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Auctions to reveal consumers' willingness-to-pay for low-carbon hydrogen projects: combining lessons from renewables and natural gas industries

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Abstract

Low-carbon hydrogen is expected to play a key role in realizing net-zero and sustainable development plans. Nonetheless, there is a gap between the cost of producing low-carbon hydrogen and its potential users' willingness to pay for such hydrogen. In order to implement support for the industry's development, we propose using low-carbon hydrogen long-term agreements allocated through auction mechanisms. These are contracts between producers and consumers that specify the production price, and the price consumers are willing to pay (the reference price). The reference price is indexed to liquid international indexes of natural gas, the main product that low-carbon hydrogen aims to substitute with an international market price. Thus, the reference price is set by the natural gas index plus a premium, representing the extra price consumers are willing to pay for low-carbon fuels. The gap between the two prices is covered through public policy funds. The premium and the production cost are defined through a double-sided auction. This aims to minimize the public policy funds required to incentivize the low-carbon hydrogen market, while facilitating long-term agreements and mitigating price risks that may hinder investment.

Key words: Hydrogen, Auctions, RES support mechanisms, Natural gas.

1. Introduction

Low-carbon hydrogen is expected to be key in realizing net-zero and sustainable development plans, decarbonizing the industry and the energy sector. This paper uses low carbon hydrogen following the discussion in (IEA, 2023a), which is associated with low emissions in hydrogen production. It does not define any technology but excludes the traditional production from unabated fossil fuels. Although this interpretation, within the scope of this paper, is broad, the suggested methodology could be adaptable to any subset within the low-carbon hydrogen spectrum (such as renewable hydrogen) under the condition that it is clearly defined and certified (Vazquez and Hallack, 2022).

However, currently, there is a gap between the cost of producing low-carbon hydrogen and the willingness to pay for such hydrogen among its potential users (potential hydrogen users). We may classify potential users of low-carbon hydrogen under two broad headers. On the one hand, it is possible to identify those already consuming hydrogen produced by Steam Methane Reforming (SMR). This kind of demand is largely associated with industrial applications, especially related to chemicals and refining (IEA, 2022). The current hydrogen production to satisfy this demand uses natural gas as input. According to (IRENA, 2022), at the end of 2021, 47% of the global hydrogen production is from natural gas. In the United States, it was estimated at 95%, (EERE, 2023).

The second group of users is made up of those who currently use other forms of fuels that could be substituted by hydrogen as an energy carrier, such as the energy provider to hard-to-abate sectors, e.g. industry, transport, buildings, and electricity sectors, (IEA, 2022). While the role of hydrogen in each potential demand is still dubious, energy uses for steel, shipping, and jet aviation are considered promising areas, (Liebreich, 2023). Overall, even if the traditional uses of hydrogen drove the demand increase in the last years (IEA, 2022), the new demand is expected to led the growth in the following decades, especially in transport, industry, and power generation (IEA, 2023b). Considering 2030 and 2035, industry will lead to the potential to decarbonize hydrogen, both considering the traditional and the new uses as energy vectors.

In any case, regardless of the announced low-carbon hydrogen projects, and the major expected role roles of low-carbon hydrogen in decarbonization, few projects are achieving the final investment decision (Hydrogen Council, 2023). Besides the extra cost associated with low-carbon technologies with respect to traditional ones, high transaction costs (including those associated with the lack of contract standardization that comes with an organized market) may be slowing the industry's development. In this context, the absence of an offtake agreement hampers the financial structuring of the project, which delays achieving the final decision phase. This means less investment, lower scale, and thus further delays in the industry development.

This is a typical situation when an industry with significant economies of scale is immature. Low-carbon hydrogen development may be compared to renewable energy industries, e.g. solar and wind electricity generation. Support mechanisms were deemed necessary to scale up the technology, facilitating their cost drop. Currently, in many markets, they are competitive technologies. Support mechanisms involved in practice either the use of some kind of subsidies to cover the cost gap, or the obligation of regulated, captive, electricity consumers to pay for this gap. The lessons learned from the renewable electricity generation mechanism can be valuable in designing the low-carbon hydrogen mechanism.

Furthermore, although a comparison can be made to renewable energy projects, low-carbon hydrogen projects share several characteristics with natural gas industries. It is not unusual to call them "molecules" with the aim of generalizing. From this paper's point of view, this idea is relevant because hydrogen may be considered as a potential low-carbon substitute of natural gas. Hence, the design of support mechanisms is critically affected by the relationship between natural gas and hydrogen.

The interplay between natural gas and low-carbon hydrogen has several dimensions. First, they compete both considering that natural gas is the main producer of hydrogen through SMR (which may be categorized as grey hydrogen) and also regarding the future potential market for low hydrogen as in the industry and power sectors (as a source of balancing services for grids). For instance, natural gas was the source of about 41% of the United States industrial sector's end-use energy consumption, (EIA, 2022). Natural gas can also be complementary to low-carbon hydrogen if the solution of CCS (Carbon Capture and Storage), often called blue hydrogen, is considered. Recently, in the context of the energy crisis in 2022, EU natural gas prices peaked and resulted in cheaper production costs for ammonia produced with green hydrogen (without any subsidy) than with natural gas, (Hydrogen Central, 2022) in some regions in the European Union. That was not the case in China, the US, or UAE, where natural gas prices were lower.

Continuing with the analogue of power systems, support is frequently channeled through a contract for differences. Broadly, subsidies just cover the gap between short-term prices and a reference price when they exist. This mechanism implies that, when prices are higher than the reference, no extra support is necessary. At the same time, it guarantees the minimum price that the supplier will receive for renewable generation, (May et al., 2018), (Kozlov, 2014) or (Welisch and Poudineh, 2020).

In the context of low carbon hydrogen, we propose a combination of the idea of using a contract for difference to allocate support and the netback pricing logic applied in gas markets development when they are illiquid. Netback prices were used in gas long-term contracts to allocate part of the price risk faced by oil users, potentially willing to switch to natural gas, to suppliers. The aim was to facilitate the development of gas industry when markets lacked liquidity. As low-carbon hydrogen aims to be a substitute for natural gas, we propose to use natural gas prices as the reference for the long-term contract. However, differently of natural gas industry, the energy transition to achieve the climate change goals, as observed in the development of renewables markets, requires long-term commitments that allow suppliers cover for their costs. This is turn is central to scale up the technology and to reduce costs so that projects become competitive.

The incentives for investment associated with this kind of contract are associated both with guarantee of demand and price hedge. In this solution, future price variation risks are covered by a support mechanism, so gas price peaks may result in a situation where low or no extra support is required.

In order to complete the reasoning, it is necessary to define a mechanism to select the most efficient projects to be subsidized. We propose that the previous contracts are allocated according to the results of an auction. There is considerable experience in the use of auctions to allocate support for new technologies in power systems. These instruments have enabled governments to procure renewable electricity for the least cost, reducing expenditure on support, improving control of the budget allocation, and reveling the information about which are the most efficient projects and what are the minimum support levels that are necessary to promote investment, see for instance (Kruger and Eberhard, 2023), (Fleck and Anatolitis, 2023), (Jansen et al., 2022) or (del Río and Linares, 2014). We apply this approach to the allocation of low-carbon hydrogen agreements. Although auctions alone may not be enough to reduce the cost of capital, (Breitschopf and Alexander-Haw, 2022), they play an important role in support allocation, especially in developing countries concerned with tight budget constraints, (IRENA, 2015).

This paper focuses on proposing an auction mechanism to promote investment in low-carbon hydrogen inspired by renewables lessons and traditional gas pricing. The mechanism considers the specificities of low-carbon hydrogen demand, which does not rely on captive consumers but on industrial users with heterogenous profiles and competitive markets. Second section gives a general overview of the logic behind supporting instruments to promote low-carbon hydrogen. Third section focuses on the main support mechanisms based on auctions in the international experience. Fourth section discusses design of an off-take agreement, including the logic and justification for the low-carbon hydrogen agreement, based on the natural gas market. The auction design to allocate such agreements is discussed in section five. Sixth section analyses the relation between consumers' payments and product definition in this kind of design. The last section focuses on discussing the main results of our proposal, limits, and needs of further research.

2. Review of the proposed mechanism to allocate subsidies for low-carbon hydrogen

The rationale behind this overview is to place auction mechanisms to facilitate the development of low-carbon hydrogen projects into context. We may consider an infrastructure project, in general, to be made up of three phases according to the potential income flow associated with them: i) the "project design phase", where relatively little investment is required, but it is considerably risky, ii) "construction phase", where most of the investment is expended and little to no income flow is received; and iii) the "operation phase", where the majority of income is received and less investment is typically required.

In this context, we focus on risk allocation mechanisms that are termed revenue-enhancement instruments in (Vazquez et al., 2018). This differentiation intends to highlight that we only deal with measures that reduce risks involved in the transactions between producers and off-takers. A particular instrument that is becoming popular in the EU is the public hedging of the risk associated with the price received by low-carbon hydrogen undertakings. Next section reviews several proposals that are either already implemented or soon-to-be implemented.

In that context, it is difficult to assess the value that off-takers give to the fact that the hydrogen consumed is labelled low-carbon hydrogen. One possible approach is for public administrations to act in the name of off-takers and select the level of hedge against off-take risk that project developers will receive from public funds. This would imply pursuing a similar strategy to the implementation of long-term contracts with public hedges (see PPAs in Brazil). Even a more direct approach is based on the idea of establishing minimum levels of investment for the product, and then use subsidies to guarantee the undertaking of the required projects (such as US IRA approach).

Alternatively, it is possible to index the price of the long-term contracts to a reference price that defines the level of hedge that the contracts offer. A typical example is to use the fossil-fuel hydrogen price as a reference. That is, to design a contract that hedges off-takers against prices above the fossil-fuel hydrogen. The logic for this is the intention to establish incentives to use low-carbon hydrogen instead of fossil-fuel hydrogen.
From the public administration point of view, this second alternative (price indexation) may be understood as a tool to estimate the value of low-carbon characteristics as the difference between low-carbon production price and fossil-fuel hydrogen cost. Many proposals in the EU travel down that path. Nevertheless, the lack of an international hydrogen price is a challenge.

We are concerned with mechanisms hinged on price discovery. To that end, several EU experiences are relevant to the mechanism proposed in this paper.

2.1 Portugal

Portugal is an example of hydrogen auctions where the product is hydrogen mixed with natural gas transported through national pipelines. It is a single-buyer model, in which GALP Energia buys 120 GWh/year renewable hydrogen for a fixed price (the cap is fixed at 127 EU/MWh through a 10-year duration contract, (SEAE, 2023). The company is responsible for reselling to consumers. According to (Reuters, 2023), a budget of 6 billion dollars has reached the final investment decision.

The logic for this strategy Is to provide a firm off-taker for blended hydrogen. The initial target composition, tested by the gas distribution company Floene, is 2% hydrogen, which is intended to serve industrial and residential consumers in the Seixal region. Plans include increasing the percentage of hydrogen in the future. In this model, all the captive natural gas consumers using the regulated asset become hydrogen users. It follows the same logic behind of renewables policy in the electricity sector based on captive consumers and cost-sharing through regulated tariffs.

2.2 Germany

The German government launched the H2 Global initiative in 2022, (H2Global, 2022). Its basic idea is to implement a mechanism to cover the cost gap between, low-carbon hydrogen production while purchasing low-carbon ("renewable") hydrogen globally at the lowest cost, and then selling it to the EU users that value the low-carbon hydrogen the most.

Using an intermediary, the mechanism builds on long-term agreements with low-carbon hydrogen producers, including hydrogen derivatives such as ammonia, methanol, etc. Such long-term agreements consist of 10-year off-take commitments. The off-taker can be the final user directly (competing in its own market) or it can sell to final users. In the second case, low-carbon hydrogen consumers commit to 1-year supply contracts with typically large final user. Even if the price of low-carbon hydrogen is fixed in this scheme, consumers have still a price risk related to reselling it or to compete in the final market.

The idea is that this transaction would not be economically viable alone, so the government decided to complement the transaction with a subsidy (the initial budget was 900 million euro). This subsidy consists of bridging the difference between offer and demand-cleared bids. Participation rules in the auction are defined by the obligation for the low-carbon hydrogen producers to sell their production to EU auction participants. Besides, in general, each auction will have specific conditions associated with participation:

- The products to be promoted, e.g. hydrogen, ammonia, methanol...
- The geographical definition of the funding considered.
- Product requirements and criteria.

It is expected that the gap between production and demand prices will decrease over the duration of the long-term production contract, thus reducing the need for subsidies. However, when the contract is done this gap is fixed through the contract duration.

2.3 The European Commission

The European Commission has scheduled its first low-carbon auction for November 2023. It will be funded by the Innovation Fund (under the EU Hydrogen Bank). The budget for this auction is 800 million euros for low-carbon ("renewable") hydrogen projects. The logic for this auction is similar to the German one: de-risking projects, hydrogen price discovery, reducing the cost gap between renewable and fossil hydrogen, besides reducing administrative costs. Contracts, as in the other case, will have a 10-year duration.

Different from the German model, participation in this first auction is restricted to projects in the European Economic Area. Moreover, the subsidy will be allocated as a fixed payment based on the difference between supply and demand prices. In that view, the German solution might be seen as a feed-in premium, whereas the EU option might be considered as a kind of "feed-in tariff".

2.4 United Kingdom

The UK strategy builds on the HAR auctions, (Martin, 2023) and . The first one was implemented in 2022, resulting in 20 projects with 408MW. This first round also allowed for up to 20% of the project's financing from the government's 300-million-dollar Net Zero Hydrogen Fund. For the second auction, the government announced that this additional source of funding would not be available, (Collins, 2023).

The mechanism awards contracts for difference. This might be defined as a variable premium over the price paid by the demand side of the auction. The subsidy is then calculated as the difference between a strike price defined by the cost of producing low-carbon hydrogen, and the market price for grey hydrogen, which is, in turn, supposed to be associated with gas prices. So, if the price of grey hydrogen (which is related to the natural gas price) goes down, the subsidy would fall accordingly, with the opposite being true if the price rises. The price of grey hydrogen, however, is local. There is no international grey hydrogen reference price.

2.5 Summary of the main characteristics of EU proposals

The proposals based on price discovery typically hinge on the use of auctions, and they typically use double-side auctions. Portugal represents an exception in that it does not use subsidies because the mechanism consists of selling hydrogen blended with natural gas to captivated customers. Hence, it might be viewed as a single-buyer auction, being GALP, together with Floene, responsible for defining the demand. Moreover, most proposals are intended to incentivize the substitution of fossil-fuel hydrogen by using its price as a reference to the need for subsidization of low-carbon hydrogen, given the production cost. Of the three mechanisms, the UK is the most complex, focusing on substituting grey hydrogen for low-carbon technology. However, the use of grey hydrogen can be a limit for using for international contracts, as seen in the lack of an international grey hydrogen market, and also because it limits, to some extent, the direct demand for clean hydrogen to those already using hydrogen.

3. Contracts for low-carbon hydrogen based on natural gas substitution

The logic for our proposal builds on the same idea discussed in the examples above: low-carbon hydrogen will benefit from a revenue-enhancing mechanism. The rationale for the mechanisms can be motivated by the fact that there is an interest in commercializing low-carbon hydrogen, but there is not a market for it yet. It means the willingness of the demand to pay for such a product is unknown.

3.1 Pricing

Therefore, two main options are available. The first approach is setting the low-carbon hydrogen price based on its production cost. The challenge with this approach is that it is not easy to define such cost because of the heterogeneity of input costs (such as electricity prices); even less easy when we consider the long horizons for the contract. Moreover, defining the clean hydrogen cost does not inform the willingness of demand to pay for it, especially for the clean attribute of low-carbon hydrogen. It is also well known that carbon prices, at this point, are not enough to define the willingness to pay for the clan attribute of hydrogen.

The second approach, the one chosen in this paper, is setting the price to something similar to a "market value". Theoretically, the market value would be the one associated with the substitute product for low-carbon hydrogen. The rationale behind the approach would be close to the one used for netback pricing in gas industries, see for instance (Melling, 2010). Note that this is implicitly following the same logic of the approach adopted in the UK, considering that the substitute product is fossil-fuel hydrogen.

In this context, the approach based on indexation to fossil-fuel hydrogen faces the difficulties of:

- It implies the substitution of fossil-fuel hydrogen, not other kinds of fossil fuels (e.g. natural gas).
- Fossil-fuel hydrogen does not have a global, liquid market that results in a price that may serve as an efficient index for the mechanism proposed. It can be practical for the local market in which gray hydrogen has a transparent price but cannot be applied for international contracts.

From this point of view, this paper proposes the idea that a product that acts as a substitute for low-carbon hydrogen is natural gas. With it, two direct advantages are enjoyed. The first one is the incentive to the use of low-carbon hydrogen instead of traditional fuels. The second one is to benefit from the existence of more efficient pricing mechanisms for natural gas, which in turn allows a more efficient indexation of the product.

Finally, the fact that we consider indexation to natural gas has an impact on security of supply planning for EU industries. High natural gas prices make investment in low-carbon energy more attractive, however, the uncertainty about the future of natural gas prices prevents investment in the moment it is mostly necessary and potentially more economically efficient. The points of high natural gas prices would reduce the volume of public funds that are required to scale up the low-carbon hydrogen industry.

Consequently, the auction proposed in this paper, which will be described in detail in the following sections, follows the same lines of the one proposed in the UK, if the reference is the natural gas price instead of the price for fossil-fuel hydrogen.

In this context, we consider a product that represents this interaction among three types of agents: producers, consumers, and institutional investors willing to subsidize low-carbon hydrogen to scale up its production as part of an energy transition policy (typically consisting of public funds). We also consider that consumers will have a maximum price that they are willing to pay for low-carbon hydrogen. It is defined by the fact that if low-carbon hydrogen is more expensive than the alternative (plus a green premium that consumers are willing to pay), consumers will switch.

Thus, the product assumes that, for most low-carbon potential consumers, the alternative available is natural gas. In that context, we may represent the marginal willingness-to-pay of the demand curve as a function of contract duration. That is, each period of the contract corresponds to a demand-side willingness-to-pay. This is represented in Figure 1 by the gray curve.

Additionally, we consider that the production of hydrogen can be represented by the long-term marginal cost of projects. Analogously, we may represent that each period of the contract corresponds to a supply-side marginal cost. This curve is depicted by the black curve in Figure 1.

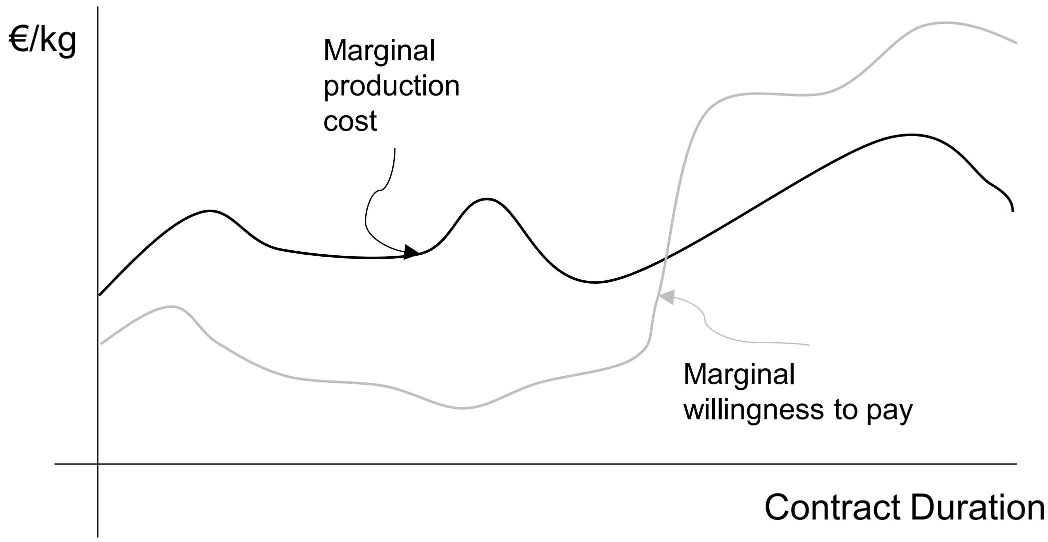

Figure 1. Supply and demand curves of the low-carbon hydrogen market.

In order to apply the "market value" approach described above, the marginal willingness-to-pay must be equal to the natural gas price plus a green premium, as represented in Figure 2. If consumers are indifferent to the origin of the fuel they purchase, the premium will be zero. In that case, the buyers' curve will choose natural gas when it is cheaper than hydrogen.

The green premium may vary depending on the industry considered. For instance, automobile carmakers may value green steel for than green fertilizers. Moreover, the value depends on how the industry see the expected evolution of green premia, considering consumers' preferences and policy restrictions. Industrial players will likely know more than policy makers regarding the low carbon premium in their markets, and their willingness to pay in order to move first, considering their strategy in low carbon markets. As low-carbon products will be often competing with the traditional products[1]. The auction is proposed as a mechanism where users define the low carbon premium. Hence, this definition involves a risk borne by users, and it represents a strategic decision variable in the bidding process. The premium will be also impacted by the expected cost of carbon (or other policy restrictions that create premium markets).

In this transaction, the remaining party to be represented is the public administration. In the product defined in this section, the criterion to allocate low-carbon hydrogen subsidies will be to cover for the difference between both curves.

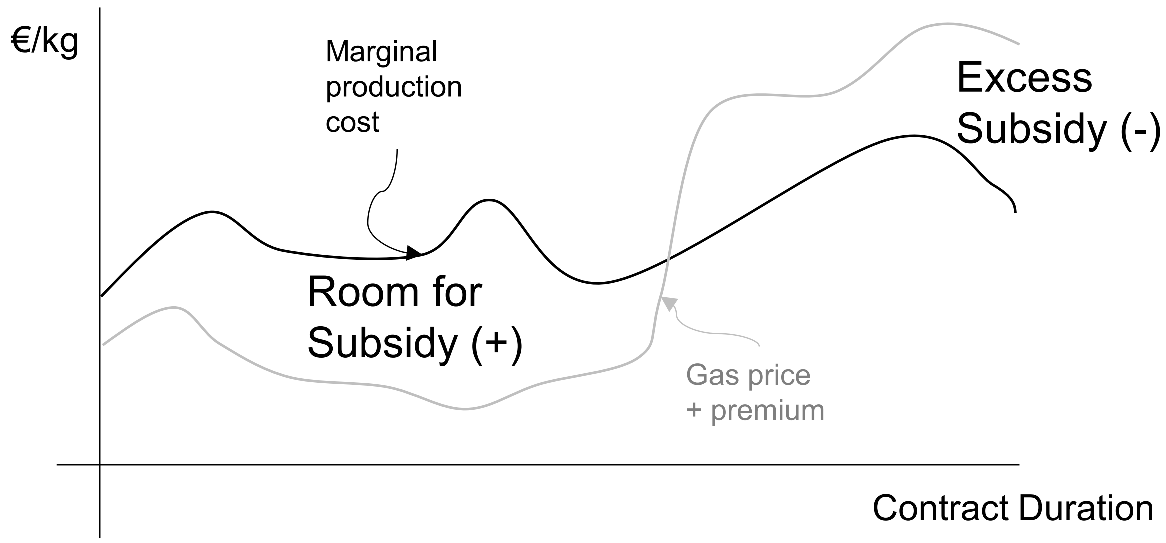

Figure 2. Subsidies covering for the difference between cost and willingness-to-pay.

[1] They will compete except in the case that there is a niche market for low carbon products. Even there, there is a limit, because if the over-cost is too high, it may impact the competitiveness of the economy (or value chain) as a whole.

Figure 2 shows that the maximum injection of funds, represented by the variable "Room for Subsidy", would cover for the difference between hydrogen consumers' willingness-to-pay and production costs at each period of the contract duration. When the difference is negative, as shown in Figure 2 with the variable "Excess Subsidy" at each period of the contract when production costs are lower than willingness-to-pay, the intervention of public administrations is not required.

In the context that we are considering, the difference will be normally positive. Nonetheless, when natural gas prices are high, the difference will tend to be smaller, and hence, the required subsidy will be smaller too. This is relevant in environments where gas prices tend to be very volatile. Moreover, this is also relevant when policy makers seek to decrease the dependence of natural gas, and it is willing to pay players to invest in other solutions, whereas guaranteeing that if gas price decreases, their competitiveness will not be impacted. The auction design proposed in this paper can reflect such dynamics in the subsidy provided to hydrogen producers.

Furthermore, if the gas price is high enough, the subsidy might become negative, which means the subsidy is not required for the auction clearing. Section 6 discusses two options: i) making consumers pay the negative subsidy to the public administration, or ii) zeroing any subsidy below zero.

3.2 Additional clauses

We propose an example of the kind of contract that may be auctioned. The price is defined by the "market value" methodology described above, complemented by the corresponding subsidy. Besides it, one needs to define quantity, flexibility, and potential renegotiation.

The quantity associated with the contract allocated in the auction may be defined as an annual contracted quantity, as in most of the products proposed so far in the EU experience. Low-carbon hydrogen off-takers purchase the quantity that they will require in one year at a certain price to be defined in the auction.

Additionally, contracts need to take into account that some flexibility may be needed. In that view, a possible solution would be for low-carbon hydrogen producers to offer certain modulation of the off-take defined in the annual contracted quantity. Such modulation would be typically associated with an additional capacity charge. Alternatively, the contract could imply a minimum quantity to be consumed, say around 85% of the annual quantity contracted, and a maximum off-take, e.g. 115% of the annual contracted quantity.

Finally, these contracts should reflect that, in the calculation of the contract price defined by its "market value," one needs to take into account that the parameters used for the value calculation may change over the contract duration. For instance, the substitute fuel may not be natural gas in the future, etc. To reflect such possibilities, the contract may have a re-negotiation clause (a re-opener) in order to formalize a periodic price revision (under pre-agreed conditions) of the contracts allocated in the auction.

4. The auction

The rationale behind the auction approach is that both curves in Figure 2 are implicitly revealed in the auction; see for instance (Wilson, 1993). Actually, one of the main motivations for introducing an auction mechanism comes from the fact that it is not obvious to reveal the willingness to pay for the low-carbon characteristic of hydrogen consumers.

The mechanism proposed in this paper involves three sides: producers, consumers, and public financial institutions. The offer in the hydrogen market will be defined by producers' unit cost. Public funds will be allocated to facilitate investment in those low-carbon hydrogen projects. Those funds are supposed to be allocated with the aim of maximizing the number of projects that will be undertaken.

The building block of the auction that we are designing is the contract representing the transaction between buyers and sellers. To define such a contract, we need to define its price formation process and the duration of the contract. First, we will describe the price formation process proposed in this paper, and then we will discuss relevant aspects to define contract duration.

We may consider the transaction organized through a contract (as in the UK auctions, we may call it a low-carbon hydrogen agreement, LCHA) where the seller receives a payment from off-takers of hydrogen plus a subsidy from the public fund over the contract duration. In order to set the nomenclature to describe the auction, from the supply-side viewpoint, if the contract is sold, producer's block j receives the auction price, which must be enough to cover production costs (including investment costs), c_j. From the demand-side viewpoint, if the contract is bought, consumer i pays the minimum of

- k_i, which is the maximum price she is willing to pay for low-carbon hydrogen. This is the reference price that represents the alternative.
- b_i, which represents the bid for low-carbon hydrogen to purchase in the auction, as long as it is below the price of the alternative. It is defined by consumers' preferences.

That is, the demand for hydrogen will be calculated as $min\,(b_i\,, k_i)$.

In this strategic setting, the producers' bidding process is assumed to be driven by bids that consist of calculations of risk-neutral expected costs of the blocks over the contract duration, in addition to reasonable return on investment. Note that risk-neutral expectations mean the result of taking expectations using risk-neutral probabilities, which take into account the interaction among risk attitudes of market participants, for instance (Eydeland and Wolyniec, 2002) or (Vazquez and Barquin, 2013).

On the other hand, consumers' bidding process will depend partly on the definition k_i. This maximum price depends, in turn on the substitute for low-carbon hydrogen, which is natural gas, so we define this maximum price as the natural gas price plus such premium. That is, the maximum hydrogen price of consumer i as the expected willingness to pay over the contract duration. We write that $k_i = p_g + \alpha_i$, where p_g is the risk-neutral expectation of the gas price over the contract time scope, and α_i is the premium that the consumer is willing to pay for low-carbon activities. Hence, consumers' bids are $min\ (b_i, p_g + \alpha_i)$.

We consider a double-auction mechanism to clear the supply and demand curves. The bids are:

- For producers, pairs of quantities and prices such that they define the volume of low-carbon hydrogen are willing to sell at a certain price, $\{q_j, c_j\}$, being c_j the production cost defined above, and q_j the amount of hydrogen bid at that production cost.

- For consumers, pairs of quantities and prices such that they define the maximum price at which they are willing to purchase low carbon hydrogen, $\{q_i, min\ (b_i, p_g + \alpha_i)\}$. Consequently, the competition among agents will be associated with bids on α_i, as $k_i = p_g + \alpha_i$ and we consider the natural gas price exogenously defined.

Total quantities cleared in the auction are denoted by

$$\sum_{j=1}^{j*} q_j = \sum_{i=1}^{i*} q_i$$

That is, supply equal demand.

4.1 Auction clearing

If we assume that no subsidy is provided by public authorities, the clearing of the auction results in

$$c_{j*} = min\ (b_{i*}, p_g + \alpha_{i*})$$

where $j*$ is the most expensive block for which there is a high enough purchase bid, and $i*$ is the most expensive purchase bid able to match with a sale bid.
The situation at the center of our analysis is one where $c_j > p_g + \alpha_i$, for most offers q_j. In this case the cleared quantity $\sum_{j=1}^{j*} q_j$ is small and thus the investment in low-carbon hydrogen is limited.

Because of this, public administrations may decide to introduce subsidies to low-carbon hydrogen blocs to increase the volume resulting from the auction (committed through LCHAs). As shown above, subsidies cover for the difference $c_j - p_g - \alpha_i$ (in this case, the maximum price constraint will be always active). Let us term S the amount of subsidies that are available. The auction will define the J cheapest blocks that can be subsidized with S. When the auction is cleared, the maximum consumer bid accepted is characterized by $p_g + \alpha_{i^*}$, and $c_{j^*} = p_g + \alpha_{i^*} + S$.

In order to calculate the available budget S, it is necessary to consider the projection of natural gas prices over the contract duration. To that end, public administrations would produce their own estimates of c_j and α_i over the contract time scope. For instance, they could consider that the total budget for low-carbon hydrogen is given by $s_t = [c_{j^*} - p_g + \alpha_{i^*}]_t$, where $[\cdot]_t$ is and evaluation at period t. As the values are not observable, public administrations need to solve a stochastic mathematical program. A possible way to do that is to define scenarios for gas price evolution, denoted by the sub-index e, so we consider $p_{g,t,e}$, $c_{j^*,t,e}$, and $\alpha_{i^*,t,e}$ in order to obtain $s_{t,e}$. With than, public administrations solve the problem:

$$\begin{aligned} max \quad & [Ms_{t,e}] \\ s.t. \quad & \sum_t s_{t,e} < S \end{aligned}$$

where $[Ms_{t,e}]$ denotes some measure of the set of scenarios, e.g. the scenario that happens with at least 95% probability.

4.2 Product duration and lag period

Lag period refers to the time between entering into the contract and the contractual obligation to trade hydrogen. It approximately represents the construction phase for the kind of project that is allowed to participate in the auction and benefit from subsidies.

As for the duration of the contract, two forces need to be balanced. On the one hand, contracts (LCHAs) need to offer enough hedge for producers to represent a revenue-enhancement mechanism to facilitate undertakings in low-carbon technologies. On the other, too long contracts hamper competition in future markets as the make entry in the market more challenging. In addition, limiting the ability of off-takers to switch between suppliers makes the contract less attractive, thus reducing demand's willingness-to-pay.

5. Consumers' payments and product definition

The last point that will be discussed is the relationship among consumers and public administration. From the point of view of payments, we consider two possibilities: i) payments are only subsidies from public administrations to consumers in the way that was defined when designing the auction mechanism, or ii) consumers pay the difference between hydrogen price and maximum price to public administrations when the hydrogen price is lower.

5.1 Option 1: Variable payments for consumers

In this option, the idea is that subsidies are allocated in order to covering for the positive difference between p_h and k_h. That is, when hydrogen prices are larger that the marginal maximum price, the public administration covers for the difference. On the other hand, when the hydrogen price is lower than the marginal maximum price, the public administration does nothing, and subsidies are not activated.

This mechanism implies, consequently, that producers pay a constant price, and consumers pay a variable price. This is the option described in the previous section. It might be considered close to a subsidized financial insurance contract.

5.2 Option 2: Fixed payments for consumers

In the second option considered in this paper, the starting point is the same one as before: subsidies are allocated in order to covering for the positive difference between p_h and k_h. When the low-carbon hydrogen price is above the maximum price that consumers are willing to pay for it, public administrations cover for the difference.

However, in this case, when the hydrogen price is lower than the maximum price, consumers pay the difference to public administrations. Consequently, consumers will always pay the maximum price they are willing to pay (which is indexed to the gas price at each point in time).

The only variability is thus concentrated in the public administrations, who observe period where they need to subsidize hydrogen trading, and period when they receive payments from trading.

The advantage of this mechanism is that it is generally cheaper the option 1, which means that more projects may be subsidized. On the other hand, it might be more unpredictable, it is more difficult to forecast each $s_{t,e}$. Besides, the hydrogen price affects less to producers and consumers, hence weakening the signal associated with them and thus hampering the coordination of offer and demand. This may be viewed as a version of a contract for differences among consumers and public administrations.

6. Final remarks

In this paper, we propose a mechanism to choose the most cost-effective low-carbon hydrogen projects and the users with highest willingness to pay for low-carbon premium and to allocate the corresponding subsidies. Nowadays, scaling up low-carbon hydrogen projects requires some form of support to make projects competitive with respect to traditional technologies. The rationale in many jurisdictions is to introduce a general support mechanism to reduce the gap between project cost and end-users' willingness to pay. In this context, the definition of the gap is not straightforward, as the cost gap is not directly observable.

We propose to coordinate the transaction between producers and consumers through a contract for differences. This contract is based on identifying the cost gap with the difference between project cost and natural gas prices plus a premium. The premium represents the extra cost that consumers are willing to pay for low-carbon fuels. The second pillar is the implementation of a double-sided auction that reveals the premium associated with low-carbon projects. In it, suppliers bid their production costs, consumers bid their premia over natural gas prices, and the subsidies bridge the gap between purchase and sale offers that are cleared in the auction.

The approach proposed in this paper may be seen as a mixture between auction-based support mechanisms for renewable energy sources and traditional natural gas contracts. As in renewable energy projects, auctions are used to select the most cost-efficient projects to be subsidized. As in natural gas contracts, this paper's approach involves setting the price akin to a "market value," which theoretically aligns with the substitute product's value for low-carbon hydrogen. This offers two key advantages: incentivizing the use of low-carbon hydrogen over traditional fossil fuels and benefiting from more efficient natural gas international pricing mechanisms, enabling a more effective indexation of the product. Moreover, indexing to natural gas may facilitate security planning for EU industries, as uncertainty about future natural gas prices hinders investment when most necessary and potentially more economically efficient. High natural gas prices, which is a security of supply concern, would also reduce the public funds required to scale up the low-carbon hydrogen industry.

Several relevant issues remain to be explored in more detail. In general, this paper assumes that the projects to be subsidized are well-defined. Such definition is often a complex process involving many dimensions (industrial, regional, climate policies...). Moreover, the interaction among different policies may be difficult, e.g., EU policies may not be perfectly aligned by Member States policies. The discussion of these topics is beyond the scope of this paper. For instance, applying this mechanism requires further analysis of the interaction with carbon policies (such as the EU Carbon Adjustment Board), with carbon markets (as the application of Paris Agreement article 6), and with carbon pricing evolution.

Furthermore, the design of financial aid may be more complicated than structuring simple subsidies through the contracts for differences proposed in this paper. Various additional de-risking instruments can be used to facilitate the transition to low-carbon hydrogen projects. Guarantees, financial insurance, etc., are relevant, complementary tools to support low-carbon hydrogen projects.

In the context of low-carbon hydrogen markets, the long-term contracts proposed in this paper are intended to be, within well-functioning markets, one of the contractual solutions that might be used for market participants. Short-term transactions resulting in a liquidly formed short-term index (often called hub pricing) may be viewed as a further development of the basic market mechanism proposed in this paper. In this context, the standardization of short-term contracts (delivery point, duration…) is typically important for the design of the short-term market.

Moreover, we need to consider that the evolution of the low-carbon hydrogen market will take several steps. The mechanism proposed in this paper is expected to be important in the process of market development and should become less important when low-carbon hydrogen markets become more liquid and the costs drop.

7. References

Breitschopf, B., Alexander-Haw, A., 2022. Auctions, risk, and the WACC. How auctions and other risk factors impact renewable electricity financing costs. Energy Strategy Reviews 44, 100983.

Collins, L., 2023. UK intends to begin annual tenders for green hydrogen production by 2025 [WWW Document]. Hydrogen news and intelligence | Hydrogen Insight. URL https://www.hydrogeninsight.com/policy/uk-intends-to-begin-annual-tenders-for-green-hydrogen-production-by-2025/2-1-1495049 (accessed 10.31.23).

del Río, P., Linares, P., 2014. Back to the future? Rethinking auctions for renewable electricity support. Renewable and Sustainable Energy Reviews 35, 42–56.

EERE, D., 2023. Hydrogen Production: Natural Gas Reforming.

EIA, U.E.I.A., 2022. Use of natural gas.

Eydeland, A., Wolyniec, K., 2002. Energy and power risk management: New developments in modeling, pricing, and hedging.

Fleck, A.-K., Anatolitis, V., 2023. Achieving the objectives of renewable energy policy – Insights from renewable energy auction design in Europe. Energy Policy 173, 113357. https://doi.org/10.1016/j.enpol.2022.113357

H2Global, 2022. The H2Global Instrument.

Hydrogen Central, 2022. Green hydrogen cheaper than natural gas in Europe boosts investment.

Hydrogen Council, 2023. Hydrogen Insights.

IEA, I.E.A., 2023a. Towards hydrogen definitions based on their emissions intensity.

IEA, I.E.A., 2023b. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach.

IEA, I.E.A., 2022. Global Hydrogen Review 2022.

IRENA, 2022. Hydrogen.

IRENA, 2015. Renewable Energy Auctions: A Guide to Design.

Jansen, M., Beiter, P., Riepin, I., Müsgens, F., Guajardo-Fajardo, V.J., Staffell, I., Bulder, B., Kitzing, L., 2022. Policy choices and outcomes for offshore wind auctions globally. Energy Policy 167, 113000. https://doi.org/10.1016/j.enpol.2022.113000

Kozlov, N., 2014. Contracts for difference: risks faced by generators under the new renewables support scheme in the UK. Journal of World Energy Law and Business 7, 282–286.

Kruger, W., Eberhard, A., 2023. The impact of competition, trust and capital on renewable energy auction outcomes in sub-Saharan Africa: Analysing auctions in South Africa, Zambia and Namibia. Energy Policy 178, 113572. https://doi.org/10.1016/j.enpol.2023.113572

Liebreich, M., 2023. Clean Hydrogen Ladder, Version 5.0,.

Martin, P., 2023. UK proposes looser criteria for second round of hydrogen auctions, with extra subsidies being considered [WWW Document]. Hydrogen news and intelligence | Hydrogen Insight. URL https://www.hydrogeninsight.com/policy/uk-proposes-looser-criteria-for-second-round-of-hydrogen-auctions-with-extra-subsidies-being-considered/2-1-1452777 (accessed 10.31.23).

May, N., Neuhoff, K., Richstein, J.C., 2018. Affordable electricity supply via contracts for difference for renewable energy. DIW Weekly Report 8, 251–259.

Melling, A., 2010. Natural gas pricing and its future: Europe as the battleground.

Reuters, 2023. Portugal to launch Europe's first auction for piped hydrogen (Sergio Goncalves and Charlie Devereux, March 27, 2023).

SEAE, (Secretaria de Estado do Ambiente e da Energia), 2023. Portaria n.o 15/2023. Diário da República n.o 3/2023, Série I de 2023-01-04.

Vazquez, M., Barquin, J., 2013. Representing the effects of oligopolistic competition on risk-neutral prices in power markets. The Journal of Energy Markets 6.

Vazquez, M., Hallack, M., 2022. The international implications of the European process for low-carbon hydrogen certification. European Energy & Climate Journal 11, 66–75.

Vazquez, M., Hallack, M.C.M., Andreão, G.O., Tomelin, A.C., Botelho, F., Perez, Y., Di Castelnuovo, M., 2018. Financing the Transition to Renewable Energy in the EU, Latin America and the Caribbean. EU-LAC reports.

Welisch, M., Poudineh, R., 2020. Auctions for allocation of offshore wind contracts for difference in the UK. Renewable Energy 147, 1266–1274.

Wilson, R.B., 1993. Design of efficient trading procedures, in: The Double Auction Market: Institutions, Theories and Evidence. Daniel Friedman.

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