Guarantees of Origin and Competition in the Spot Electricity Market*

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Abstract

We study the effect of introducing a market for green energy attributes on the market for the energy itself. In Europe, renewable energy producers receive Guarantees of Origin (GOs) that they can sell to consumers who wish to declare their electricity consumption as "green". In a model of price competition, we show how the introduction of such a GO market can increase competition in the spot electricity market, leading to reduced electricity prices. In the current market design, the trade of GOs is not restricted by the physical transmission capacity in the spot electricity market. However, since the production capacity of GOs is still limited by the total dispatch of electricity, suppliers have incentives to compete more fiercely in the spot market. This pro-competitive effect disappears if the physical transmission capacity is also imposed on the GO market.

Keywords: Electricity market, competition, pricing, guarantees of origin

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1 Introduction

For consumers with a preference for renewable energy, the homogeneous nature of electricity creates an obstacle. Because electrons cannot be tracked, consumers cannot be sure of the origin of the electricity they consume and whether it comes from renewable energy sources. To solve this information asymmetry, the European Union (EU) has created the world's largest certification system for energy attributes known as Guarantees of Origin (GOs). European producers of renewable energy are issued GOs for the amount of energy they produce and can sell these to consumers who prefer environmentally friendly attributes of their electricity. Although electricity and GOs are sold in separate markets, they are nevertheless interlinked as producers cannot sell more GOs than their supply of renewable energy. Using a stylized model of the electricity market, we find that introducing a sequential GO market can, in fact, have a pro-competitive effect, leading to reduced electricity prices and increased consumer welfare.

GOs were first introduced in the EU Directive 2001/77/EC, which recognized that an important prerequisite for renewable energy policies is a common standard to document renewable energy generation.[1] The development of GOs is also closely linked with the promotion of consumer protection in the internal electricity market. Electricity retailers are required to disclose the energy sources and the environmental impact of their supply to consumers.[2] Furthermore, to disclose their electricity supply as "green", retailers must do so by purchasing GOs.[3]

A GO is an electronic certificate that contains information on how a unit (MWh) of electricity has been produced. All member states of the internal electricity market are required

[1]Given the increase in cross-country electricity flows, the fuel mix of national energy production was no longer considered a good proxy for the share of renewables in national consumption, and therefore, member states were prompted to develop a system for tracking energy attributes.

[2]The objective of the Electricity Market Directive (2009/72/EC) is to provide consumers with relevant information to allow them to choose retailers based on not only price.

[3]The 2009 Renewable Energy Directive stated that electricity suppliers were allowed to use GOs to disclose the share of renewables in their electricity supply, whereas the 2018 Renewable Energy Directive made the use of GOs a requirement.

to issue GOs and maintain national registries that ensure that the same unit of renewable energy is issued a GO only once. Importantly, once issued, producers are free to sell the GOs separately from the energy itself. End-users consume GOs by canceling them (or having them canceled on their behalf by retailers) to ensure that they cannot be used twice.[4] Once a GO is canceled, the end-user can claim to have consumed the unit of electricity for which the GO was issued, along with its attributes.

Although GOs are optional, their sale has grown rapidly in recent years. Panel (a) in Figure 1 shows the number of GOs canceled (i.e., consumed) as a share of total electricity consumption in the EU. In 2022, more than 30% of the electricity consumption was backed by GOs. In the absence of GOs, retailers must instead rely on the national residual mix when disclosing their energy mix to consumers.[5] For countries active in the GO market, there can be large differences between actual production and the national residual mix.[6] Panel (b) in Figure 1 shows that the GO market has historically been characterized by oversupply. Currently, more GOs are being issued than consumed, as some GOs are never sold (or they expire without being canceled). However, the gap between the supply and demand for GOs is projected to close in the coming years (RECS, 2021).

Despite its growing importance, the GO market has so far received little attention in the literature. In the few studies that have explored GOs, the focus has mainly been on the GO market in isolation from the electricity markets and, in particular, its impact on additional investment in renewable energy capacity (e.g. Mulder and Zomer, 2016, Hulshof, Jepma, and

[4] The life cycle of a GO consists of three phases: issuance, transfer, and cancellation. A GO is valid for 12 months after issuance and can be transferred to new owners multiple times within this period. If the GO has not been canceled after 12 months, it automatically expires 18 months after issuance.

[5] These are based on the European residual mix, which is a pool of energy attributes of electricity consumption in member states that has not been tracked with GOs. It is the Association of Issuing Bodies (AIB) that calculates the European residual mix: https://www.aib-net.org/facts/european-residual-mix

[6] For example, Norway is currently the largest exporter of GOs (see Table B1 in the Appendix). However, despite the high share of hydro in national electricity production ($\approx 99\%$), the low domestic demand for GOs results in a disclosure of the fuel mix that for most Norwegians contains approximately two-thirds fossil fuels: https://www.nve.no/energy-supply/electricity-disclosure/

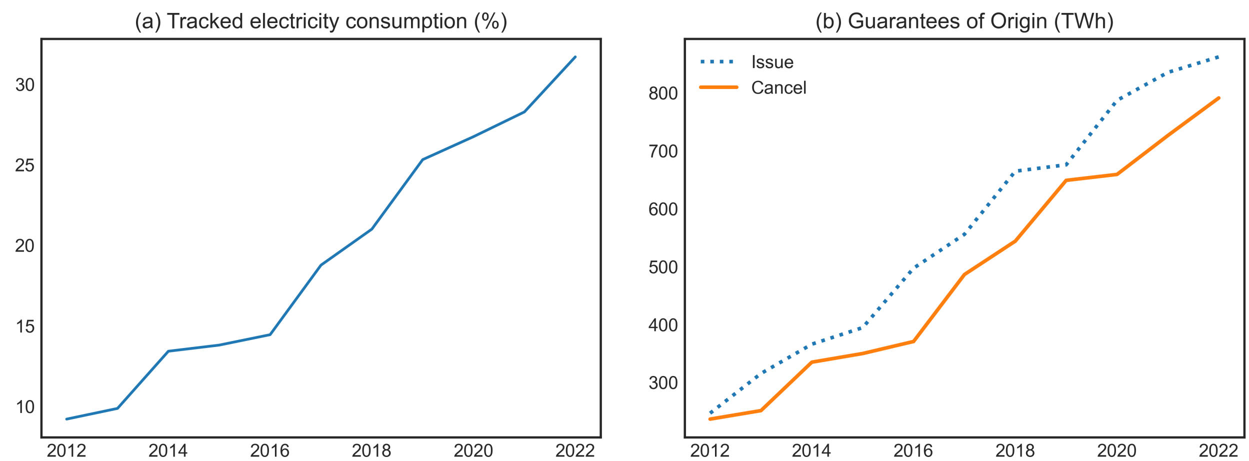


Figure 1: Panel (a): annual number of GOs canceled as a share of total electricity consumption in the EU, in percent. Panel (b): annual number of GOs issued and canceled in Europe, in TWh. Own calculations based on AIB statistics: https://www.aib-net.org/facts/market-information/statistics. Annual electricity consumption is measured as the electricity available for final consumption from Eurostat.

Mulder, 2019, Herbes et al., 2020, Galzi, 2023).[7] Although the main objective of the GO market is to facilitate consumer choice and increase investment in renewables, an unintended effect of introducing such markets could be to affect output decisions in markets for the energy itself. Furthermore, whereas cross-border electricity trade is limited by transmission capacities between countries, there are no such restrictions on the trade of GOs, which has led some countries to become major exporters or importers of GOs (see Table B1). In many cases, the sale of GOs even far exceeds the amount of electricity that is physically possible to transfer.[8]

To explore these issues, we introduce a market for energy attributes in a model of the spot electricity market with price competition and capacity constraints. In the model, there are

[7]In general, it has been found that the GO market has mainly benefited older hydroelectric plants and therefore has not contributed to the expansion of renewables.

[8]As a case in point, Norway and Germany are connected by a cable with a capacity of 1400 MW. In 2022, Norway exported 5.4 TWh of electricity to Germany. During the same year, Norway exported 117.4 TWh of GOs to Germany. In other words, the trade in GOs was more than 20 times the trade in physical electricity and almost ten times the amount of electricity that it is physically possible to transfer via the cable.

two suppliers with identical production capacities that compete in prices when competition in the spot and GO markets is imperfect and when demand is inelastic. In both markets, there is an auction where the supplier with the lowest price is dispatched first, whereas the other supplier is dispatched last and must satisfy residual demand. This assumption of an auction in the GO market is a simplification as there is currently no centralized exchange to trade GOs.[9] The setup and timing of the game are otherwise in line with the current design of the electricity and GO markets. Importantly, depending on who was dispatched first in the spot market, suppliers will have different sets of production capacities to compete with in the GO market.

In line with the standard modeling of electricity markets, the demand is located in two different nodes that are connected by a transmission line that may be congested (e.g. Borenstein, Bushnell, and Stoft, 2000, Joskow and Tirole, 2000, Escobar and Jofré, 2010). In Blázquez de Paz (2018), the standard equilibrium in price models is modified to accommodate the transmission constraints in electricity markets. We extend this model by introducing a downstream GO market. In the main model, we align our modeling assumptions with the current market design, where the sale of GOs is not restricted by the transmission line. However, in an extension of the model, we consider an alternative market design in which the transmission constraint in the spot market is taken into account in the GO market as well.

In the current market design, we find that the introduction of a downstream GO market can have a positive effect on competition in the spot electricity market. When suppliers can make additional profits from GOs, they will compete more fiercely in the spot market to increase their dispatch, and thus potential production capacities in the GO market. Furthermore, this pro-competitive effect of the GO market can be strengthened either by an increase in the demand for GOs or by a reduction in the share of energy supply that qualifies

[9]Instead, GOs are traded wholesale either through brokers or directly between electricity producers and large companies, whereas households and small companies purchase GOs mainly from their electricity retailers (Oslo Economics, 2017). Given the lack of public price data, Mulder and Zomer (2016) and Hulshof, Jepma, and Mulder (2019) infer prices from other sources of market data in their empirical analysis.

for a GO. In both cases, suppliers find it less profitable to become the residual producer in the spot market and will therefore compete more fiercely to be dispatched first. In contrast, imposing the transmission constraint in the GO market removes this pro-competitive effect. When suppliers cannot export their entire production capacity of GOs, the value of the GO market shrinks, and suppliers no longer have incentives to compete more fiercely in the spot market.

These findings have important policy implications. Although the GO market has historically suffered from oversupply, reducing the supply of GOs by limiting the cross-country flows of GOs can eliminate the pro-competitive effect of the GO market. Instead, oversupply can be alleviated by reducing the amount of renewable energy that qualifies for a GO or increasing demand for GOs. This would not only strengthen the pro-competitive effect of the GO market but potentially also incentivize additional investment in renewable capacity.

Our model relates to several strands of the industrial organization literature. Models of price competition with production capacity constraints have been widely used in the literature, in particular in models that endogenize the emergence of a price leader in duopoly (e.g. Osborne and Pitchik, 1986, Deneckere and Kovenock, 1992, Canoy, 1996). Price models have also been used to endogenize decisions about production capacities as in Kreps and Scheinkman (1983), who characterize the subgame perfect Nash equilibrium when suppliers first invest in production capacity and then compete in prices.[10] We extend this literature by characterizing the equilibrium when suppliers compete in prices with capacity constraints in two markets that operate sequentially. To some extent, our model resembles that of Kreps and Scheinkman (1983), but rather than directly investing in (physical) production capacities, suppliers must compete in prices in the first market to determine their production capacities in the second market.

The strand of the literature on sequential markets has studied whether the introduction

[10] Crampes and Creti (2005), Le Coq (2002) and Moreno and Ubeda (2006) extend this model by introducing a uniform price auction in the second stage of the game.

of forward markets has affected competition in the spot electricity market. For example, Allaz and Vila (1993) find a pro-competitive effect of the forward market on the spot market in a model where suppliers compete in quantities. However, in a similar setup, but when suppliers instead compete in prices, Mahenc and Salanié (2004) find an anti-competitive effect of the forward market. Using market data, Ito and Reguant (2016) find empirical evidence of this type of strategic behavior in sequential markets when there is imperfect competition and restricted entry in arbitrage.[11] We depart from the previous literature on sequential markets in two important aspects. First, instead of a model in which suppliers sell the same product multiple times, we characterize the equilibrium in which suppliers sell different products (electricity and GOs). Second, instead of a forward upstream market, we explore the competition effects of a downstream market on the spot electricity market.

The remainder of the paper is organized as follows. Section 2 presents the setup and timing of the model, and Section 3 characterizes the equilibrium. Section 4 analyzes the competition effects of the introduction of the GO market, as well as changes in the structure of the market. Section 5 extends our analysis to explore an alternative market design in which the GO market is restricted by transmission capacity. Section 6 offers some concluding remarks. All proofs are found in the Appendix.

2 The model

In this section, we present the details of our model set-up. There is a spot electricity market and a GO market that operate sequentially. The markets are interlinked because the production quantities in the GO market are given by the dispatched quantities in the spot market.

[11]In particular, they find that suppliers with higher production capacity withhold capacity in the spot market to increase prices in that market, whereas suppliers with lower production capacity oversell electricity in the spot market and buy capacity in the intraday market at a lower price. However, Borenstein et al. (2008) and Saravia (2003) modify the analysis by introducing traders (arbitragers) and find that the introduction of traders has a pro-competitive impact in the spot electricity market.

Model setup: We consider a model with two nodes, $i = 1, 2$, in which consumers demand electricity and producers supply electricity. These nodes are connected by a transmission line with capacity T. The demand for electricity in the two nodes (a_1^s, a_2^s) is inelastic and market clearing is guaranteed by the price cap ($\overline{P}^s$) in the market.[12] There are two suppliers with symmetric production capacities k^s, which satisfy the following requirements: First, $k^s + T > max\,\{a_1^s, a_2^s\}$, that is, the demand in a node can be satisfied by the production capacity of the supplier in that node plus the electricity flow from the other node. Second, $T \leq k^s$, that is, the suppliers cannot sell their entire production capacity to the other node, which means that the transmission constraint could be binding if demand is high.

The spot electricity market is organized as a nodal price market. This results in different equilibrium prices at nodes 1 and 2 when the transmission line is congested, in which case it becomes profitable to buy electricity at the cheap node and sell it at the expensive node. However, we assume that these congestion rents are captured by the transmission system operator (and not by the suppliers), which is in line with the current design of European electricity markets.

The demand for GOs (a_1^{go}, a_2^{go}) is also inelastic and market clearing is guaranteed by the price cap ($\overline{P}^{go}$) in the GO market. We restrict the demand for GOs to be less than or equal to the demand for electricity in both nodes. The production capacity of supplier i in the GO market, k_i^{go}, is determined by its dispatch in the spot market. Furthermore, only a share $\alpha_i \in [0, 1]$ of supplier i's dispatch in the spot market is produced from renewable energy sources and thus qualifies for a GO.[13]

Note that an alternative interpretation of α_i is that only some types of renewable energy production qualify for GOs, e.g. non-hydro or only recently installed production capacity. However, for simplicity, we refer to α_i as the "greenness" of the suppliers. Additionally, in

[12] This price cap can be interpreted either as a regulatory price cap or the price at which all consumers are indifferent between consuming and not consuming (Fabra, Von Der Fehr, and Harbord, 2006).

[13] When $\alpha_i = 1$, the entire dispatch of supplier i in the spot market is green, and when $\alpha_i = 0$, nothing in the dispatch qualifies for a GO. This distinction is important because it allows us to study the impact of a change in the "greenness" of the suppliers in Section 4.

our main analysis, we assume that there is no transmission constraint in the GO market, which is in line with the current market design.[14]

Timing of the game: The timing of the game is as follows:

1. Suppliers observe demand in both nodes (1 and 2) and markets (spot and GO) and set their prices $p^s = (p_1^s, p_2^s)$, simultaneously and independently, in the spot market.

2. The spot market clears and quantities $q^s = (q_1^s, q_2^s)$ are dispatched.

3. GO capacities, $k^{go} = (k_1^{go}, k_2^{go})$, are determined by the quantities in the spot market. Suppliers, simultaneously and independently, set their prices $p^{go} = (p_1^{go}, p_2^{go})$ in the GO market.

4. The GO market clears at quantities $q^{go} = (q_1^{go}, q_2^{go})$.

The timing of the game is illustrated in Figure 2. In the left branch of the tree $p_1^s < p_2^s$ and supplier 1 is dispatched first in the spot market, whereas in the right branch $p_1^s > p_2^s$ and supplier 1 is dispatched last. In models of price competition with capacity constraints, the tie-breaking rule is crucial to determine the existence of equilibrium (Dasgupta and Maskin, 1986). We give priority to the supplier located in the high-demand node to minimize the flows of electricity, and thus the losses due to those flows. However, note that our chosen tie-breaking rule does not affect the equilibrium, as there are no production or transmission costs in the model.[15]

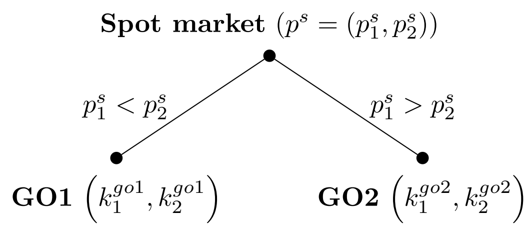
Because the GO production capacities of the suppliers depends on their dispatch in the spot market, suppliers will have different sets of capacities to compete with in the GO market in the left (k_1^{go1}, k_2^{go1}) and right (k_1^{go2}, k_2^{go2}) branches of the tree in Figure 2.[16]

[14]In Section 5, we extend our analysis to explore the introduction of a transmission constraint in the GO market.

[15]For a complete characterization of the equilibrium in models of price competition with capacity constraints and positive costs, see e.g. Osborne and Pitchik (1986), Deneckere and Kovenock (1996), Fabra, Von Der Fehr, and Harbord (2006), Blázquez de Paz (2018).

[16]Note that we use the superindex $go1$ ($go2$) to refer to the GO market when supplier 1 is dispatched first (last) in the spot market.

Figure 2: Spot electricity and GO markets



Output formulations: After the first stage, when prices in the spot market are set, the transmission system operator collects the prices and calls the suppliers into operation in stage 2. Supplier i's output in the spot market is defined by:

$$q_i^s(p^s) = \begin{cases} min\{a_1^s + a_2^s, a_i^s + T, k^s\} & \text{if } p_i^s < p_j^s \\ max\{0, a_i^s - T, a_1^s + a_2^s - k^s\} & \text{if } p_i^s > p_j^s. \end{cases} \tag{1}$$

When supplier i sets the lowest price in the spot market, it is dispatched first on the market. If the transmission line is not congested and supplier i has sufficient production capacity, it satisfies the demand in both nodes $(a_1^s + a_2^s)$. However, if the line is congested, supplier i satisfies the demand in node i and the demand in node j up to the transmission constraint $(a_i^s + T)$. Finally, supplier i cannot sell more than its production capacity.

If supplier i instead sets the higher price in the spot market, it is dispatched last and must satisfy residual demand. When the transmission line is not congested and the other supplier has sufficient production capacity to meet the total demand, supplier i will not be called into operation. However, when the transmission line is congested, supplier i will satisfy the residual demand in its own node $(a_i^s - T)$, and if the demand is sufficiently high, it will satisfy the residual demand in both nodes $(a_1^s + a_2^s - k^s)$. Recall that priority is given to the supplier located in the high-demand node in the case of ties $(p_i^s = p_j^s)$.

After knowing their dispatch in the spot market (and thus their GO production capacities), the suppliers set their prices in the GO market, simultaneously and independently. We denote these prices by $p^{go} = (p_1^{go}, p_2^{go})$. The transmission system operator collects the prices and calls the suppliers into operation. Recall that supplier i's production capacity of GOs is given as a share of its dispatch in the spot market, that is, $k_i^{go} = \alpha_i q_i^s(p^s)\ \forall\ i = 1, 2$.

Supplier i's output in the GO market is defined by:

$$q_i^{go}(p^{go}, p^s) = \begin{cases} min\{a_1^{go} + a_2^{go}, k_i^{go}(p^s)\} & \text{if } p_i^{go} < p_j^{go} \\ max\{0, a_1^{go} + a_2^{go} - k_j^{go}(p^s)\} & \text{if } p_i^{go} > p_j^{go}. \end{cases} \tag{2}$$

When supplier i sets the lowest price in the GO market, then depending on its GO production capacity it satisfies the total demand $(a_1^{go} + a_2^{go})$ or the demand up to its production capacity (k_i^{go}). If supplier i instead submits the highest price in the GO market, it satisfies the residual demand. However, if the demand for GOs is low, the residual demand could be nil. We assume the same tie-breaking rule in the GO market as in the spot market.

After the suppliers are put into operation, the profits are realized for the spot and the GO market. As congestion rents are captured by the transmission system operator, profits of the suppliers are given by their dispatched quantities multiplied by the bids. However, from now on we make the following assumptions. First, to ensure positive prices on GOs, we assume that residual demand is positive for at least one supplier in the GO market.[17] Second, for simplicity, we assume that the transmission line is always congested in the spot market, that is, $a_i^s + T < k^s\ \forall\ i = 1, 2$, which is usually the case in most electrical systems. In our model this means that equilibrium is determined by the transmission capacity constraint and we ignore outcomes where equilibrium is determined by the supplier's production capacity constraint.[18]

[17] If none of the suppliers face a positive residual demand we will have Bertrand competition where suppliers compete until the price of GOs is equal to the suppliers' marginal cost, which in this case is zero.

[18] Note that this is also the only relevant scenario to analyze a change in the design of the GO market where the sale of GOs is restricted by the transmission capacity in Section 5.

Supplier i's profits from both the spot market and the GO market are defined by:

$$\pi_i(p^s, p^{go}) = \begin{cases} p_i^s(a_i^s + T) + p_i^{go} q_i^{go}(p^{go}, p^s) & \text{if } p_i^s < p_j^s \\ p_i^s(a_i^s - T) + p_i^{go} q_i^{go}(p^{go}, p^s) & \text{if } p_i^s > p_j^s. \end{cases} \tag{3}$$

Importantly, when supplier i is dispatched first in the spot market, its capacity in the GO market $(\alpha_i(a_i^s+T))$ is greater than when the supplier is dispatched last $(\alpha_i(a_i^s-T))$. Therefore, bids in the spot market will not only affect expected profits from the spot market, but they will also affect expected profits from the GO market. The output in the GO market (q_i^{go}) is defined in equation (2) as a function of the bids of the suppliers, and thus both output and profits are now expressed as functions of prices in the spot and GO markets (p^s, p^{go}).

3 Equilibrium

We now characterize the subgame perfect Nash equilibrium of the sequential game with both a spot market and a GO market.[19] We first work out the equilibrium in the GO market, and then, based on the equilibrium in the GO market, we characterize the equilibrium in the spot market. To characterize the equilibrium in both markets, we follow the procedure in Blázquez de Paz (2018). First, we prove that a pure strategies equilibrium does not exist. Second, we find the support of the mixed strategies equilibrium. Third, we find the mixed strategies equilibrium.

GO market: We begin by characterizing the equilibrium in the GO market. First, we prove that a pure strategies Nash equilibrium does not exist:

Lemma 1. *Given our assumption that at least one supplier faces a positive residual demand in the GO market, a pure strategies Nash equilibrium does not exist.*

[19] Recall that we have made the assumption that the transmission line is always congested. However, if the line were not congested, the equilibrium would be as in Fabra, Von Der Fehr, and Harbord (2006).

Second, as a pure strategies Nash equilibrium does not exist, the next step is to find the support of the mixed strategies equilibrium:

Lemma 2. *Given prices p^s on the spot market, in the mixed strategies equilibrium in the GO market, both suppliers randomize on the interval $\left[\underline{p}^{go}, \overline{P}^{go}\right]$; where $\underline{p}^{go} = max\left\{\underline{p}_1^{go}, \underline{p}_2^{go}\right\}$ and $\underline{p}_i^{go}$ solves:*

$$\underline{p}_i^{go} min\{a_1^{go} + a_2^{go}, k_i^{go}(p^s)\} = \overline{P}^{go} max\{0, a_1^{go} + a_2^{go} - k_j^{go}(p^s)\}.$$

Lemma 2 states that both suppliers will randomize on the interval $[\underline{p}^{go}, \overline{P}^{go}]$, where $\overline{P}^{go}$ is the price cap in the GO market. The lower bound of the support is pinned down by the fact that, in equilibrium, suppliers must be indifferent between being dispatched first at a price equal to the lower bound and dispatched last at the price cap. Note that because supplier i's production capacity in the GO market (k_i^{go}) depends on its dispatch in the spot market, the lower bound of the support in the GO market ($\underline{p}^{go}$) is also a function of prices in the spot market (p^s). Therefore, there will be a different lower bound in each branch of the GO market in Figure 2.

Given the bound of the support in Lemma 2, we can work out the equilibrium in the GO market by characterizing the cumulative distribution function of the suppliers:

Proposition 1. *Given prices p^s on the spot market, in the mixed strategies equilibrium in the GO market, the suppliers randomize by using the following cumulative distribution function:*

$$F_i(p^{go}, p^s) = \begin{cases} 0 & \textit{if } p^{go} < \underline{p}^{go}(p^s) \\ \dfrac{\left[p^{go} - \underline{p}^{go}(p^s)\right] min\{a_1^{go} + a_2^{go}, k_j^{go}(p^s)\}}{p^{go}\left[min\{a_1^{go} + a_2^{go}, k_j^{go}(p^s)\} - max\{0, a_1^{go} + a_2^{go} - k_i^{go}(p^s)\}\right]} & \textit{if } p^{go} \in \left(\underline{p}^{go}(p^s), \overline{P}^{go}\right) \\ 1 & \textit{if } p^{go} = \overline{P}^{go} \end{cases} \tag{4}$$

Proposition 1 defines the cumulative distribution function of suppliers in the GO market. However, the cumulative distribution function in the GO market depends on the prices in the spot market, p^s, as they determine both the lower bound of the support, $\underline{p}^{go}$, and the set of production capacities (k_1^{go}, k_2^{go}) in the GO market.

Spot market: To work out the equilibrium in the spot market, it is necessary to take into account not only the expected profits from the spot market, but also the expected profits from the sale of GOs. Furthermore, the expected profits from the GO market depend on the dispatch of the suppliers in the spot market, and thus the expected profits from the GO market will be different in each branch of the tree in Figure 2.

First, we work out the support of the mixed strategies equilibrium in the spot market. As the lower bound of the support in the GO market is different in each branch of the tree in Figure 2, we denote it by $\underline{p}^{go1}$ (respectively $\underline{p}^{go2}$) when supplier 1 is dispatched first (respectively last) in the spot market:

Lemma 3. *In the mixed strategies equilibrium in the spot market, both suppliers randomize on the interval* $\left[\underline{p}^s, \overline{P}^s\right]$*; where* $\underline{p}^s = max\left\{\underline{p}_1^s, \underline{p}_2^s\right\}$ *and* $\underline{p}_i^s$ *solves:*

$$\underline{p}_i^s(a_i^s + T) + \underline{p}^{goi}\ min\{a_1^{go} + a_2^{go}, \alpha_i(a_i^s + T)\} = \overline{P}^s(a_i^s - T) + \underline{p}^{goj}\ min\{a_1^{go} + a_2^{go}, \alpha_i(a_i^s - T)\}.$$

Lemma 3 states that the suppliers will randomize on the interval $[\underline{p}^s, \overline{P}^s]$, where $\overline{P}^s$ is the price cap in the spot market. The lower bound of the support in the spot market is pinned down by the fact that, in equilibrium, suppliers must be indifferent between being first dispatched at a price equal to the lower bound and last dispatched at the price cap, while taking into account the expected profits from the GO market given their production capacity.

We complete the characterization of the equilibrium by working out the cumulative distribution function of the suppliers in the spot electricity market:[20]

Proposition 2. *In the mixed strategies equilibrium in the spot market, the suppliers randomize by using the following cumulative distribution function:*

$$F_i(p^s) = \begin{cases} 0 & \mathit{if}\ p^s < \underline{p}^s \\ \dfrac{(p^s - \underline{p}^s)(a_j^s + T)}{p^s\left[(a_j^s + T) - (a_j^s - T)\right] + \underline{p}^{goj} min\{a_1^{go} + a_2^{go}, \alpha_j(a_j^s + T)\} - \underline{p}^{goi} min\{a_1^{go} + a_2^{go}, \alpha_j(a_j^s - T)\}} & \mathit{if}\ p^s \in \left(\underline{p}^s, \overline{P}^s\right) \\ 1 & \mathit{if}\ p^s = \overline{P}^s \end{cases} \quad (5)$$

[20] Recall that we are assuming that the transmission line in the spot market is congested in both directions. However, note that Proposition 2 can easily be modified to reflect all the cases in equation (1).

The cumulative distribution function in Proposition 2 determines the expected bids in the spot market when the bids will affect not only the expected dispatch of the suppliers in the spot market, but also their expected production capacity in the GO market. Proposition 2 modifies the probabilities in the spot market to take into account the expected profits from the GO market associated with the different strategies in the spot market. Specifically, suppliers will assign probabilities to each potential bid so that the other supplier is indifferent between all its strategies in both the spot and GO markets simultaneously.

Benchmark: Finally, before we proceed with the analysis, we provide some benchmark results for the case without a GO market. This benchmark could also be interpreted as the scenario where the GO market operates independently of the spot market, that is, when GOs are issued independently of how much electricity has been sold in the spot market. In this scenario without GOs, the model and timeline are reduced to the first two bullet points in the overview of the timing in Section 2. As shown in Blázquez de Paz (2018), there is no pure strategies Nash equilibrium in this scenario, and instead we find the support of the mixed strategies equilibrium:

Lemma 4. *In the mixed strategies equilibrium in the spot market, both suppliers randomize on the interval* $\left[\underline{p}^b, \overline{P}^s\right]$*; where* $\underline{p}^b = max\left\{\underline{p}_1^b, \underline{p}_2^b\right\}$ *and* $\underline{p}_i^b$ *solves* $\underline{p}_i^b(a_i^s + T) = \overline{P}^s(a_i^s - T)$.

In the absence of a GO market, the mixed strategies equilibrium simplifies to the following:

Proposition 3. *In absence of a GO market, in the mixed strategies equilibrium in the spot market, the suppliers randomize using the following cumulative distribution function:*

$$F_i(p^b) = \begin{cases} 0 & \text{if } p^b < \underline{p}^b \\ \dfrac{(p^b - \underline{p}^b)(a_j^s + T)}{p^b\left[(a_j^s + T) - (a_j^s - T)\right]} & \text{if } p^b \in \left(\underline{p}^b, \overline{P}^s\right) \\ 1 & \text{if } p^b = \overline{P}^s \end{cases} \tag{6}$$

Proposition 3 determines the cumulative distribution function (CDF) of suppliers in the spot market when there are no additional profits to be made in the GO market. We will use this as a benchmark when we analyze the effect of introducing the GO market on competition in the spot market. Equation (6) from our no-GO benchmark may at first glance seem to be a particular case of equation (5) in Proposition 2. However, because the lower bound of the support in the benchmark ($\underline{p}^b$) could be different from the lower bound when there is a GO market ($\underline{p}^s$), the comparison between the CDFs of the suppliers in the spot market in the absence of a GO market and when the spot and GO markets operate sequentially is more elaborate. We study this in the next section.

4 Analysis of competition

In this section, we analyze the effect of the GO market on competition in the spot electricity market and how changes in structural parameters of the model affect the relationship between the spot and the GO market. Recall that in our model (and in the current design of the European GO market) the transmission line is not taken into account in the GO market, which means that suppliers can sell their entire GO production capacity to the other node even when the transmission line is congested in the spot market.[21]

The suppliers' production capacities in the GO market are given by their dispatched quantities in the spot market, which means that for each pair of demand in the spot market (a_1^s, a_2^s), there is a different set of production capacities in the GO market. Furthermore, as not all electricity is produced from renewable sources, only a share α_i of supplier i's dispatch in the spot market qualifies for a GO. Therefore, to isolate the impact of introducing a GO market, we make two additional assumptions. First, we assume that the demands in the spot market are symmetric, $a_1^s = a_2^s = a^s$. Second, we assume that suppliers have the same share of green production capacities, $\alpha_1 = \alpha_2 = \alpha$.

Despite the assumed symmetry in demand and green production capacities, note that

[21] This assumption is relaxed in Section 5, where we consider the case where the transmission line capacity is taken into account when clearing the GO market.

asymmetries will naturally emerge in the GO market due to the structure of the game. Although suppliers are symmetric in the spot market, they will nonetheless have different production capacities to compete with in the GO market depending on which supplier is dispatched first in the spot market. Thus, to make the analysis tractable, it is necessary to keep the suppliers symmetric in the spot market. Otherwise, we would have asymmetries on top of asymmetries, in which case it becomes unclear which economic forces determine the equilibrium. In the following propositions, we rely on these assumptions to determine the effect of the GO market on competition in the spot market.[22]

We start our analysis by comparing the effect of introducing a GO market on equilibrium prices in the spot electricity market:

Proposition 4. *The introduction of a GO market has a pro-competitive effect on the spot electricity market.*

The intuition behind this result is simple. Although the GO market offers suppliers an additional source of revenue, the sale of GOs is limited by the suppliers' dispatch of electricity in the spot market. Therefore, to maximize their production capacity in the GO market, suppliers must compete more fiercely than before to be dispatched first in the spot market. In the Appendix, we formally prove this intuition. Specifically, we prove that $\underline{p}^s \leq \underline{p}^b$, and that $F^s \geq F^b \; \forall \; p^s = p^b \in [\underline{p}^s, \overline{P}^s]$. In other words, introducing the GO market reduces the lower bound of the support for equilibrium prices in the spot market and shifts the CDFs of the suppliers so that they first-order stochastic dominate the CDFs when the spot market operates independently. This is illustrated in Figure 3.

Introducing the GO market has a pro-competitive effect on the spot market, which reduces equilibrium spot prices. This is illustrated in Table 1, row Prop 4. As a consequence of the decrease in equilibrium spot prices (column $E[p_i^s]$), there is a decrease in expected profits

[22] However, note that the equilibrium analysis in Section 3 does not depend on the assumptions of symmetric demand and green production capacities.

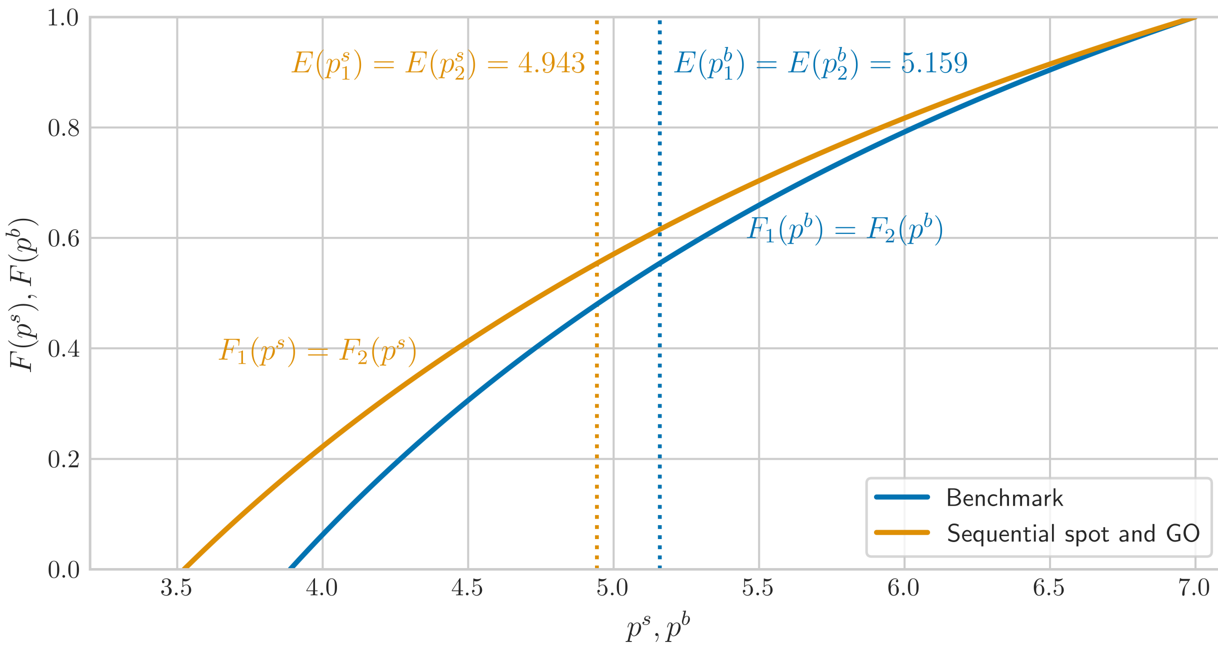


Figure 3: Proposition 4 ($a^s = 7$; $a_1^{go} = a_2^{go} = 4.4$; $\alpha = 1$; $\overline{P}^s = 7$; $\overline{P}^{go} = 2$; $T = 2$). Solid lines are the cumulative distribution functions of the suppliers, and dotted lines are their expected bids in the spot electricity market. Note that supplier 1 and 2 have the same CDFs given the assumption of symmetric demand and green production capacities.

(column $E[\pi_i^s]$) and an increase in consumer surplus (column $E[CS^s]$) in the spot market.[23] As noted above, although suppliers are symmetric in the spot market, they will have different expected bids in the GO market (columns $E[p_1^{go1}]$ and $E[p_2^{go1}]$) due to their different GO production capacity.[24] In the GO market, there is an additional stream of revenue for renewable energy suppliers (columns $E[\pi_1^{go1}]$ and $E[\pi_2^{go1}]$) and a positive consumer surplus for consumers with a preference for green energy (column $E[CS^{go1}]$).[25] However, the reduction

[23] When the transmission line is congested, consumers located at different nodes pay different prices in the spot market. In that case, the consumer surplus is given by the difference between the price cap and the expected price in each node multiplied by the demand in that node $((\overline{P}^s - E[p_1^s])a^s + (\overline{P}^s - E[p_2^s])a^s)$.

[24] Note that the values for the GO market in Table 1 are calculated when supplier 1 is dispatched first in the spot market (left branch, Figure 2). However, because suppliers are symmetric, expected profits and prices are the same, but with opposite subscripts, when supplier 2 is first dispatched in the spot market.

[25] As the transmission line is neglected in the GO market, all consumers pay the same price for GOs, which we assume to be equal to the average bids of suppliers. In that case, the consumer surplus is given by the difference between the price cap minus the average price multiplied by the total demand $(((E[p_1^{go1}] +$

in equilibrium spot prices means that the GO market benefits even consumers who do not have a demand for GOs.

Table 1: Summary of expected values from propositions.

	Spot market			GO market				
Variables	$E[p_i^s]$	$E[\pi_i^s]$	$E[CS^s]$	$E[p_1^{go1}]$	$E[p_2^{go1}]$	$E[\pi_1^{go1}]$	$E[\pi_2^{go1}]$	$E[CS^{go1}]$
Bench.	5.159	35.00	25.78	-	-	-	-	-
Prop 4	4.943	31.72	28.80	1.592	1.282	7.60	4.32	4.95
Prop 5	5.158	34.98	25.79	0.337	0.271	0.40	0.38	8.82
Prop 6	5.001	32.60	27.99	1.742	1.536	5.40	3.00	1.87

Notes: Expected profits are calculated as $\underline{p}^s(a_i^s + T)$ and $\underline{p}^{go1} min\{a_1^{go} + a_2^{go}, \alpha_i k_i^{go1}\}$ in the spot and GO markets, respectively (see equations (10) and (14) in the Appendix). Consumer surpluses are calculated as $(\overline{P}^s - E[p_1^s])a^s + (\overline{P}^s - E[p_2^s])a^s$ in the spot market and $((E[p_1^{go1}] + E[p_2^{go1}])/2)(a_1^{go} + a_2^{go1})$ in the GO market (see footnotes 23 and 25 in the text). Note that the expected values for the GO market are calculated when supplier 1 is dispatched first in the spot market (left branch, Figure 2).
Prop 4: $a^s = 7$; $a_1^{go} = a_2^{go} = 4.4$; $\alpha = 1$; $\overline{P}^s = 7$; $\overline{P}^{go} = 2$; $T = 2$.
Prop 5: $a^s = 7$; $a_1^{go} = a_2^{go} = 2.6$; $\alpha = 1$; $\overline{P}^s = 7$; $\overline{P}^{go} = 2$; $T = 2$.
Prop 6: $a^s = 7$; $a_1^{go} = a_2^{go} = 2.6$; $\alpha = 0.5$; $\overline{P}^s = 7$; $\overline{P}^{go} = 2$; $T = 2$.

For the remainder of this section, we analyze the impact of a change in the structural parameters of the model on the pro-competitive effect of the GO market that we found in Proposition 4. Specifically, we study changes in demand for GOs and the share of green production capacity in the spot market. These impacts will be different depending on the level of demand for GOs. First, when demand for GOs is sufficiently low, both suppliers have enough production capacity to satisfy total demand if they are dispatched first in the spot market. Second, when the demand for GOs is sufficiently high, neither supplier has enough production capacity to satisfy the total demand even when it is first dispatched in the spot market.

In the following proposition, we analyze the effect of reduced demand in the GO market

$E[p_2^{go1}])/2)(a_1^{go} + a_2^{go1}))$. Note that although this assumes that there is no demand rationing rule, this assumption is innocent, as the choice of demand rationing rule affects equilibrium only when demand is elastic (Davidson and Deneckere, 1986, Allen and Hellwig, 1993).

on competition in the spot market for the two cases of demands:

Proposition 5. *A decrease in demand for GOs:*

- *decreases the pro-competitive effect of the GO market on the spot electricity market when the demand for GOs is sufficiently low, i.e., when* $\alpha(a^s - T) < a_1^{go} + a_2^{go} < \alpha(a^s + T)$.

- *does not change the pro-competitive effect of the GO market on the spot electricity market when the demand for GOs is sufficiently high, i.e., when* $\alpha(a^s - T) < \alpha(a^s + T) < a_1^{go} + a_2^{go}$.

When the demand for GOs is sufficiently low, the potential profits in the GO market are also low. In that case, suppliers have less incentives to compete more fiercely in the spot market to increase their production capacities of GOs. In fact, when the demand for GOs is low, the pro-competitive effect of introducing the GO market almost disappears (Table 1, row Prop 5). With low demand for GOs ($a_1^{go} = a_2^{go} = 2.6$), the residual demand in the GO market is close to nil, resulting in equilibrium spot prices almost identical to those when the spot market operates independently.

However, a reduction in the demand for GOs reduces the pro-competitive effect of the GO market only when the initial demand for GOs is sufficiently low. When the demand for GOs is sufficiently high, a reduction in the demand has no effect on the relationship between the spot and GO markets. In that case, both suppliers are already constrained by their production capacities in the GO market, and a change in demand has no effect on their output decisions.

We end this section by analyzing the effect of a reduction in the green production capacity of the suppliers on the relationship between the spot and GO markets. As in Proposition 5, there is no change in the pro-competitive effect of the GO market when the demand for GOs is high, and therefore we focus on the case where demand is sufficiently low:

Proposition 6. *When the demand for GOs is sufficiently low* ($\alpha(a^s - T) < a_1^{go} + a_2^{go} < \alpha(a^s + T)$)*, a decrease in the green production capacity increases the pro-competitive effect of the GO market on the spot electricity market.*

Again, the reason for this result is intuitive. When suppliers have less green production capacity to begin with and if they are dispatched last in the spot market, they will have even less production capacity of GOs to sell than before. Consequently, they must now compete more fiercely to be dispatched first in the spot market to ensure their profits from the GO market. Therefore, a reduction in the green production capacity of suppliers has the opposite effect on competition to that of a reduction in the demand for GOs.

In Table 1, row Prop 5, we found that the pro-competitive effect of the GO market almost disappeared when the demand for GOs was low ($a_1^{go} = a_2^{go} = 2.6$). However, this is no longer the case when there is also a decrease in the green production capacity of the suppliers (row Prop 6). When suppliers cannot sell their entire production capacity in the GO market ($\alpha = 0.5$) the pro-competitive effect of the GO market reappears. Despite the low demand for GOs, the green production capacity of the suppliers is not sufficient to satisfy the total demand for GOs. Because the residual demand in the GO market is large, introducing the GO market again has a strong pro-competitive effect on the spot market compared to when the spot market operates independently.

5 Market design

In the main analysis, we aligned our model assumption with the current design of the European GO market, which does not restrict the flow of GOs by the transmission capacity of electricity between countries. As noted in the introduction, this has led to a handful of countries becoming major exporters of (cheap) GOs. Now we analyze an alternative market design in which the GO market takes into account the physical constraint in the spot market.

In the new market design, the model setup remains the same as that presented in Section

2 with the exception that equation (2), which defined the supply of GOs, must now take into account the transmission constraint in the spot market. Supplier i's supply in the GO market is now defined by:

$$q_i^{go}(p^{go}, p^s) = \begin{cases} min\{a_1^{go} + a_2^{go}, a_i^{go} + T, k_i^{go}(p^s)\} & \text{if } p_i^{go} < p_j^{go} \\ max\{0, a_i^{go} - T, a_1^{go} + a_2^{go} - k_j^{go}(p^s)\} & \text{if } p_i^{go} > p_j^{go}. \end{cases} \tag{7}$$

The characterization of equilibrium is analogous to the case without a transmission constraint in the GO market, but where the output is defined by equation (7) rather than equation (2). As before, we assume that priority is given to the supplier located in the high-demand node in the case of ties ($p_i^{go} = p_j^{go}$) and in the case of equal demand, priority is given to the supplier in the high-demand node. We refer to the proofs in the Appendix for further details.

To allow a comparison between the two market designs, we maintain the assumption of symmetric demand in the spot market, $a_1^s = a_2^s = a^s$, and symmetric green production capacity, $\alpha_1 = \alpha_2 = \alpha$. In addition, we assume that when the transmission line is introduced in the GO market, the capacity of the line is binding. Specifically, we assume that $min\{a_1^{go} + a_2^{go}, a_i^{go} + T, k_i^{go}(p^s)\} = a_i^{go} + T$ and $max\{0, a_i^{go} - T, a_1^{go} + a_2^{go} - k_j^{go}(p^s)\} = a_i^{go} - T$, which implies that the transmission capacity constraint is more stringent than the (green) production capacity constraint in the GO market. As noted in the Introduction, the trade of GOs is in many cases considerably higher than the physical transmission capacity between countries.

In our main model, equilibrium was determined by the green production capacity of the suppliers, whereas in the new market design, equilibrium will instead be determined by the transmission capacity. Recall that we have already assumed that the transmission capacity is smaller than the production capacity in the spot market, and it is therefore natural to make the same assumption in the GO market. Importantly, this assumption allows us to isolate the impact of a change in market design on the relationship between the spot and GO markets.

In Proposition 4 we found a pro-competitive effect of introducing the GO market on the spot electricity market. Interestingly, our next result shows that this pro-competitive effect disappears when the current market design is changed to one where the transmission line is taken into account in the GO market:

Proposition 7. *When the transmission constraint from the spot electricity market is taken into account in the GO market (and the transmission constraint is binding), then there is no longer a pro-competitive effect from the introduction of the GO market.*

When the sale of GOs was not limited by the transmission line, suppliers could earn additional revenue by selling potentially more GOs to the other node than they could physically sell electricity. This created incentives for suppliers to compete more fiercely in the spot market to increase their GO production capacity and satisfy a larger share of demand in the GO market. This is no longer the case when the sale of GOs is restricted by the transmission capacity.

Although the GO market still offers an additional source of revenue, the sale of GOs is now limited not only by the supplier's dispatch of electricity in the spot market but also by the physical transmission capacity of the grid. When suppliers cannot export more GOs than electricity, they no longer have incentives to increase their production capacity in the GO market. Therefore, imposing the transmission constraint in the GO market removes the pro-competitive effect of the GO market on the spot electricity market.

6 Concluding remarks

In Europe, consumers have the right not only to know the origin of their electricity, but also to choose the attributes of the electricity that they consume. To facilitate this, the EU has set up a market of energy attributes known as Guarantees of Origin (GOs). GOs are issued to producers of renewable energy, which they can sell to consumers who wish to declare their electricity consumption as “green”. Importantly, GOs are sold separately from the electricity for which they were issued, resulting in a market of energy attributes downstream of the market for the energy itself.

It has been argued that decoupling the sale of GOs from the sale of energy is preferable because it limits the impact of GOs on the electricity markets (e.g. Lise et al., 2007). However, because energy producers cannot sell more GOs than their dispatch of electricity, we argue that there is nevertheless an impact that warrants further analysis. Despite its size and rapid growth, the GO market has received surprisingly little attention in the literature. We contribute by analyzing the effect of introducing a sequential GO market on the spot electricity market in a stylized model in which two suppliers compete in prices.

In the current market design, suppliers can make additional profits in the GO market without being restricted by the transmission capacity in the spot market. In that case, we find that suppliers will compete more fiercely than before to be dispatched first in the spot market to increase their production capacity in the GO market. Therefore, the introduction of the GO market has a pro-competitive impact on the spot market, leading to reduced electricity prices. In contrast, imposing the transmission constraint on the GO market kills its pro-competitive effect. When suppliers cannot export more GOs than electricity, they no longer have incentives to increase their GO production capacity.

We explore the impact on equilibrium of changes in the structural parameters of the GO market. First, a decrease in the demand for GOs reduces the pro-competitive impact of the GO market. Less demand reduces the potential profits from the GO market, and thus suppliers have less incentives to compete more fiercely in the spot market to increase their production capacity of GOs. Second, a reduction in the green production capacity of the suppliers, that is, the share of their output that qualifies for GOs, strengthens the pro-competitive effect. In that case, it becomes more risky for suppliers to be dispatched last in the spot market given their relatively lower production capacity of GOs, and they must therefore compete more fiercely in the spot market than before.

The GO market has historically suffered from oversupply, which could potentially distort investment decision in renewable energy capacity. To satisfy the demand for renewable energy among consumers, suppliers can buy cheap GOs from abroad (especially from Nordic hydropower) instead of investing in renewable production capacity at home (Mulder and Zomer, 2016, Herbes et al., 2020, Galzi, 2023). One way to alleviate this problem is to restrict the trade of GOs to align with the actual transmission capacities of electricity. However, as we have shown, this could remove the pro-competitive impact of the GO market on the spot electricity market.

Alternatively, policymakers can instead bring the market into balance by increasing the demand for GOs or reducing the production capacity of renewable energy that qualifies for GOs. The former can be achieved by introducing mandatory GO quotas for electricity retailers, and the latter can be achieved by issuing GOs only to recently installed production capacity. This would not only reduce the oversupply of GOs but also strengthen the pro-competitive effect of the GO market. In addition, it could potentially also increase incentives to invest in additional renewable capacity.

The objective of this paper is to study the effect of introducing a market for energy attributes on the market for energy itself. An important caveat to our results is the assumption of symmetry in demand in the spot market and in the "greenness" of the suppliers. Although these assumptions were necessary to facilitate our analysis and comparison of equilibrium outcomes, we have characterized the equilibrium for any set of parameters where the residual demand is positive. Therefore, the model presented here can be useful in addressing other relevant questions about the spot and GO markets, such as asymmetries in green production capacity and long-term investment incentives in the spot electricity market. We leave these questions to future research. Another interesting avenue for future research is to relax the assumptions of a price auction in the GO market and investigate what happens when GOs are traded in a decentralized market, e.g. through brokers.

A Proofs

Lemma 1. In the proof, we assume that both suppliers face a positive residual demand.[26] To prove that a pure strategies Nash equilibrium does not exist, we show that suppliers will enter a price war where they undercut each other to be dispatched first in the auction in any pure strategy candidate equilibrium. In particular, a pair of prices $p_1^{go} = p_2^{go} = 0$ is not a pure strategies Nash equilibrium, because at least one supplier has incentives to increase its price and satisfy the residual demand. A pair of prices $p_1^{go} = p_2^{go} > 0$ is not a pure strategies Nash equilibrium, because both suppliers have incentives to reduce their price to be dispatched first in the auction. A pair of prices $p_1^{go} > p_2^{go} \geq 0$ (or $p_2^{go} > p_1^{go} \geq 0$) is not a pure strategies Nash equilibrium, because the low-price supplier has incentives to increase its price, but still undercutting the other supplier to be dispatched first. □

Lemma 2. In the proof, we assume that both suppliers face a positive residual demand.[27] Each supplier can guarantee its own residual profit by setting the price cap in the GO market and satisfying the residual demand ($\overline{P}^{go} max\{0, a_1^{go} + a_2^{go} - k_i^{go}(p^s)\}$). Therefore, supplier i will not set a price lower than $\underline{p}_i^{go}$, where $\underline{p}_i^{go}$ solves

$$\underline{p}_i^{go} min\{a_1^{go} + a_2^{go}, k_i^{go}(p^s)\} = \overline{P}^{go} max\{0, a_1^{go} + a_2^{go} - k_j^{go}(p^s)\}.$$

The right-hand side of the equation is the profit of supplier i in the GO market when it sets the price cap and serves the residual demand in that market. Because supplier i can always guarantee this profit, it will never submit a bid for which its profits are lower than this. The left-hand side of the equation is the same supplier's profits when it instead submits a bid equal to the lower bound of the support, in which case the supplier knows that it will be dispatched first.

[26]The proof follows the same principles when only one supplier faces a positive residual demand. When none of the suppliers faces a positive residual demand, the equilibrium in the GO market is the Bertrand equilibrium where the equilibrium price is equal to the suppliers' marginal cost, i.e., the equilibrium price is equal to zero. The latter case is ruled out by our model assumptions.

[27]The proof follows the same principles when only one supplier faces a positive residual demand.

In addition, none of the suppliers will set a price $p^{go} \in \left[min\left\{\underline{p}_1^{go}, \underline{p}_2^{go}\right\}, max\left\{\underline{p}_1^{go}, \underline{p}_2^{go}\right\}\right]$, as the supplier for which $\underline{p}_i^{go}$ is lower knows that the other supplier will never set a price lower than $\underline{p}_j^{go}$. In that case, the supplier can increase its bid but still undercut the other supplier, and increase its profits. Therefore, the lower bound of the support of the mixed strategies equilibrium is $max\left\{\underline{p}_1^{go}, \underline{p}_2^{go}\right\}$, and both suppliers will randomize on the interval $p^{go} \in \left[max\left\{\underline{p}_1^{go}, \underline{p}_2^{go}\right\}, \overline{P}^{go}\right]$. □

Proposition 1. To work out the cumulative distribution function (CDF), we follow Varian (1980) and Kreps and Scheinkman (1983). The proof focuses on supplier 2' s CDF, as the steps to work out supplier 1's CDF are identical.

The proof follows five steps. In the first step, the payoff function for any supplier is:

$$\begin{aligned} \pi_1(p^{go}, p^s) &= F_2(p^{go}, p^s)\left[p^{go} max\{0, a_1^{go} + a_2^{go} - k_2^{go}(p^s)\}\right] + \\ &\quad (1 - F_2(p^{go}, p^s))\left[p^{go} min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\}\right] = \\ &= -p^{go}\ F_2(p^{go}, p^s)\left[min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} - max\{0, a_1^{go} + a_2^{go} - k_2^{go}(p^s)\}\right] + \\ &\quad p^{go}\ min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} \end{aligned} \tag{8}$$

With probability F_2, supplier 2 sets the lowest price, and supplier 1 is dispatched last in the auction. In that case, supplier 1's profits are $p^{go} max\{0, a_1^{go} + a_2^{go} - k_2^{go}(p^s)\}$. With probability $1 - F_2$, supplier 2 sets the higher price, and supplier 1 is dispatched first in the auction. In that case, the profits of supplier 1 are $p^{go} min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\}$.

In the second step, $\pi_1 = \overline{\pi}_1^{go}\ \forall\ p^{go} \in S$, where S is the support of the mixed strategies in Lemma 2 and $\overline{\pi}_1^{go}$ is the average profit, i.e., each strategy in the support generates the same expected payoff. Then,

$$\begin{aligned} \overline{\pi}_1^{go} &= -p^{go}\ F_2(p^{go}, p^s)\left[min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} - max\{0, a_1^{go} + a_2^{go} - k_2^{go}(p^s)\}\right] + \\ &\quad p^{go}\ min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} \Rightarrow \\ F_2(p^{go}, p^s) &= \frac{p^{go}\ min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} - \overline{\pi}_1^{go}}{p^{go}\left[min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} - max\{0, a_1^{go} + a_2^{go} - k_2^{go}(p^s)\}\right]} \end{aligned} \tag{9}$$

The third step uses the fact that $F_2 = 0$ when $p^{go} = \underline{p}^{go}(p^s)$. This implies that

$$\overline{\pi}_1^{go} \quad = \quad \underline{p}^{go}(p^s) min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} \tag{10}$$

In the fourth step, plugging equation (10) into equation (9), we obtain supplier 2's mixed strategies:

$$\begin{aligned} F_2(p^{go}, p^s) &= \frac{p^{go}\ min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} - \underline{p}^{go}(p^s)\ min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\}}{p^{go}\,[min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} - max\{0, a_1^{go} + a_2^{go} - k_2^{go}(p^s)\}]} = \\ &= \frac{min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\}}{min\{a_1^{go} + a_2^{go}, k_1^{go}(p^s)\} - max\{0, a_1^{go} + a_2^{go} - k_2^{go}(p^s)\}} \frac{p^{go} - \underline{p}^{go}(p^s)}{p^{go}} \ \ \forall\ p^{go} \in S \end{aligned} \tag{11}$$

In the fifth step, using Lemma 2, we insert the value of the lower bound of the support in the GO market, $\underline{p}^{go}$, into equation (11), and use the fact that $F_2 = 1$ when $p^{go} = \overline{P}^{go}$. This last step concludes the proof. □

Lemma 3. The proof of Lemma 3 is as in Lemma 2, but to work out $\underline{p}_1^s$ and $\underline{p}_2^s$ in the spot market, it is necessary to take into account the expected profits of the suppliers in the GO market. Because the lower bound of the support in the GO market is a function of the spot prices, we denote it by $\underline{p}^{go1}$ (resp. $\underline{p}^{go2}$) when supplier 1 is dispatched first (resp. last) in the spot market.

In particular, to work out $\underline{p}_i^s$, it is necessary to solve

$$\underline{p}_i^s(a_i^s + T) + \underline{p}^{goi}\ min\{a_1^{go} + a_2^{go}, \alpha_i(a_i^s + T)\} = \overline{P}^s(a_i^s - T) + \underline{p}^{goj}\ min\{a_1^{go} + a_2^{go}, \alpha_i(a_i^s - T)\}.$$

On the right-hand side, the first term is the profits of supplier i in the spot market when it serves the residual demand in that market at the price cap, and the second term is the expected profits in the GO market. Because supplier i can guarantee these profits by setting a price equal to the price cap in the spot market, it will never set a price in the spot market for which its profits are lower than those on the right-hand side. The price that makes the supplier indifferent between satisfying residual demand at the price cap and being dispatched first is $\underline{p}_i^s$. This price equalizes supplier i's profits in the spot market when it is instead first dispatched in the spot market ($\underline{p}_i^s(a_i^s+T)$) plus the expected profits in the GO market ($\underline{p}^{goi}\ min\{a_1^{go}+a_2^{go},\alpha_1(a_i^s+T)\}$). $\square$

Proposition 2. The proof follows the same logic as the proof of Proposition 1. The proof focuses on supplier 2's CDF, as the steps to work out supplier 1's CDF are identical. Recall that we denote the lower bound of the support in the GO market as $\underline{p}^{go1}$ (resp. $\underline{p}^{go2}$) when supplier 1 is dispatched first (resp. last) in the spot market. Furthermore, to simplify the notation, we denote the production capacity of supplier i in the GO market as k_i^{go1} (resp. k_i^{go2}) when supplier 1 is dispatched first (resp. last) in the spot market.

In the first step, the payoff function for any supplier is:

$$\begin{aligned}
\pi_1(p^s) \quad &= \quad F_2(p^s)\left[p^s(a_1^s-T)+\underline{p}^{go2}min\{a_1^{go}+a_2^{go},k_1^{go2}\}\right]+\\
&\quad\ (1-F_2(p^s))\left[p^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}\right]=\\
&= \quad -p^s\ F_2(p^s)\\
&\quad\ \left[p^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}-p^s(a_1^s-T)-\underline{p}^{go2}min\{a_1^{go}+a_2^{go},k_1^{go2}\right]+\\
&\quad\ p^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}
\end{aligned} \tag{12}$$

With probability F_2, supplier 2 sets the lowest price, and supplier 1 is dispatched last in the auction. In that case, supplier 1's profits in the spot market are $p^s(a_1^s-T)$, and its expected profits in the GO market are $\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}$. With probability $1-F_2$, supplier 2 sets the highest price, and supplier 1 is dispatched first in the auction. In that case, supplier 1's profits in the spot market are $p^s(a_1^s+T)$, and its expected profits in the GO market are $\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}$.

In the second step, $\pi_1=\overline{\pi}_1^s\ \forall\ p^s\in S$, where S is the support of the mixed strategies in Lemma 3 and $\overline{\pi}_1^s$ is the average profit, i.e., each strategy in the support generates the same expected payoff. Then,

$$
\begin{aligned}
\overline{\pi}_1^s &= -p^s \; F_2(p^s) \\
&\quad \left[p^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}-p^s(a_1^s-T)-\underline{p}^{go2}min\{a_1^{go}+a_2^{go},k_1^{go2}\right]+ \\
&\quad p^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\} \Rightarrow \\
F_2(p^s) &= \frac{p^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}-\overline{\pi}_1^{go2}}{p^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}-p^s(a_1^s-T)-\underline{p}^{go2}min\{a_1^{go}+a_2^{go},k_1^{go2}\}} \\
&= \frac{p^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}-\overline{\pi}_1^{go2}}{p^s\left[(a_1^s+T)-(a_1^s-T)\right]+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}-\underline{p}^{go2}min\{a_1^{go}+a_2^{go},k_1^{go2}\}} \qquad (13)
\end{aligned}
$$

The third step uses the fact that $F_2 = 0$ when $p^s = \underline{p}^s$. This implies that

$$
\overline{\pi}_1^s = \underline{p}^s(a_1^s+T)+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\} \qquad (14)
$$

In the fourth step, by plugging equation (14) into equation (13), we obtain supplier 2's mixed strategies:

$$
\begin{aligned}
F_2(p^s) &= \frac{(p^s-\underline{p}^s)(a_1^s+T)}{p^s\left[(a_1^s+T)-(a_1^s-T)\right]+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},k_1^{go1}\}-\underline{p}^{go2}min\{a_1^{go}+a_2^{go},k_1^{go2}\}} \\
&= \frac{(p^s-\underline{p}^s)(a_1^s+T)}{p^s\left[(a_1^s+T)-(a_1^s-T)\right]+\underline{p}^{go1}min\{a_1^{go}+a_2^{go},\alpha_1(a_1^s+T)\}-\underline{p}^{go2}min\{a_1^{go}+a_2^{go},\alpha_1(a_1^s-T)\}} \\
&\quad \forall \; p^s \in S \qquad (15)
\end{aligned}
$$

In the fifth step, using Lemma 3, we plug the value of the lower bound of the support ($\underline{p}^s$) into equation (15), and use the fact that $F_2 = 1$ when $p^s = \overline{P}^s$. This last step concludes the proof. □

Proposition 3. The proof follows the same steps as the proofs of Propositions 1 and 2. □

Proposition 4. We prove that $\underline{p}^s \leq \underline{p}^b$ and $F^s \geq F^b \; \forall \; p^s = p^b \in [\underline{p}^s, \overline{P}^s]$. These two relations imply that the equilibrium spot prices are lower when the spot and GO markets operate sequentially compared to when the spot market operates independently, that is, the introduction of a GO market has a pro-competitive effect on the spot market. Recall that we have assumed $a_1^s = a_2^s = a^s$ and $\alpha_1 = \alpha_2 = \alpha$. However, we sometimes keep subscripts to make it easier to distinguish between the two suppliers and branches of the GO market in Figure 2.

We start by proving that $\underline{p}^s \leq \underline{p}^b$. We proceed in two steps. First, we prove that $\underline{p}^{go1} = \underline{p}^{go2}$. By Lemma 2, we know that:

$$\begin{aligned}
\underline{p}^{go1} &= max\left\{\frac{\overline{P}^{go} max\left\{0, a_1^{go} + a_2^{go} - k_2^{go1}\right\}}{min\left\{a_1^{go} + a_2^{go}, k_1^{go1}\right\}}, \frac{\overline{P}^{go} max\left\{0, a_1^{go} + a_2^{go} - k_1^{go1}\right\}}{min\left\{a_1^{go} + a_2^{go}, k_2^{go1}\right\}}\right\} \\
&= max\left\{\frac{\overline{P}^{go} max\left\{0, a_1^{go} + a_2^{go} - \alpha_2(a_2^s - T)\right\}}{min\left\{a_1^{go} + a_2^{go}, \alpha_1(a_1^s + T)\right\}}, \frac{\overline{P}^{go} max\left\{0, a_1^{go} + a_2^{go} - \alpha_1(a_1^s + T)\right\}}{min\left\{a_1^{go} + a_2^{go}, \alpha_2(a_2^s - T)\right\}}\right\} \\
\underline{p}^{go2} &= max\left\{\frac{\overline{P}^{go} max\left\{0, a_1^{go} + a_2^{go} - k_2^{go2}\right\}}{min\left\{a_1^{go} + a_2^{go}, k_1^{go2}\right\}}, \frac{\overline{P}^{go} max\left\{0, a_1^{go} + a_2^{go} - k_1^{go2}\right\}}{min\left\{a_1^{go} + a_2^{go}, k_2^{go2}\right\}}\right\} \\
&= max\left\{\frac{\overline{P}^{go} max\left\{0, a_1^{go} + a_2^{go} - \alpha_2(a_2^s + T)\right\}}{min\left\{a_1^{go} + a_2^{go}, \alpha_1(a_1^s - T)\right\}}, \frac{\overline{P}^{go} max\left\{0, a_1^{go} + a_2^{go} - \alpha_1(a_1^s - T)\right\}}{min\left\{a_1^{go} + a_2^{go}, \alpha_2(a_2^s + T)\right\}}\right\} \qquad (16)
\end{aligned}$$

When $a_1^s = a_2^s = a^s$ and $\alpha_1 = \alpha_2 = \alpha$, it is straightforward to check that $\underline{p}^{go1} = \underline{p}^{go2} = \underline{p}^{go}$.

Second, using the previous result, we show that $\underline{p}^s \leq \underline{p}^b$. From Lemma 3, we know that $\underline{p}^s = min\left\{\underline{p}_1^s, \underline{p}_2^s\right\}$, where

$$\begin{aligned}
\underline{p}_1^s &= \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, k_1^{go2}\right\} - \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, k_1^{go1}\right\}}{(a_1^s + T)} \\
&= \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, \alpha_1(a_1^s - T)\right\} - \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, \alpha_1(a_1^s + T)\right\}}{(a_1^s + T)} \\
\underline{p}_2^s &= \frac{\overline{P}^s(a_2^s - T) + \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, k_2^{go1}\right\} - \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, k_2^{go2}\right\}}{(a_2^s + T)} \\
&= \frac{\overline{P}^s(a_2^s - T) + \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, \alpha_2(a_2^s - T)\right\} - \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, \alpha_2(a_2^s + T)\right\}}{(a_2^s + T)}
\end{aligned}$$

When $a_1^s = a_2^s = a^s$ and $\alpha_1 = \alpha_2 = \alpha$, it is easy to see that $\underline{p}_1^s = \underline{p}_2^s$.

Recall that we have assumed that at least one supplier must face a positive residual demand in the GO market.[28] However, we can still prove that $\underline{p}^s < \underline{p}^b$ both for when demand

[28] Otherwise, the equilibrium in that market is equal to the suppliers' marginal cost, i.e., the equilibrium price is zero and this is ruled out by assumption.

is high and low in the GO market. First, when demand in the GO market is sufficiently low, that is, $\alpha(a^s - T) < a_1^{go} + a_2^{go} < \alpha(a^s + T)$:

$$\begin{aligned} \underline{p}^s \leq \underline{p}^b \quad &\Leftrightarrow \quad \frac{\overline{P}^s(a^s - T) + \underline{p}^{go}\alpha(a^s - T) - \underline{p}^{go}(a_1^{go} + a_2^{go})}{a^s + T} \leq \frac{\overline{P}^s(a^s - T)}{a^s + T} \\ &\Leftrightarrow \quad \underline{p}^{go}(\alpha(a^s - T) - (a_1^{go} + a_2^{go})) \leq 0 \end{aligned} \tag{17}$$

The inequality in (17) is true, because when demand in the GO market is sufficiently low, $a_1^{go} + a_2^{go} \geq \alpha(a^s - T)$. Second, when demand in the GO market is sufficiently high, that is, $\alpha(a^s - T) < \alpha(a^s + T) < a_1^{go} + a_2^{go}$:

$$\begin{aligned} \underline{p}^s \leq \underline{p}^b \quad &\Leftrightarrow \quad \frac{\overline{P}^s(a^s - T) + \underline{p}^{go}\alpha(a^s - T) - \underline{p}^{go}\alpha(a^s + T)}{a^s + T} \leq \frac{\overline{P}^s(a^s - T)}{a^s + T} \\ &\Leftrightarrow \quad \underline{p}^{go}(\alpha(a^s - T) - \alpha(a^s + T)) \leq 0 \end{aligned} \tag{18}$$

The inequality in (18) is also true, because when demand in the GO market is sufficiently high, $\alpha(a^s + T) \geq \alpha(a^s - T)$.

We proceed to prove that $F^s \geq F^b \ \forall \ p^s \in [\underline{p}^s, \overline{P}^s]$. However, we focus on supplier 2 as the proof for supplier 1 follows the same steps. First, we define F_2^b and F_2^s:

$$\begin{aligned} F_2^b(p^s) &= \frac{(p^s - \underline{p}^s)(a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)]} \\ &= \frac{[p^s(a_1^s + T) - \overline{P}^s(a_1^s - T)](a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)]} = \frac{A(a_1^s + T)}{B} \\ F_2^s(p^s) &= \frac{(p^s - \underline{p}^s)(a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)] + \underline{p}^{go}min\left\{a_1^{go} + a_2^{go}, k_1^{go1}\right\} - \underline{p}^{go}min\left\{a_1^{go} + a_2^{go}, k_1^{go2}\right\}} \\ &= \frac{[p^s(a_1^s + T) - \overline{P}^s(a_1^s - T) + \underline{p}^{go}min\left\{a_1^{go} + a_2^{go}, k_1^{go1}\right\} - \underline{p}^{go}min\left\{a_1^{go} + a_2^{go}, k_1^{go2}\right\}}{p^s[(a_1^s + T) - (a_1^s - T)] + \underline{p}^{go}min\left\{a_1^{go} + a_2^{go}, k_1^{go1}\right\} - \underline{p}^{go}min\left\{a_1^{go} + a_2^{go}, k_1^{go2}\right\}} \\ &= \frac{(A + C)(a_1^s + T)}{B + C} \end{aligned} \tag{19}$$

where $A = [p^s(a_1^s + T) - \overline{P}^s(a_1^s - T)]$, $B = p^s[(a_1^s + T) - (a_1^s - T)]$, and $C = \underline{p}^{go}min\left\{a_1^{go} + a_2^{go}, k_1^{go1}\right\} - \underline{p}^{go}min\left\{a_1^{go} + a_2^{go}, k_1^{go2}\right\}$. It is important to note that $A \leq B \ \forall \ p^s \in [\underline{p}^s, \overline{P}^s]$, and $A = B$ when

$p^s = \overline{P}^s$. It is also important to note that $C > 0$ when demand in the GO market is sufficiently low $\left(k_1^{go2} \equiv \alpha_1(a^s - T) < a_1^{go} + a_2^{go} < \alpha_1(a^s + T) \equiv k_1^{go1}\right)$ and when it is sufficiently high $\left(k_1^{go2} \equiv \alpha_1(a^s - T) < \alpha_1(a^s + T) \equiv k_1^{go1} < a_1^{go} + a_2^{go}\right)$.

By using equation (19), it is easy to prove that $F^s \geq F^b \; \forall \; p^s = p^b \in [\underline{p}^s, \overline{P}^s]$:

$$\begin{aligned}
F_2^b(p^s) \leq F_2^s(p^s) \quad &\Leftrightarrow \quad \frac{A}{B} \leq \frac{A+C}{B+C} \Leftrightarrow \frac{B-\epsilon}{B} \leq \frac{(B-\epsilon)+C}{B+C} \\
&\Leftrightarrow \quad (B-\epsilon)(B+C) \leq ((B-\epsilon)+C)B \Leftrightarrow B^2 + BC - \epsilon B - \epsilon C \leq B^2 - \epsilon B + CB \\
&\Leftrightarrow \quad -\epsilon C \leq 0
\end{aligned} \tag{20}$$

where $\epsilon = B - A$ is a positive constant. The inequality in (20) holds as both $\epsilon > 0$ and $C > 0$. Recall also that $F_2^s(\overline{P}^s) = F_2^b(\overline{P}^s) = 1$. □

Proposition 5. We prove the effect of a change in the demand for GOs on the equilibrium prices in the spot market. Specifically, we compare the lower bound of the support ($\underline{p}^s$) and the CDFs (F^s) in the spot market when there is an increase in the demand for GOs, that is, $\hat{a}_1^{go} + \hat{a}_2^{go} > a_1^{go} + a_2^{go}$. As before, we still use subscripts, although we have assumed symmetric demand ($a_1^s = a_2^s = a^s$) and green production capacities ($\alpha_1 = \alpha_2 = \alpha$).

First, we prove that $\hat{\underline{p}}^s \leq \underline{p}^s$, where $\hat{\underline{p}}^s$ is the lower bound of the support in the spot market when the demand in the GO market is given by $\hat{a}_1^{go} + \hat{a}_2^{go}$. In Proposition 4, we proved that $\underline{p}^{go1} = \underline{p}^{go2} = \underline{p}^{go}$. Therefore,

$$\begin{aligned}
\underline{p}_1^s &= \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, k_1^{go2}\right\} - \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, k_1^{go1}\right\}}{(a_1^s + T)} \\
&= \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, \alpha_1(a_1^s - T)\right\} - \underline{p}^{go} min\left\{a_1^{go} + a_2^{go}, \alpha_1(a_1^s + T)\right\}}{(a_1^s + T)}
\end{aligned} \tag{21}$$

Note that equation (21) varies depending on the realization of the demand in the GO market. When the demand for GOs is sufficiently low, that is, $\alpha_i(a_i^s - T) < a_1^{go} + a_2^{go} < \alpha_i(a_i^s + T)$, equation (21) becomes:

$$\begin{aligned}\underline{p}_1^s &= \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go}k_1^{go2} - \underline{p}^{go}(a_1^{go} + a_2^{go})}{(a_1^s + T)} \\ &= \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go}\alpha_1(a_1^s - T) - \underline{p}^{go}(a_1^{go} + a_2^{go})}{(a_1^s + T)}\end{aligned} \tag{22}$$

By taking the derivative of $\underline{p}_1^s$ with respect to $(a_1^{go} + a_2^{go})$ in equation (22), we obtain that:[29]

$$\frac{\partial \underline{p}_1^s}{\partial(a_1^{go} + a_2^{go})} = -\frac{\underline{p}^{go}}{a_1^s + T} < 0 \tag{23}$$

However, when the demand in the GO market is sufficiently high, that is, $\alpha_i(a_i^s - T) < \alpha_i(a_i^s + T) < a_1^{go} + a_2^{go}$ (and given that $\alpha_1 = \alpha_2 = \alpha$), equation (21) becomes:

$$\begin{aligned}\underline{p}_1^s &= \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go}k_1^{go2} - \underline{p}^{go}k_1^{go1}}{(a_1^s + T)} \\ &= \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go}\alpha_1(a_1^s - T) - \underline{p}^{go}\alpha_1(a_1^s + T)}{(a_1^s + T)}\end{aligned} \tag{24}$$

which does not depend on a_1^{go} or a_2^{go}. In other words, a change in the demand for GOs does not affect the lower bound of the support in the spot market when the demand in the GO market is sufficiently high.

The CDF also depends on the realization of the demand in the GO market. However, as with the lower bound of the support, when the demand for GOs is sufficiently high, the production capacity is binding, in which case the CDF becomes independent of the demand in the GO market. Therefore, we focus our attention on the case where demand in the GO market is sufficiently low. We prove that $\hat{F}^s \geq F^s \ \forall \ p^s \in [\underline{p}^s, \overline{P}^s]$, where $\hat{F}^s$ is the CDF when demand in the GO market is given by $\hat{a}_1^{go} + \hat{a}_2^{go}$.

[29]Note that we can take the derivative of $\underline{p}_1^s$ with respect to either a_1^{go} or a_2^{go}, and we would obtain a similar result.

From equation (19), we know that,

$$\begin{aligned}
F_2^s(p^s) &= \frac{(p^s - \underline{p}^s)(a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)] + \underline{p}^{go}(a_1^{go} + a_2^{go}) - \underline{p}^{go}\alpha_1(a_1^s - T)} \\
&= \frac{[p^s(a_1^s + T) - \overline{P}^s(a_1^s - T) - \underline{p}^{go}\alpha_1(a_1^s - T) + \underline{p}^{go}(a_1^{go} + a_2^{go})](a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)] + \underline{p}^{go}(a_1^{go} + a_2^{go}) - \underline{p}^{go}\alpha_1(a_1^s - T)} = \frac{(A + C)(a_1^s + T)}{B + C} \\
\hat{F}_2^s(p^s) &= \frac{(p^s - \underline{p}^s)(a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)] + \underline{p}^{go}(\hat{a}_1^{go} + \hat{a}_2^{go}) - \underline{p}^{go}\alpha_1(a_1^s - T)} \\
&= \frac{[p^s(a_1^s + T) - \overline{P}^s(a_1^s - T) - \underline{p}^{go}\alpha_1(a_1^s - T) + \underline{p}^{go}(\hat{a}_1^{go} + \hat{a}_2^{go})](a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)] + \underline{p}^{go}(\hat{a}_1^{go} + \hat{a}_2^{go}) - \underline{p}^{go}\alpha_1(a_1^s - T)} = \frac{(A + \hat{C})(a_1^s + T)}{B + \hat{C}}
\end{aligned} \tag{25}$$

where $A = \left[p^s(a_1^s + T) - \overline{P}^s(a_1^s - T)\right]$, $B = p^s\left[(a_1^s + T) - (a_1^s - T)\right]$, $C = \underline{p}^{go}(a_1^{go} + a_2^{go}) - \underline{p}^{go}\alpha_1(a_1^s - T)$, and $\hat{C} = \underline{p}^{go}(\hat{a}_1^{go} + \hat{a}_2^{go}) - \underline{p}^{go}\alpha_1(a_1^s - T)$. It is important to note that $A \leq B \ \forall \ p^s \in [\underline{p}^s, \overline{P}^s]$, and that $A = B$ when $p^s = \overline{P}^s$. It is also important to note that when demand in the GO market is sufficiently low, $a_1^{go} + a_2^{go} > \alpha_1(a_1^s - T)$ and $\hat{a}_1^{go} + \hat{a}_2^{go} > \alpha_1(a_1^s - T)$, in which case $C > 0$ and $\hat{C} > 0$.

Second, by using equation (25), it is easy to prove that $\hat{F}^s \geq F^s \ \forall \ p^s \in [\underline{p}^s, \overline{P}^s]$:

$$\begin{aligned}
\hat{F}_2^s(p^s) \geq F_2^s(p^s) \quad &\Leftrightarrow \quad \frac{A + \hat{C}}{B + \hat{C}} \geq \frac{A + C}{B + C} \Leftrightarrow \frac{(B - \epsilon) + (C + \delta)}{B + (C + \delta)} \geq \frac{(B - \epsilon) + C}{B + C} \\
&\Leftrightarrow \quad [(B - \epsilon) + (C + \delta)]\,(B + C) \geq [(B - \epsilon) + C]\,[B + (C + \delta)] \\
&\Leftrightarrow \quad (B - \epsilon)B + (B - \epsilon)C + (C + \delta)B + (C + \delta)C \geq \\
&\qquad\ (B - \epsilon)B + (B - \epsilon)(C + \delta) + BC + C(C + \delta) \\
&\Leftrightarrow \quad (B - \epsilon)C + BC + \delta B \geq (B - \epsilon)C + (B - \epsilon)\delta + BC \\
&\Leftrightarrow \quad \delta B \geq \delta B - \epsilon\delta \Leftrightarrow 0 \geq -\epsilon\delta
\end{aligned} \tag{26}$$

where $\epsilon = B - A$ and $\delta = \hat{C} - C$ are positive constants. The inequality in (26) holds as both $\epsilon > 0$ and $\delta > 0$. Recall that $\hat{F}_2^s(\overline{P}^s) = F_2^s(\overline{P}^s) = 1$. $\square$

Proposition 6. We prove the effect of a change in the green production capacity of the suppliers on the equilibrium prices in the spot market. Specifically, we compare the lower bound of the support ($\underline{p}^s$) and the CDFs (F^s) in the spot market when there is a decrease in the share of the dispatches in the spot market that qualifies for a GO, that is, $\hat{\alpha} < \alpha = 1$. In Proposition 5, we proved that when the demand in the GO market was sufficiently high, an increase in the demand for GOs does not affect the equilibrium in the spot market. Therefore, in Proposition 6, we focus our attention on the case where the demand in the GO market is sufficiently low, that is, $\alpha(a^s - T) < a_1^{go} + a_2^{go} < \alpha(a^s + T)$.

First, we prove that $\hat{\underline{p}}^s \leq \underline{p}^s$, where $\hat{\underline{p}}^s$ is the lower bound of the support when the green production capacity of the suppliers is given by $\hat{\alpha} < 1$. By using Lemma 3, we know that,

$$\begin{aligned}
\underline{p}_1^s &= \frac{\overline{P}^s(a^s - T) + \dfrac{\overline{P}^{go}(a_1^{go} + a_2^{go} - \alpha(a^s - T))}{a_1^{go} + a_2^{go}}\alpha(a^s - T) - \dfrac{\overline{P}^{go}(a_1^{go} + a_2^{go} - \alpha(a^s - T))}{a_1^{go} + a_2^{go}}(a_1^{go} + a_2^{go})}{a^s + T} \\
&= \frac{\overline{P}^s(a^s - T) + \dfrac{\overline{P}^{go}(a_1^{go} + a_2^{go} - \alpha(a^s - T))}{a_1^{go} + a_2^{go}}\left[\alpha(a^s - T) - (a_1^{go} + a_2^{go})\right]}{a^s + T} \qquad (27)
\end{aligned}$$

By using equation (27), we take the derivative of $\underline{p}_1^s$ with respect to α:

$$\begin{aligned}
\frac{\partial \underline{p}_1^s}{\partial \alpha} &= -\frac{\overline{P}^{go}(a^s - T)}{a_1^{go} + a_2^{go}}\left[\alpha(a^s - T) - (a_1^{go} + a_2^{go})\right] + \frac{\overline{P}^{go}(a_1^{go} + a_2^{go} - \alpha(a^s - T))}{a_1^{go} + a_2^{go}}(a^s - T) \\
&= -\overline{P}^{go}(a^s - T)\alpha(a^s - T) + \overline{P}^{go}(a^s - T)(a_1^{go} + a_2^{go}) + \overline{P}^{go}(a_1^{go} + a_2^{go})(a^s - T) - \overline{P}^{go}\alpha(a^s - T)(a^s - T) \\
&= \overline{P}^{go}(a^s - T)\left[2(a_1^{go} + a_2^{go}) - 2\alpha(a^s - T)\right] > 0 \qquad (28)
\end{aligned}$$

where the result in (28) is valid because the demand in the GO market is sufficiently low, in which case $(a_1^{go} + a_2^{go}) > \alpha(a^s - T)\ \forall\ \alpha \in [0, 1]$.

Second, we prove that $\hat{F}^s \geq F^s\ \forall\ p^s \in [\underline{p}^s, \overline{P}^s]$, where $\hat{F}^s$ is the CDF when the green production capacity of the suppliers is given by $\hat{\alpha} < 1$. From equation (19), we know that,

$$\begin{aligned}
F_2^s(p^s) &= \frac{[p^s(a^s + T) - \overline{P}^s(a^s - T) - \alpha \underline{p}^{go}(\alpha)(a^s - T) + \underline{p}^{go}(\alpha)(a_1^{go} + a_2^{go})](a^s + T)}{p^s[(a^s + T) - (a^s - T)] + \underline{p}^{go}(\alpha)(a_1^{go} + a_2^{go}) - \alpha \underline{p}^{go}(\alpha)(a^s - T)} = \\
&= \frac{(A + C)(a^s + T)}{B + C} \qquad (29)
\end{aligned}$$

where $A = \left[p^s(a^s+T) - \overline{P}^s(a^s-T)\right]$, $B = p^s\left[(a^s+T)-(a^s-T)\right]$ and

$$\begin{aligned} C &= \underline{p}^{go}\left[(a_1^{go}+a_2^{go}) - \alpha(a^s-T)\right] \\ &= \frac{\overline{P}^{go}(a_1^{go}+a_2^{go}) - \alpha(a^s-T)}{a_1^{go}+a_2^{go}}\left[(a_1^{go}+a_2^{go}) - \alpha(a^s-T)\right] \\ &= \frac{\overline{P}^{go}}{a_1^{go}+a_2^{go}}\left[(a_1^{go}+a_2^{go})^2 + \alpha^2(a^s-T)^2 - 2\alpha(a_1^{go}+a_2^{go})(a^s-T)\right] \end{aligned} \tag{30}$$

Note that $A \le B \; \forall \; p^s \in [\underline{p}^s, \overline{P}^s]$, and $A = B$ when $p^s = \overline{P}^s$. It is also important to note that the lower bound of the support in the GO market ($\underline{p}^{go}$) is a function of the green production capacity (α). By using equation (30), we take the derivative of C with respect to α,

$$\begin{aligned} \frac{\partial C}{\partial \alpha} &= 2\alpha(a^s-T)^2 - 2(a^s-T)(a_1^{go}+a_2^{go}) \\ &= 2\alpha(a^s-T)\left[(a^s-T)-(a_1^{go}+a_2^{go})\right] < 0 \end{aligned} \tag{31}$$

which is negative because demand in the GO market is sufficiently low.

However, to prove that $\hat{F}^s \ge F^s \; \forall \; p^s \in [\underline{p}^s, \overline{P}^s]$, we have to prove that,

$$\frac{(A+C)(a^s+T)}{B+C} \le \frac{(A+\hat{C})(a^s+T)}{B+\hat{C}} \tag{32}$$

where $\hat{C} = \frac{\overline{P}^{go}}{a_1^{go}+a_2^{go}}\left[(a_1^{go}+a_2^{go})^2 + \hat{\alpha}^2(a^s-T)^2 - 2\hat{\alpha}(a_1^{go}+a_2^{go})(a^s-T)\right]$. From (31), we know that $\hat{C} > C$ when $\hat{\alpha} < \alpha$. Therefore,

$$\begin{aligned} \frac{(A+C)(a^s+T)}{B+C} \le \frac{(A+\hat{C})(a^s+T)}{B+\hat{C}} \quad &\Leftrightarrow \quad \frac{((B-\epsilon)+C)}{B+C} \le \frac{((B-\epsilon)+(C+\delta))}{B+(C+\delta)} \\ &\Leftrightarrow \quad (B-\epsilon)B + (B-\epsilon)(C+\delta) + BC + C(C+\delta) < \\ &\qquad (B-\epsilon)B + (B-\epsilon)C + (C+\delta)B + (C+\delta)C \\ &\Leftrightarrow \quad (B-\epsilon)C + (B-\epsilon)\delta + BC < (B-\epsilon)C + (C+\delta)B \\ &\Leftrightarrow \quad (C+\delta)B - \epsilon\delta < (C+\delta)B \Leftrightarrow -\epsilon\delta < 0 \end{aligned} \tag{33}$$

where $\epsilon = B - A$ and $\delta = \hat{C} - C$ are positive constants. The inequality in (33) holds as both $\epsilon > 0$ and $\delta > 0$. Recall that $\hat{F}_2^s(\overline{P}^s) = F_2^s(\overline{P}^s) = 1$. $\square$

Proposition 7. We prove that $\underline{p}^s = \underline{p}^b$ and $F^s = F^b \;\forall\; p^s = p^b \in [\underline{p}^s, \overline{P}^s]$ when the transmission constraint is taken into account when working out the equilibrium in the GO market. This implies that when the sale of GOs is restricted by the capacity of the transmission line, the introduction of a sequential GO market no longer has an effect on equilibrium spot prices. Recall that to isolate the impact of introducing the transmission line in the GO market, we assume that the transmission capacity becomes binding once introduced, that is, $min\{a_1^{go} + a_2^{go}, a_i^{go} + T, k_i^{go}(p^s)\} = a_i^{go} + T$ and $max\{0, a_i^{go} - T, a_1^{go} + a_2^{go} - k_j^{go}(p^s)\} = a_i^{go} - T$. Also, note that we keep subscripts, although we still assume symmetric demand in the spot market and in green production capacities.

We start by proving that $\underline{p}^s = \underline{p}^b$ when the transmission capacity constraint is introduced in the GO market. We proceed in two steps. First, we prove that $\underline{p}^{go1} = \underline{p}^{go2}$. By Lemma 2, we know that:

$$\begin{aligned} \underline{p}^{go1} &= max\left\{\frac{\overline{P}^{go}(a_1^{go} - T)}{a_1^{go} + T}, \frac{\overline{P}^{go}(a_2^{go} - T)}{a_2^{go} + T}\right\} \\ \underline{p}^{go2} &= max\left\{\frac{\overline{P}^{go}(a_1^{go} - T)}{a_1^{go} + T}, \frac{\overline{P}^{go}(a_2^{go} - T)}{a_2^{go} + T}\right\} \end{aligned} \tag{34}$$

It is important to note that in equation (34), the lower bound of the support is determined exclusively by the transmission constraint. This contrasts with equation (16), where the lower bound is determined exclusively by the green production constraint. In that sense, the assumptions introduced to prove Proposition 7 are crucial, as they allow us to isolate the impact of the market design on the determination of the lower bound of the support. Given these assumptions, it is easy to see that $\underline{p}^{go1} = \underline{p}^{go2} = \underline{p}^{go}$.

Second, using the previous result, we show that $\underline{p}^s = \underline{p}^b$. From Lemma 3, we know that,

$$\begin{aligned} \underline{p}^s &= max\left\{\underline{p}_1^s, \underline{p}_2^s\right\} \qquad (35) \\ &= max\left\{\frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go}(a_1^{go} + T) - \underline{p}^{go}(a_1^{go} + T)}{a_1^s + T}, \frac{\overline{P}^s(a_2^s - T) + \underline{p}^{go}(a_2^s + T) - \underline{p}^{go}(a_2^{go} + T)}{a_2^s + T}\right\} \end{aligned}$$

Given that $a_1^s = a_2^s$ and $\underline{p}_1^s = \underline{p}_2^s$, we obtain that,

$$\underline{p}^s = \underline{p}^b \quad \Leftrightarrow \quad \frac{\overline{P}^s(a_1^s - T) + \underline{p}^{go}(a_1^{go} + T) - \underline{p}^{go}(a_1^{go} + T)}{a_1^s + T} = \frac{\overline{P}^s(a_1^s - T)}{a_1^s + T} \tag{36}$$

We proceed to prove that $F^s = F^b \; \forall \; p^s = p^b \in [\underline{p}^s, \overline{P}^s]$. As before, we focus on supplier 2 as the proof for supplier 1 follows the same steps. First, we define F_2^s and F_2^b:

$$\begin{aligned} F_2^b(p^s) &= \frac{(p^s - \underline{p}^b)(a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)]} \\ F_2^s(p^s) &= \frac{(p^s - \underline{p}^s)(a_1^s + T)}{p^s[(a_1^s + T) - (a_1^s - T)] + \underline{p}^{go}(a_1^{go} + T) - \underline{p}^{go}(a_1^{go} + T)} \end{aligned} \tag{37}$$

Second, it is easy to see that $F_2^s = F_2^b \; \forall \; p^s \in [\underline{p}^s, \overline{P}^s]$ in equation (37). $\square$

B Additional figures and tables

Table B1: Transactions of GOs by country, 2022.

	Issue	**Export**	**Import**	**Expire**	**Cancel**	**Net export**
Austria	53,8	16,7	28,3	6,8	54,9	-11,6
Belgium	14,8	35,3	45	1,4	20,6	-9,7
Switzerland	59,7	3	15,2	8,8	60,2	-12,2
Cyprus	0,3	0	0	0,3	0	0
Czech Republic	6,4	4,1	2,7	0,1	4,2	1,3
Germany	24,9	22,9	161,9	2,4	142,1	-139
Denmark	26,2	37,3	27,2	0,8	14,3	10,2
Estonia	2,6	5,4	3,7	0,2	1,1	1,7
Spain	33,6	32,2	28,9	0,4	20,4	3,3
Finland	47,7	32,5	26	0,2	31,1	6,5
France	91,9	73,2	46,7	1,6	68,1	26,5
Croatia	6,5	5	0,3	0	3,9	4,8
Hungary	2,5	2,9	2,7	0	1,6	0,1
Ireland	1,9	0,9	18,9	0	20,2	-18,1
Iceland	20,3	16,5	0,8	0	4,7	15,7
Italy	94,4	54,6	41,4	0,9	70,9	13,2
Lithuania	0,9	0,4	0,5	0	0,8	-0,1
Luxembourg	0,7	0,9	3	0,1	3,3	-2,1
Latvia	3,9	3,7	0,4	0	0,7	3,3
Netherlands	91,5	27,3	52,6	35,6	105,5	-25,3
Norway	142,1	386,5	299,8	4	67,8	86,7
Portugal	26,2	29,8	7,5	1,3	14,5	22,3
Serbia	1,5	0	0	0	1,5	0
Sweden	94,7	75,2	54	2,4	71,4	21,2
Slovenia	9,5	3,9	2,9	0	2	0,9
Slovakia	3,5	1	1	0,3	5,1	0,1

Notes: Own calculation based on AIB statistics: https://www.aib-net.org/facts/market-information/statistics. Note that the summary statistics are in TWh and are based on the transaction date (and not the production date) of the GOs.

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