A Taxonomy of Support Mechanisms for the Low-Carbon Hydrogen Supply Chain

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A TAXONOMY OF SUPPORT MECHANISMS FOR THE LOW-CARBON HYDROGEN SUPPLY CHAIN

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Abstract

Although the actual scope of the hydrogen sector is still uncertain, many support mechanisms for low-carbon hydrogen have been introduced at the global level in recent years, with billions of dollars of funding soon to be disbursed. This article presents a comprehensive taxonomy of these support schemes, based on a global review of international experience covering more than 20 jurisdictions in different regions of the world. Hydrogen support schemes have been categorised according to the segment of the supply chain they target (production, transport, storage, consumption and cross-chain mechanisms). The majority of hydrogen support mechanisms introduced so far target production, consumption and cross-chain projects (either through risk-hedging contracts or direct grants), while there is limited experience with support for hydrogen transport and storage. The article identifies the main design elements of hydrogen support mechanisms and some initial trends in international experience, shedding a light on a topic that is dramatically underrepresented in the academic literature.

Keywords

Hydrogen; Supply chain; Support mechanism; Risk-hedging; Direct grant; Fixed premium; Variable premium.

1 INTRODUCTION

All the energy transition pathways proposed over the past decade envision a pivotal role for low-carbon hydrogen [1][2][3]. In addition to its role as a sustainable feedstock for the chemical industry, low-carbon hydrogen is anticipated to become an essential energy carrier in the future, facilitating the decarbonisation of numerous end uses that cannot be electrified;

it will also benefit the power sector, by providing flexibility services as the share of renewables increases. However, the real scope of hydrogen as an energy vector is subject to very large uncertainties [4][5], and many experts stress that this is not the first time that a hydrogen revolution has been claimed to be around the corner. While it is true that hydrogen hype has risen and fallen many times over the past decades[6][7], this time it seems to be backed by a strong political commitment, that is materialising into support mechanisms for different elements of the low-carbon hydrogen supply chain [8][9][10].

Support mechanisms for low-carbon hydrogen have been introduced or are being developed in the United States, the European Union, Great Britain, Australia, Canada, Japan, South Korea, India, Egypt, Germany, Denmark, the Netherlands, Portugal, Spain, Italy, Sweden and Romania. These schemes are rapidly evolving from small demonstration programmes to large and complex support mechanisms meant to build a new hydrogen economy. The goal of this article is not to assess the need or convenience of introducing support mechanisms for low-carbon hydrogen, but rather to review the schemes that have been introduced so far in order to build a comprehensive taxonomy of the different designs that regulators can choose from. This topic is dramatically underrepresented in the academic literature, and we believe there is an urgent need to provide a robust theoretical framework for policymakers tasked with designing the next generation of hydrogen support schemes.

The article is structured as follows. Section 2 examines the scope of the economic aid for low-carbon hydrogen and identifies the elements of its supply chain that can be supported. The article then classifies the support mechanisms for electrolyser manufacturing of (section 3), low-carbon hydrogen production (section 4), transport (section 5), storage (section 6), consumption (section 7), cross-chain programmes (section 8), and the enabling framework for these schemes to operate (section 9). Section 10 draws conclusions and policy implications. This article does not present a conventional review of international experiences[1]. The information is restructured here to present a taxonomy of the design elements of hydrogen support schemes. For each design element, references to real support schemes implemented around the world are included to give the reader an insight into the approach followed in different jurisdictions.

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[1] For a brief country-by-country assessment of hydrogen support mechanisms, the reader may refer to [8].

2 SCOPE OF THE ECONOMIC AID

2.1 The supply chain of low-carbon hydrogen

The first question when designing a hydrogen support mechanism is which element of the supply chain is the target of the scheme. Figure 1 shows a schematic representation of the hydrogen supply chain. The economic aid is more commonly provided to each element of the chain in isolation (e.g., for the production of low-carbon hydrogen and, potentially, its auxiliary storage). However, some schemes support hydrogen production/consumption pairs, while others may seek to coordinate support for transport and storage.

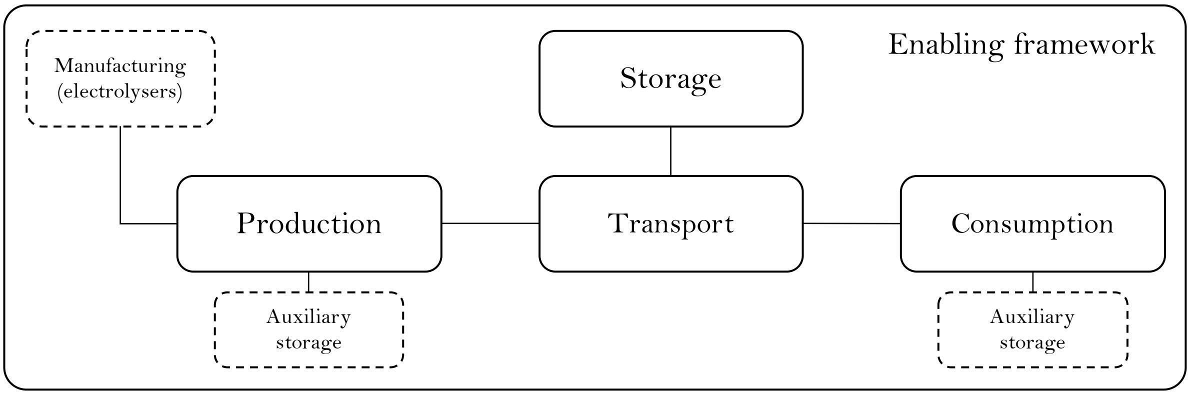

Figure 1. Low-carbon hydrogen supply chain

If a hydrogen support mechanism encompasses several elements of the supply chain that need to be installed together, it can be classified as cross-chain support (e.g., for the deployment of hydrogen valleys or clusters, see section 8). In this case, the scheme could also cover the installation of renewable electricity generation and electricity storage (in the case of hydrogen from electrolysis). If the support mechanism covers several elements of the supply chain, but without imposing any correlation between them, it can be classified as inter-chain support, such as the four Important Projects of Common European Interest (IPCEI) implemented for hydrogen (Hy2Tech, Hy2Use, Hy2Infra, Hy2Move), which provided direct grants to a set of supply chain elements defined for each call [11].

Other initiatives to promote the hydrogen economy constitute the enabling framework within which support mechanisms operate. Hydrogen roadmaps, international trade agreements and certification schemes can be considered as part of the enabling framework (see section 9).

2.2 The underlying product

A further decision to be taken by the regulator is the underlying product that can benefit from the economic aid, both in terms of energy carrier and environmental properties. Regarding the carrier, the regulator can decide to limit the scope of the aid to gaseous hydrogen, liquid hydrogen or hydrogen derivatives (ammonia, methanol, or other synthetic fuels), or to leave this decision to project developers (see sections 4 to 7 for details).

In terms of environmental properties, support mechanisms generally do not provide economic aid to carbon-intensive hydrogen (i.e., the so-called grey hydrogen) and limit the participation to projects involving clean or low-carbon hydrogen projects and/or its derivatives. The definition of low-carbon hydrogen may be specified in the legislation governing the support mechanism, but is more commonly found in elements of the enabling framework, such as the certification or the guarantees of origin. Within the low-carbon hydrogen category, the regulator may choose to limit participation to certain types of hydrogen, such as hydrogen from electrolysis or renewable hydrogen (e.g., from the electrolysis of renewable electricity), among others. Details on hydrogen labels can be found in [12]. The vast majority of hydrogen support mechanisms reviewed for this taxonomy target hydrogen from the electrolysis of renewable electricity.

3 SUPPORT FOR ELECTROLYSER MANUFACTURING

The manufacture of electrolysers for low-carbon hydrogen production is a niche in the hydrogen support sector that is still worth mentioning. Pioneering experiences can be found in Italy [13] and India [14]. In Italy, 100 M€ are earmarked for direct grants for the installation of new electrolyser manufacturing plants, with shares of capital expenditure ranging from 15% to 55% and technical requirements on the efficiency of the electrolyser. In India, electrolyser manufacturers receive a premium on the electrolysing capacity they sell in the market, with the premium following a decreasing pattern, from 53 to 17 $/kW_e$; factories are selected based on the efficiency of their electrolysers and the local value they produce.

4 SUPPORT FOR PRODUCTION

Low-carbon hydrogen production is by far the element of the hydrogen supply chain where more support mechanisms have been registered to date and will therefore be discussed in more detail in this article. The design elements of these schemes are summarised in Table i and are assessed in detail below. Some of these design elements may be common to other support schemes targeting different elements of the hydrogen supply chain.

Table i. Design elements of support mechanisms for low-carbon hydrogen production

Technical requirements and eligibility criteria (section 4.1)

Size	Efficiency	Water use	Emissions	Configuration	Limitations on end use	Electricity sourcing	Off-taker contract

Type of support and product design (section 4.2)

Product	Direct grant	Risk-hedging contract					Contract duration
kgH_2	CAPEX	Price risk			Volume risk		Lag period
MWh	OPEX	Fixed price	Fixed premium	Variable premium	Availability payments	Government off-take	Penalties
MW_e	DEVEX						Guarantees

Selection process and auction design (section 4.3)

Direct contracting	Multi-criteria evaluation	First-come first-served	Competitive auction (price-based)			
			Clearing	Price threshold	Anti-monopoly	Quotas

Cost allocation (section 4.4)

State budget	Regional funds	Revenues from emission allowances	Charge on energy services

4.1 Technical requirements and eligibility criteria

Participation in hydrogen support mechanisms is subject to a number of technical requirements and eligibility criteria. These requirements and criteria can be applied in different ways. Typically, they are assessed in a pre-qualification phase and compliant projects proceed to the next phase. In other cases, such as the British Hydrogen Allocation Rounds (HAR) [15] or the Australian Hydrogen Headstart (HH) [16], these criteria are part of the evaluation phase (multi-criteria approach), which is usually followed by a negotiation phase. Finally, requirements and criteria can also be used to define the economic aid that the project is entitled to receive, as in the case of the tax credits introduced in the United States by the Inflation Reduction Act (IRA 45V) [17], where the amount of the tax credit depends on the greenhouse gas (GHG) emissions of the project.

Technical requirements commonly applied in hydrogen support schemes relate to the technology used to produce hydrogen (e.g., limiting participation to hydrogen from electrolysis), the size of the plant (e.g., maximum and minimum capacity of the electrolyser), water use, GHG emissions from the process, the efficiency of the electrolyser, its operating hours (e.g., in Denmark, where there is a 5 500-hour cap [18]) or the configuration of the plant (where the clearing of the auction seeks a balance between islanded, grid-connected, and hybrid electrolysers). Most hydrogen support schemes are open only to new production capacity.

Among the eligibility criteria, the most are restrictions on the end use that the supported hydrogen can supply. For instance, supported hydrogen may (Australia [16]) or may not (Great Britain [19]) be exported. Some end uses may be prohibited (feedstock, as originally proposed in Great Britain [20], or electricity generation, as in Italy [21]) or the support mechanism may directly specify the target end use (as in Portugal [22], where all supported hydrogen must be blended with gas in the network). Several hydrogen support schemes require project developers to sign a contract with an off-taker for a percentage of the production capacity. In the case hydrogen from electrolysis, project developers may also be required to sign a long-term contract for electricity supply. There may also be regulatory restrictions (e.g., the project developer cannot be the gas system operator to comply with vertical unbundling) and limitations on the cumulation of aid (the same hydrogen production cannot receive economic incentives from other policies). Other criteria commonly used at the evaluation stage include the financial capability of the developer, the local value of the project, job creation, or the involvement of local communities.

4.2 Type of support and product design

A hydrogen production support scheme typically rewards projects according to a quantity measured in terms of:

- kgH_2, weight of hydrogen (or its derivatives, whose weight must be converted into an equivalent weight of hydrogen); support schemes based on this physical product are the European Hydrogen Bank (EHB) auction [23], the Australian HH [16] and the IRA 45V in the United States [17].
- MWh or GJ, energy content; this physical product, which allows hydrogen or its derivatives to be procured without any conversion, is found in the British Low Carbon Hydrogen Agreements (LCHA) [19], the German H2Global scheme [24], the Danish Power-to-X scheme [18], and the Portuguese auction for renewable gases [22].
- MW_e, electrolysing capacity; this physical product, which is limited to schemes focusing on hydrogen from electrolysis, is found in the support schemes implemented in Romania [25] and Italy [21], the Dutch hydrogen auctions [26][27], and the IRA 48 in the United States [17].

Irrespective of the unit of measurement ($\$/kgH_2$, $/MWh, or $\$/MW_e$), the economic aid can basically take two forms: a direct grant covering part of the expenditure or a financial contract hedging part of the risk of the project's uncertain cash flow. Direct grants (subsection 4.2.1) are clearly easier to design and implement than risk-hedging contracts (subsection 4.2.2). However, hydrogen production projects are characterised by a low share of capital expenditure in the so-called Levelised Cost of Hydrogen (LCOH) [27]. A direct grant may increase the expected profits of the project, but it does not affect the probability distribution of these expected profits, which is dominated by operating costs and sales prices. For this reason, although the design of risk-hedging contracts has to be very complex in this early phase of hydrogen deployment, they are prevalent in hydrogen support mechanisms, sometimes accompanied by direct grants (as in the British HARs [15] or in the Dutch hydrogen auctions [26][27]).

4.2.1 Direct grant

Direct grants for hydrogen production usually target capital expenditure (CAPEX). The share of CAPEX covered by the grant can be administratively defined, as in the US IRA 48 (1.2% to 30%, depending on GHG emissions and compliance with labour conditions), the support schemes announced in Egypt [29] and Canada [30], or the British HARs (where projects compete for a risk-hedging contract, the LCHA, but selected projects also receive a 20% CAPEX grant from the Net Zero Hydrogen Fund). Another option is to let project developers compete and ask them to bid for the required level of grant, as in the Dutch hydrogen auctions, the Romanian support scheme or the Italian support scheme for hydrogen valleys.

In a few support mechanisms, direct grants can also cover so-called development expenditures (DEVEX), such as those for Front End Engineering Design (FEED) studies and post-FEED costs. The British HARs and the Australian HH provide grants for 50% of DEVEX [15][16].

4.2.2 Risk-hedging contract

Risk-hedging contracts for hydrogen production can be classified in three main categories: fixed price (the German H2Global scheme and the Portuguese auction), fixed premium (the EHB auction, the Danish Power-to-X scheme, the US IRA 45V and the Indian incentive scheme for green hydrogen [31][32][33]), and variable premium (the British LCHAs, the Dutch hydrogen auctions and the Australian HH).

Many support schemes based on risk-hedging contracts require the project developer to sign a contract with an off-taker and internalise this in the economic aid the project receives (e.g., based on the sales price). This approach may end up supporting production/end use pairs. Together with the imposition of restrictions on the end uses that the supported hydrogen can supply (subsection 4.1), this can lead to an artificial segmentation of the initial hydrogen market. This segmentation can lead to inefficient outcomes, requires complex monitoring that is prone to fraud, and is not conducive to price discovery. This issue has been assessed in detail in [34].

Fixed price

One way of dealing with the uncertainty of future cash flows of hydrogen production projects is to guarantee a fixed price for the expected hydrogen production. The fixed price is usually determined through a competitive process with pay-as-bid clearing. In the German H2Global scheme [24], which targets hydrogen imports, separate auctions are held for different hydrogen derivatives. The auction is two-sided and both production projects and potential end users bid a fixed price at which they would be willing to produce/consume each derivative. The supply and demand curves do not match and the difference is covered by the budget of the mechanism. Also in Portugal, hydrogen production projects bid and, if selected, receive a fixed price, although the hydrogen produced is blended into the gas network and sold at the price of natural gas [22]. The difference between the fixed prices paid to the producers and the price of natural gas is covered by the budget of the support scheme.

The settlement of a fixed-price contract can be schematised as shown in Figure 2. The project developer is not exposed to any hydrogen market price, as it delivers all its production to a central buyer (Hintco in the case of the German scheme, Galp in the case of the Portuguese scheme) and receives a fixed price for it. However, production costs (including a reasonable return on investment) may differ from those expected when the bid was set and this may result in additional profits or losses for the project.

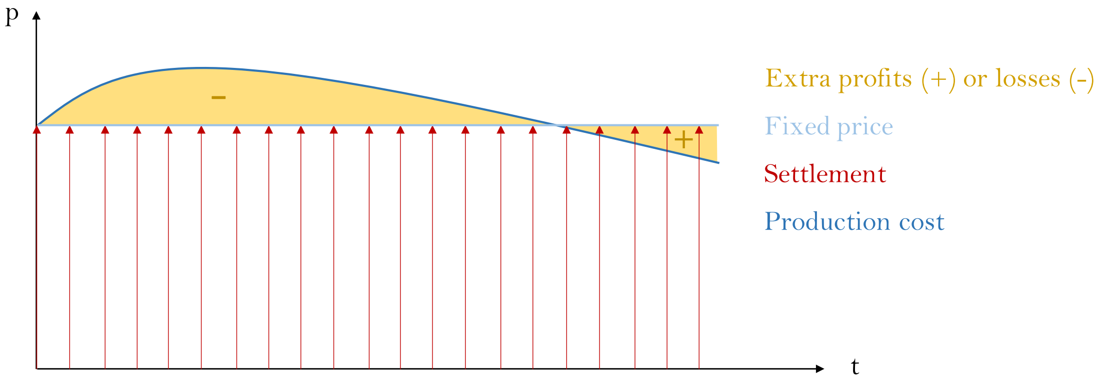

Figure 2. Settlement of a risk-hedging contract for hydrogen based on a fixed price

Fixed premium

In support schemes based on fixed premia, the project developer sells its hydrogen production at the market price and receives a fixed premium (e.g., in €/kgH_2, as in the US IRA 45V or the EHB auction) on the volume produced, which complements its market revenues. Also in this case, the fixed premium can be set administratively (US IRA 45V and the Indian incentive scheme for green hydrogen – modes 2A and 2B) or determined by agent bids in a competitive tender (the EHB auction, the Danish Power-to-X scheme and the Indian incentive scheme for green hydrogen – mode 1).

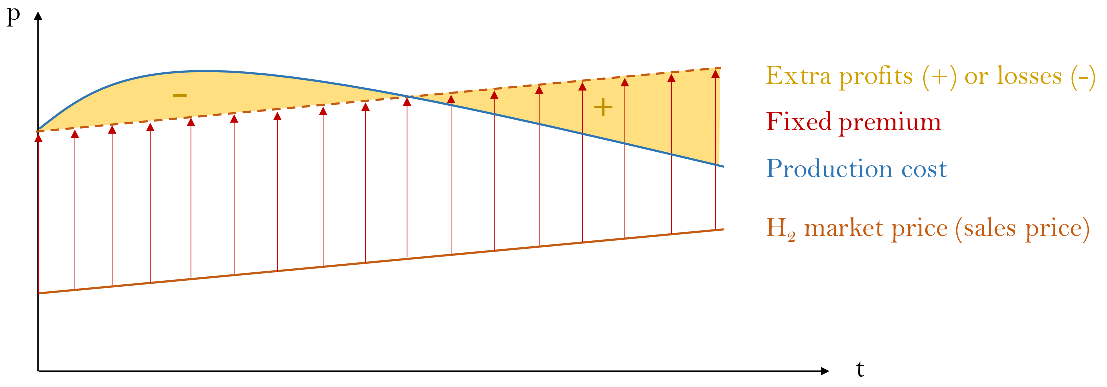

Figure 3. Settlement of a risk-hedging contract for hydrogen based on a fixed premium

The settlement of a fixed-premium contract can be schematised as shown in Figure 3. The project developer sells its production on the low-carbon hydrogen market or through a bilateral contract and receives a certain sales price. This sales price is unlikely to initially cover the cost of hydrogen production, but the project developer also receives a premium from the support mechanism that is not adjusted according to the evolution of either the sales price or the production cost. This is likely to result in additional profits or losses for the project.

The fixed premium is usually not indexed and does not vary during the contract duration (the EHB auction, the Danish Power-to-X scheme), or it may follow a pre-defined pattern, as in the Indian incentive scheme for green hydrogen (modes 2A and 2B), where the premium follows a declining pattern over the three-year contract period, from 0.60 $/kg$H_2$ in the first year to 0.36 $/kg$H_2$ in the third year.

Variable premium

In a risk-hedging contract based on a variable premium, the support mechanism covers the difference between a reference price, which should reflect the price that the project developer can obtain from the hydrogen market, and a strike price, which is bid by the agent in a competitive tender and should reflect the expected production cost. Changes in the reference and strike prices are reflected in the premium, which varies over the duration of the contract, as shown in Figure 4. If the reference price exceeds the strike price, the developer may also be required to return the difference to the support scheme operator.

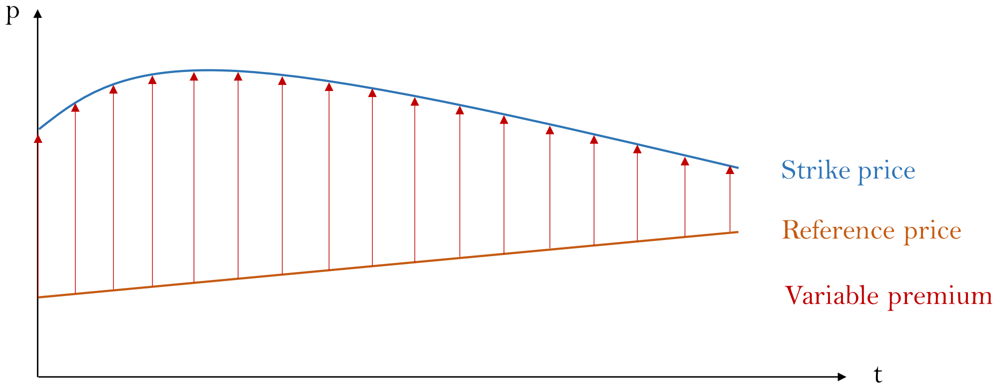

Figure 4. Settlement of a risk-hedging contract for hydrogen based on a variable premium

The main drawback of hydrogen risk-hedging contracts based on a variable premium is that, unlike other energy commodities, there is no liquid market whose price can be used as a reference for the settlement of the contract. The three regulators that have introduced support mechanisms based on this design have implemented different solutions for setting the reference price and settling the contract. In the Australian HH scheme, the project developer bids a production credit based on its estimates of production cost and sales price, which it must include in its bid. If the gap between production cost and sales price decreases during the contract period, the production credit is recalculated based on a 50-50 benefit sharing rule [16], i.e., if the developer manages to obtain a higher sales price than expected, it could retain 50% of the difference.

In the British LCHAs, the reference price is set at the higher of the achieved sales price and a floor price equal to the price of natural gas (Figure 5). This settlement is complemented by a price discovery incentive that allows project developers to retain 10% of the difference between the achieved sales price and the floor price, if positive [19]. This rule is designed to incentivise developers to seek sales prices above the natural gas price. The strike price can be a fixed value or a price profile over the duration of the contract and its indexation depends on the energy source (either natural gas or electricity) from which it is produced.

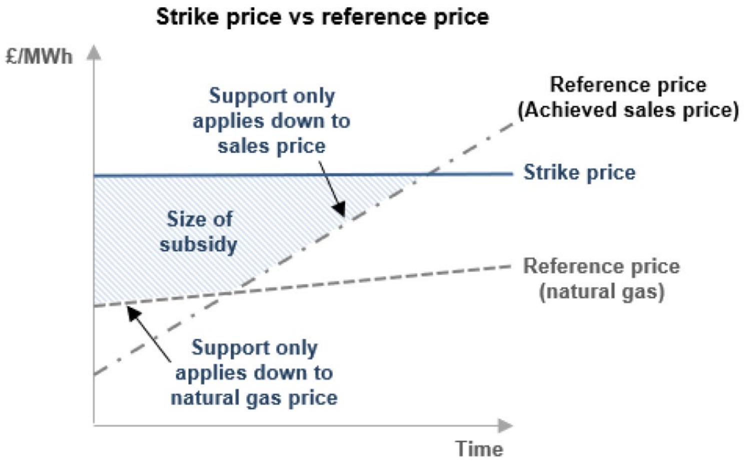

Figure 5. Reference price proposed for the British Low Carbon Hydrogen Agreement (chart from [27])

In the case of the Dutch hydrogen auctions, the variable premium is calculated via a proxy reference price, which is the sum of i) the cost of producing the same amount of hydrogen by steam methane reforming, ii) the value of the hydrogen guarantee of origin and iii) the revenue or avoided cost that the beneficiary receives from the EU ETS [26][27]. The Dutch financial contract has a one-way settlement, i.e., if the proxy reference price exceeds the strike price offered by the developer, no repayment is required.

Treatment of volume risk

Risk-hedging contracts target the so-called price risk, but the volume of hydrogen production is also subject to uncertainty. Due to the current lack of large-scale storage, the hydrogen volume is limited not only by the operational constraints of the plant, but also by the ability of the off-taker to withdraw the product from the producer's facility. Risk-hedging contracts typically specify an expected volume to be produced in each settlement period (e.g., one year), but leave some flexibility to the project developer. If the actual production volume is less than the expected volume, the premium is usually paid on the actual volume. If the actual volume is higher than the expected volume, the premium is usually paid on the expected volume, but some schemes allow for a degree of banking. For instance, the fixed premium of the European Hydrogen Bank can be paid on a volume that can be up to 140% of the expected volume [23], although the total support during the whole contract duration cannot exceed the total expected volume multiplied by the premium.

This flexibility is also limited by termination clauses for under- or over-production. For example, if the actual volume produced by a project selected in the EHB auction is less than 30% of the expected volume for three consecutive years, the contract must be cancelled. The same can happen in the British LCHA if the actual volume exceeds 125% of the expected volume for two years during the contract period.

The British LCHA is the only scheme that will provide project developers with a real hedge against volume risk (beyond the one for price risk). The so-called Sliding Scale Volume Support, which is still being developed at this writing, will administratively increase the strike price of the contract if sales are below a certain percentage of the expected volume, although no premium will be paid if sales fall to zero [19]. Another option considered by the regulator was a partial government off-take for initial hydrogen production, but this design was dismissed due to the potential negative impact it could have on market formation.

4.2.3 Other design elements

In addition to deciding on the type of support that hydrogen producers receive (direct grants or risk-hedging contracts), the regulator needs to define other design elements, such as the lag period and contract duration, penalties and guarantees. The lag period is the time the developer has to bring its production project into operation. It is usually set by the regulator as a threshold, subject to penalties for delay. Lag periods typically found in hydrogen production support schemes are three years (as in Portugal and Romania), four years (as in Denmark and the Netherlands) and five years (as in the EHB auction). In some support schemes, such as the Australian HH, the lag period is defined by the developer and is part of the multi-criteria evaluation for project selection.

Contract duration is a key design element for hydrogen support schemes based on risk-hedging contracts, as it defines the number of years for which the project is shielded from price risk. Contract durations in the mechanisms examined in this article range from three years (India) to 15 years (British LCHAs), although most risk-hedging contracts have a duration of ten years (EHB auction, German H2Global, US IRA 45V, Portuguese and Danish auctions). In the Dutch hydrogen auctions, project developers can choose a contract duration between seven and 15 years [26] (a duration reduced to five to ten years for the 2024 auction [27]), which is taken into account in the evaluation phase.

The support schemes for hydrogen production include penalties for non-compliance with the lag period and the expected production volume. Developers who do not comply with the lag period can have their contract cancelled in Portugal or have their economic aid reduced in Germany and Denmark. For example, in the German scheme for green hydrogen production in Just Transition Fund regions (JFT auction) [35], the developer loses one thirty-sixth (1/36) of the total economic aid for each month of delay. Non-compliance with the expected volume can also be penalised by cancellation of the contract, as analysed in the previous subsection for the EHB auction and the British LCHA.

4.3 Selection process and auction design

Once the type of support has been defined, there are several alternatives for selecting the projects that will benefit from the support. Some hydrogen production support may be granted through a bilateral negotiation with a developer followed by a direct contracting. Other schemes may provide support on a first-come first-served basis, subject to budget constraints. However, the two most widespread approaches are multi-criteria evaluation (Australian HH or British HARs) and price-based auctioning (EHB auction, Portuguese auction, German H2Global, Dutch hydrogen auctions, Danish Power-to-X). In a multi-criteria evaluation, projects receive a score for a set of criteria, are ranked according to the total score and negotiations are initiated with the projects with the higher scores. Techno-economic criteria tend to have a greater weight in the overall score, but other social criteria may also be included (see section 4.1).

In a price-based auction, hydrogen producers compete by bidding an economic variable that reflects the economic aid they need to develop the project. Hydrogen auctions held so far have all been based on a pay-as-bid clearing. They are usually subject to price thresholds. For example, the 4.5 €/kgH_2 cap on the fixed premium in the EHB auction [23], the 9 €/kgH_2 cap on the aid intensity in the Dutch hydrogen auction [26][27], the 16 €/GJ cap on the fixed premium in Denmark [18], or the 127 €/MWh cap on the fixed price in Portugal [22]. Auction schemes also often include anti-monopoly rules, usually expressed as a maximum economic aid that each project can receive (one third of the total budget in the EHB auction or 50 M€ per project in Romania [25]), with the aim of encouraging the participation of a larger number of market agents.

Hydrogen auctions may also internalise some quotas in their clearing. For example, the Indian auction (mode 1) has a target volume of 450 ktonH_2/year, but with a quota of 40 ktonH_2/year to be met by hydrogen production from biomass [31]. Quotas can also be imposed on the geographical scope, as in the Auction-as-a-Service within the European Hydrogen Bank auction. This service allows Member States to define an additional budget for the auction to support projects on their national territory. For instance, the first EHB auction had a budget of 800 M€, which was allocated to the most competitive projects without any geographic limitation, plus a budget of 350 M€ for projects one German territory, as this country activated the Auction-as-a-Service option [36].

4.4 Cost allocation

Like any support mechanism, hydrogen support schemes have a positive net cost. These costs can be covered by the state budget, as is the case in the support mechanisms implemented in Australia, Germany, Denmark, the Netherlands or Portugal. In the European Union, some hydrogen support mechanisms have also been financed by the regional funds of the Recovery and Resilience Facility, as in Italy, Spain [37] or Romania. Another potential source of funding for hydrogen support can be found in the revenues from the sale of GHG emission allowances, as it was the case for the EHB auction. Finally, some regulators have chosen to recover the cost of hydrogen support through new charges or levies on energy services, as is expected to happen with the British LCHA.

5 SUPPORT FOR TRANSPORT

One of the bottlenecks to the deployment of hydrogen as an energy carrier is the current lack of infrastructure [38]. Most grey hydrogen for industrial use is currently produced near consumption sites and it matches demand in time, with limited need for storage. Low-carbon hydrogen, like all energy carriers, will require a whole new infrastructure for its transportation and storage and there are major uncertainties about how this infrastructure will develop. Nevertheless, some regulators have already introduced or are developing support schemes for hydrogen transport.

As with hydrogen production, support mechanisms for hydrogen transport must first define their scope. Hydrogen can be transported as a gas, as a liquid or after conversion into its derivatives. Ground transport of hydrogen gas can take place in new dedicated pipelines or by using the existing natural gas network after repurposing interventions. The regulator must then choose which transport solution will be the target of the support scheme. The design of the latter will also be influenced by the regulatory model defined for the transport activity, which could be competitive (as is currently the case for maritime transport of energy carriers, such as LNG) or regulated (as is the case for most network activities, which are usually considered to be natural monopolies). Another decision that the regulator has to make when introducing support schemes for hydrogen transport is who is the recipient of the aid, either the hydrogen transport operator or the transport end user.

5.1 Type of support

The support schemes for hydrogen transport examined in this article can be classified into three broad categories: subsidies for the reduction of end-user charges, soft loans and direct grants.

Subsidies for the reduction of end-user charges have been proposed in Great Britain [39]. The support scheme targets the transport of hydrogen by pipeline. As a network activity, hydrogen transport will be subject to regulated remuneration, through a Regulatory Asset Base (RAB), which will allow to calculated the allowed revenues of the activity in each regulatory period and to set cost-reflective charges to recover these allowed revenues. The regulator anticipates that these cost-reflective charges will be too high for first movers, i.e., early hydrogen production/consumption projects that will be the first to use the network. Therefore, a subsidy will be used to decouple the allowed revenues from the charges applied to first movers, which will be set at a level that allows the early development of hydrogen projects. This subsidy will be financed through the state budget or through specific charges on energy services.

Soft loans for the development of the Hydrogen Core Network (HCN) have been proposed in Germany [41]. Also in this case, the target is to transport hydrogen gas over land through pipelines. Transport operators will receive a soft loan to cover their capital expenditure. Repayment of the loan will be linked to revenues from regulated charges levied on end users.

Examples of direct grants for hydrogen transport deployment can be found in several cross-chain support schemes (section 8), which may include transport as an eligible cost, or in inter-chain support initiatives, such as the European Hy2Infra programme. Direct grants are also being used to develop the hydrogen maritime connection between Australia and Japan [42].

6 SUPPORT FOR STORAGE

There are three broad alternatives for hydrogen storage [39][43][44]: i) geological storage (e.g., in salt caverns or depleted gas fields), ii) above-ground storage of gaseous or liquid hydrogen in tanks and iii) chemical storage, where hydrogen is stored in another compound in a reversible process. There is currently no technology-neutral support scheme for hydrogen storage and the regulator usually selects a target technology. Also in the case of storage, the regulator has to decide whether the economic aid will be given to the storage operator or end user. There may also be specific regulatory requirements, e.g., whether the facility can only store low-carbon hydrogen or also hydrogen from fossil fuels, or intermediate solutions, as in the Spanish support scheme, where 75% of the hydrogen stored in the facility must be of renewable origin.

6.1 Type of support

There is little experience of support for hydrogen storage. The British regulator has proposed the introduction of a revenue floor for hydrogen storage facilities (15-year risk-hedging contract). The floor would be set at a level that would allow the recovery of CAPEX, fixed OPEX and a relatively low return on investment [39]. The settlement of the contract would be dynamic. If the revenues of the storage facility are zero in a settlement period, it receives the floor revenues from the entity managing the support scheme. If revenues increase, the settlement would consider a gainshare mechanism that should encourage the storage operator to pursue an efficient commercial strategy and increase the sale of storage services. A schematisation of how this gainshare mechanism would work is shown in Figure 6. The British Hydrogen Storage Business Model (HSBM) would also include incentives to keep the asset available and to comply with the lag period. In an initial phase, the HSBM will focus on geological hydrogen storage.

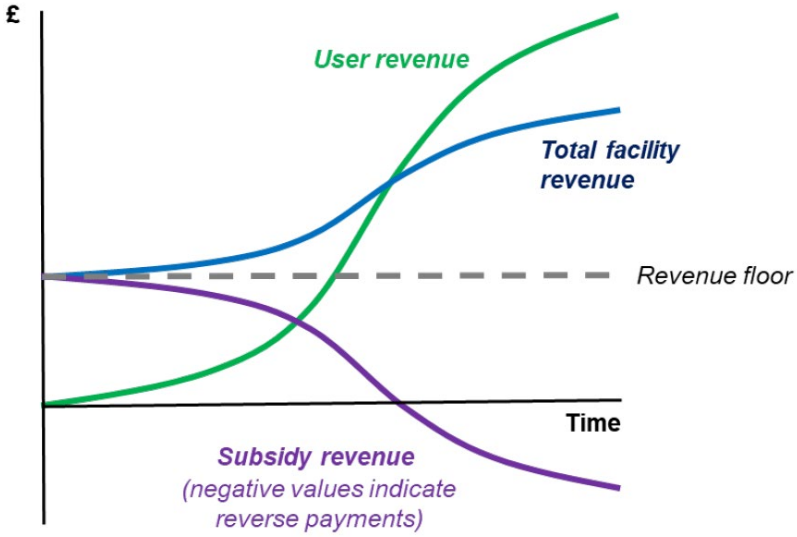

Figure 6. Gainshare mechanism proposed for the British Hydrogen Storage Business Model (chart from [39])

Hydrogen storage can also receive direct grants in the framework of cross-chain or inter-chain support schemes, such as the European Hy2Tech and Hy2Use programmes.

6.2 Transport/storage coordination

The deployment of the hydrogen network and storage facilities must be coordinated, particularly in the case of geological storage, whose construction is subject to geographical constraints. The British regulator has proposed a cohort assessment of transport and storage [40]. In a first phase, transport and storage projects will be assessed separately, although each project has to specify the agreements reached with developers of the other activity. Following the separate assessments, transport and storage projects will be paired and assessed in cohorts. Pairs are formed on the basis of the original agreements, but the regulator may also rearrange projects and create new pairs, where physically feasible. The final selection is based on the cohort assessment, not the separate assessments.

7 SUPPORT FOR CONSUMPTION

Low-carbon hydrogen consumption can be supported indirectly through production support schemes, as analysed in section 4.2.2, but it can also be the subject of specific consumption support schemes, which have been classified in this section into the four broad categories analysed below.

7.1 Decarbonisation support policies

Several countries have introduced support mechanisms for decarbonisation projects. Examples of these policies include the German Climate Protection Agreements [45] and the Dutch SDE++ scheme [46]. The German mechanism incentivises decarbonisation projects through a Carbon Contract for Difference (CCfD), which allows project developers to set a carbon price (strike price) they need to make the project viable. If the price of allowances in the EU ETS is lower than the strike price, the developer receives a variable premium. The Dutch mechanism, which pioneered this type of system-wide decarbonisation policies, is also designed to guarantee a fixed carbon price for decarbonisation projects.

These mechanisms can include specific quotas of the emission reduction target to be achieved by hydrogen projects. End users willing to decarbonise their industrial process through hydrogen, for example, can apply to decarbonisation support mechanisms and receive an economic stream that improves their willingness to pay for low-carbon hydrogen.

7.2 Quotas on end uses

Another way to incentivise hydrogen demand is to set quotas for specific end uses. For instance, the revised European Renewable Energy Directive (RED III) requires that 42% of hydrogen currently used in industry must be renewable by 2030 and 60% by 2035 [47]. It should be noted, however, that low-carbon hydrogen can have several different end uses. Quotas risk skewing the supply of hydrogen towards certain end uses, which may not be the most efficient, and different quotas should be coordinated to avoid a possible lack of hydrogen supply to meet all quotas.

7.3 Operational support for end uses

Low-carbon hydrogen end users may receive operational support in the same way as producers. This operational support can be made available regardless of the end use. For instance, Colorado [48] and Illinois [49], in the United States, have announced a 1 $\$/kgH_2$ tax credit for low-carbon hydrogen consumers. This type of support should be coordinated with support for hydrogen production in order to avoid a double remuneration. Other regulators provide operational support only for some specific end uses. Examples of such policies are the support mechanism that the British regulator is developing for Hydrogen-to-Power projects (H2P, i.e., electricity generation from hydrogen) [50], or the conditional payment mechanism that the German regulator has introduced to incentivise low-carbon hydrogen use in the steel industry [51].

7.4 Direct grants for switching

Hydrogen end users may also receive direct grants to cover the capital expenditure required to switch to hydrogen. In recent years, grants have been provided in the transport sector for the installation of hydrogen refuelling stations (Germany [52], Poland [53], Canada [54]), the procurement of hydrogen vehicles (Germany [52]), or the development of pilot projects on hydrogen rail mobility (Italy [55]). The steel industry has also received direct grants to replace blast furnaces with direct reduction plants and/or electric arc furnaces (Germany [52], Spain [56], Sweden [57], Italy [58]). Another sector that received direct grants to switch to hydrogen in the past is Combined Heat & Power (CHP) [59].

8 CROSS-CHAIN SUPPORT

Some hydrogen support schemes do not target a single element of the supply chain, but rather provide economic aid to a project that includes several elements of the chain, potentially creating a self-sufficient hydrogen environment from production to end use. The rationale behind these cross-chain mechanisms is to avoid all the coordination problems that could arise if separate support were provided to each element of the supply chain. These cross-chain projects should also help to demonstrate the financial viability of hydrogen applications.

The design elements of cross-chain support mechanisms are similar to those analysed so far. Some examples of cross-chain support are listed below.

- German scheme for Just Transition Fund regions [35] (electrolyser with grid connection plus hydrogen storage).
- Italian scheme for brownfield industrial areas [21] (electrolyser, hydrogen storage and renewable electricity generation).
- Spanish scheme for hydrogen valleys [37] (electrolyser plus hydrogen storage).
- Polish LOTOS green hydrogen project [60] (electrolyser, renewable electricity generation and battery storage to supply hydrogen to refineries).
- Lithuanian scheme to decarbonise fertiliser production [61] (electrolyser to supply low-carbon hydrogen to a fertiliser production process)
- The H2Hubs programme in the United States [62] (production, transport and end use).

9 ENABLING FRAMEWORK

There are several initiatives that, without providing explicit economic aid, can create a favourable environment for the development of the hydrogen economy, as analysed in this section.

9.1 National hydrogen roadmaps or strategies

National hydrogen roadmaps are published to demonstrate political commitment to the hydrogen sector and to improve investor confidence. They can set binding or non-binding targets for hydrogen production or electrolysing capacity and announce key initiatives that will be implemented to reach these targets. The Center on Global Energy Policy at Columbia University has a tracker of national hydrogen roadmaps [63] that can be consulted for more details.

9.2 International trade agreements

Another initiative that can promote the deployment of hydrogen is the signature of international trade agreements. These agreements usually take the form of a Memorandum of Understanding and do not contain binding commitments. Again, the aim is to create a favourable environment for investments. IRENA has published a comprehensive review of international trade agreements [64]. The majority of these agreements revolve around the two main import centres that are expected to attract most of the international hydrogen trade, i.e., Central Europe and Japan.

9.3 Certification and guarantees of origin

Certification schemes and guarantees of origin are a key element of any hydrogen strategy. Guarantees of origin are labels issued by a specific entity that should allow the recipient to sell the guaranteed product at a higher price than the market price; guarantees are usually based on thresholds that the product must meet to receive the guarantee. Certification schemes issue certificates indicating the environmental properties of a product for its participation in a particular scheme. However, the two terms are often used interchangeably in the hydrogen literature. Hydrogen support mechanisms may rely on these certification schemes to limit the participation.

The design of hydrogen certification schemes exceeds the scope of this article. An overview of hydrogen certification initiatives can be found in [65]. Further details on additionality rules and temporal and spatial correlations can be found in [66][67].

9.4 Matchmakers

The market for low-carbon hydrogen needs to be developed from scratch. In order to improve the visibility of the hydrogen sector and to help actors identify potential collaborations, some jurisdictions have created specific matchmakers, i.e., map-based websites showing the location of hydrogen production and consumption projects. One example is the H2 Matchmaker created by the Hydrogen and Fuel Cell Technologies Office in the United States [68].

10 CONCLUSIONS

The International Energy Agency [69] recently highlighted that the hydrogen industry is at the technology development stage where wind and solar were two decades ago and urged governments to use the experience gained from supporting renewable energy to target economic aid to low-carbon hydrogen in the most efficient way. To this end, this article presents a comprehensive taxonomy of support mechanisms for low-carbon hydrogen. The classification is based on a global review of international experience covering more than 20 jurisdictions in different regions of the world. The aim of this classification is to identify the key design elements of these mechanisms, which represent the main choices that the regulator has to make when introducing them. This approach allows to capture the wide variety of designs that can currently be observed worldwide. In this article, hydrogen support has been divided according to the supply chain element it targets (production, transport, storage, consumption, and cross-chain mechanisms). The design elements that characterise hydrogen support schemes have been divided into technical requirements and eligibility criteria, type of support and product design, selection process and auction design, and cost allocation.

The majority of hydrogen support mechanisms target production, consumption and cross-chain projects, while there is limited experience of support for hydrogen transport and storage. For hydrogen production support, the review shows that risk-hedging contracts predominate over direct grants. The three main designs of risk-hedging contracts are fixed price, fixed premium and variable premium. The article highlights the complexity of designing these contracts in the absence of a reference market for low-carbon hydrogen, and the risk of segmenting the new hydrogen market by supporting production/end use pairs or limiting the end uses that can be supplied by supported hydrogen.

As regards hydrogen consumption support, the most widespread design at this stage is direct grants to cover the costs of switching to hydrogen, especially in the industrial and mobility sectors. In the future, decarbonisation policies, based on CCfDs or other designs, may take the lead and improve the end-user willingness to pay for low-carbon hydrogen. Each jurisdiction should ensure that support schemes for hydrogen production and consumption are appropriately coordinated to avoid the risk of overcompensation.

Initial experience with hydrogen transport support shows the importance of targeting economic aid to reduce the charges for the use of transport services that first movers in the hydrogen sector may face. In the storage segment, regulators stress the need to guarantee a floor to the revenues of hydrogen storage operators, whose market revenues depend on the development of the whole sector and are subject to large uncertainties.

This article classifies hydrogen support mechanisms and identifies some trends based on international experience, but does not provide a critical assessment of the different designs. Once these support schemes are operational and the first data on their performance are available, future work should identify the advantages and disadvantages of each design for each element of the hydrogen supply chain. The best design for hydrogen support will depend on the characteristics of each energy system and the key objectives of the regulator, but it is critical to alert policymakers to the impact that each of the design elements may have on the effectiveness of hydrogen support mechanisms.

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