	0.6	0.7	0.4	0.9	0.9	0.4	0.5	0.3	0.7	0.4	0.3	0.6	0.7	0.6	0.9
IE	0.2	0.5	0.5	0.4	0.5	0.5	0.9	0.5	1	0.8	0.3	0.5	0.5	0.4	0.6	0.4	0.2	0.4	0.3	0.3	0.7	0.3	0.5	0.3	0.4	0.4
NL	0.6	0.9	0.7	0.7	0.6	0.9	0.8	0.6	0.8	1	0.2	0.4	0.4	0.4	0.6	0.5	0.3	0.5	0.5	0.3	0.5	0.4	0.8	0.4	0.5	0.5
NOR	0.2	0.3	0.3	0.4	0.2	0.2	0.3	0.2	0.3	0.2	1	0.2	0.3	0.5	0.3	0.2	0.1	0.2	0.3	0.2	0.4	0.3	0.2	0.2	0.2	0.2
PO	0.4	0.5	0.4	0.3	0.6	0.4	0.5	0.6	0.5	0.4	0.2	1	0.9	0.5	0.6	0.5	0.3	0.5	0.3	0.5	0.2	0.3	0.4	0.4	0.4	0.4
ES	0.4	0.5	0.4	0.4	0.7	0.4	0.5	0.7	0.5	0.4	0.3	0.9	1	0.5	0.7	0.6	0.4	0.5	0.3	0.6	0.3	0.3	0.5	0.4	0.5	0.5
SW	0.6	0.6	0.8	0.9	0.4	0.5	0.4	0.4	0.4	0.4	0.5	0.5	0.5	1	0.6	0.6	0.4	0.3	0.5	0.7	0.4	0.5	0.7	0.5	0.3	0.4
CH	0.9	0.7	0.6	0.6	0.8	0.9	0.8	0.9	0.6	0.6	0.3	0.6	0.7	0.6	1	0.6	0.3	0.7	0.4	0.6	0.3	0.4	0.8	0.5	0.5	0.5
HR	0.7	0.5	0.4	0.4	0.6	0.6	0.4	0.9	0.4	0.5	0.2	0.5	0.6	0.4	0.6	1	0.4	0.6	0.4	0.7	0.3	0.4	0.5	0.9	0.8	0.9
CY	0.4	0.3	0.3	0.2	0.4	0.4	0.3	0.4	0.2	0.3	0.1	0.3	0.4	0.3	0.3	0.4	1	0.3	0.3	0.8	0.1	0.3	0.3	0.4	0.4	0.4
CZ	0.9	0.6	0.6	0.5	0.5	0.9	0.5	0.5	0.4	0.5	0.2	0.5	0.5	0.5	0.7	0.6	0.3	1	0.6	0.4	0.4	0.6	0.7	0.5	0.9	0.6
EST	0.7	0.5	0.7	0.9	0.4	0.6	0.3	0.3	0.3	0.5	0.3	0.3	0.3	0.7	0.4	0.4	0.3	0.6	1	0.3	0.3	0.9	0.5	0.4	0.5	0.5
GR	0.6	0.3	0.3	0.3	0.6	0.5	0.2	0.7	0.3	0.3	0.2	0.5	0.6	0.4	0.6	0.7	0.8	0.4	0.3	1	0.1	0.4	0.4	0.7	0.6	0.6
IC	0.3	0.3	0.4	0.5	0.4	0.4	0.6	0.4	0.7	0.5	0.4	0.3	0.3	0.5	0.3	0.3	0.1	0.4	0.3	0.1	1	0.3	0.3	0.2	0.2	0.2
LI	0.4	0.5	0.7	0.9	0.5	0.6	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.7	0.4	0.4	0.3	0.6	0.9	0.4	0.3	1	0.4	0.4	0.5	0.5
LUX	0.5	0.9	0.7	0.6	0.9	0.9	0.6	0.6	0.5	0.8	0.2	0.4	0.5	0.5	0.8	0.5	0.3	0.7	0.5	0.4	0.3	0.4	1	0.4	0.5	0.6
SE	0.6	0.5	0.4	0.3	0.4	0.5	0.4	0.7	0.3	0.4	0.2	0.4	0.4	0.3	0.5	0.9	0.4	0.5	0.4	0.7	0.2	0.4	0.4	1	0.7	0.7
SK	0.9	0.6	0.5	0.5	0.5	0.6	0.5	0.6	0.4	0.5	0.2	0.4	0.5	0.4	0.5	0.8	0.4	0.9	0.5	0.6	0.2	0.5	0.5	0.7	1	0.9
SL	0.9	0.6	0.5	0.5	0.6	0.6	0.5	0.9	0.4	0.5	0.2	0.4	0.5	0.4	0.5	0.9	0.4	0.6	0.5	0.6	0.2	0.5	0.6	0.7	0.9	1

Abbreviations used: AT: Austria, BE: Belgium; DK: Denmark; FI: Finland; FR: France; DE: Germany, UK: United Kingdom; IT: Italy; IE: Ireland; NL: Netherlands; NO: Norway; PO: Portugal; ES: Spain; SW: Sweden; CH: Switzerland; CZ: Czech Republic; ET: Estonia; GR: Greece; IC: Iceland; LI: Lithuania; LU: Luxembourg; SE: Serbia; SL: Slovenia; SK: Slovakia; CY: Cyprus. Sources: Own estimations

Table A-6. Derating factors D_t for a GO of technology *t* applied to consumer *k*'s $WTP_{max,k}$

Technology *t*	Derating factor D_t
Biomass	0.7
Geothermal	1
Hydro	0.5
Solar	0.9
Wind	0.8
Other	0.8

Notes: Technology preferences are assumed to be independent of a consumer *k*'s country *c*.

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2020

Klie L., Madlener R. (2020). Optimal Configuration and Diversification of Wind Turbines: A Hybrid Approach to Improve the Penetration of Wind Power, FCN Working Paper No. 1/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January.

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Ghafuri F., Madlener (2020). A Real Options Analysis of the Investment in Mobile Battery-Enhanced Fast-Charging Stations, FCN Working Paper No. 14/2020, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October.

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