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A Bank to Boost Renewable Hydrogen

In search of policies to establish a first-mover-advantage

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Renewable hydrogen is in the midst of an upscaling process in the EU and worldwide. But revenue uncertainty and coordination externalities in market development threaten to restrain Europe in this race. Policymakers need new means to counter the disincentive of the "second-mover advantage" and initiate long-term investments. In this spirit, the Commission is currently launching a new funding instrument, the European Hydrogen Bank.

Key propositions:

- The auctioning of production premiums for renewable hydrogen implemented by the European Hydrogen Bank fills a gap in the hydrogen funding landscape. **It could become an effective tool for stimulating capacity-building** by providing compensation for system-wide cost and revenue uncertainties. However, the terms and conditions of the auction applicable in the pilot phase risk giving rise to **excessive support for large hydrogen producers** and generally low support efficiency.
- **The maximum permitted bidding level (ceiling price) should be reduced significantly**. At the same time, participation should be opened up to smaller producers to generate more competition. The conditions for cumulation with other subsidies should also be reviewed, to avoid the risk of the Hydrogen Bank contributing to a sectoral misallocation of renewable hydrogen.
- The premium scheme can only be effective if it is embedded in a **holistic support framework addressing bottlenecks in all parts of the supply chains**. The establishment of an H_2-certification system, the reduction of barriers to infrastructure investment and the promotion of the industrial transformation all remain key policy priorities for market formation.

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1 Background

The EU's ambitious goal of decarbonizing production while preserving its industrial base will require it to draw on the full range of climate-friendly technologies. In this respect, hydrogen produced by means of renewable sources represents an indispensable piece of the puzzle by creating an opportunity to decarbonize particularly emission-intensive hard-to-abate sectors like steel and parts of the chemical industry. In general, the current conditions for the establishment of a European hydrogen economy are favourable. A significant rise in the price of CO_2-allowances, expected in the nearer future, increases the incentive for timely investment in low-emission technologies. Natural gas will remain a scarce and therefore expensive resource for large parts of Europe in the years to come, which will push back fossil-based hydrogen production in the medium-term. And the strong global increase in demand for electrolysers implies that economies of scale can be expected to result in a significant reduction in the capital costs of electrolytically produced hydrogen. In fact, recent simulations suggest that, in a cost-optimal system, long-term EU hydrogen demand could be met entirely by domestic sources.[1]

Nevertheless, systemic uncertainty remains a stumbling block. The fact that not only hydrogen production capacities but entire supply chains - from infrastructure to end applications - need to be established from scratch creates a considerable coordination problem. Due to the lack of interregional markets, that could perform a coordinating role, no decentral mechanism exists to overcome this. In the absence of external stimulus, one individually beneficial strategy may be to wait for further developments. Such a "second-mover advantage"[2] would delay domestic market development and increase the risk of creating new dependencies for Europe in the long term. A global race to build up production capacities and reduce the cost of long-distance hydrogen transport has long since emerged. This increases the pressure on Europe to scale up quickly.

The Commission has recently provided important impetus with, among other initiatives, the development of a legal definition of renewable hydrogen, the initiation of a certification system, and proposals for a reform of the internal gas markets. However, still missing are direct incentives for the expansion of production, and thus for a rapid realization of economies of scale that are crucial for long-term competitiveness. The European Hydrogen Bank is now dedicated to filling this gap by auctioning production premiums for renewable hydrogen. The first Pilot Auction will start in November 2023.

In this cepInput, we examine the incentive effects of this instrument and its role within a holistic support framework. We first examine the underlying conditions for establishing a European hydrogen economy and identify the current barriers to rapid market development. We then analyse the effectiveness of the new incentive instrument in terms of investment incentives using a Real Options approach. The investor perspective is complemented by a discussion of its wider implications for the burden on government budgets and the overall efficiency of hydrogen production in Europe. From this we derive some proposals for a modification of the auctioning conditions. Finally, we place the Hydrogen Bank in the overall framework of hydrogen-related transformation policies and identify key areas of action for a rapid development of H_2-supply chains in Europe.

1 Fleiter, T., Al-Dabbas, K., Clement, A., & Rehfeldt, M. (2023). METIS 3, study S5. The impact of industry transition on a CO_2-neutral European energy system. Report for the European Commission.

2 Odenweller, A., Ueckerdt, F., Nemet, G. F., Jensterle, M., & Luderer, G. (2022). Probabilistic feasibility space of scaling up green hydrogen supply. Nature Energy, 7(9), 854-865.

2 Scenarios for European hydrogen markets

2.1 Demand projections and investment needs

Despite the marked upsurge in political attention in recent years, commercial hydrogen production from renewable sources is still in its infancy. At the global scale, less than 1 % of the hydrogen currently used stems from renewable sources.[3] Moreover, beyond pilot projects, the application of hydrogen is still almost exclusively limited to traditional fields. These are the chemical industry and the mineral oil processing industry. In the chemical industry, pure hydrogen is used together with nitrogen to produce ammonia and other fertilizers derived from it. In combination with carbon monoxide, hydrogen is used to produce the important basic chemical methanol. In the mineral oil industry, hydrogen is utilized both as a raw material and as an energy carrier in the processing of crude oil. In various hydrogenation processes, hydrogen is used to remove impurities, especially sulphur.[4]

In the EU, hydrogen accounted for less than 2 % of total energy consumption in 2022. Around 96 % of the hydrogen used was produced as so-called "grey" hydrogen by steam reforming of natural gas, a process accompanied by considerable CO_2 emissions.[5] Another significant and likewise emission-intensive production route is the gasification of hard coal ("black" hydrogen) or lignite ("brown" hydrogen). Despite numerous successful pilot projects[6], the electricity-based production of hydrogen by means of electrolysis is still in the start-up phase in the EU.

On the demand side, two levers are crucial for accelerating the future expansion of electrolysis capacities in Europe. One is a technology switch in the existing fields of application which primarily applies to basic chemicals. A switch to electrolysis for producing the hydrogen used as a raw material for ammonia and methanol offers major decarbonization potential because both chemical feedstocks will be in high demand. As the world's population grows, global demand for fertilizers will increase significantly, putting ammonia in a key position as the basis for nitrogen fertilizers.[7] Its use as a transport medium for the long-distance transport of hydrogen by ship will also gain strategic importance in the future. In a decarbonized world, green methanol will play an important role as a raw material for producing plastics and synthetic fuels, among other materials.

One advantage of the fact that hydrogen is already used as a raw material in the chemical industry today is the existing local infrastructure, in particular the existence of hydrogen pipelines as a means of transport over medium-sized distances. A specific challenge in the switch to electrolysis-based hydrogen, however, is the procurement of raw materials that have so far been obtained as co-products in the context of fossil-based hydrogen production. For example, the carbon source required to produce methanol from hydrogen must be extracted from other processes. The development of corresponding supply routes raises investment needs. To achieve climate-neutrality from a supply chain perspective, this carbon source would have to come from biogenic sources (or in the long term: be obtained via air capture), which involves additional hurdles for the technology switch[8]. Against this

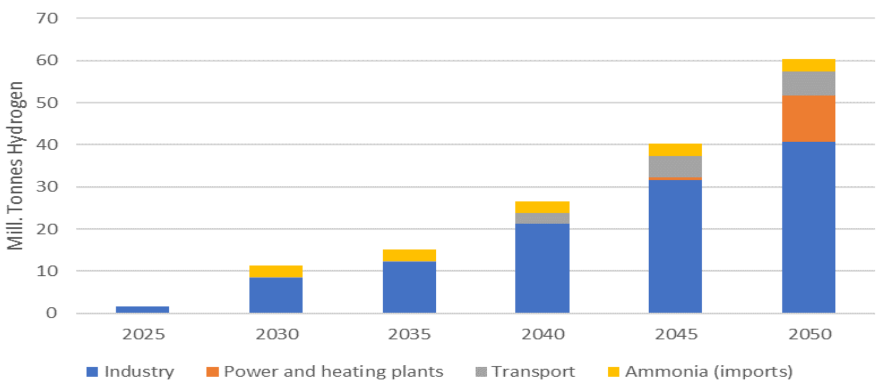
3 IEA (2023a). Tracking hydrogen. International Energy Agency.
4 IEA (2019). The future of hydrogen. International Energy Agency.
5 European Commission (2023a). Energy, Climate Change, Environment - Hydrogen.
6 Wolf, A. (2023a). Establishing hydrogen hubs in Europe. cepInput No.1/2023.
7 IRENA (2022). Green hydrogen for industry – a guide to policy making. International Renewable Energy Agency.
8 See IRENA (2022).

background, the National Hydrogen Council of Germany is not expecting renewable hydrogen to really get going in the chemical industry in Germany before 2030.[9]

The second lever for market development is a demand increase through expansion of the existing range of applications for hydrogen. In the short term, the steel industry in Europe will be a key driver for this. In the H_2-based direct reduction process, hydrogen is used as a reduction agent for iron ore. The sponge iron obtained must then be melted into crude steel in an electric arc furnace using large amounts of electrical energy. Provided that both the hydrogen and the electricity used are generated in a low-emission manner, this process enables a significant reduction in emissions compared with the currently dominant method of steel production which uses coking coal as a reducing agent. In other energy-intensive industries such as glass and paper, low-emission hydrogen could replace natural gas as an energy carrier in the future. However, there is strong technological competition with the direct use of electricity, which is largely more efficient due to the shorter process chain. The medium-term utilization potentials are therefore classified as comparatively low and limited to high-temperature processes.[10] Moreover, in the energy system, hydrogen can be used as a storage medium for electricity and - through its use in H_2-ready power plants - as an energy carrier for the generation of electricity and heat. Finally, in the transport sector, applications focus on heavy goods transport and aviation and shipping. In addition to fuel cell mobility, potential also lies in renewable hydrogen-based synthetic fuels used in shipping (green methanol, green ammonia) and aviation (synthetic kerosene).

Figure 1 shows a current long-term forecast by Fraunhofer CINES on the development of overall European demand for hydrogen, obtained by a market-based multi-period planning model of the European hydrogen and natural gas infrastructure.[11] Accordingly, demand growth until 2030 will be less dynamic than expected by the EU (approx. 11 million tonnes of hydrogen instead of the 20 million tonnes expected by the EU) but will develop more strongly in the longer term. The main driver in both the short and the long term is the industrial sector, above all steel and chemicals (with ammonia purely sourced from imports). The transport sector will be of relevance in the medium term, and the energy sector will further stimulate demand after 2040.

Figure 1: Forecast EU hydrogen demand by sector



Source: Fraunhofer CINES (2023); own illustration

9 Nationaler Wasserstoffrat (2023). Treibhausgaseinsparungen und der damit verbundene Wasserstoffbedarf in Deutschland. Grundlagenpapier, 1.Februar 2023.

10 See IRENA (2022).

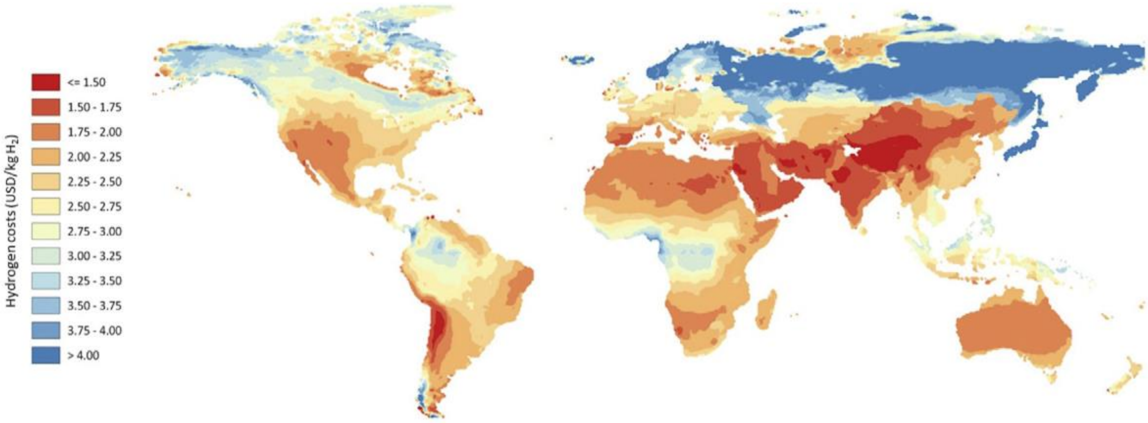
11 Fraunhofer CINES (2023). Clean hydrogen deployment in the Europe-MENA region from 2030 to 2050 - A technical and socio-economic assessment. Fraunhofer Cluster of Excellence “Integrierte Energiesysteme”.

Such an exponential growth in demand involves enormous investment requirements. Deloitte estimates the cumulative global investment needs of emerging H_2-supply chains (production, applications, storage, transport) at 9.4 trillion US dollars for the period up to 2050. Renewable hydrogen is expected to account for more than 75 % of this.[12] The ability of European hydrogen production to attract a significant share of these investments depends on two interrelated questions.

The first question is how the relative competitiveness of distinct types of hydrogen will evolve. Renewable hydrogen is not only competing with traditional forms of hydrogen production, but also with other innovative, low-emission approaches. Firstly, there is competition with "blue" hydrogen, i.e. hydrogen produced by means of steam reforming or coal gasification and subsequent CO_2 capture. Although this technology cannot be described as completely climate-neutral (methane emissions in gas transport) and does not end dependence on fossil resources, its advantage lies in the fact that it does not require a complete conversion of the generation process. In addition, it is not dependent on a naturally fluctuating supply source like electricity from wind and sun. Secondly, there is competition with "red" hydrogen, i.e. hydrogen produced on the basis of electrolysis using nuclear power. This technology is also not completely climate-neutral, but is less costly to manage than renewable hydrogen, likewise due to the more stable energy source. In the future, renewable hydrogen will also have to compete with further low-emission forms of production such as turquoise (pyrolysis of methane) hydrogen.

The second question is how well renewable hydrogen from Europe will be able to compete with non-European imports in the medium-term future. The fact that other regions, some of which are close to Europe (e.g. MENA), have locational advantages in the generation of electricity from wind and sun due to their climatic conditions, represents a competitive disadvantage (see Figure 2). The crucial question is to what extent the existence of transport costs and the advantage of proximity to important sales markets can compensate for this disadvantage in the long term. The answer to both questions requires forecasts on the development of costs.

Figure 2: Forecast hydrogen production cost from hybrid solar PV and wind systems in 2030



Source: Acosta et al. (2022)[13]

[12] Deloitte (2023). Green hydrogen: Energizing the path to net zero. Deloitte's 2023 global green hydrogen outlook.

[13] Acosta, K., Salazar, I., Saldaña, M., Ramos, J., Navarra, A., & Toro, N. (2022). Chile and its potential role among the most affordable green hydrogen producers in the world. Frontiers in Environmental Science, 10.

2.2 Evolution of production and transport costs

In the absence of transparent markets, there are currently no Europe-wide reference prices for trading low-emission hydrogen. At the national level, the HYDRIX index of the European power exchange EEX has recently become the first reference for trading in renewable hydrogen across Germany.[14] Public rule-of-thumb estimates for prices currently paid in Germany and the Netherlands comprise a spectrum from 7 to 8 EUR/kg of renewable hydrogen.[15]

The Levelized Costs of Hydrogen (LCOH) are usually applied as a benchmark for evaluating the relative competitiveness of different forms of hydrogen production. They measure the total production costs (fixed and variable costs) per kg of hydrogen. They differ from delivery prices in that they do not include transportation costs, taxes, and excess profits. According to the global hydrogen review of the International Energy Agency (IEA), hydrogen from wind or solar power could become cost-competitive with grey and brown hydrogen in some global regions by 2030. Cost reduction potentials are also expected to be stronger than for red hydrogen, making the use of electricity from renewables competitive in some regions until 2030. Compared with blue hydrogen, however, a universal cost disadvantage is predicted for 2030. Despite additional long-term cost reduction potentials, this disadvantage is going to persist in some regions even until 2050.[16]

For the EU region, the latest estimates tend to be more optimistic. The main reasons for this are the politically induced dynamics in the expansion of renewable energies, the expected increase in the CO_2 price and long-term uncertainty related to the availability of natural gas for hydrogen production. CRU analysts predict that the production of renewable hydrogen in the EU will be cheaper than the production of grey and blue hydrogen from 2035 onwards.[17]

However, an important premise behind these and other forecasts is that cost development will be characterized by economies of scale over time through fixed cost degression and learning effects. This is based on the assumption that large-scale investment in generation capacities is made today rather than in 2035, even if renewable hydrogen is not yet price competitive. **From a societal perspective, the development of a hydrogen economy is thus mainly a problem of transition management.**

At the same time, the EU is engaged in a global race with many other world regions that are investing heavily in supply chains for renewable hydrogen, with some of them exhibiting natural cost advantages (availability of wind and solar energy). Currently, the high costs of the interregional transport of hydrogen still represent a protection for EU-internal production. Basically, a total of four transport technologies for the transport of larger quantities of hydrogen are currently considered to have a promising future. For overland transport, pipelines are clearly favoured. The conversion of existing natural gas pipelines, in particular, offers an option for rapid infrastructure expansion.[18] For sea transport by ship, three main variants are being investigated: transport as liquid hydrogen, transport by means of liquid organic carriers, and transport after conversion into ammonia. Currently, all these technologies are

[14] EEX (2023). EEX hydrogen index. European Energy Exchange.
[15] Hydrogeninsight (2023). How much does a kilogram of green hydrogen actually cost? Well, it's complicated.
[16] IEA (2023b). Global hydrogen review 2023. International Energy Agency.
[17] CRU (2023). Energy from green hydrogen will be expensive, even in 2050. Posted 24 February, CRU Group.
[18] EHB Initiative (2023). European Hydrogen Backbone Maps. European Hydrogen Backbone Initiative.

associated with considerable fixed costs and energy consumption required for the necessary conversion steps prior to transport.[19]

Current forecasts expect a significant reduction in these costs through scaling and learning effects. They disagree on whether this will be sufficient to make intercontinental hydrogen transport competitive in the foreseeable future. While Aurora (2023)[20] believes that price competitiveness of hydrogen from Chile and Australia transported to Europe by ship will be achieved as early as 2030, Galimova et al. (2023)[21] predict that long-distance transport to Europe will still not be able to compete with domestic production by 2050. Fraunhofer CENIS (2023)[22] identify a business case for hydrogen imports from the MENA region by 2030, provided that the bulk of transport volumes is handled by pipelines.

In any case, shrinking transport costs imply that the cost disadvantages of domestic hydrogen compared to imports will be increasingly reflected in future price offers. **Domestic production can only survive this trend if it stays one step ahead in the exploitation of economies of scale.** Thus, the speed of capacity-building in production and infrastructure will be crucial for the evolution of cost differentials not just across technologies, but also across regions. **A rapid development of domestic supply chains for renewable hydrogen is therefore essential in two respects**:

1) To quickly guide renewable hydrogen into its long-term profit zone and thus break the fossil lock-in (→ **elimination of existing dependencies**).
2) To avoid creating new one-sided external dependencies in a strategic segment of the climate-neutral energy system (→ **avoidance of new dependencies**).

To be effective, policy instruments designed to support this development must address the specifics of the cost situation of renewable hydrogen.

3 Barriers to investment in renewable hydrogen production

3.1 Cost determinants

The evolution of the LCOH is governed by a complex interplay of technological and economic factors. To achieve the cost reductions necessary to make renewable hydrogen competitive, capital and operating costs need to be significantly reduced in the future. Capital costs comprise the expected return (interest payments on debt and market return on equity) and depreciation on investments in equipment for water electrolysis. Operating costs comprise the cost of inputs needed in the operation of the electrolysers.

First, costs depend on the choice of electrolyser, i.e., the device needed to split the water molecules into hydrogen and oxygen. By now, three basic types of electrolysers have received the most attention commercially, distinguished by the nature of the electrolysis cells: Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane Electrolysis Cells (PEMEC) and Solid Oxide Electrolysis Cells (SOEC). The AEC technology is the oldest method of water electrolysis. It requires low investment per kW, since no

[19] Roland Berger (2021). Hydrogen transportation – the key to unlocking the green hydrogen economy. Roland Berger Focus.
[20] Aurora (2023). Renewable hydrogen imports could compete with EU production by 2030. January 23, Aurora Energy Research.
[21] Galimova, T., Fasihi, M., Bogdanov, D., & Breyer, C. (2023). Impact of international transportation chains on cost of green e-hydrogen: Global cost of hydrogen and consequences for Germany and Finland. Applied Energy, 347, 121369.
[22] See Fraunhofer CINES (2023).

expensive metals are used in its construction, and it is durable. However, the conversion efficiency (i.e. amount of electricity needed per kg of hydrogen produced) is relatively low and operations are not very flexible. Operating costs are thus relatively high. PEMEC technology achieves higher efficiencies and is more flexible in operation. However, the use of precious metals such as platinum and iridium in production raises purchasing prices.[23] The SOEC-technology is currently the least mature technology, operating in high-temperature mode. It offers the potential to unify very high conversion efficiencies with low material costs and initial large-scale applications have proven to be successful.[24] However, the high temperature mode is associated with technical issues, especially heat use and material degradation. Moreover, the current low production volumes imply very high purchasing prices.[25] Given these trade-offs, the choice of electrolyser technology crucially depends on expected operation modes.

For the future, the upscaling of hydrogen production is expected to yield significant cost reduction potentials in the production of electrolysers. This includes economies of scale in manufacturing (fixed costs degression), efforts to reduce the intensity of platinum and iridium use as catalysers in the PEMEC technologies and learning effects in system operation.[26] With the current pipeline of projects, the IEA expects a 60-70 % reduction in the costs of an installed electrolyser by 2030.[27]

Besides the conversion efficiency of electrolysers, another very relevant factor for operating costs is the electricity price. As a rule-of-thumb for current electrolysis technology, an electricity intensity of 50 kWh per kg of hydrogen is found in the literature.[28] The European Hydrogen Observatory estimates current wholesale electricity costs for grid-connected electrolysis for most EU countries to be in a range of about 1 Euro per kg of hydrogen, amounting to a share of 20 to 50 % of total LCOH.[29] Given the currently high volatility and long-term uncertainty on EU electricity wholesale markets, these estimates only provide a short-term view. Besides autonomous on-site electricity production, a promising way of eliminating electricity price uncertainty is the conclusion of long-term Power Purchase Agreements (PPAs) with external suppliers of electricity from renewables. The long-term purchase guarantees involved in these contracts allow for a price reduction as compared to spot market prices. The other components of variable operating costs, water, and auxiliary materials (e.g., nitrogen and lye), are estimated to amount to a negligible cost share.[30] Network charges and taxes as state-related cost components differ by Member State.

Moreover, one inherent aspect of electricity as an input also plays an important role regarding capital costs. Natural volatility in the production of wind and PV electricity used in electrolysis is a factor that needs to be accounted for in capacity planning. To capture supply peaks, high electrolyser capacities are required, which in turn lead to low average utilization rates raising capital costs per kg of hydrogen.

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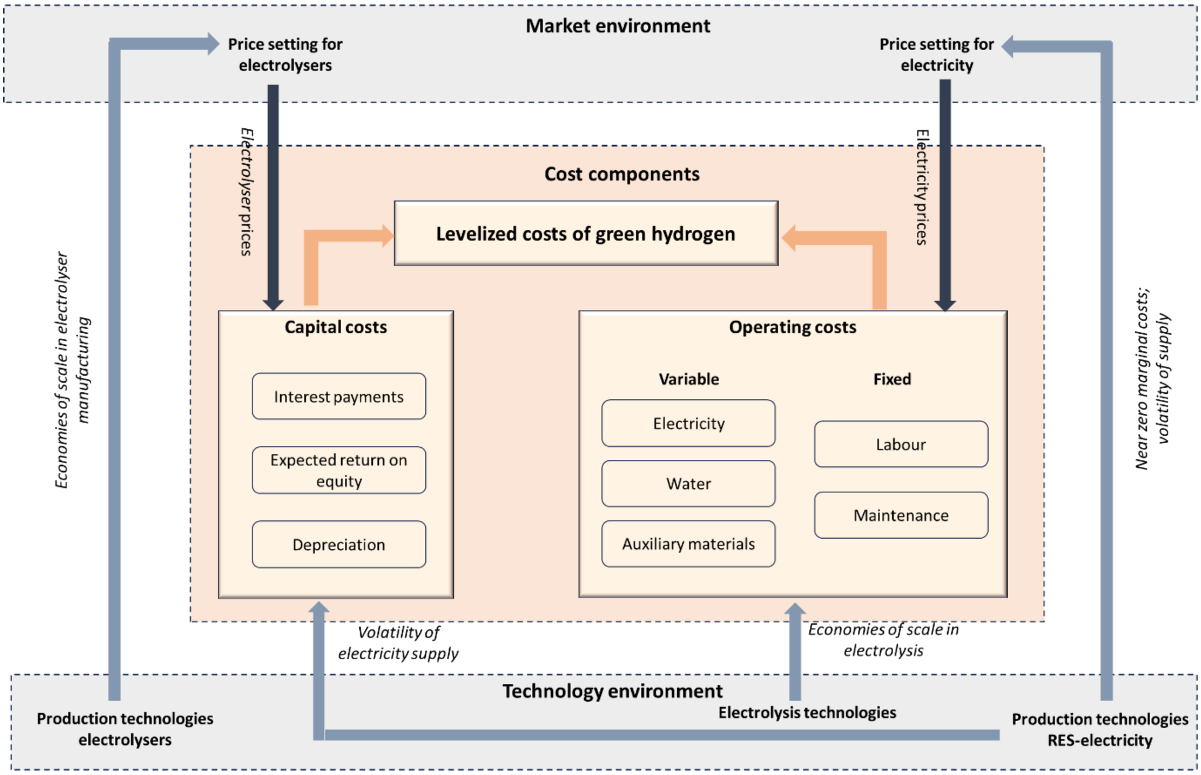
23 Hydrogen Newsletter (2023). A comprehensive analysis on PEM electrolyzer vs AEM electrolyzer.
24 Hydrogen Tech World (2022). World's largest SOEC electrolyzer achieves record efficiency.
25 Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. International Journal of Hydrogen Energy, 42(52), 30470-30492.
26 Badgett, A., Ruth, M., James, B., & Pivovar, B. (2021). Methods identifying cost reduction potential for water electrolysis systems. Current Opinion in Chemical Engineering, 33, 100714.
27 See IEA (2023).
28 Carbon Commentary (2021). Some rules of thumb of the hydrogen economy.
29 EHO (2023). Cost of hydrogen production. European Hydrogen Observatory. https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production
30 Kuckshinrichs, W., Ketelaer, T., & Koj, J. C. (2017). Economic analysis of improved alkaline water electrolysis. Frontiers in Energy Research, 5, 1.

In its delegated act on renewable fuels, the EU has defined clear requirements for the temporal and spatial correlation of electrolysis and electricity generation patterns.[31] Maximizing operating hours of electrolysers under these conditions will be crucial for the future competitiveness of renewable hydrogen, especially in relation to red hydrogen, which does not exhibit this volatility problem. Storage solutions can offer a remedy but give rise to additional capital and maintenance costs.

Finally, hopes for future economies of scale not only rest on electrolyser manufacturing but also on operation. Cumulative experience in production should improve the efficiencies of existing technologies and thus reduce the required electricity consumption per kg of hydrogen. Improvements in the durability of materials, especially in high-temperature electrolysis, can be a further beneficial result of learning processes. Figure 3 summarizes the relevant cost components and their influencing factors.

Figure 3: Central cost determinants of renewable hydrogen production



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3.2 Uncertainties

The description of cost determinants has uncovered significant uncertainties related to future prices and availability of electricity (*input uncertainties*) as well as to future costs of electrolysers and conversion efficiencies (*technological uncertainties*). However, besides these risks directly associated with the electrolysis process, there is a more fundamental systemic risk on the sales side. Currently, Europe and other parts of the world are in the process of not just increasing production capacities of renewable hydrogen but designing whole new hydrogen supply chains. Under these conditions, the buildup of production capacities can only be profitable if both investments in the necessary transport

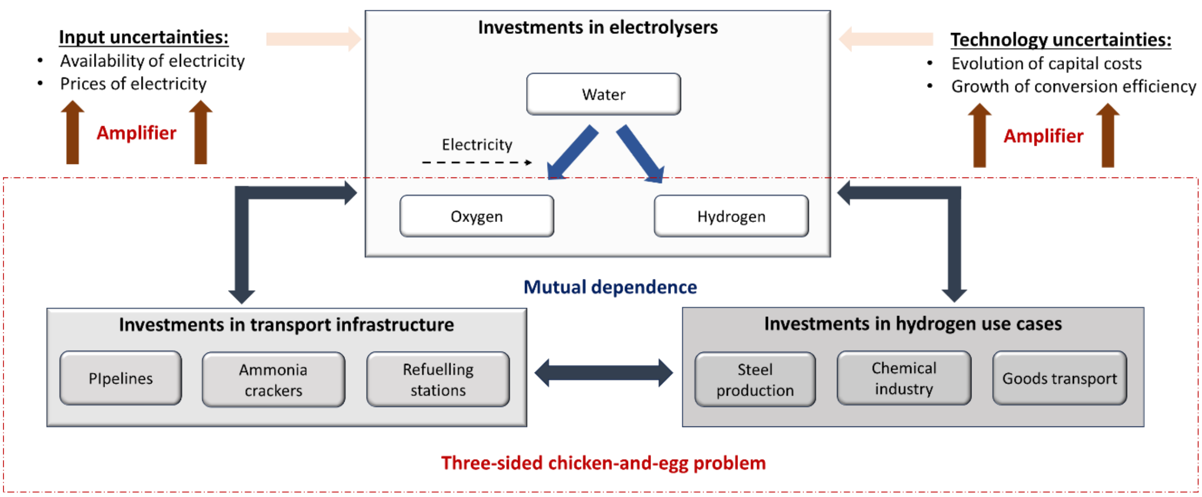
[31] European Union (2023a). Commission delegated regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin.

infrastructure (primarily pipelines within Europe) and in H_2-application technologies in industry and transport (see Section 2.1) keep pace with capacity development. Here, too, considerable sums are at stake: The European Hydrogen Backbone Initiative has developed a vision for a European hydrogen pipeline network that requires an estimated total investment of 80-143 billion EUR by 2040.[32]

Agents on the user side and in network operation face the same kind of uncertainty. Their capacity planning is based on assumptions about the development of production capacities, whose implementation they themselves cannot control. This systemic uncertainty has a direct effect on the return to present investments. It generates downside risks that not only reduce expected revenues, but also increase the cost of capital via risk-dependent interest rates. **The result is a three-sided chicken-and-egg problem between hydrogen production, distribution, and use.**[33] Since these components are interdependent in their development and centralized (negotiations, sovereign control) or decentralized (markets) coordination mechanisms are still underdeveloped, there is a natural tendency towards a wait-and-see attitude on all sides.

The first-mover advantage, which is a frequent characteristic of emerging markets, is thus reversed. Odenweller et al. (2023) rightly speak of a "second-mover advantage" instead. Under these circumstances, reticence in the initial phase generates information advantages about the actual speed of the transformation. Since hydrogen is a completely homogeneous product in terms of its properties, there is also no concern that first movers could pursues strategies of monopolization through branding. On producers of renewable hydrogen, this second-mover advantage has a particularly strong effect. This is because the systematic uncertainty reinforces the production-specific uncertainties. Lack of substantial knowledge about the future development of demand not only creates sales risks, but also increases uncertainty about future cost reductions through scale economies (technological uncertainties). In addition, it represents a further unknown parameter in the long-term development of electricity demand, and thus also in the evolution of market prices for electricity (input uncertainties). Figure 4 summarizes the problem.

Figure 4: Uncertainties and their interplay in the hydrogen supply chain



Source: own illustration

32 See EHB Initiative (2023).
33 See Odenweller et al. (2022).

To break this vicious cycle, external regulatory impulses are required. Given the time pressure exerted by the climate targets for the transformation of production technologies, these impulses should not be limited to a specific market side but address all stages of future supply chains with equal directness. In doing so, one difficulty is to avoid excessive support for specific groups of agents, which would provide them with artificial competitive advantage. Moreover, measures should be designed from the outset to be temporary, rendering themselves superfluous through their effectiveness over time. Both conditions demand that natural cost advantages existing within the boundaries of a climate-neutral system are allowed to unfold freely in the current phase of market formation. **Consequently, from the perspective of regulators as well, a major challenge lies in coordination - the coordination of different policy instruments on different levels of decision-making.**

4 Overview on support instruments

4.1 Categorization

The set of instruments to promote the development of a hydrogen economy is as diverse as the emerging hydrogen supply chains themselves. Figure 5 provides an overview of instruments conceivable at different stages of a supply chain. A key target of the support provided in the EU to date has been investment in electrolysis capacities. The aim is to reduce capital unit costs, which are still high at the beginning of the scaling-up phase (see Section 3.1), to accelerate the build-up of production capacity. This can be achieved by direct public subsidies to acquisition expenditures for electrolysers, or by lowering the interest costs for invested debt capital through favourable government loans or government guarantees. Another form of investment-related support concerns the approval procedures for electrolysis plants. Depending on the national frameworks, these can affect a variety of legal areas such as immission control, water law or nature conservation. Possible forms of support range from the publication of guidelines and the establishment of administrative one-stop shops to measures to simplify and accelerate the procedures themselves.

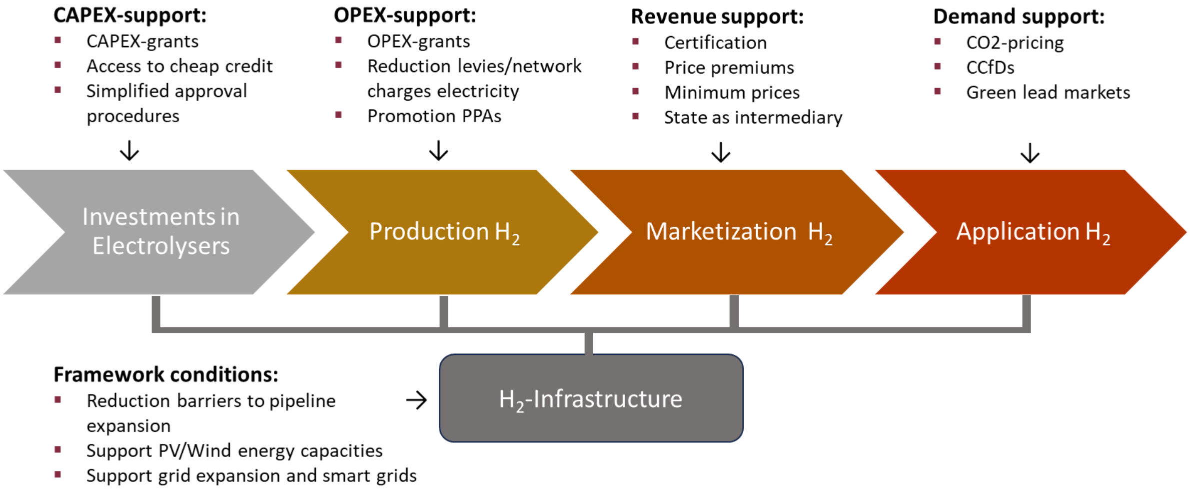
This is to be distinguished from measures that target hydrogen production. In this case, the direct impact is a reduction in OPEX, which is intended to increase the price competitiveness of hydrogen. Promotion could refer to OPEX as a whole or specifically to electricity costs as a central cost component (see Section 3.1). On the one hand, this could involve a reduction or abolition of the levies and charges that are regularly levied on the purchase of electricity. On the other hand, the market-side costs of electricity procurement could be reduced by providing government support (e.g., through subsidies) for long-term power purchase agreements (PPAs). In connection with purchase guarantees, such long-term contracts not only enable lower electricity prices, but also a reduction in cost-relevant uncertainty due to the longer-term price hedging.

Another starting point is the marketing of hydrogen. The goal is to create an improved revenue base that renders the initially high levelized cost economically viable. An indirect way to achieve this is the development of a uniform certification system for sustainably produced hydrogen based on regulatory criteria. In this way, a signal effect is created on the market, which allows to exploit an increased willingness to pay for sustainable hydrogen on the part of customers. At the same time, such a certification also forms the basis for comparable labels for downstream products, and thus the possibility of allowing sustainability preferences on the part of end consumers to disseminate throughout the entire supply chains.

More direct forms of support can take the form of government-backed minimum prices or premium payments, such as those being launched in the EU with the European Hydrogen Bank (see Section 4.3). In the most interventionist form of support, the state itself becomes an intermediary by initially buying expensive hydrogen at high prices and then selling it to consumers at lower prices.

Public support can also target the demand side. For the market development phase, large-scale industrial applications are particularly worthy of consideration. To incentivize the necessary investments in the technology switch, additional measures to promote the costs (e.g., via Carbon-Contracts-for-Difference[34]) and revenues (e.g., via procurement quotas for low-emission products) of H_2-application technologies can be taken in addition to the market-related instrument of CO_2-pricing. Finally, an equally important starting point against the background of the chicken-and-egg problem (see Section 3.2) is the promotion of infrastructure development. To accelerate the development of pipeline infrastructure, existing profitability barriers for network operators (e.g., regarding requirements for unbundling of natural gas and hydrogen-related businesses) can be removed. Electricity-related infrastructure is just as important for the adequate and reliable supply of renewable electricity. This concerns the expansion of generation capacities as well as the improved integration of volatile wind and PV power through grid expansion and measures to strengthen demand-side flexibility.

Figure 5: Overview of support instruments for different stages of hydrogen supply chains



Source: own illustration

In addition to differences in the immediate target, instruments must be distinguished according to other dimensions. In the case of financial support, for example, the criteria used to determine the level of support are relevant. The level could be directly determined by law, through bilateral bargaining or be the result of market-based procedures such as auctions. The choice of the mechanism can be decisive for economic efficiency. Another dimension concerns the types of quantitative restrictions set to support volumes. For example, support could be limited to a certain amount of production capacity to

[34] Wolf, A. (2023b). Market instruments for a climate-neutral industry. cepInput No. 7/2023.

be created, or to a regular amount of annual production. Finally, the subsidy budget itself may be capped, as is the case with the European Hydrogen Bank (see Section 4.3).

4.2 Current production support in the EU

At the EU level, the publication of the **European Hydrogen Strategy** in 2020 was the starting point of new ambitious policy initiatives for the roll-out of a European hydrogen economy. It focused on the cross-sectoral use of renewable hydrogen and defined concrete targets (40 GW of electrolysis capacity in 2030).[35] In this context, the *European Clean Hydrogen Alliance* was created as an instrument for better coordination of stakeholders and investment projects. In December 2020, 22 EU Member States and Norway committed themselves in a manifesto to building European value chains in the field of "Hydrogen Systems and Technologies" and announced the deployment of *Important Projects of Common European Interest* as an instrument for this purpose.[36] An initial technology wave called *Hy2Tech* saw 41 such cross-border projects approved by the European Commission in July 2022. The approval of a second wave of *Hy2Use* projects with a total volume of more than 5 billion EUR, focusing on application technologies and infrastructure, took place only a short time later in September 2022.[37]

The energy crisis sparked by the Ukraine war has fuelled further activity. Renewable hydrogen is expected to make a significant contribution to the decarbonisation of European process chains in the medium term. In May 2022, the European Commission formulated, for the first time, concrete volume targets for the production of renewable hydrogen, as part of its **RePowerEU** plan: By 2030, 10 million tonnes of renewable hydrogen will be produced in the EU, supplemented by imports also amounting to 10 million tonnes. For this purpose, the Commission is aiming, among other things, to double the number of Hydrogen Valleys in Europe by way of increased funding activities under the *Horizon Europe* umbrella.[38]

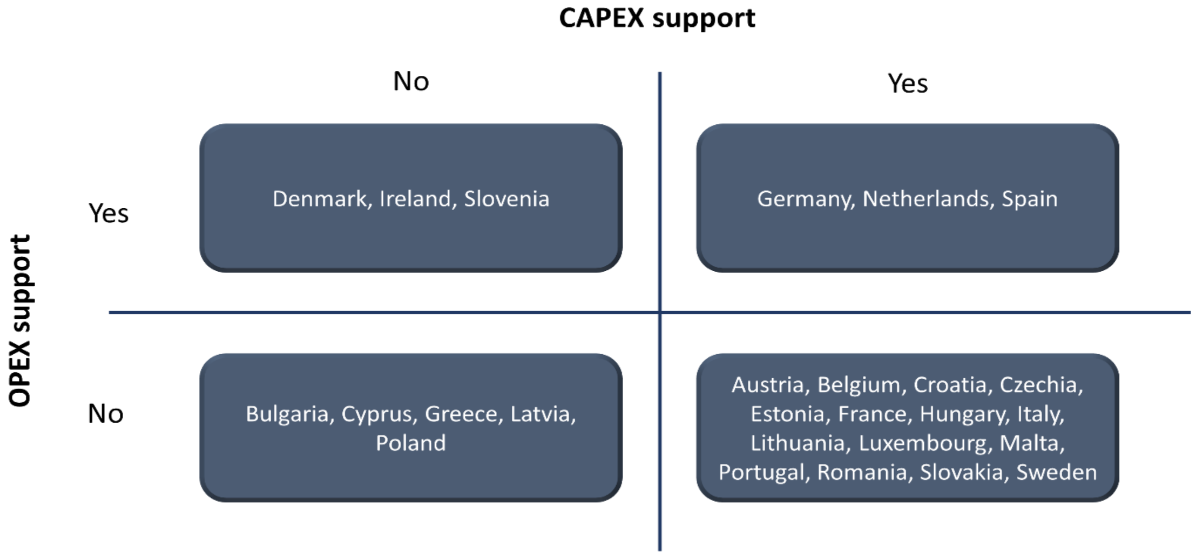
At the level of Member States, the market ramp-up is currently supported by the governments through a variety of fiscal instruments. Here, too, different stages of the value chain are being addressed, from production (exemption from state electricity price components, CAPEX subsidies for electrolysers in industry) and distribution (exemption/reduction of gas grid fees, investment subsidies for hydrogen filling stations) through to application technologies (purchase premiums for fuel-cell vehicles). The EU is far from being harmonised in this regard: the type and level of the incentives differ significantly from one Member State to another.

Figure 6 gives an overview of the use of CAPEX and OPEX support to hydrogen production in the Member States, according to information from the European Hydrogen Observatory's policy monitoring.[39] Measures of CAPEX support are already implemented in a majority of Member States (18). OPEX support is still far less frequent (six Member States), probably partly because of more severe restrictions to OPEX support in EU state aid rules. Currently, only three Member States (Germany, Netherlands, Spain) are reported to have both CAPEX and OPEX support measures in place. It should be noted that

[35] European Commission (2020). A hydrogen strategy for a climate neutral Europe. 8 July 2020.
[36] EU-Countries/Norway (2020). Manifesto for the development of a European "Hydrogen Technologies and Systems" value chain.
[37] European Commission (2022a). State Aid: Commission approves up to €5.2 billion of public support by thirteen Member States for the second Important Project of Common European Interest in the hydrogen value chain. Press release, 21 September 2022.
[38] European Commission (2022b). REPowerEU: affordable, secure and sustainable energy for Europe. Communication COM(2022) 108 final.
[39] EHO (2023a). National Policies and Legislation. European Hydrogen Observatory.

the scope of the respective incentive measures can vary greatly from country to country. This concerns, first, the type of specific instrument chosen. For instance, current OPEX support in Germany does not take the form of grants to production costs, but of an exemption of electricity used in electrolysis from network fees and electricity tax. Second, the technological scope of the supported production plants varies. Third, some of the measures are time limited or linked to certain forms of hydrogen utilisation.

Figure 6: CAPEX and OPEX support schemes for hydrogen production in Member States



Source: EHO (2023a) – Status: August 2023; own representation. No data for Finland.

These differences also make fiscal incentive policy a potentially significant location factor for the development of regional H_2 value chains in intra-European comparison. Direct measures to reduce costs or increase demand will increase expected operating surpluses and shorten the payback period of H_2 investment projects, thus also improving their financing possibilities. Only a detailed analysis of the national legal frameworks can clarify the extent to which the different national policies in the EU area work in this respect.

4.3 The envisaged framework of the European Hydrogen Bank

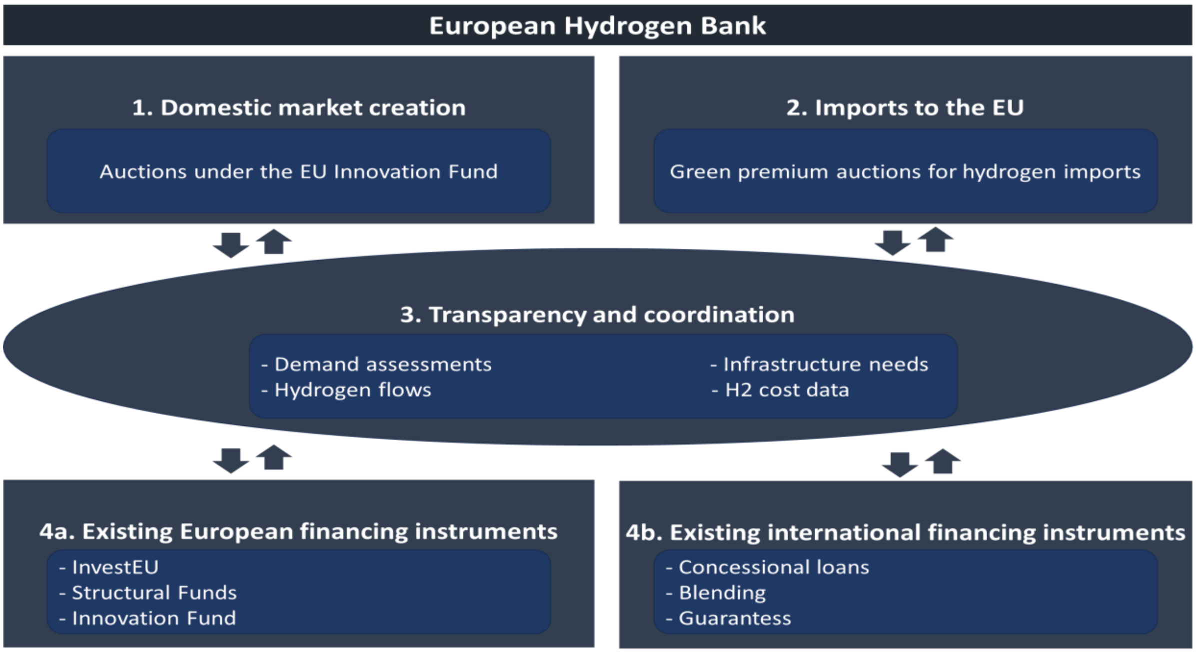
The idea of a European Hydrogen Bank as a new funding instrument for the development of the European hydrogen economy was first formulated by Commission President von der Leyen in her State of the Union Speech in September 2022. The bank was announced to be endowed with a total investment budget of 3 billion EUR and its core objective was to accelerate the development of future hydrogen markets.[40] The plans for the design and implementation of the hydrogen bank were then specified by the Commission in a Communication in March 2023.[41] The instrument is based on four pillars (see Figure 7): domestic market creation, imports to the EU, transparency and coordination, better coordination of existing project financing. Prime focus of domestic market creation is incentivizing EU-based hydrogen production through an auction-based financial support scheme. This takes the form of fixed

[40] Von der Leyen, U. (2022). State of the Union Address 2022 by President von der Leyen at the European Parliament Plenary. 14 September 2022.

[41] European Commission (2023b). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the European Hydrogen Bank. COM(2023) 156 final.

premiums granted per kg of hydrogen produced for a maximum of ten years operation. Producers bid as participants in a reverse auction for the expected amount of the premium. The funds are provided from the EU Innovation Fund. The Commission offers to open the created auction platform also for the allocation of subsidies by the Member States ("Auctions-as-a-Service"). For this purpose, joint auctions are to be held, in which, after the Innovation Fund resources have been exhausted, subsequent grants are awarded via the funds made available by the respective Member States (without prejudice to existing state aid regulations).

Figure 7: Future pillars of the European Hydrogen Bank



Source: European Commission (2023b); own representation.

The import pillar of the Hydrogen Bank is intended to promote the development of hydrogen production capacities outside the EU in the medium term. To this end, instruments are to be developed that enable off-take agreements with international suppliers while keeping an eye on supply diversification to avoid new external dependencies. As a first approach, the Commission is considering a green premium system for international hydrogen producers, comparable to the one to be introduced for domestic production. For the medium term, double-sided auctions with international producers and domestic consumers are to be considered an option, comparable to the German H2Global program.[42] In the meantime, an agreement on this point has been reached between EU Energy Commissioner Kadri Simson and German Economics Minister Robert Habeck. The H2Global system is to be made accessible to other Member States for the procurement of imported hydrogen. In addition, joint EU-wide auctions of imported hydrogen are to be set up.[43]

The third task of the Hydrogen Bank is to improve market transparency on costs, prices, and hydrogen flows, both by producing own market information through the auction results and by collecting information from external sources. It is also supposed to exercise a coordinating role for the implementation of the green hydrogen partnerships the EU has signed with several third countries. Finally,

[42] H2Global Stiftung (2023). Shaping the global energy transition.
[43] Hydrogen Europe (2023). European Hydrogen Bank and H2Global join forces to boost global hydrogen ramp-up. June, 2023.

coordination of and information sharing among the various existing hydrogen funding channels at the European and Member State level is defined to be a task as well.

The practical focus is initially on auctions to promote domestic production. The first Pilot Auction Program has an initial size of EUR 800 million. The auction will open on November 23, 2023.[44] The terms and conditions of the Pilot Auction were published on August 30, 2023. The bids consist of the level of a **fixed premium granted per kg of hydrogen produced over a period of ten years**. Only projects that are carried out within the EU and have (non-pooled and newly installed) electrolysis capacities of at least 5 GW are eligible to participate. In addition, they must fulfil numerous eligibility requirements. Besides compliance with general criteria (anti-bribery clauses, etc.), these include specific requirements that are intended to ensure two things in particular: technical feasibility and a production method that is compatible with the EU's climate policies. The first is to be ensured by defining a maximum time to entry into operation. This is uniformly five years. Auction participants must present evidence that administrative procedures for environmental impact assessments have been initiated with the aim of obtaining approval within these five years. In the case of grid-connected electrolysis, a strategy must also be presented to achieve grid connection within the five years. Moreover, financial security shall be increased by submitting a letter of intent from a financial institution to provide a completion guarantee for a timely implementation of the project in case of auction success.[45]

Compliance with the climate targets is to be ensured by the fact that, from the outset, only hydrogen whose production meets the EU definition of non-renewable fuels of biological origin[46] is eligible for subsidies. Thus, only hydrogen produced electrolytically using renewables-based electricity (other than biomass) is eligible for funding. In addition, the criteria of additionality and temporal and spatial correlation required by the definition must be met (see Section 6.1). Participants must also demonstrate that their total amount of hydrogen produced can achieve at least 70 % GHG reduction compared to conventional production methods according to Delegated Act C(2023) 1086 supplementing Directive (EU) 2018/2001.[47]

Cumulation with funding from other EU programs or state aid is not generally prohibited. The terms and conditions list which other funding instruments are compatible. Under certain conditions, cumulation with other forms of public support is permitted, if it refers to the upstream (promotion of electrolyser manufacturing) or downstream (development of infrastructure, H_2-applications) level. The prerequisite is that such support does not make the Hydrogen Bank superfluous as a funding instrument, i.e., does not lead to double funding. For instance, in the case of state aid granted to contracted hydrogen off-takers, the prerequisite is that such aid does not cover the additional costs of procuring renewable instead of grey hydrogen. By contrast, cumulation with other forms of OPEX and CAPEX aid

[44] European Commission (2023c). Upcoming EU Hydrogen Bank pilot auction: European Commission publishes Terms & Conditions. News Article, August 2023. https://climate.ec.europa.eu/news-your-voice/news/upcoming-eu-hydrogen-bank-pilot-auction-european-commission-publishes-terms-conditions-2023-08-30_en

[45] European Commission (2023d). Innovation Fund Auction – Terms and Conditions. Date: 29 August 2023. https://climate.ec.europa.eu/system/files/2023-08/innovationfund_pilotauction_termsandconditions_en.pdf

[46] See European Union (2023a).

[47] European Union (2023b). Commission delegated regulation (EU) of 10.2.2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels.

granted at the level of hydrogen production itself is not permitted. The cost advantage of projects funded elsewhere would otherwise threaten to render bidding procedures economically inefficient.

The auction design itself is a static one-bid auction with pay-as-bid pricing. This means that participants submit their bids once for the required amount of subsidy per kg of produced hydrogen. In ascending order of bids, participants are then awarded the subsidy according to their individual bids until the total budget of EUR 800 million is exhausted. There is no minimum price, but a maximum bid of 4.50 EUR per kg. In addition, the individual grant amount is limited to a maximum of one third of the total budget (i.e. approx. 266 million EUR). The expectations are that such a grant amount would be sufficient to reduce the cost of the subsidized hydrogen to below 1 euro per kg.[48]

The described support system thus exhibits some fundamental conceptual and practical differences to the H2Global auction instrument established in Germany.[49] This starts with the geographical focus. While H2Global is focused on non-EU procurement, the Hydrogen Bank is in its pilot phase limited to promoting EU-internal production. While the Hydrogen Bank initially only promotes producers in a one-sided auction, H2Global uses two-sided auctions to balance the gap between suppliers' production costs and buyers' willingness to pay. This also results in fundamentally different roles for the public side. In the case of the Hydrogen Bank, the government acts only as a grantor, qualitatively comparable to the granting of CAPEX or OPEX subsidies. Public agents do not engage in the marketization of hydrogen and thus does not relieve the producers of the sales risks. With H2Global, on the other hand, the state acts as an intermediary that buys and pools hydrogen, and in turn takes the role of a reliable supplier to domestic customers. This difference also concerns price risks. The fixed subsidies granted by the Hydrogen Bank are not a hedge against future market price volatility, ensuring that the steering effect of price signals is maintained. With H2Global, on the other hand, the demand-side auctions determine a fixed price at which the state delivers the purchased hydrogen to the customers over the contract period. Market price risks are thus borne by the state budget over the term of the contract.

5 Addressing the tendency to wait: a Real Options perspective

5.1 The Real Options method and its relevance for hydrogen investments

The core objective of the European Hydrogen Bank is to accelerate the development of markets for renewable hydrogen in Europe. In addition to the information function, the focus in the initial phase is clearly on the auction system described above. The additional state funds provided for this purpose can only be justified if they do not represent a mere redistribution instrument between the stakeholders. Their effectiveness must be measured by the extent to which they generate additional and long-term competitive production capacities for renewable hydrogen in Europe. This is also expressed in the qualification criteria of the auction, which require newly installed and otherwise not directly promoted capacities.

Ideally, the auctioned premiums could have two positive effects on investment decisions. First, as an additional source of revenue, they could increase the expected return to investments in hydrogen

48 ICIS (2023). EU Hydrogen Bank could bring renewable hydrogen costs below €1/kg. Independent Commodity Intelligence Service.
49 See H2Global Stiftung (2023).

production capacities. Secondly, they could mitigate the effects of potential downside scenarios on returns, and thus also contribute to reducing the capital costs of investments through de-risking.

In principle, the desired effect can take two forms. First, the premium payments could incentivize the implementation of investments that would otherwise not be carried out at all (or at least not in the EU). Second, they could motivate the acceleration of investments that would otherwise be carried out at a later date due to current uncertainty. Both effects lead to an accelerated capacity build-up over time, which, as a signal to the demand side, can also incentivize the expansion of infrastructure and application technologies and thus contribute to combating the triple chicken-and-egg problem (see Section 3.2).

To assess the effectiveness of the new incentive instrument ex ante, a method is needed that captures the time sensitivity of investment behaviour against the background of existing uncertainty. Classical investment valuation methods such as the Net Present Value (NPV) method are unsuitable for this purpose. They evaluate the profitability of carrying out an investment at an isolated point in time. Implicitly, they assume that the investment could not be postponed to later times. In reality, however, investment evaluations are in many cases not "now-or-never" decisions. This is also true in the context of the hydrogen economy, especially for independent hydrogen producers.[50]

Real Options Analysis is an established method for answering not only the question if, but also the question when a certain investment will be made. It is based on the evaluation of classical financial options from financial market theory.[51]. Its principles are transferred to the option to invest in tangible assets. This option can be exercised at any time within a predefined period. Uncertainty about future cash flows is explicitly reflected in the valuation by assuming probability distributions for key revenue and cost parameters. On this basis, the optimal investment timing can be determined as a solution to a dynamic optimization problem under uncertainty. An intuitive and widely used statistical method to solve this optimization problem is the Least Squares Monte Carlo (LSM) method developed by Longstaff & Schwarz (2001).[52] It consists of the calculation of return distributions based on a large number of random draws from the underlying probability distributions (Monte Carlo simulation) and the subsequent intertemporal optimization of the investment timing using the classical least squares approach.

The variety of policy and market uncertainties faced by stakeholders in the energy system turns investments in energy production/distribution into an ideal use case for Real Options Analysis.[53] Indeed, several energy-related scenarios have been investigated in the scientific literature (e.g., Locatelli et al. (2016)[54]; Moon & Baran (2018)[55]). However, hydrogen was so far only topic of very few investigations

[50] Such an assumption would be most justifiable for industrial actors on the demand side, whose pre-determined, long investment cycles make the technology decision necessary at very specific points in time (see Wolf, A. (2023b).

[51] Black, F., & Scholes, M. (1973). The pricing of options and corporate liabilities. Journal of political economy, 81(3), 637-654.

[52] Longstaff, F. A., & Schwartz, E. S. (2001). Valuing American options by simulation: a simple least-squares approach. The review of financial studies, 14(1), 113-147.

[53] Santos, L., Soares, I., Mendes, C., & Ferreira, P. (2014). Real options versus traditional methods to assess renewable energy projects. Renewable Energy, 68, 588-594.

[54] Locatelli, G., Invernizzi, D. C., & Mancini, M. (2016). Investment and risk appraisal in energy storage systems: A real options approach. Energy, 104, 114-131.

[55] Moon, Y., & Baran, M. (2018). Economic analysis of a residential PV system from the timing perspective: A real option model. Renewable energy, 125, 783-795.

in this field. To the best of our knowledge, investments in electrolytic hydrogen production were only investigated by Kroniger & Madlener (2014)[56] and Parot (2022)[57] based on a Real Options approach. Kroniger & Madlener (2014) investigate the role of hydrogen as a storage medium for electricity, without considering the temporal dynamics (economies of scale, price development) of hydrogen markets. Parot (2022) examines the option of investing in hydrogen production in Chile. What is currently missing is an analysis specific to the situation in Europe, considering its geographic (RES-E generation costs), economic (hydrogen market evolution) and political (extent of subsidies) conditions.

In what follows, we conduct such an analysis for Europe's regions. We use this setting as a basis for estimating to what extent premium payments of the European Hydrogen Bank could contribute to an acceleration of investments, and how this effect is likely to differ between regions.

5.2 Policy incentives in Real Options perspective: a simulation approach

The technical basis of our simulations is the scenario of electrolytic hydrogen production based on PEM electrolysers using electricity from wind power or photovoltaics (PV) capacities. We consider the option to invest in an electrolyser with 5 MW capacity, the minimum size required for participation in the Pilot Auctions of the European Hydrogen Bank (see Section 4.3). As spatial dimension, we work at the level of EU NUTS-2 regions (242 regions in total). We assume that the electricity used in electrolysis is produced based on additional PV or wind power capacities build in the same region as the hydrogen. This is generally in line with the principles of additionality and spatial correlation underlying the EU definition of renewable hydrogen (see Section 4.2). Therefore, the costs of electricity procurement are shaped by the regional electricity generation costs.

For the representation of electricity generation in the model, we follow Parot (2022) in not estimating any temporal resolution of generation profiles but instead working with the average expected electricity yield at the annual level. The relevant efficiency parameter is the ratio of the average annual yield to the maximum generation volume, the so-called capacity factor. Estimates of this capacity factor for representative generation plants in the NUTS-2 regions are taken from the EU database *ENSPRESO*, both for PV[58] and for wind power (onshore)[59]. We supplement these with estimates of capital expenditures per kw of installed capacity, annual fixed costs of operations & management and economic lifetime of installations, all obtained from the International Renewable Energy Agency.[60] These parameters constitute the basis for calculating the Levelized Cost of Electricity per MWh (e.g. the net present cost of generating 1 MWh over the lifetime of a generation unit) for PV and wind power, applying the standard formula.[61] The lowest of the two values is used as the starting value for the regional electricity

[56] Kroniger, D., & Madlener, R. (2014). Hydrogen storage for wind parks: A real options evaluation for an optimal investment in more flexibility. Applied energy, 136, 931-946.

[57] Parot, T. O. (2022). Hydrogen production economics: A Compound Real Options Analysis (Doctoral dissertation, Pontificia Universidad Catolica de Chile (Chile)).

[58] JRC (2023a). ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. ENSPRESO - SOLAR - PV and CSP dataset. Joint Research Centre of the European Union.

[59] JRC (2023b). ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. ENSPRESO – Wind-onshore and offshore dataset. Joint Research Centre of the European Union.

[60] IRENA. (2022). Renewable Power Generation Costs in 2021. Abu Dhabi: International Renewable Energy Agency. https://irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

[61] See e.g. Kost, C., Shammugam, S., Fluri, V., Peper, D., Davoodi Memar, A., & Schegl, T. (2021). Levelized cost of electricity renewable energy technologies. Report June 2021. file:///C:/Users/user/Downloads/EN2021_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf

procurement costs of the electrolysers per MWh of electricity. We thus assume that the electricity used in electrolysis is either self-generated or purchased from external RE plants within the same region via (economically fair) producer contracts. Furthermore, it is assumed to be exempt from any grid charges and electricity taxes, as is currently already the case in Member States like Germany (see Section 4.2). For the electricity intensity of electrolysis, we assume a demand of 50 kWh of electricity per kg of hydrogen produced, following Matute et al. (2023)[62] and other studies.

Other relevant cost parameters for electrolysis include the level of CAPEX. These can be approximated by benchmarks for the cost of purchasing and installing electrolysers per MW of capacity. For this purpose, we use current estimates of the IEA as a starting value.[63] CAPEX are annualized with an interest rate of 8 %, as in Matute et al. (2023). The other operating costs besides electricity (water, nitrogen, electrolytes, operation & management (O&M)) are determined based on current estimates by the European Hydrogen Observatory.[64] It reports country-level estimates for non-electricity OPEX in a range of 0.44 - 1.06 EUR/kg hydrogen. We use the respective national estimates as estimators for the regional residual OPEX. On this basis, we calculate the regional Levelized Cost of Hydrogen (LCOH). The resulting regional distribution is shown in Figure A1 in the appendix. As initial market price for hydrogen we set a value of 6 Euro per kg (producer price, without transport costs). This corresponds to the value used in the most recent analysis by Matute et al. (2023) and is somewhere at the lower end of the informal prices currently reported for Europe (see Section 3.1).

Crucial for model dynamics is the choice of variables that are considered stochastic over time. Following Parot (2022), we consider four variables as stochastic: the development of the electricity purchase costs for PV as well as for wind power, the price for electrolysers and the price for hydrogen. As is common in Real Options Analysis, the evolutions of all three quantities are modelled as Brownian Motions.[65] Each Brownian Motion is determined by two parameters: the drift and the volatility. The drift parameter determines the long-term trend of the time series, the volatility parameter the intensity of random deviations from the trend. In the case of electricity purchase costs, the drift parameter reflects the long-term development of the regional Levelized Cost of Electricity (LCOE). Forecasts are typically based on assumptions about the expected learning rate of capacity expansion, i.e., the relative reduction of the LCOE in the case of a doubling of generation capacities. We adopt expected learning rates for wind power (15 %) and PV (24 %) from a recent empirical study by Bolinger et al. (2022).[66] Combined with forecasts scenarios from a recent large-scale study by Ember (2022)[67] on the future evolution of EU wind power and PV capacities, a trend path and a range for the percentage decline in LCOE over time is derived. This allows us to calibrate drift and volatility parameters for the costs of PV and wind power.

62 Matute, G., Yusta, J. M., & Naval, N. (2023). Techno-economic model and feasibility assessment of green hydrogen projects based on electrolysis supplied by photovoltaic PPAs. International Journal of Hydrogen Energy, 48(13), 5053-5068.

63 See IEA (2023). It reports an estimate of 2 Mill. USD / MW electrolysis capacity for PEM and alkaline electrolysers. This was converted by us into Euro, based on the average exchange rate in 2022 (0.951 USD/EUR).

64 EHO (2023b). Cost of hydrogen production. European Hydrogen Observatory. https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production

65 Uhlenbeck, G. E., & Ornstein, L. S. (1930). On the theory of the Brownian motion. Physical review, 36(5), 823.

66 Bolinger, M., Wiser, R., & O'Shaughnessy, E. (2022). Levelized cost-based learning analysis of utility-scale wind and solar in the United States. Iscience, 25(6).

67 Ember (2022). New Generation - Building a clean European electricity system by 2035. https://ember-climate.org/insights/research/new-generation/#supporting-material

IEA forecasts are used for the development of prices for electrolysers. They expect the costs of installed electrolysers to fall by 60 to 70 % by 2030 compared with 2023. [68] We assume an average reduction of 65 % and consider the specified interval as a fluctuation range of a uniformly distributed interval. On this basis, we calibrate the drift and the volatility parameter for the Brownian motion of the electrolyser price.

A forecast of the development of hydrogen prices is particularly difficult, since in addition to the cost development, implicit assumptions must be made about the future market structure. Our assumption is that superregional competitive markets for renewable hydrogen will establish themselves relatively quickly in Europe, due to progress in certification[69] and expansion of cross-regional pipeline infrastructure[70]. Consequently, the future price development of hydrogen will be governed by its marginal costs of production. Based on the current cost structure (see Section 3.1), it is to be expected that the costs of electricity provision will remain the key influencing factor on marginal costs. We reflect this fact by applying the same drift parameter for the Brownian motion of the hydrogen price as for the development of wind power costs.

The potential investment horizon considered in the analysis is 15 years from the present. The same value is chosen for the lifetime of electrolysers, following KPMG (2022).[71] Hence, if the investment is carried out today, the electrolyser would be completely depreciated at the end of the period under consideration. If the investment is carried out at a later point in time within the investment horizon, a proportional residual value (resale value) remains at the end of the horizon, which is modelled as an additional source of income at the end of the 15 years.

Table 1 summarizes our parameter choices and their sources. For the calibrated model, the LSM-method is used to estimate the (region-specific) optimal investment timing for our 5 MW model plant, as well as the underlying probability distributions of the Real Option value and other relevant indicators. All simulations were performed in the statistical program *R*, using the statistical package *LSMRealOptions*.

[68] See IEA (2023).
[69] CHP (2023). CertifHy - Accelerating the Certification of Hydrogen. Clean Hydrogen Partnership.
[70] See EHB Initiative (2023).
[71] KPMG (2022). How to evaluate the cost of the green hydrogen business case? Assessing green hydrogen production costs. KPMG Advisory N.V.

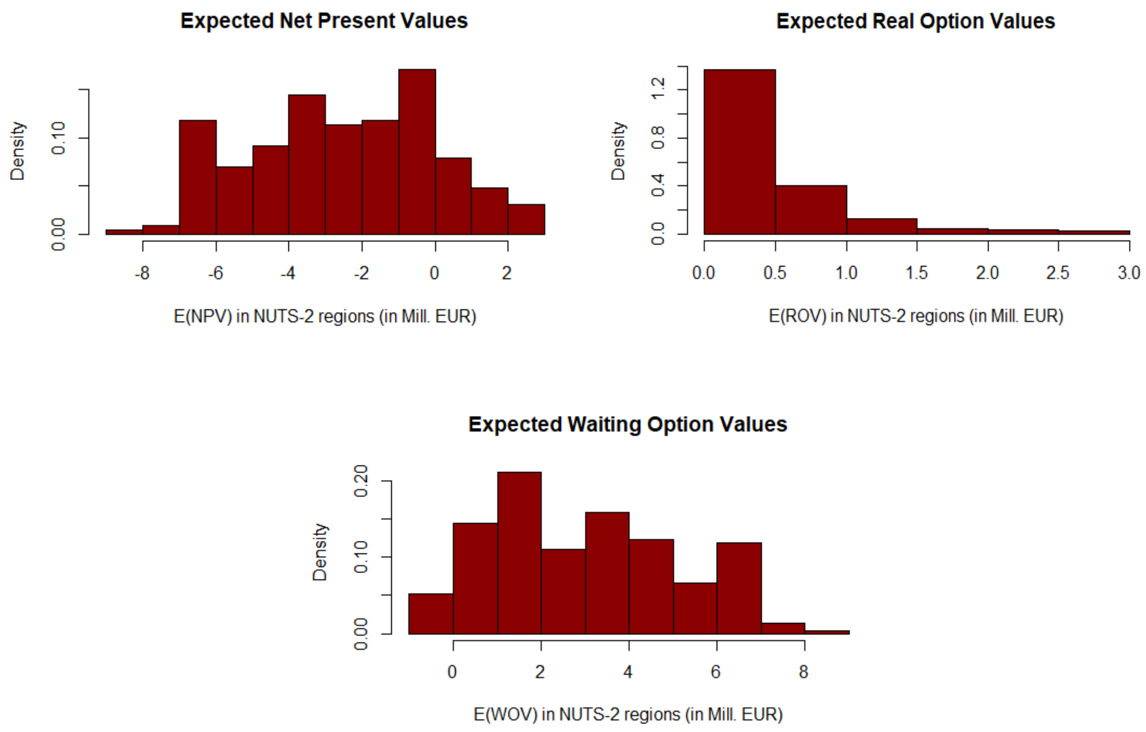
Table 1: Overview on parameter values of the Real Options model

Parameter	Value	Source
General		
Discount rate	8 %	Matute et al. (2023)
Electricity sources		
PV plants: lifetime	25 years	IRENA (2022)
PV plants: CAPEX	697,000 EUR/MW	IRENA (2022)
PV plants: OPEX (O&M)	15,000 EUR/MW/year	IRENA (2022)
PV plants: capacity factors	region-specific	JRC (2023a)
Evolution electricity costs PV: drift	-7.19 %	Calibrated based on Bolinger et al. (2022); Ember (2022)
Evolution electricity costs PV: volatility	10.08 %	Calibrated based on Bolinger et al. (2022); Ember (2022)
Wind power plants (onshore): lifetime	25 years	IRENA (2022)
Wind power plants (onshore): CAPEX	1,425,000 EUR/MW	IRENA (2022)
Wind power plants (onshore): OPEX (O&M)	31,000 EUR/MW/year	IRENA (2022)
Wind power plants (onshore): capacity factors	region-specific	JRC (2023b)
Evolution electricity costs wind: drift	-2.92 %	Calibrated based on Bolinger et al. (2022); Ember (2022)
Evolution electricity costs wind: volatility	3.87 %	Calibrated based on Bolinger et al. (2022); Ember (2022)
Electrolysis: CAPEX parameters		
Electrolyser: lifetime	15 years	KPMG (2022)
Electrolyser: capacity	5 MW	Minimum level pilot auction
Electrolyser: annual operating hours	3,285 hours/year	Matute et al. (2023)
Current price electrolyser	2,000,000 EUR/MW	IEA (2023)
Evolution price electrolyser: drift	-12.30 %	Calibrated based on IEA (2023)
Evolution price electrolyser: volatility	2.89 %	Calibrated based on IEA (2023)
Electrolysis: OPEX parameters		
Electricity intensity	0.05 MWh/kg H_2	Matute et al. (2023)
Residual OPEX	region-specific	EHO (2023b)
Hydrogen market		
Current reference price hydrogen	6 EUR/kg H_2	Matute et al. (2023)
Evolution price hydrogen: drift	-2.92 %	Calibrated based on Bolinger et al. (2022); Ember (2022)
Evolution price hydrogen: volatility	3.87 %	Calibrated based on Bolinger et al. (2022); Ember (2022)

Source: own representation

As a first simulation exercise, we analyse the investment decisions in the absence of government support, i.e., without the European Hydrogen Bank or other fiscal support tools in place. Figure 8 shows histograms of the distributions of expected Net Present Value (NPV), expected Real Options Value (ROV), and expected Waiting Option Value (WOV) across the NUTS-2 regions from the perspective of the present (time t=0).

Figure 8: Regional distributions of investment metrics in the no-support-scenario

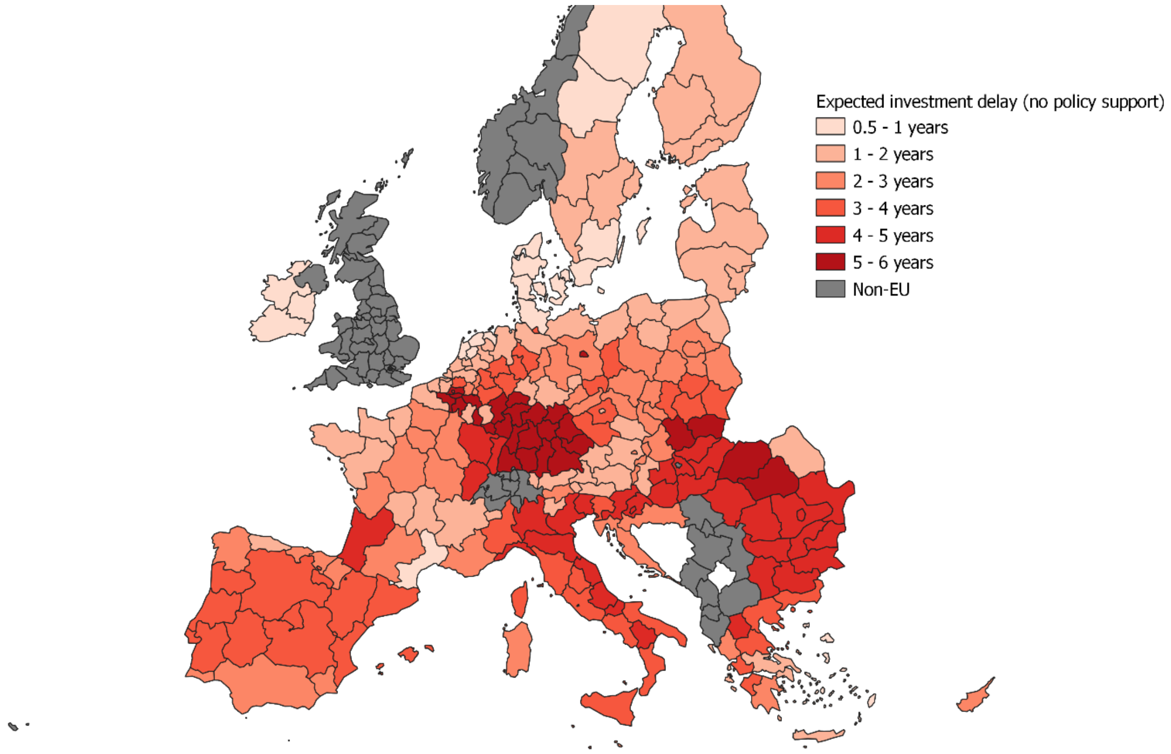


Source: own calculations

First, the distribution of the expected NPV shows the expected returns to a present investment in electrolysis capacity in the EU-regions. The simulation results show a wide range. Investment incentives are thus very heterogeneous between regions. The decisive driving force behind this are the regional differences in the costs of electricity procurement, and thus the operating costs of hydrogen production. In an overwhelming majority of regions (about 85 %), the expected NPV is negative in the absence of public support. Hence, in these regions there is no economic incentive from today's point of view to invest in electrolysis capacities immediately. Conversely, a positive expected NPV alone does not imply present investment to be sensible. This is because, depending on the future development of the framework conditions (in our case: electricity production costs, prices for electrolysers and for hydrogen), the intertemporal value of investments could still increase in the future. In our model context, this rational is reflected by the ROV. From the investors' point of view, it indicates the economic value of having the option under investigation, i.e., the option to invest in the electrolyser at any time within the simulation period of 15 years. As long as this value exceeds the NPV of an instant investment, it is not yet advisable to exercise the option, i.e., to carry out the investment. A crucial indicator is therefore the difference between ROV and NPV, the so-called Waiting Option Value (WOV). Our simulations show that from today's perspective the expected WOV is positive in most of the regions in the absence of state support. Only in 11 EU NUTS-2 regions it is negative, i.e., it makes sense to invest immediately.

Another insightful metric that can be derived from the Real Options analysis is the expected investment timing. Starting from today, it indicates the expected optimal investment timing in the individual regions obtained as a result of the dynamic optimization of the LSM algorithm. This corresponds to the expected investment delay from today's point of view. Figure 9 depicts the pattern of expected investment timings across NUTS-2 regions. Most fundamentally, there exists no region for which an investment is diagnosed as unprofitable over the entire simulation period of 15 years. However, there are significant discrepancies in the exact timing of the investment within the 15 years, mainly due to the regional differences in the costs of electricity input. A very short waiting period of less than one year is mainly expected for the regions bordering the North Sea, as well as for Ireland and parts of Sweden. In contrast, a considerable investment delay of 5 to 6 years is expected for the southern part of Germany and for certain regions in Belgium, Romania, and Slovakia.

Figure 9: Expected timing of electrolysis investments in NUTS-2 regions in the no-support scenario

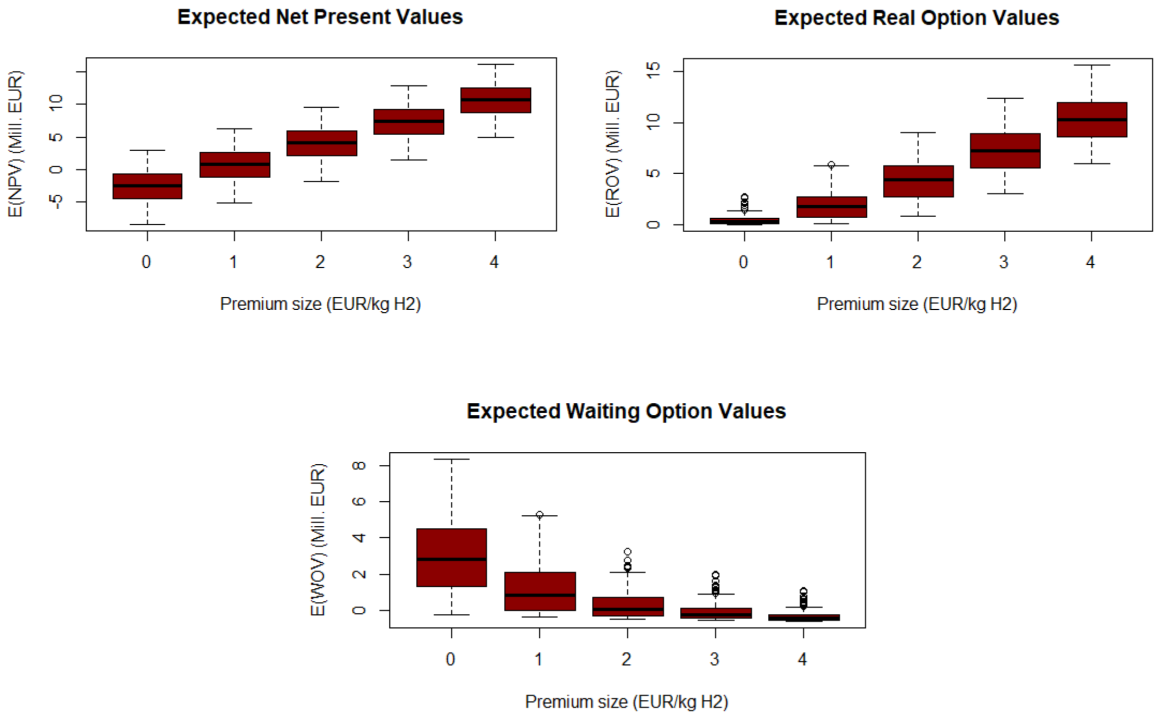


Source: own calculations

As a next scenario, we introduce public support in the form of fixed premiums per kg hydrogen into the model, imitating the future support scheme of the European Hydrogen Bank. As explained in Section 4.3, the future size of the premium and the range of beneficiaries will both be determined through a pay-as-bid auction scheme and are therefore difficult to predict. Nevertheless, our modelling framework allows us to simulate the consequences of different premium levels on investment incentives and investment timing. We simulate the impacts of premiums with a size of 1, 2, 3 and 4 EUR/kg hydrogen, thus remaining within the limits set for the Pilot Auction of the European Hydrogen Bank. These are modelled to be granted over a ten-year horizon, likewise matching the terms of the Pilot Auction. A prerequisite for obtaining the premium is to invest within five years from now, reflecting the time-to-entry conditions (see Section 4.3).

Figure 10 shows the distribution results of the different premium simulations as boxplots. In general, the results demonstrate that premium payments of the magnitude granted by the European Hydrogen Bank are likely to have a significant effect on expected returns and thus on investment incentives from today’s perspective. Accordingly, already at a fixed premium of 1 EUR/kg hydrogen, the median of the expected NPVs in the NUTS-2 regions would be in the positive range. At a premium of 2 EUR/kg hydrogen, the median of the expected WOVs would already be close to zero, i.e., the option to wait would no longer be valuable in almost half of the NUTS-2 regions. For premiums above 3 EUR/kg hydrogen, the expected NPVs would be positive in all NUTS-2 regions and the WOVs almost consistently close to zero. An investment in electrolysis capacities would then be profitable already today in all regions; a small delay would only result from the remaining option values.

Figure 10: Regional distributions of investment metrics with premiums



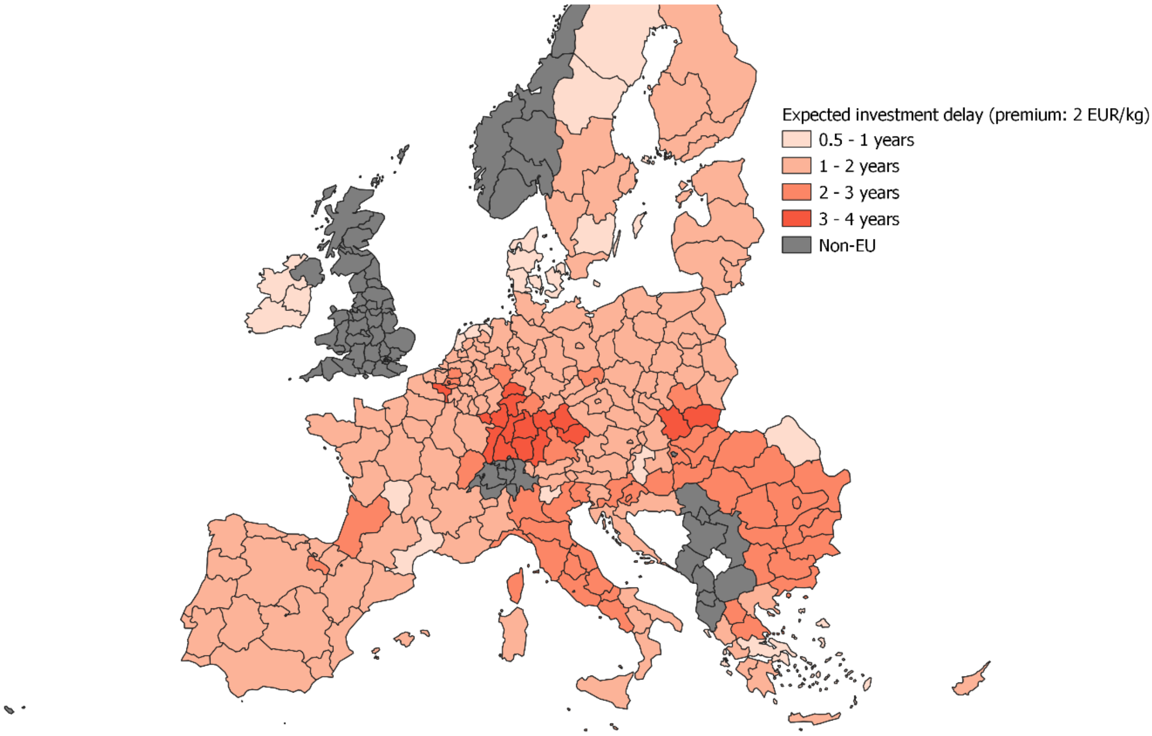
Source: own calculations

This effect is reflected in a reduction of the expected investment time. Figure 11 shows an example of the regional pattern with a homogeneous premium of 2 EUR/kg hydrogen. Comparing this picture to the pattern in Figure 9 shows that the expected delay is significantly reduced, especially in regions with otherwise late investment timing. In those regions where investments would be made early anyway, due to their good starting conditions, the subsidy leads to only a slight reduction in the investment delay. On average across all regions, the expected investment delay is reduced by 1.25 years at this premium level compared to the no-support-scenario.

The results hint at a significant overall effectiveness of this funding measure for capacity building in the field of renewable hydrogen production. However, effectiveness alone is not a sufficient criterion for evaluating such an instrument, especially in view of the considerable competition for public funds between industries and technologies in the current stage of transformation. It should also be efficient, i.e., the volume of funds used should be commensurate with the impact achieved. In addition to the system-wide implications, which we discuss in more detail below, the first immediate issue is the risk of overfunding individual players in hydrogen production. This question is also important because the conditions of participation in the pilot auction of the European Hydrogen Bank significantly limit the potential group of participants (e.g., minimum capacity of 5 MW, rather strict cumulation conditions).

An unnecessarily high level of support for some auction participants could lead to distortions in the spatial evolution of hydrogen supply in Europe, which would endanger the long-term competitiveness of domestic supply chains.

Figure 11: Expected timing of electrolysis investments in NUTS-2 regions with premiums

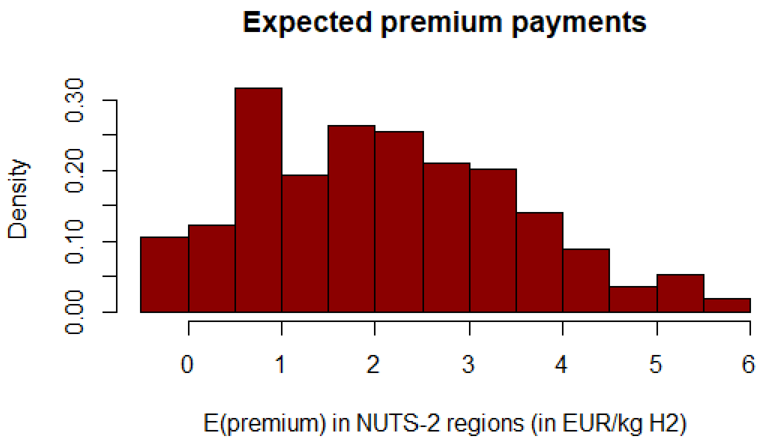


Source: own calculations

One way to approach this problem is to estimate a meaningful minimum level of support. The core objective of the European Hydrogen Bank is to accelerate capacity investments. The minimum level could thus be understood as the level of support just necessary to eliminate the incentive to wait with the investment from today's perspective. In our modelling framework, this corresponds to a situation where the expected Waiting Option Value (WOV) is reduced to zero. Based on our results for WOVs in the situation without subsidies, we can directly calculate the required subsidy level. Because of the considerable regional differences in electricity costs, this also varies strongly between the NUTS-2 regions. Figure 12 depicts the resulting distribution. The median of expected premiums among the regions amounts to only about 2 EUR/kg hydrogen. In about 27 % of regions, the expected premiums amount to less than 1 EUR/kg hydrogen. At the other end of the distribution, in only about 5 % of regions do the expected premiums exceed the ceiling price of 4.50 EUR set for the Pilot Auction.[72] These are regions with particularly unfavourable natural conditions for PV and wind electricity generation. A subsidy-induced buildup of renewable hydrogen production in those regions can be expected to create particularly high opportunity costs of resource usage.

[72] This includes a few extreme cases of regions where the expected premium is actually higher than the present levelized costs of hydrogen production. This is explicable by the fact that for being willing to invest instantly, investors do not only require compensation for high current production costs, but also for giving up the opportunity to wait for cost reductions within the specified time to entry.

Figure 12: Regional distribution of expected premium levels



Source: own calculations.

The results suggest that the ceiling price set for the Pilot Auction of the European Hydrogen Bank is in all likelihood unnecessarily high. At the same time, in view of the presumably low initial number of participants and the fact that the auctions are performed in pay-as-bid mode, it is conceivable that successful bids will be realized in this order of magnitude. Depending on the spatial distribution of the respective bidders and their electricity sources, this could imply two things. Producers in regions with low levelized costs of hydrogen production receive inadequately high subsidies and/or hydrogen production in regions with above-average levelized costs and scarce local renewable sources is subsidized. Both effects imply an inefficient use of public resources.

Such an excess subsidy could only be justified if a significant portion of it were passed on to the demand side to incentivize hydrogen-driven transformation, i.e., investment in significant H_2-application projects. However, this can be doubted for several reasons. For example, the European Hydrogen Bank's cumulation criteria exclude subsidies for renewable hydrogen that is already subsidized on the demand side through Carbon-Contracts-for-Difference (CCfDs) or similar instruments (see Section 4.3). A strategically important part of industrial H_2-demand is thus threatened to be excluded from the support scheme. **In the worst case, this could even result in an allocative distortion of future hydrogen use - away from core industrial demand and toward applications where more efficient technologies are available as alternatives**. This would weigh on overall systemic efficiency - and impair the integration of renewable hydrogen into the energy system.

But even if cumulation criteria are softened, production subsidies are not likely to significantly stimulate hydrogen demand, at least initially. This is because the price elasticity of the large industrial demand sinks chemicals and steel, in particular, is likely to be low in the initial phase, as they have few alternatives to hydrogen in decarbonization. Unlike CCfDs, the price subsidies also do not lower cost uncertainties for industries during the transformation, as they do not compensate for fluctuations in future market prices of hydrogen.

The auction terms of the European Hydrogen Bank should therefore be modified. The ceiling price should be set at a significantly lower level than 4.50 EUR/kg hydrogen. This reduces the consequences of inefficiencies in the bidding process, which are to be expected in the early stages, lowers the risk of over-subsidization and leaves room for other instruments. In addition, the regulations on cumulation with demand-side instruments should be relaxed as a transitional measure. The prerequisite should be that these instruments are also designed to be close to the market, i.e. conditional on the development of hydrogen prices. In this way, the Hydrogen Bank could set impulses on the supply side without displacing valuable support instruments for the industrial transformation or leading to persistent double subsidies. In addition, the minimum capacity of the electrolysers should be reduced to allow low-scale, local electrolysis models to participate and to strengthen the competitive character of the auctions.

Another prerequisite for effectiveness of this instrument is its integration into a stringent EU-wide support framework. To solve the chicken-and-egg problem (see Section 3.2), this framework should address as many stages as possible in the future supply chains of renewable hydrogen. In the following sections, we define general criteria for the instruments of such a framework and give recommendations for urgent steps to be taken.

6 Recommendations for a holistic support framework

6.1 Criteria and evaluation

Given the intense competition between sectors and the variety of technologies in accessing government support for decarbonization, any funding decision necessarily involves numerous trade-offs. The assessment of the effectiveness of a measure in terms of investment incentives must therefore be complemented by other targets. First, an important criterion is the avoidance of persistent distortions in input use. Support measures should be designed in such a way that they do not contribute to a permanent misallocation of resources.

In this regard, a key aspect is the competition for the use of electricity from renewable sources. Due to the rapidly increasing range of applications, green electricity will remain a scarce resource in the medium term, even if ambitious expansion targets are achieved. Renewable hydrogen competes directly or indirectly with forms of direct electrification in industry, transport, and the building sector. The fact that due to the conversion losses the production of renewable hydrogen has a negative direct system-wide efficiency effect must be considered. In addition to the total amount of electricity consumed in electrolysis, the temporal and spatial pattern of use is also important in view of system stability. The demand pattern of electrolysers should serve the grid and the work of network operators, i.e., should adapt as flexibly as possible to the volatile generation patterns of Wind and PV electricity.

The EU considered these requirements in its delegated act on the definition of renewable gases of non-biological origin, through the criteria of additionality and temporal as well as geographic correlation with electricity generation.[73] The criterion of additionality is intended to ensure that the electricity used in electrolysis comes from newly created sources, such that no existing generation capacities are withdrawn from supply to direct electrification activities. The temporal and geographic correlation sets minimum requirements for the temporal and geographic proximity between electricity generation and its use in electrolysis. However, all these criteria are defined relatively softly by the delegated act for an initial phase, to ensure compliance with the goal of market development. For example, additionality is already fulfilled if the power generation capacities used do not receive any support in the form of operating or investment aid and came into operation not earlier than 36 months before the electrolysis

[73] See European Union (2023a).

plant. The actual contribution to the efficiency of the energy system should therefore still be kept in mind as a criterion for funding instruments.

Moreover, the question of efficiency also arises regarding the use of renewable hydrogen. This is especially true for the phase of building markets and infrastructure, in which price mechanisms representing the basis for cross-regional allocation have only limited effect. Funding instruments should support the development of efficient allocation channels. Technology competition within the sectors plays an important role. In view of the energy conversion losses, hydrogen should be channelled into applications where alternatives such as direct electrification are technologically infeasible, reach resource limits, and/or are uneconomical. Finally, as a further system-wide criterion, the magnitude of the administrative costs of a measure should also be considered in the evaluation.

In the following, we qualitatively judge different types of support instruments for domestic electrolysis by means of these criteria, distinguished based on the supply chain view from Section 4.1. Table 2 presents an overview of our assessment. The hitherto dominant support instrument of investment promotion strengthens investment incentives through its contribution to a reduction of the cost of capital. By means of direct subsidies (grants) or the provision of cheap loans, the required demand for private capital is reduced. The reduction in the cost of capital directly implies an increase in expected returns. However, it does not immediately affect expected revenues and operating costs. Thus, it does not contribute to reducing uncertainty in future cost and revenue developments over the lifetime of the investment. Due to this neutrality, it also does not directly influence the patterns of electricity use by electrolysers and the distribution of the produced hydrogen.

The assessment comes to different results for the various forms of operational support. A regular government subsidy to OPEX not only increases the expected returns of the investments in electrolysis capacities, but also reduces the costs. Provided that support is granted based on a regularly updated cost assessment, it also covers a part of the future cost risks. This will mostly concern electricity prices. The downside of such a targeted OPEX support is a potential increase in the risk of misallocation of electricity, as price signals are weakened from the perspective of electrolysers. This does not apply to some more indirect forms of operating support. For instance, reducing or abolishing taxes and network fees on electricity used in transformation technologies cannot be seen as a source of distortion, provided it is granted in a technology-neutral manner. The specific promotion of a market for long-term Power Purchase Agreements (PPAs), e.g., through state guarantees or the sponsoring of pooling platforms, is also non-distortive in the sense that it is not exclusively targeted at electrolysis applications. Quite the opposite, it can even be expected to be beneficial for overall electricity market efficiency, as it provides new stable distribution channels. Moreover, both instruments exhibit the advantage of comparatively low administrative costs. They avoid the continuous reporting and monitoring obligations associated with OPEX grants.

Instruments to support the revenue side are still in their infancy. The first key issue for market formation is certification. The certification system for renewable hydrogen currently being developed in the EU based on the new legal definition will provide an important stimulus for market ramp-up, as it makes compliance with the required properties transparent. However, certification alone is unlikely to initiate a market ramp-up at the necessary speed since it does not compensate for the current gap between production costs and willingness to pay. In addition to the instrument of fixed production premiums discussed in Section 5, there are various other forms of direct price support. These include the option of extending the H2Global program implemented in Germany for hydrogen import to domestic production. Here, the state actively intervenes in the allocation process as an intermediary. By conducting two-sided auctions among sellers and among buyers, and by compensating the price differences through the program budget, the state takes over the allocation function of the market. It concludes long-term purchase contracts with producers who are successful in the auction. In this way, it contributes to a reduction of price and sales risks of hydrogen production. Recent experimental evidence suggests that there is indeed a strong aversion of investors to energy market price risks, and a preference for stable cash flows through fixed term contracts.[74] Moreover, the additional auctioning process conducted on the side of the buyers promotes an allocation of hydrogen according to actual willingness to pay. On the other hand, the guaranteed purchase price could permanently compensate unsustainably high electricity costs, which - besides having a negative impact on state budgets - would impair the allocative efficiency of electricity from renewables. In addition, the extension of the program to domestic production could cause a considerable administrative burden.

Table 2: General evaluation of support instruments

	Contribution to hydrogen production roll-out				**Compatibility with system-wide-goals**		
Instrument	Raising expected returns	Reducing cost risk	Reducing price risk	Reducing sales risk	Efficient hydrogen allocation	Efficient electricity use	Low administrative costs
Investment support							
CAPEX grants / credit promotion	Green	Grey	Grey	Grey	Grey	Grey	Yellow
Operation support							
OPEX grants	Green	Green	Grey	Grey	Grey	Yellow	Red
Reduction levies electricity	Green	Grey	Grey	Grey	Grey	Grey	Green
Promotion PPAs	Green	Green	Grey	Grey	Grey	Green	Green
Revenue support							
Certification	Green	Grey	Grey	Green	Grey	Grey	Green
Price premiums (Hydrogen Bank)	Green	Grey	Grey	Grey	Yellow	Yellow	Yellow
Minimum prices	Green	Grey	Green	Grey	Yellow	Red	Yellow
State as intermediary (H2Global)	Green	Grey	Green	Green	Green	Red	Red
Demand support							
CCfDs	Grey	Grey	Grey	Green	Green	Yellow	Red
Green lead markets	Grey	Grey	Grey	Green	Green	Yellow	Yellow

Green	Positive impact expected /compatibility
Red	Negative impact expected/conflict
Yellow	Type of impact highly design-dependent
Grey	No immediate impact expected/neutral

Source: own representation.

The allocation problem also arises to a greater or lesser extent (depending on the price level) in the case of a regulatory fixed minimum price for hydrogen. In the case of fixed premium payments per kg hydrogen, instead, the signalling effect of changes in the market price of hydrogen is preserved. To what extent fixed premiums act as a cost shield and thus contribute to inefficiency depends strongly on the efficiency of the auction process and its conditions for participation (see Section 5.2).

74 Côté, E., & Salm, S. (2022). Risk-adjusted preferences of utility companies and institutional investors for battery storage and green hydrogen investment. Energy Policy, 163, 112821.

On the demand side, besides classical forms of CAPEX support, two innovative instruments for promoting investments in hydrogen-based technologies have become the focal point of discussion: Carbon-Contracts-for-Difference (CCfDs) and green lead markets. Both play an important and complementary role in stimulating long-term investments, by eliminating carbon price uncertainty (CCfDs) and creating additional revenue potential to compensate the costs of the transformation (green lead markets).[75] As these measures are (or will be) highly focused on core industrial application areas – also to put a limit to costs- they are apt to promote a channelling of initially scarce renewable hydrogen to hard-to-abate sectors. At the same time, their influence on allocative efficiency of electricity use is highly design dependent. For instance, a dynamic version of CCfDs, where the guaranteed carbon price is adjusted based on changes in the input costs of electricity, would conflict with allocative neutrality. The same goes for green quotas if the application criteria favour electricity-intensive green technologies.

6.2 Key areas of action

Based on the general analysis of the landscape of support instruments and our detailed findings for the incentive effect of the European Hydrogen Bank, we provide a set of specific policy recommendations for the current build-up phase. **The guiding idea is to accelerate the market build-up as a key driver for a competitive domestic hydrogen economy**. Only if renewable hydrogen is soon allocated based on actual willingness-to-pay, its contribution to decarbonization will be adequately rewarded and the efficient use of scarce renewable energy ensured. Central planning cannot achieve this; it requires the decentralized effect of price mechanisms. The following measures can contribute to this.

1. **Implementation of a modified version of the production premium scheme**: In general, the premium scheme developed for the Pilot Auction of the European Hydrogen Bank is apt to close an important gap in the current hydrogen support landscape. Since it directly targets production, it provides an impulse for upscaling and thus market formation in this crucial phase. However, our simulations indicate that under the framework conditions set for the Pilot Auction, such a system carries the risk of over-subsidization and an inappropriate concentration of subsidies on individual large producers. The EU should therefore modify the conditions with a view to future auctions. Specifically, it should set a lower permitted maximum level (ceiling price) for the premium payments per kg of hydrogen, and at the same time reduce the minimum production capacity required for participation. This increases the chances of competitive auctions and reduces the risks of distortive impacts. In addition, it should, at least in the initial phase, relax the criteria set for the avoidance of support cumulation. Cumulation with demand-side instruments should be allowed in cases where these instruments likewise exhibit a market-oriented design limiting the extent of double subsidization. This avoids that the Hydrogen Bank undermines the steering effect of demand-side instruments, preserving the chances for a targeted allocation of renewable hydrogen to hard-to-abate sectors.

2. **Establishment of a differentiated EU-wide certification system**: A rapid development and implementation of a certification system for renewable hydrogen in Europe is another key to the emergence of cross-regional markets. It creates transparency on the side of buyers and the signal of reliability. It thus decisively strengthens the demand for this form of hydrogen, without reducing

[75] See Wolf (2023b).

incentives to improve production efficiency. To develop its full signal effect, such a certification system should not stop at signalling compliance with the conditions for electricity procurement laid down in the EU legal definition (see Section 6.1). In the medium term, certificates should also contain more detailed information on production technologies and estimates of the carbon footprint of the associated supply chains, setting the stage for a system of differentiated certificates to optimize user information.

3. **Introduction of well-designed green quotas for industrial H_2-applications**: Supply-side measures alone will not be sufficient to build up large capacities in the future; an orchestrated demand pull is needed. This requires funding that also creates sufficient revenue potential in the downstream segment. This applies especially to industrial H_2-applications. The technology shift to hydrogen is associated with long-term investment decisions, in which cost and revenue uncertainty play a major role. The idea of creating a secure form of revenue potential via quota requirements for public (or in an extended form private) procurement is important for creating demand capacities in the transition phase. If applied to private procurement, it also helps relieve the burden on government budgets caused by subsidies. However, such a quota system must be carefully conceptualized. It should be designed in a technology neutral way and in consideration towards the competitiveness of downstream industries, also in the interest of avoiding carbon leakage.

4. **Reduction of barriers to investments in a European H_2-pipeline infrastructure:** At the technological level, the necessity to develop a Europe-wide infrastructure of hydrogen pipelines represents a decisive restriction for market integration (see Section 2.1). For this, the package on a future internal market for renewable gases proposed by the Commission in December 2021 is of vital importance. The proposals, consisting of a directive[76] and a regulation[77], are intended to help decarbonize the gas sector and build an infrastructure for alternative gases. The political points of contention include the question of the preference of renewable over low-carbon hydrogen, the permitted blending rate of hydrogen with natural gas, and the requirements for the unbundling of the management of natural gas and hydrogen networks. The trilogue negotiations should reach an agreement on this package as quickly as possible, to create planning certainty for long-term investments in the conversion of gas pipelines and the construction of dedicated hydrogen pipelines. In particular, rules should follow the premise that network operators are given sufficient economic incentives for the expansion of hydrogen transport capacities, especially in the direction of industrial regions with high future demand potential.

5. **Creation of strategic partnerships to avoid new resource dependencies:** While representing an important puzzle piece in the EU's strategy of moving away from fossil resources, the electrolytic production of hydrogen comes with its own resource issues. This mostly relates to the upstream stage**,** the raw materials used in the production of electrolysers. According to the latest EU strategic foresight study on material demand, a range of raw materials considered critical by the EU enter the production process of electrolyser stacks. In particular, the resource dependence of PEM electrolysers is a source of concern, as their flexibility of operation will continue to be needed for

[76] European Commission (2021a). Proposal for a directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen. COM/2021/803 final.

[77] European Commission (2021b). Proposal for a regulation of the European Parliament and of the Council on the internal markets for renewable and natural gases and for hydrogen (Recast). COM/2021/804 final.

aligning hydrogen with electricity generation from volatile renewables. This mostly concerns the use of the critical metals platinum and iridium as catalysts in the electrolysis cells.[78] Not only do their high prices impair the overall price competitiveness of PEM electrolysers versus the simpler, but less flexible alkaline technology. The sourcing of these platinum-grouped metals is also geographically highly concentrated. In the case of platinum, the market share of top producer South Africa in global mining amounted to 74 % in 2022.[79] To secure the EU's currently significant share on the global market for electrolysers[80], the EU should engage in long-term partnerships with producers like South Africa and promising future resource champions. In its Action Plan on Critical Raw Materials[81] and the currently negotiated draft of a Critical Raw Materials Act[82], the Commission has presented and elaborated its concept of strategic resource partnerships with third countries. To be an effective tool, however, these partnerships should leave the current stage of pure memoranda of understanding as soon as possible and agree on concrete roadmaps of cooperation.[83]

78 JRC (2023c). Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study. Joint Research Centre of the European Union. Luxembourg.

79 USGS (2023). Mineral commodity summaries 2023. U.S. Geological Survey.

80 European Commission (2023e). Investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity. Commission Staff Working Document. SWD(2023) 68.

81 European Commission (2020). Critical raw materials resilience: charting a path towards greater security and sustainability. Communication from the European Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions. (2020) 474 final.

82 European Commission (2023f). Proposal for a regulation of the European Parliament and of the Council on establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020 (COM(2023) 160 final).

83 Wolf, A. (2023c). Strategic resource partnerships. cepInput No.4/2023.

7 Conclusion

The conditions for a large-scale commercialization of renewable hydrogen in the EU are more favourable today than ever. The political goal of a rapid decarbonization of all sectors requires a variety of technological solutions. In this respect, the role of climate-friendly hydrogen for reducing the carbon footprint of hard-to-abate sectors is no longer seriously questioned. Prospects for technologically induced cost reductions also turn hydrogen into an interesting business case. For the market to develop at the necessary speed, however, policymakers must address the uncertainty caused by the coordination problem of stakeholders along the supply chain.

To complement existing initiatives, the EU is currently establishing a new funding channel in the form of the European Hydrogen Bank. Its first instrument is the auctioning of subsidy payments to producers of renewable hydrogen in the form of fixed premium payments per kg. Such auctioned premiums have the potential to compensate for coordination-related uncertainty in a market-based fashion. In addition, unlike government guarantee contracts, they avoid cancelling out market-related price and demand signals.

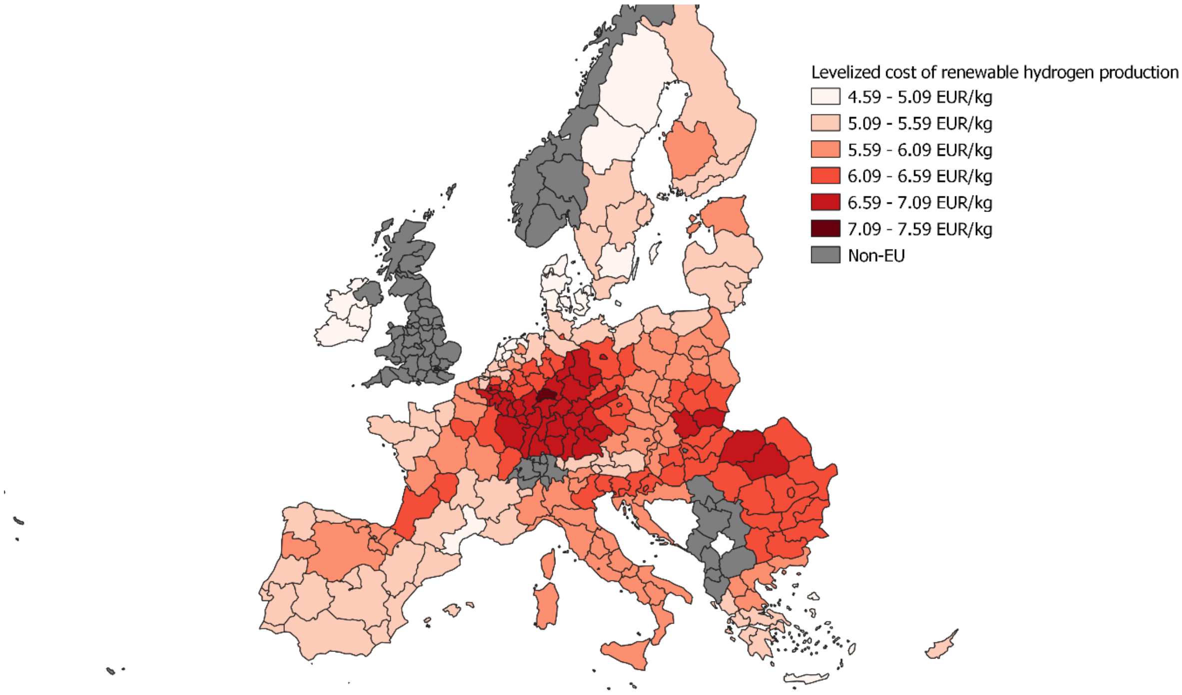
Our simulation results, obtained from a Real Options Analysis, indicate that the premium system can indeed be effective in accelerating capacity building. It acts as a secure complement to uncertain future market revenues and thus creates an incentive to accelerate investments. Since the size of the premiums is determined based on an auction mechanism, it also has the potential to become an efficient and flexible instrument. However, the terms and conditions applicable to the Pilot Auction carry risks. Our simulations reveal that, in view of the local cost situation in most EU regions, a subsidy at the maximum level specified would be inappropriately high in view of the objectives pursued. Since the degree of competition is initially limited by the restricted group of participants - and the pay-as-bid mode creates an incentive for strategic bidding - it is not unlikely that bids close to the maximum level will be successful. This would result in an over-subsidization of efficient large-scale hydrogen producers and/or the promotion of electrolysis in regions with poor access to renewables.

To address this risk, the maximum level of support should be lowered significantly and, at the same time, restrictions on participation should be relaxed to strengthen competition. This will affect the minimum level of electrolysis capacity, in particular, thus allowing small-scale producers to benefit as well. The criteria for cumulation with other forms of support should also be reconsidered. Otherwise, an overly strict interpretation runs the risk that the premium system will direct hydrogen into sectors for which fundamentally better alternatives for decarbonization are available. In general, lessons learned from the Pilot Auction should be used to continuously optimize the premium system.

At the same time, the establishment of the European Hydrogen Bank must not tempt regulators to give up on a holistic supply chain perspective. The market uptake of renewable hydrogen will continue to hinge on long-term investment decisions across all stages of the supply chains, requiring targeted policy support. This applies most prominently to the expansion of renewable energies as a fundament for long-term decarbonization, but also to the establishment of H_2-certification for trade, the Europe-wide development of pipeline capacities and support for the industrial transformation. A support system for hydrogen production can only be one piece of the puzzle. Its effectiveness and efficiency will always depend on the existence of a coherent policy strategy which places the EU's overall long-term competitiveness at the centre of its considerations.

8 Appendix

Figure A 1: Estimated current production costs of renewable hydrogen in EU NUTS-2 regions



Source: own calculations

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