

Geßner, Daniel

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Rethinking renewable energy policies for hydrogen – How the intercept of electricity and hydrogen markets can be addressed

Daniel Geßner*

*University of Wuerzburg, Graduate School of
Law, Economics and Society & Robert Bosch GmbH

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Daniel Geßner

Graduate School of Law, Economics and Society, University of Würzburg
97070 Würzburg, Germany
daniel.gessner@uni-wuerzburg.de

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Julius-Maximilians-Universität Würzburg
Volkswirtschaftliches Institut
Sanderring 2
97070 Würzburg

<https://www.wiwi.uni-wuerzburg.de/fakultaet/institute-und-lehrstuehle/vwl/>

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Am Hubland <https://opus.bibliothek.uni-wuerzburg.de>
97074 Würzburg
Tel.: +49 931 - 31-85906

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Rethinking renewable energy policies for hydrogen – How the intercept of electricity and hydrogen markets can be addressed

Daniel Geßner*

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Abstract

A lot of countries have recently published updated hydrogen strategies, often including more ambitious targets for hydrogen production. In parallel, accompanying ramp-up mechanisms are increasingly coming into focus with the first ones already being released. However, these proposals usually translate mechanisms from renewable energy (RE) policy without considering the specific uncertainties, spillovers, and externalities of integrating hydrogen electrolysis into electricity grids. This article details how different aspects of a policy can address the specific issues, namely funding, risk-mitigation, and the complex relation with electricity markets. It shows that, compared to RE policy, subsidies need to emphasize the input side more strongly as price risks and intermittency from electricity markets are more prominent than from hydrogen markets. Also, it proposes a targeted mechanism to capture the positive externality of mitigating excess electricity in the grid while keeping investment security high. Economic policy should consider such approaches before massively scaling support and avoid the design shortcomings experienced with early RE policy.

Keywords: hydrogen policy, renewable energy policy, support mechanisms, contracts for difference

JEL Codes: O25, O38, Q42, Q48

*University of Wuerzburg Graduate School of Law, Economics and Society & Robert Bosch GmbH
Email: daniel.gessner@uni-wuerzburg.de

1 Introduction

Governments mobilize large financial resources to support green technologies, predominantly to achieve two goals: first, to aid the transition to a carbon neutral society and fight climate change and second, to transition domestic industries and develop competitive advantages. Generally, green technologies that do not yet scale sufficiently cannot compete effectively on the market without government support. This can be due to different reasons. On the one hand, costs may be too high such as when externalities of pollution and/or CO₂-emissions are not internalized – for instance if carbon schemes invoke inadequate price levels (Hepburn et al., 2020; Pigou, 1920). These technologies are then unable to compete with fossil solutions on a level playing field, which is the case for most economies (Boyce, 2018).¹ But even if sufficiently priced, some carbon-neutral solutions may be more developed to scale than others, effectively requiring the government to intervene for them to compete on an equal footing.² On the other hand, new technologies also come with higher levels of uncertainty regarding properties like durability, degradation, utilization rate, achievable sales volume and price, etc. Interventions to mitigate these uncertainties can aid the development of such new technology markets (Mazzucato, 2011).

In looking for suited instruments to promote hydrogen, policymakers usually draw on experiences with other green technologies.³ Yet, hydrogen is not a primary energy source like solar and wind. As a storable energy carrier, it possesses properties that enable many useful features like sector coupling or aiding electricity grids in dealing with increasing shares of intermittent RE (see e.g., Grüger et al., 2019; Macedo & Peyerl, 2022; Nascimento da Silva et al., 2022; Nasiraghdam & Safari, 2020). These features represent positive externalities for which policy should account to effectively achieve the integration into the energy system. By implementing dedicated measures on the supply side, policymakers can manage these issues at the intersection with the electricity system to address the complexity at its focal point and leverage grid-conducive behavior.

To provide steppingstones for the current hydrogen policy debate, this article explores the distinctions between RE and hydrogen to derive how experiences from RE policy can be adapted. Emphasis is placed on the different functions that hydrogen policy can fulfill, namely (1) close a funding gap, (2) mitigate risks associated with an emerging industry and the uncertainty induced by the electricity sector, and (3) leverage positive externalities. Initial remarks therefore focus on technological and economics differences between RE

¹E.g. for Germany, even in a best-case scenario with production in times of low price and if no surcharges on electricity would be charged, hydrogen production costs would be about 30% above (fossil) hydrogen market price (Grüger et al., 2019).

²This aspect refers to an industrial policy (or infant industry) argument stressing competitive disadvantages of upcoming technologies relative to established competitors due to, amongst others, economies of scale and scope as well as learning-by-doing effects (Hepburn et al., 2020; Liebensteiner & Naumann, 2022; Reichenbach & Requate, 2012).

³Literature on RE delivers many evaluations on the performance of these policies. For instance, Kilinc-Ata (2016) and Bersalli et al. (2020) empirically show FITs to have had a positive impact on RE capacity expansion. Winkler et al. (2016) favor FIPs for efficiency reasons.

and hydrogen and the transferability of previous experiences. Next, feasible policies to close the funding gap are explored before the issue of investment security and its trade off with masking electricity price signals is addressed. Further emphasis is placed on the role that targeted policies can play in enabling electrolyzers to serve as a stabilizing force for the energy system and capture this externality for society. Lastly, proposed measures are discussed, and recommendations to policymakers are given.

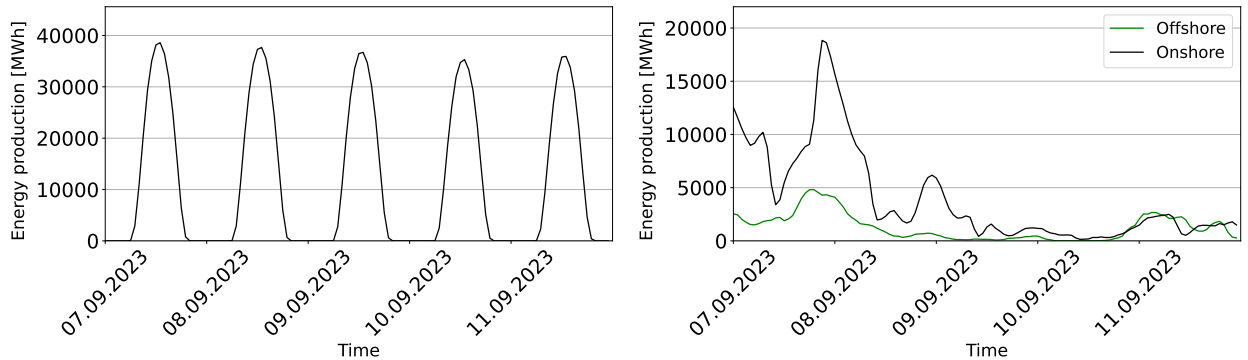
2 Comparability with renewable energy

As the hydrogen economy is just developing, one can currently only draw on limited experience with respective support policies. Referring to other sectors is therefore necessary, with early RE policy representing a particularly comparable field (see also International Renewable Energy Agency (IRENA), 2021). Yet, there are distinct differences to be aware of in order to gain the right inferences.

2.1 Renewable energy technologies

The business case for most RE technologies is characterized by high upfront investment and very low operating costs, respectively marginal costs of near zero (Fabra, 2021). Once in operation, these plants produce electricity cheaply, mostly from naturally occurring wind and sunlight, and are therefore intermittent as shown in figure 1.⁴ After achieving massive cost reductions and nowadays usually being the lowest-priced source of electricity (Neuhoff et al., 2022), their production is however volatile and as such constitutes a negative externality. With electricity having to be utilized in the same instance as it is produced, it is required to be supplemented by costly storage and/or flexible supply or load capacity (Hirth et al., 2016; Imprim et al., 2020).

Fig. 1. Exemplary production profiles for solar (left) and wind energy (Data: Bundesnetzagentur, 2024a).



⁴The profiles are exemplary for a period of about average production (September) in Germany (production peaks are in early summer for PV and in early winter for wind).

Compared to legacy fossil technologies, RE used to not be cost-competitive and received support in many economies to ramp sufficiently (REN21, 2022). A further reason for state interventions roots in technological and economic uncertainty, which initially required policymakers to offer reliable business cases to attract private investment. Accordingly, many economies first largely decoupled RE’s from market forces to provide investment security and only later increasingly exposed them to market feedback (e.g. in the EU, European Commission, 2011).

2.2 Hydrogen technology, industry, and economics

A hydrogen economy is characterized by many similarities to RE, but also exhibits differences which entail contrasting economic drivers and divergent needs for intervention. Like electricity, hydrogen is versatile and can serve many use cases. Yet, as a molecule it can be stored more easily, transported over large distances, and e.g., bridge into processes to reduce carbon emissions in chemical reactions; so-called hard to abate sectors (Capurso et al., 2022). Additionally, when used to stabilize fluctuations within the electricity grid,⁵ it exerts positive externalities. These properties make hydrogen very flexible, yet they also imply that its applications are particularly diverse and integrated into various sectors, making pathway projections and policy intervention more complex (see, e.g. Farrell, 2023; Hanley et al., 2018). Moreover, and unlike renewable electricity, hydrogen cannot rely on an available infrastructure and appliances – at least not without retrofit.⁶ This further increases economic and technological risk and necessitates high initial investments.

Cost structures differ widely depending on the technology. While building infrastructure and retrofitting for instance blast furnaces requires high capital investments (Pawelec & Fonseca, 2022), operating costs dominate in many applications. These operating costs on the usage side predominantly stem from prohibitively high prices of green hydrogen compared to using grey hydrogen or natural gas and are due to high electrolysis costs. Also, for electrolyzers, electricity and maintenance account for the majority of total costs with their relative shares increasing even further with scaling electrolyzer production (and decreasing capital investment) (Nami et al., 2022). Moreover, investments in hydrogen projects are associated with additional uncertainty due to electricity prices being volatile, difficult to predict, and dependent on country-specific regulation. Modelling thus shows that the introduction of hydrogen pathways is particularly susceptible to the availability of an infrastructure and suited risk-reducing policy measures (Hanley et al., 2018).

⁵For technical properties and viability, see Buttler and Spliethoff (2018).

⁶Hydrogen transport infrastructure and hydrogen ready-appliances are currently scarce with e.g., 1,600 miles of pipelines in operation in the U.S. vs. 3,000,000 miles for natural gas (Department of Energy (DOE), 2023; US energy information administration (eia), 2022).

3 Policies to close the funding gap

Hydrogen and RE policies are numerous and diverse. At least when considering financial policies, their primary goal is usually to close a funding gap. This chapter lays out common properties and illustrates policy mechanisms. The focus here is however on key supportive instruments for the hydrogen sector, so that only a selection is presented. Moreover, it addresses interactions along the value chain and vis-a-vis other sectors.

3.1 Properties of support policy

Hydrogen or RE policies can be classified in different dimensions. Usually, they are clustered according to product maturity into R&D, industrialization, and operations or similarly as technology push vs. demand pull. While technology push describes the use of science and technology with the aim of reducing the costs of emerging technologies through e.g., R&D (Henrique de Mello Santana et al., 2019), demand pull instruments then again aim at generating a market need, inciting suppliers to invest in R&D and production capacity. On the other hand, policies can also be structured by the value chain stage they address e.g., equipment manufacturing as well as hydrogen production, transport, storage, and usage.

Table 1

Clustered overview of feasible hydrogen policies (exemplary selection).

	R&D	Ramp-up		Operations	
		Industrial-ization	Infra-structure	Supply	Demand
Financial (fixed)	Research projects, grants, demonstration projects	Investment subsidies, favorable loans & depreciations	Investment subsidies, favorable loans & depreciations	Investment subsidies, capacity schemes	Investment subsidies, purchase premiums
Financial (variable)	Cost-based compensation, milestone payments	Production credits, pilot projects	Levy's, fuel subsidies, credits	<i>Fixed credits, fixed and floating premiums, CfDs, tax exemptions</i>	<i>Fixed credits, fixed and floating premiums, CfDs, CCfDs</i>
Non-financial	Guarantees and favorable loan access, leaner administration and permitting			Guarantees and favorable loan access, <i>quotas and portfolio standards</i> , leaner administration and permitting	

Conversely, classifying policies as primary or secondary is more common in the literature (e.g., del Río et al., 2017; Huber et al., 2007; Kitzing et al., 2012). This distinction developed from early policy analysis when instruments such as quotas, feed-in-tariffs (FITs), or tendering dominated (del Río & Mir-Artigues,

2014). Another approach is to distinguish if policies use financial incentives or are non-financial, such as command-and-control measures (see e.g., Henrique de Mello Santana et al., 2019). Additionally, financial mechanisms can be based on fixed payments, usually at the beginning of a project, or be recurring and variable, e.g., according to output. Table 1 provides an illustration of policies clustered according to the described properties. Primary policies are depicted in italics.

3.2 Operating policies for green technologies

Initially, hydrogen technologies have often been supported through research policy and demonstration projects. The aim of these instruments is to accelerate the technical development and illustrate first applications which would then attract demand in the market. These measures are typical technology-push. Subsequently, many governments moved on to industrialization measures by setting up grants, subsidies, or pilot projects that benefit specific technologies, particularly in an early phase of ramp-up (Henrique de Mello Santana et al., 2019). By now, operating measures aimed at scaling the adoption of hydrogen technologies increasingly come into the focus for policymakers.

3.2.1 Primary operating schemes

Many countries plan to introduce or have already launched operating policies to create a hydrogen market (demand pull measures) (see e.g., International Energy Agency (IEA), 2023), including 15 of the G20 members (see table 2). These policies address a high number of market participants at high volumes so that they are usually leaner, less bureaucratic, and aim more strongly at efficiency compared to project specific funding

in R&D or industrialization. They can be divided into quantity instruments like quotas or portfolio standards on the one hand, which function e.g., as command-and-control measures by regulating certain usage shares that must be met, or as incentives by being awarded tradable certificates that can be sold (Abolhosseini & Heshmati, 2014). In the past, these instruments have seldomly lived up to expectations because they provide a low level of investment security (see e.g., Butler & Neuhoff, 2008; del Río & Mir-Artigues, 2014; European Commission, 2013; Mitchell & Connor, 2004).

On the other hand, literature on RE delivers many evaluations on the performance of price-based instruments with most of them favoring FITs and feed-in-premiums (FIPs) (Bersalli et al., 2020; Kilinc-Ata, 2016; Winkler et al., 2016). Such mechanisms incite operations via output-based payments and lead investors to aim for maximized production. Due to this, they resulted in superior outcomes for RE and are now again frontrunners in proposals for hydrogen (see e.g., Özdemir et al., 2020; Talebian et al., 2021; Zheng et al., 2022). In general,

Table 2

Overview of hydrogen operating policies among G20 members (proposed law and in force).

Country	Policy or Scheme	Mechanism	Source
Australia	Hydrogen Headstart Program	Fixed Premium (w/ Upside Sharing)	Australian Renewable Energy Agency (2023)
Brazil	National Hydrogen Program	Investment & tbd Production Subsidy	Proposed Artt. 26 ff. Bill 2308/23, Chamber of Deputies (2023)
Canada	Investment Tax Credit for Clean Hydrogen	Investment Subsidy	Proposed Sec. 127.45 Income Tax Act, Bill C-59, Parliament of Canada (2024)
China	New Energy Vehicles Dual Credit Policy	Tradeable Credits Scheme	Government of the People’s Republic China (2020)
European Union	EU Hydrogen Bank Innovation Fund Auctions	CfD	European Commission (2023), with Art. 10 par. 8 subpar. 11 Directive (EU) 2023/959
France	Support for the Production of Renewable and Low-Carbon Hydrogen	CfD	Artt. L812-2 ff. Code de l’énergie
Germany	1) Innovation Fund Auctions-as-a-Service 2) Climate Protection Contracts	1) CfD 2) CCfD	1) Federal Ministry for Economic Affairs and Climate Action (2023) 2) Federal Ministry for Economic Affairs and Climate Action (2024)
India	Incentive Scheme for Green Hydrogen Production	Fixed Premium	Order No. 353/40/2023-NT, Ministry of New and Renewable Energy (2023)
Italy	Production Incentives for Gaseous Fuels from Renewable Sources	CfD	Ministero dell’Ambiente e della Sicurezza Energetica (2024)
Japan	Supply Chain Subsidies	CfD	Ministry of Economy, Trade and Industry (2024)
Russia	Implementation Cost Compensation	Investment Subsidy	Ordinance No. 1679, Government of the Russian Federation (2023)
South Africa	Green Hydrogen Commercialisation Strategy	No final decision yet (probably CfD)	The Department of Trade Industry and Competition (2022)
South Korea	Hydrogen Power Generation Bidding Market	Portfolio Standard	Art. 25-6 Hydrogen Economy Promotion and Hydrogen Safety Management Act
United Kingdom	The Hydrogen Production Business Model	CfD	Sec. 57 f., 65 f. Energy Act 2023
United States	Hydrogen Production Tax Credits	Fixed Premium	26 U.S. Code 45V

payments are realized through direct payments, tax credits,⁷ or by representing a fixed or floating premium on top of the market price up to purely financial contracts for difference (CfDs). The amount of these payments can either be determined administratively, yet then they suffer from time-lag and information asymmetry, or be competitive and auction-based (Fabra, 2021; Haufe & Ehrhart, 2018).

Table 3

Properties of typical operating mechanisms.

Type	Most notable properties
Quota Instruments	<ul style="list-style-type: none"> - Little investment security due to uncertain future demand and prices - Full market integration and no government payments needed
Fixed (Indexed) Price or Tariff	<ul style="list-style-type: none"> - High level of investment security through feed-in and price guarantee - No price incentives (at least not without additional design features) - Incites maximized production
Fixed Premium	<ul style="list-style-type: none"> - Low level of investment security due to price uncertainty - Medium production incentive due to low prices at high electricity supply - Increased incentives for system conducive control interventions
Floating Premium	<ul style="list-style-type: none"> - Effectively very similar to FIT, including strong investment security - Increased market integration with no price risk (possibly even upside potential) - Incites maximized production in its standard design
CfD	<ul style="list-style-type: none"> - High level of investment security coupled with a market integrative process - Entirely financial nature enables designs with strong market incentives

CCfDs are a specific type of CfDs and provide investors with a guaranteed carbon price above the actual level, the so-called strike price (European Commission, 2022; Richstein & Neuhoff, 2022). This mechanism facilitates in its basic form a reliable payment per abated unit of carbon emissions. However, CCfDs come in different designs such as with or without a payback requirement when carbon prices are above the strike price or with administrative or auction-based price determination. Also, different award procedures can be leveraged to achieve specific goals, for instance, auction-based awards are preferable to achieve static cost-efficiency while multi-criteria procedures can be used to prioritize effectiveness in CO₂ reduction (Rilling et al., 2022). CCfDs are usually deemed to be a suitable policy for the energy intensive or hard to abate industry in hydrogen usage sectors, such as steel or fertilizer production (Richstein & Neuhoff, 2022).

Guaranteed sales prices or FITs offer output-based payments for a pre-determined timeframe and thus provide independence from market demand and prices. Conversely, premiums can either be a fixed markup to market revenues or floating to pay for the difference to a reference price. As such, floating premiums are comparable to FITs but entail deeper market integration and can yield proceeds above the reference value (Klobasa

⁷Many European publications do not classify tax credits as a primary support measure e.g., del Río et al. (2017) and Kitzing et al. (2012). Yet, they have a long tradition in US RE policy, see Murray et al. (2014), and are now again used as the primary US scheme for hydrogen support, see Sec. 45V of the Internal Revenue Code, as enacted by the Inflation Reduction Act

et al., 2013). CfDs operate similarly but with the key distinction that operators are required to pay back such extra proceeds (Kitzing et al., 2012; Neuhoﬀ et al., 2022). As a targeted instrument for risk reduction, they are also economically more eﬃcient, even more so when technologies mature (Neuhoﬀ et al., 2022). Particularly in EU policy, auctioned CfDs are therefore the favored incentive mechanism (see e.g., Council of the European Union, 2023). CfDs, premiums, and fixed prices can moreover take many diﬀerent designs regarding contracting partner, payout scheme, reference period, unit of reference (e.g. actual production or reference plant), etc (see e.g., Beiter et al., 2023; Rilling et al., 2022; Schlecht et al., 2024).

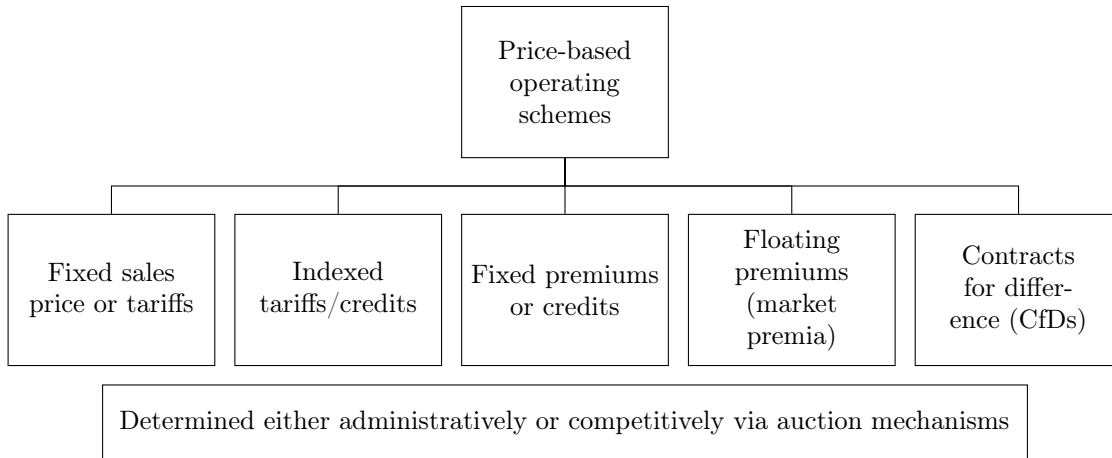


Fig. 2. Structure of typical operating mechanisms.

3.2.2 Relevant secondary policies

Next to these schemes, governments may employ secondary policies which supplement them or serve as an administratively leaner alternative. Combinations of instruments may particularly be justified to account for coexisting market failures or to achieve multiple goals (del Río & Mir-Artigues, 2014). A common instrument in this context are investment subsidies or grants which allow for investors to cover part of their upfront investment as a one-off non-reimbursable payment, usually at the construction of a project (Kitzing et al., 2012). They incite to take on an investment by reducing its initial burden (Abdmouleh et al., 2015), but do not encourage maximized or efficient output. These measures are thus also suited as ramp-up policies.

A similar effect can be achieved by providing preferential financing conditions, i.e., loans at lower rates, longer repayment periods, or interest holidays to investors so that taking on debt becomes less costly (del Río & Mir-Artigues, 2014). Even though these preferred conditions do not represent direct payments, they entail reduced costs which have the same effect. Capacity payments on the other hand are usually auction-determined and do not play a prominent role for RE but are regularly used in general energy policy to award fixed payments for stand-by capacity and only a minor share of payments for actual use (see e.g.,

Homan & Brown, 2021; Ocker et al., 2018; Pollitt & Anaya, 2020). Another common practice to supplement major schemes are exemptions from taxes, levies and similar electricity or gas price components which reduce operating costs (del Río & Mir-Artigues, 2014; Kitzing et al., 2012).

3.3 Value chain interrelations

Most direct support policies address a single type of technology. Yet, being linked within the value chain, they typically take effect beyond the scope of a single technology stage so that spillovers and interrelations should be carefully considered. For instance, supporting hydrogen production entails an increased supply of cheap hydrogen which contributes to closing the funding gap for application technologies, and vice-versa. Such a positive spillover from supply policy to demand sectors has already been observed for RE policy (see e.g., Yi & Feiock, 2012). Similarly, hydrogen technologies cannot be considered only by themselves, as synergies, spillovers, and externalities with other sectors are key to their development and success (Hanley et al., 2018). This is particularly the case with respect to the electricity market and application technologies for hard to abate sectors.

Drawing conclusions from RE, most primary policies address electricity supply. One reason for this could be that renewable electricity is a homogeneous good,⁸ serving as an input for a diverse market of demand applications. This might also be an advantageous strategy for green hydrogen which is expected to be produced predominantly from electrolysis (Zainal et al., 2024), while its use can lie in many different applications. Related to this, hydrogen availability represents one constraint for the ramp-up of the hydrogen economy at the moment, so that additional demand stimulus may only entail higher prices (Farrell, 2023). Modelling further shows production subsidies and corresponding electricity incentives to be more effective in reducing greenhouse gas emissions than demand side policies (Talebian et al., 2021). Moreover, supply side measures are also better suited to reduce uncertainties and mitigate externalities as described in the subsequent chapters.

These indications thus suggest that it is a reasonable strategy to provide hydrogen at competitive prices and exert influence over the entire value chain. This can be flanked by additional measures in R&D and industrialization, and, particularly at this stage of the technological development, in infrastructure and demand use cases to address further funding gaps (del Río & Mir-Artigues, 2014; International Renewable Energy Agency (IRENA), 2021). These are often related to further immature technologies and the uncertainties related to long-term commitment for infrastructure investments. Also, with demand applications requiring

⁸Electricity also exhibits properties of a heterogeneous due to different timing and properties of the generation technology, but for the argument above it can be considered homogeneous (Hirth et al., 2016).

diverse and low hydrogen prices to reach breakeven, use-case-specific policies can be utilized to balance or prioritize specific applications. The subsidies paid on the supply side should then entail that less support is needed in other sections of the supply chain.

4 Policy options to mitigate uncertainty

As the hydrogen economy is still in a nascent stage, there is significant uncertainty regarding how technology, markets, and cost factors might evolve as well as if high investments can be recouped. Such uncertainty is commonly present in early development stages of new technologies and may hinder robust inflows of private capital (Mazzucato, 2011). Particularly investments that require a long time to amortize exhibit strong risks when private contracts are only of short duration, consequently they are unsuited as hedges (Neuhoff et al., 2022; Schlecht et al., 2024). Additionally, the hydrogen economy is closely integrated into the likewise transitioning electricity market so that it faces further uncertainty from this sector interplay in an environment of firm regulatory dynamic. Hence, government policies must go beyond financial funding and accelerating the market development to address all these uncertainties as well. By implementing dedicated mechanisms, support policy can provide the required funding and simultaneously reduce uncertainty, decrease risk-related markups, and enable access to private funding by providing more attractive business cases.

4.1 Electricity markets introduce uncertainty

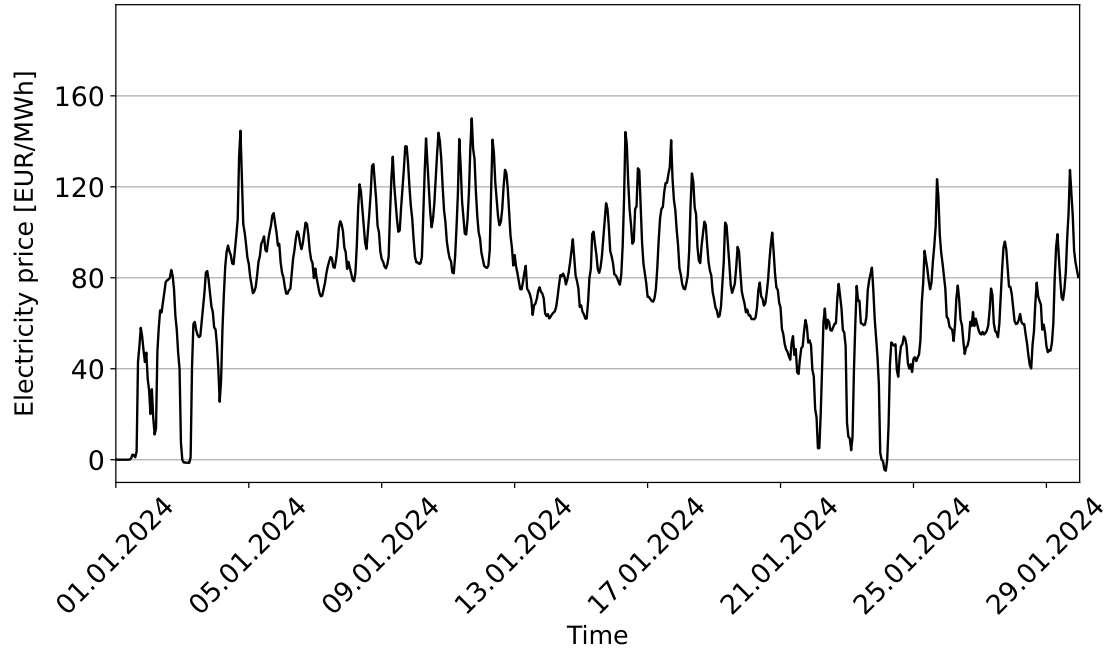
RE technologies are to a large extent non-dispatchable, so they produce electricity depending on the intermittent availability of wind and sun, and as such introduce volatility into electricity grids (see e.g., Ciarreta et al., 2020; Dong et al., 2019; Nguyen et al., 2019). With expanding RE shares and, for now, mostly inflexible electricity demand, this implies intensifying fluctuations in market clearing prices and an increasing need for storage (Hirth et al., 2015).⁹ Figure 3 illustrates the volatility of electricity prices. These developments affect the economics of electrolyzers by limiting runtime¹⁰ and increasing electricity costs so that produced quantities as well as achievable margins compress and become less predictable for investors. Additionally, many countries maintain regulations that limit the creditability of green hydrogen, for instance geographically, to periods of high RE share in the grid, or to direct line connections with RE plants (e.g., Commission Delegated Regulation (EU) 2023/1184). This further raises volume risk and/or electricity price risk which are key issues for the business case of electrolyzers.

Own production or power purchase agreements (PPAs) can stabilize the costs of electricity via fixed long-

⁹Empirical evidence from Spain: Ballester and Furió (2015).

¹⁰So-called volume risk (Schlecht et al., 2024).

Fig. 3. Development of electricity prices in Germany, Jan. 2024 (Data: Bundesnetzagentur, 2024b).



term conditions. However, with direct line connections to RE plants, such arrangements imply intermittency caused by the dependency on usually only one type of generator technology (International Renewable Energy Agency (IRENA), 2021). This is not necessarily an issue if electrolyzers are allowed to also take electricity from the grid, but in many cases, green hydrogen regulations only allow for this in limited exemptions (e.g., Commission Delegated Regulation (EU) 2023/1184, Ruhnau & Schiele, 2023). The aim behind this restriction is to guarantee hydrogen production from pure RE sources. Yet, such regulations as well contribute to increased uncertainty and provide less opportunity to use hydrogen production to mitigate excess supply in the grid (Ruhnau & Schiele, 2023). Like this, policies can hinder the inclusion of electrolyzers into electricity markets and increase business risks through further electricity price volatility and uncertainty regarding the number of achievable full load hours.

4.2 Mechanisms to foster investment security

One way to mitigate the described risks is to implement output-independent mechanisms like investment subsidies or capacity mechanisms. In this case, investment and operating risks are mitigated as the initial investment costs are recovered independently from achieved operational time at positive margin. Yet, such mechanisms in pure shape can in turn provide false incentives, leading to an under-utilization of production capacities (Winkler et al., 2016). This typically prompts policymakers to prefer output-based interventions

that provide stable selling prices, like fixed prices, floating premiums, or CfDs, leaving only the quantity risk to investors. Fixed premiums or tax credits also close the funding gap but leave investors with full exposure to hydrogen price volatility (Fabra, 2021). Consequently, the latter tend to outperform pertaining market integration but underperform in terms of investment security and support costs because investors require additional risk premiums, making debt financing more costly (Beiter et al., 2023; European Commission, 2013; Kitzing, 2014).

However, these output-based mechanisms still do not offset electricity price risks – at least not without further adjustments. One such adjustment can for instance be to **index production remuneration** respective to the electricity price¹¹ While this involves continuous changes to the level of remuneration, it stabilizes the hydrogen sales price vis-à-vis its production costs and thus preserves margins. The more frequent these adaptations, the less market integration and the fewer the risks that investors bear.

Another alternative is to directly address the electricity price risk by implementing a sufficiently low and **fixed purchase price**. With hydrogen being easily stored or buffered in pipeline networks, its price is less volatile than electricity (Zheng et al., 2022), as illustrated with figures 3 and 4. Such an approach can close the funding gap similarly to production credits while at the same time alleviating the supply cost uncertainty. A disadvantage to this is, that support levels need to be regularly adjusted because of medium- or long-term hydrogen price trends, which may pose an issue when prices and thus margins decrease or may lead to over-support vice versa. As a solution, subsidized electricity prices can be anchored or indexed to changes of the hydrogen market price. The shorter these intervals, the more dynamic the price adjustment and the less uncertainty investors bear.

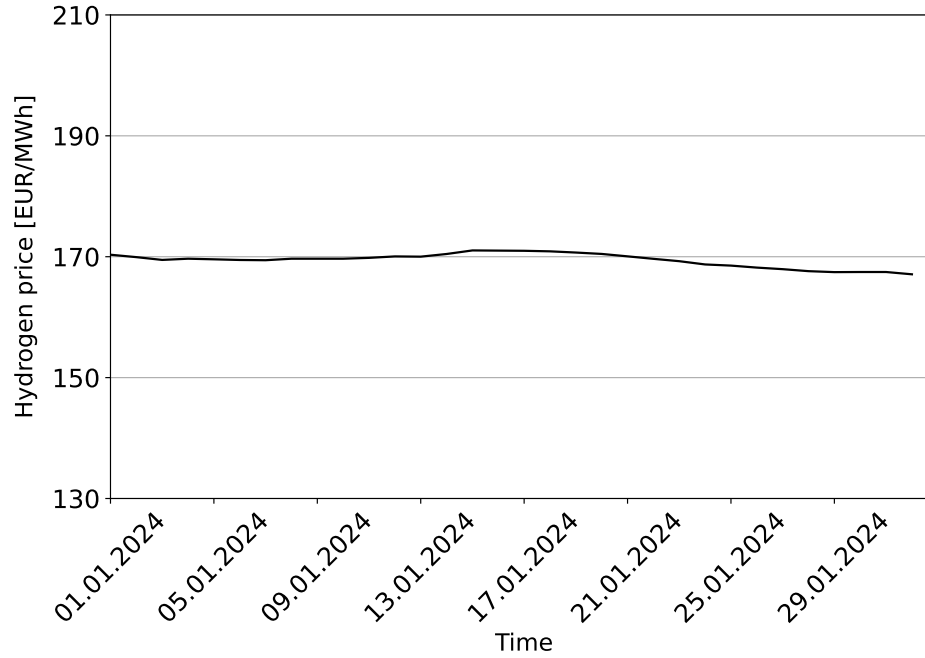
4.3 Trade-off against the permeability to price signals

Being positioned at the intersection of electricity and hydrogen markets, the design of such policies is decisive to balance the trade-off between investment security and system conduciveness. Fixed premiums or discounts for instance integrate market signals but pass through price volatility which is a key risk for plant operators. They thus contradict the initial aim of fostering investment security. This is not the case with a fixed supply price, floating premiums or CfDs. However, these mechanisms incite continuous operation at full load as price signals are covered.¹² Consequently, to achieve both goals, the subsidized price must be at least *partially decoupled from market price* volatility. Yet, it should still sufficiently *allow for market signals*, as electricity prices are uniquely suited to indicate efficient hydrogen production timing (see Griffiths et al., 2021).

¹¹Similar adjustments have been used with RE policy where FITs were indexed on e.g., exchange rates or natural gas prices (Kitzing et al., 2012), yet this can as well be done according to input costs

¹²Through fixed tariff payments above marginal costs, profit maximizing investors are incentivized to maximize production.

Fig. 4. Development of hydrogen prices in Germany, Jan. 2024 (Data: E-Bridge Consulting, 2024).



Such an intermediate solution can be achieved by implementing **extended reference periods**, used to calculate average market prices (to then determine the differential vis-à-vis a strike price) (Neuhoff et al., 2022). By basing the calculation of the average market price on a longer timeframe, intra-period price differences are no longer muted and create incentives again (Schlecht et al., 2024). Like this, indexed schemes or market premia policies become permeable to price signals while longer price trends are mitigated. This solution can be leveraged to calculate the reference value for an electricity index based on average prices for the case of a hydrogen production subsidy.

Some countries conversely stipulate policies where subsidies are only fixed up to pre-defined parameters, while they are reduced or withdrawn beyond (see e.g. § 51 sec. 1 with § 51a sec. 1 EEG and Government of the Netherlands, 2020). Such a mechanism is suited for a fixed electricity purchase price when implementing a **maximum subsidized runtime** (Newbery et al., 2018) so that electrolysis operators are incentivized to run their operation at times of peak margin to maximize profit. The government subsidy would in this case need to be a sliding discount or CfD with a reference value determined according to times of lowest electricity prices. Operating electrolyzers in times of excess electricity supply is in this case an independent decision of market participants without the need for ad-hoc government intervention – with all associated advantages. This functions best with local pricing zones if limited transmission capabilities cause local congestions (Newbery et al., 2018).

5 Addressing externalities as a third goal

Allowing for market signals to partially pass through the scheme and thus inciting system-conducive electrolysis enables an efficient integration of hydrogen technologies into the energy system. Beyond that, hydrogen production can furthermore be leveraged to explicitly reduce volatility in the grid by providing flexible offtake capacity. While electricity pathways in general exhibit a higher efficiency, making direct electrification more attractive, developments like an increased adoption of e.g., wind energy nevertheless represents a driver for flexible hydrogen production due to its potential in mitigating excess electricity (Hanley et al., 2018). While these properties are well-known, their specifics are seldomly considered when designing support schemes.

5.1 The positive externality of mitigating fluctuations

At high RE shares from wind and solar, electricity supply in grids often exhibits a strong geographic and temporal simultaneity which strains the grid’s transport capacity and subsequently necessitates re-dispatch and shut-offs (Joskow, 2011). This is rooted in technology-specific production profiles or local accumulation of e.g., wind turbines in coastal regions. With extending RE capacity, future electricity infrastructure will increasingly benefit from flexibility in production, load, or storage capacity to stabilize grids and electricity prices (Karaduman, 2021). A recent meta study estimates that 1-3 TWh of flexible capacity will be required for the European Union and the U.S. each in a scenario with over 80 % and PV-dominated variable RE share (Cebulla et al., 2018). The International Renewable Energy Agency (IRENA) (2017) estimates a required worldwide capacity of 11.9 to 15.7 TWh at an 80 % RE share, of which 52 % are solar and wind, which is about triple the current capacity. What’s more, power-to-gas technologies like electrolysis are a suited option to avert transportation bottlenecks and mitigate excess supply.

In general, all types of electrolyzers are capable of providing flexibility, yet different technologies have diverging start-up and reaction times which make them distinctly suited for specific use-cases or load profiles (see Buttler & Spliethoff, 2018). However, regulation may represent an obstacle if it hampers e.g., taking electricity from the grid or, requires simultaneity with the production of physically or virtually coupled RE plants (Ruhnau & Schiele, 2023). Beyond forgoing the chance to capture positive externalities, hydrogen generation costs even increase in such a scenario compared to an approach where the grid can be used flexibly (Terlouw et al., 2022). Allowing for *unhindered trading according to price signals* can consequently reduce the levelized costs of hydrogen by up to 50 % and decrease required subsidies (Ruhnau & Schiele, 2023).

Additionally, investments for the extension of electricity grids can be reduced by this and as such contribute further to cost savings. Yet, with these cost savings materializing outside of their scope, electrolysis oper-

ators do not consider this in dispatch or in their investment and pricing decisions – representing a positive externality. Hydrogen production thus exerts a mutual benefit when operated conducive to electricity grids. Beyond allowing for market signals to be perceptible, the value of this externality must then be priced accordingly to avoid under-investment (Fabra, 2018). Therefore, leveraging these benefits requires targeted government incentives and specific considerations when designing policies.

5.2 Low utilization rate detracts investment incentives

The key dilemma in balancing electricity grids is, that in an energy-only setting, imbalances must exert strong price peaks for investments in flexible capacity to be taken and to allow for investors to recoup their costs in these few moments (i.e., at very low utilization rate) (Fabra, 2021). Effectively predicting these peaks nonetheless comes with strong uncertainty and consequently also yields higher risk premiums. This is particularly the case for high capital expenditure technologies which require even more runtime at positive contribution margins to break even.¹³

Theory additionally predicts that such scarcity pricing leads to an inefficient allocation due to imperfect competition and restricted market entry under real conditions (Fabra, 2018).¹⁴ With price signals moreover translating into additional physical capacity after a long time-lag, energy-only remuneration induces boom and bust cycles so that the efficient functioning of such markets is hindered (Ford, 2002). Flexible power markets are therefore commonly characterized by auctioned **capacity payments**, including a compensation per utilized energy unit.¹⁵ This approach stabilizes cash-flows and reduces revenue risks for investors, yet RE research also finds capacity-based support to lead to disadvantages like unfavorable incentives for an output-oriented plant design and lower produced quantities (Winkler et al., 2016). It may therefore be better suited for the dedicated provision of flexible capacity.

Remuneration schemes for system-conducive electrolysis should consequently at least partially be based on **production incentives**. Nevertheless, being a technology not yet manufactured at scale, electrolyzers entail rather high investment costs (Buttler & Spliethoff, 2018), which then need to be recouped through contribution profit in times of operations. Because of this, limited runtime puts such high investment cost technologies at a disadvantage and tends to favor solutions with a relatively high operating cost share, such as batteries. As a result, electrolyzers cannot profitably take part in the grid-related storage market today

¹³Recouping investments in high capital technologies requires particularly high contribution profits so that peak prices must be even better timed in these cases.

¹⁴As this concerns electricity supply, it is only directly applicable to flexible fuel cells, but the general mechanism similarly relates to electrolyzers in case of electricity surplus.

¹⁵See e.g. for Australia, UK, US and Europe: Homan and Brown (2021), Ocker et al. (2018), and Pollitt and Anaya (2020). See also Kozlova and Overland (2022). RE plants are often exempted from participation in capacity schemes because they are not sufficiently reliable (Kozlova et al., 2023).

(Karaduman, 2021; Macedo & Peyerl, 2022).¹⁶

According to Nguyen et al. (2019), the cost optimum of operating electrolyzers without policy interventions lies in the range of 95-97 % utilization, depending predominantly on local electricity prices and price volatility.¹⁷ Achievable full load hours for grid services are usually much lower than this and are expected to reach for instance in most locations of Germany less than 2 %.¹⁸ Altogether, following a business model of providing flexible capacity yields limited production incentives and comes at a high cost to society due to a low utilization which increases the levelized costs of hydrogen. Hydrogen policies focused solely on providing flexibility are thus usually not economical and do not deliver the desired amounts of hydrogen.

5.3 A perspective policy approach

Society aims to achieve two goals simultaneously, namely maximize hydrogen production and at the same time utilize the stabilizing externality of electrolysis for grids. Policymakers should accordingly consider the need of electrolysis operators for a profitable and sufficiently de-risked business and the effect that this business exerts towards the electricity grid. To bring all this together, fixed output-based payments as well as pure capacity or investment-based mechanisms are not expedient. Literature thus suggests referring to intermediate solutions like **two-part-tariffs** to resolve such conflicting goals (see e.g., Fabra, 2021; Huntington et al., 2017; Lesser & Su, 2008; Newbery et al., 2018).

Typically, such a two-part-tariff would be made up of an output-independent and an output-dependent component, where the output-independent component (investment or capacity payment) covers the investment net of future profits from operations (Fabra, 2018). With respect to the outlined uncertainties in the hydrogen sector, future revenues and profits are however difficult to predict for investors. Alternatively, Andor and Voss (2016) suggest utilizing capacity and operating subsidies to offset learning-by-doing¹⁹ externalities with capacity support and environmental externalities with operating support in addition to electricity market prices. Nevertheless, this too is hard to quantify in practice, particularly for hydrogen if externalities respective to the grid are to be considered.

Recent studies point to production or electricity incentives in the form of **capacity-like solutions**, to be more cost-efficient and effective at reaching climate goals (e.g., Özdemir et al., 2020; Talebian et al., 2021). Policies based on a maximum number of full-load-hours represent such a solution as they guarantee output-based payments but with pre-determined runtime to induce flexibility. Investors thus benefit from investment

¹⁶This is still the case for a supplementary business model since low electricity prices and congestions often coincide so that utilization can increase only marginally (Larscheid et al., 2018).

¹⁷Increasing electricity price and price volatility result in an optimally lower number of full load hours (Nguyen et al., 2019).

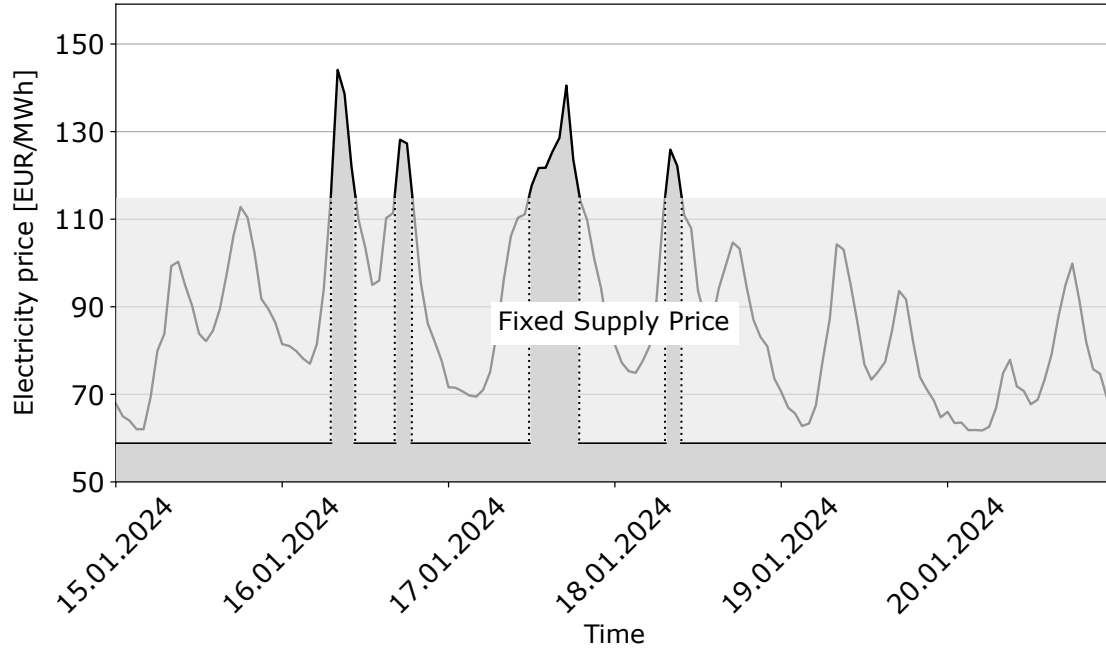
¹⁸Larscheid et al. (2018) find only 4 locations in Germany requiring more than 200 full load hours per year.

¹⁹For this effect see e.g., Andor and Voss (2016), Huntington et al. (2017), and Newbery et al. (2018).

security and reliable revenue streams while still being subjected to market forces to a substantial extent. With regulators determining a utilization rate ex-ante, competitive auctions using this mechanism ensure sufficient but efficiently low support payments for low and high runtime models alike. It allows investors to consider downtime from the start and incorporate it into bids so that grid responsiveness is no longer associated with revenue risks.

For the grid, electrolysis that, by design, incites plant operations at low electricity prices constitutes an efficiency improvement by mitigating excess electricity without further straining the grid in periods of shortage. Figure 5 illustrates operations under such a mechanism with an exemplary runtime limit of 90 %. It shows how operators can make use of subsidized fixed supply prices (Fig. 5: flat black line, here at 52 EUR/MWh) while still being incited to shut down or regulate electrolyzers to a technologically feasible minimum for electricity shortages (dark grey peaks). Regulators can also leverage this to strategically account for flexibility requirements and align the electrolysis rollout with grid development objectives to reduce the need for flexible capacity. This facilitates the advance of RE at diminished risk to grid stability and at lower cost.

Fig. 5. Illustration of plant operations with proposed mechanism (Data: Bundesnetzagentur, 2024b).

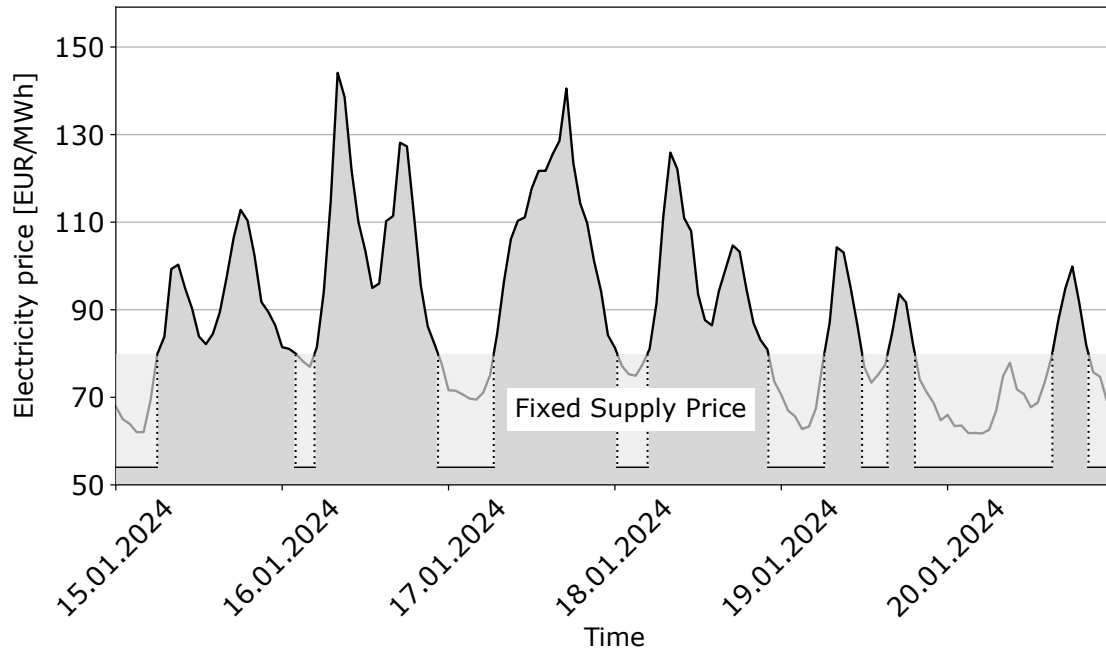


Calculating the reference value for CfDs according to the lowest electricity prices within the utilization period implies that investors only receive full profits when operating with ideal timing, while profits diminish when deviating. Implementing the subsidy payout through such CfDs ensures that incentives for all involved actors are aligned and requires electrolyzers to be closely integrated into electricity markets, thus leaving it up to investors to develop predictive solutions for optimized operating schedules. Recent advances in artificial

intelligence open new possibilities in this field (see e.g., Ahmad et al., 2021; Ali & Choi, 2020). To deter false incentives due to surplus runtime at the end of a settlement period, such an instrument could include e.g., banking mechanisms, like the Dutch SDE++ program (see, European Commission, 2020), to transfer unused or overused subsidies to the next period.

In general, regulators may choose which utilization rate to auction according to grid development requirements. This could be done in a very diverse range from “marathon runner” plants, which exhibit high utilization and only shut down in strong electricity shortages, to “sprinter” plants, which are particularly responsive to short-term fluctuations and exhibit lower utilization. Figures 5 and 6 illustrate these types each. Such categorization has the advantage of fostering self-selection among different electrolysis technologies, according to differentiated technological and economic properties (i.e., comparative cost advantages).²⁰ This further enhances the scheme’s market integration and reduces the need for policymakers to regulate aspects that require detailed assessments of technological developments.

Fig. 6. Exemplary operations for low runtime policy: "sprinter" (Data: Bundesnetzagentur, 2024b).



5.4 Geographic distribution and trade implications

Next to temporal fluctuations, electricity grids are furthermore increasingly affected by geographical imbalances when the share of RE rises. A beneficial placement of electrolyzers can contribute to reducing RE

²⁰Regarding properties and use cases see e.g., Buttler and Spliethoff (2018) For instance, PEM (proton exchange membrane) electrolyzers are often advantageous when volatility is high, while other technologies exhibit advantages when load profiles are more continuous.

curtailment in locations prone to congestions and improve the overall costs of grid operations (Larscheid et al., 2018; N.V. Nederlandse Gasunie & TenneT TSO B.V., 2020). Tenders represent an option for policymakers to incorporate additional provisions such as localization requirements so that targeted policy can contribute to reducing intermittency costs by utilizing power to hydrogen (Nasiraghdam & Safari, 2020). However, profitable full load hours are particularly high at these locations (Larscheid et al., 2018), so that projects require lower support and these bids are more likely to be awarded. Project developers could therefore be expected to develop these locations preferentially, implying that market forces might already be sufficient to address optimal location choices without a need for government intervention. Yet, sector coupling might also give way to externalities for instance when it is cheaper to transport gaseous hydrogen instead of extending the electricity grid or when long-term storage is needed (N.V. Nederlandse Gasunie & TenneT TSO B.V., 2020).²¹ Depending on the specific situation, integrating localization provisions into tenders can then still be beneficial.

Another issue to keep in mind is the effect of international trade. If the aim with supporting electrolysis is to foster the entire value chain via the affordable and abundant availability of green hydrogen, then the sale on outside markets at higher prices may be unintended. Particularly with an effective transport infrastructure in place, such a commodity below unsubsidized market prices would be a probable subject to arbitrage. To avoid this while not erecting trade barriers, boarder adjustments similar to carbon boarder adjustment mechanisms²² might be sensible.

6 Discussion

Many authors have contributed to the issue of trading off investment security and operating incentives in the context of RE. Some argue that capacity subsidies are particularly effective at generating cost decreases via learning-by-doing (e.g., Andor & Voss, 2016; Huntington et al., 2017; Newbery et al., 2018). Yet, as capacity mechanisms are less efficient, (Nguyen et al., 2019; Özdemir et al., 2020) they promote this by achieving a lot of inefficiently utilized capacity if they are the single support mechanism. Andor and Voss (2016) thus suggest utilizing both, capacity and operating subsidies for RE, to offset the learning externality with capacity support and environmental externalities with operating support in addition to electricity market prices (Andor & Voss, 2016). Nevertheless, this is difficult to achieve in practice since these externalities are difficult to quantify for RE and even more difficult for hydrogen policy if the externality of grid stabilization

²¹However, power to gas technologies for energy storage for reconversion at the same location yield poor economics (Macedo & Peyerl, 2022).

²²Boarder adjustment mechanisms are used to avoid that firms escape carbon pricing by moving production outside of the policy's applicability or to avoid competitive advantages for foreign companies (i.e., carbon leakage, see Eicke et al., 2021).

is to be considered in the support scheme.²³

A related idea to this article’s proposal was raised by Newbery et al. (2018) based on a Chinese policy, where FITs were only paid up to a specified MWh/MW cap. The authors argue to auction similar FIPs for RE plants with the aim of de-risking investments and to make payment streams more predictable (Newbery et al., 2018). This idea, while aimed at RE production, resembles the mechanism described in this article. Though, premiums imply stronger market feedback and more revenue uncertainty compared to using CfDs. More recent research has shown CfDs to outperform as a mechanism compared to FITs and premiums, especially in the long-run when a technology is maturing and the mitigation of electricity market risk becomes more relevant in a relative perspective (Neuhoff et al., 2022).

A similar²⁴ policy is used by the Netherlands, where the amount of eligible full load hours per year is capped to about 2,500. The aim behind this is to shift hydrogen production to times of peak excess electricity with high RE share in the grid, so that CO₂-intensity is reduced (Government of the Netherlands, 2020). However, the full load hour cap is rather low, implying low equipment utilization, and uniform for all bidders. This could be because the mechanism has been implemented for environmental reasons and not to better integrate hydrogen and the electricity system. Also, the scheme utilizes FIPs with a cap and floor prices (Zheng et al., 2022). The Dutch government plans to undertake a first evaluation of the scheme in 2024 which could give indications on the market interest in the scheme. Evidence on the operation, including experiences with the runtime cap, will be determined in 2030 (European Commission, 2020).

Clean energy policy is sometimes made up of multiple instruments that interact with each other, but where the respective aims are not always clear (Özdemir et al., 2020). For instance, most economies have established emission trading schemes and technology focused policies that address e.g., hydrogen. Experiences with RE shows that technology support may weaken the effect of carbon pricing by reducing emissions in the energy sector so that certificates are available for other sectors at a lower price (Wu et al., 2020). This might be transferrable to hydrogen. Nevertheless, either certificates could just be reduced accordingly, or this approach is intended to establish a mixed framework of burdens and subsidies. Moreover, research shows that supplementary carbon prices can be utilized to counteract the cannibalization problem of RE.²⁵

²³Externalities vis-à-vis the grid also exist for RE, however they are negative and were in the past seldomly considered for support schemes. Still, this shows that there are even more factors at play in reality. Andor and Voss (2016) further stress that carbon pricing represents the first-best to mitigate externalities of greenhouse gases which, due to the policies interacting, further complicates the quantification of remaining, if any, environmental externality and thus the administrative calculation of operating payments. If none remain, the authors suggest using only capacity subsidies.

²⁴Similarities focus on the fact that subsidies are capped to full load hour limits. Auctions are not simultaneous in this case, but bids can be submitted in subsequent rounds with increasing price levels. Corrective measures, like base and cap prices, emission factors, etc. are applied, (European Commission, 2020). The payout is accomplished through a FIP with cap and floor prices (Zheng et al., 2022).

²⁵At high shares, RE plants cannibalize their own profits by decreasing electricity prices at feed-in due to simultaneity. Carbon pricing can counteract this effect (Liebensteiner & Naumann, 2022).

7 Conclusion and policy recommendations

Many countries have lately introduced or are currently developing hydrogen policies. A starting point to advice policymakers with such limited data, is to derive insights from related RE policy. Yet, the economics as well as technological properties differ so that previous experiences with RE cannot be simply mirrored but need to be adapted to fit for hydrogen. This paper takes a perspective of incentives, uncertainties, and externalities to develop policy proposals that bring interests of investors, grid operators, policymakers and in extension society together. The two key takeaways are that (1) hydrogen experiences most risk from electricity markets which needs to be addressed with suited mechanisms on the supply side and (2) specific schemes can bring the goals of maximized hydrogen production, investment security and the provision of flexible load together, thus leveraging strong externalities.

Most currently discussed mechanisms prioritize production volume with little regard to the situation in electricity markets – a shortcoming that was already criticized in RE policy – or are not welfare improving due to higher uncertainty.²⁶ When considering responsiveness the key priority, low runtimes favor capacity mechanisms,²⁷ which in turn prioritize flexibility and deliver low quantities of hydrogen. Policy must be aware of this trade-off and adapt policies accordingly. Merging incentives for flexible electricity offtake and strong hydrogen production should be the key goal, so policy could aim for a hybrid model where subsidy payments are only fixed up to a predetermined number of full load hours. Combined with a specific payout scheme of auction-determined CfDs, this incites profit maximizing investors to act responsive to the grid through shutoffs or minimized operation while still providing predictable amounts of hydrogen.

Auctioning different shares of full load hours also allows regulators to acquire flexible load according to grid requirements. Notably, such categories allow for the self-selection of different electrolysis technologies into fitting use cases, for instance adjustable and capital-light versus highly efficient technologies for continuous operation. Identifying a technology-application-fit, demand prediction, and optimized operations are then handled by the market instead of regulatorily, averting inevitable distortions. Compared to current approaches, this can reduce support costs meaningfully and electrolyzers may better respond to RE availability in the grid.²⁸ Additionally, investment security is kept at a high level to safeguard the uptake of private investment – particularly as increased uncertainty generally raises overall support costs (Kitzing, 2014).

One relevant issue that is mentioned briefly in the article is the influence of specific frameworks for the

²⁶E.g., Andor and Voss (2016), Huntington et al. (2017), and Newbery et al. (2018). For FIPs and welfare losses due to uncertainty: Neuhoff et al. (2022).

²⁷This is due to low utilization, giving investors little possibilities to earn back their initial investment if very high peak prices cannot be effectively imposed (Macedo & Peyerl, 2022).

²⁸For the EU: Ruhnau and Schiele (2023). These benefits are even stronger in off-grid situations (Nguyen et al., 2019).

credibility of green hydrogen which can represent a major obstacle to the entire concept of grid responsive electrolysis. Detailed requirements like direct connections with RE plants or PPAs with exact load matching can introduce restrictions that oppose system-conducive operations. Yet, this behavior would benefit the absorption capacity of RE into the electricity grid. Regulatory interventions in this regard should thus be carefully considered. Furthermore, investors will require some time to gain experience in predicting renewable electricity intermittency. Policymakers should therefore act early on to establish a stable framework since well-designed predictive algorithms give way to noticeable increases in the economic and environmental performance of such systems (Grüger et al., 2019).

These results can serve policymakers in developing support schemes for the ramp-up of the hydrogen economy while at the same time achieving a better integration into the energy system. Based on experiences with RE, the proposals take incentives for each involved actor into consideration, aim at avoiding previous shortcomings and offer a solution for the diverging economics of the hydrogen sector. The framework can also be adapted to perform vice versa for electricity production from hydrogen. Similar to RE plants, payments could be capped after reaching a limit on full load hours per period. CfDs would then only cover the price difference for the periods of highest electricity market price to incentivize grid-conducive operations of for instance fuel cell systems. Varying the auctioned cap on full load hours can again induce self-selection into fitting use cases.

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