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Deployment of Green Hydrogen: Opening a Probabilistic Feasibility Space to Inform Policy Choices

Green hydrogen can replace fossil fuels where direct electrification is unfeasible. But its success will hinge on rapidly scaling up its supply. Based on probabilistic methods and using growth rates of technology analogs, a recent study models a feasibility space for green hydrogen, assessing the likelihood that it will play a major role before 2050. It highlights key challenges for policymakers and proposes emergency-like policy measures to boost growth.

By Anna Ploszajski

Original research: Odenweller, A., Ueckerdt, F., Nemet, G.F. *et al.* Probabilistic feasibility space of scaling up green hydrogen supply. *Nat Energy* **7**, 854–865 (2022). https://doi.org/10.1038/s41560-022-01097-4

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New Ground article reviewed by: Adrian Odenweller, Falko Ueckerdt and Gunnar Luderer

In the research and political communities alike, there is once again great interest in green hydrogen as an energy carrier. It offers a versatile replacement for non-renewable fossil energy sources, has a high energy density, can be stored as either a gas or a liquid and transported relatively easily via pipeline. If produced with renewable energy, hydrogen and hydrogen-based fuels can reduce carbon dioxide emissions and mitigate climate change – especially in some end-use applications in which emissions are difficult to reduce such as aviation, long-distance maritime transport, or in the chemical and steel industries.

In the last few years – after a wave of enthusiasm among various countries and companies in the 1990s and early 2000s, rapidly followed by disillusionment – several governments around the world have made new efforts to promote hydrogen ecosystems (see here: https://www.jstor.org/stable/resrep26335.4). In 2020, the EU also adopted a hydrogen strategy. More recently, the European energy crisis has added new momentum, as many countries' dependence on fossil-fuel imports poses major political and economic risks.

However, in 2021, more than 99% of the world's hydrogen was still produced from fossil fuels (see here: https://www.iea.org/reports/global-hydrogen-review-2022). Despite this, until now, much of the development in hydrogen technologies has been focused on end-use applications and on the demands of markets and sectors; not on greening the supply.

Global electrolyzer capacity – a major hurdle to green hydrogen's success

In their Nature Energy study "Probabilistic feasibility space of scaling up green hydrogen supply," Gunnar Luderer and his co-authors describe the need for ramping up green hydrogen supply as urgent, since they consider it to be a major hurdle to the energy carrier's success. The International Energy Agency (IEA), in the net-zero scenario put forward in the "World Energy Outlook 2022," predicts that our planet will need an installed electrolyzer capacity of 3,670 GW by 2050. The International Renewable Energy Agency (IRENA) puts the number at 5,000 GW in order to be in line with a pathway toward the Paris 1.5°C target. Global electrolyzer capacity would therefore have to grow 6,000 to 8,000-fold from 2021 to 2050, the authors claim.

The challenge of having to scale up a new technology quickly is not unique to hydrogen. Accordingly, recent retrospective research on the pattern and pace of how energy technologies developed in the past has offered valuable insights into pathways for scaling up new technologies. The authors state, however, that they took an unusual approach: while previous research "constructed feasibility spaces by looking at historical precedents of the same technology in different regions," Luderer's team argues that, since green hydrogen is uncompetitive, historical growth rates are primarily proxies of past policy support. They therefore chose to learn from "historical precedents of different technologies in the same region" and applied this approach to both the European Union and the world. In their main scenario, the authors pose the question: what if green hydrogen grew as fast as wind and solar power did in their booming years?

Uncertainty analysis of the further expansion of electrolysis capacity

Their study analyzed the possible expansion pathways of green hydrogen produced by electrolysis. To that end, the authors conducted an uncertainty analysis of the market ramp-up and the further expansion of electrolysis capacity in the EU and globally. Their work is based on a modified logistic technology diffusion model, an S-shaped model that comprises three distinct phases. The pathway begins in the formative or initial phase, in which major technical hurdles, high costs, and high levels of risk result in slow and unsteady growth. This is followed by the growth phase, during which the breakthrough point is achieved: the year in which the absolute deployment of electrolysis capacity peaks. The growth phase is characterized by increasing returns thanks to economies of scale and cost-decreasing learning effects. After reaching the maximum rate of expansion, growth slows due to technological, economic, and social constraints. This is the beginning of the saturation phase, an asymptote where the final market level is approached.

In the case of green hydrogen, the uncertainty in the initial phase stems from future electrolysis projects having to rely on final investment decisions, projects falling behind schedule, and the potential addition of new projects in the future. Uncertainties in connection with policy support, technological characteristics, and possible cost reductions govern the growth rate. The uncertainty of the final market volume stems from difficulties in predicting future demand, which are due to uncertainties concerning its future end-use applications as well as policies, regulations, and competitiveness.

Three key parameters of the logistic function

These phases define three key parameters of the logistic function: the initial capacity in 2023, the emergence growth rate – which can be interpreted as the steepness of the logistic function –, and the demand-pull. The authors determined the initial capacity by drawing on data from the IEA Hydrogen Projects Database and on their own market research. Growth rates were determined by analyzing historical analogs and fitting the data to the corresponding logistic functions. As initial capacity and growth rates were uncertain, the authors also derived probability distributions for these parameters.

The demand-pull, finally, was modeled as a fixed pathway – supplemented by a sensitivity analysis – by extracting and linearly interpolating short- and long-term targets from the REPowerEU Plan, the EU Hydrogen Strategy, and the IEA roadmap "Net Zero by 2050." Additionally, the authors differentiated between the actual magnitude of the demand pull and its anticipation – by five years, in the default setting – by investors.

On the basis of their logistic technology diffusion model, the authors derived thousands of possible electrolysis expansion pathways by combining different values for the initial capacity and emergence growth rate. This Monte Carlo simulation approach captures the nonlinear propagation of these uncertainties. Its result is a probability distribution of electrolysis capacity: the probabilistic feasibility space of scaling up green hydrogen supply.

Substantial risks if policy support is limited to historical support for wind and solar energy

Overall, the team's analysis predicts that even if electrolysis capacity grows similarly to that of wind and solar power on an EU level and on a global level – the two biggest success stories in green energy technology adoption so far – there is at least a 75% chance that green hydrogen will cover less than 1% of the overall final energy demand in the EU before 2030, and globally before 2035. In the authors' view: "Neither the EU 2024 target of 6 GW nor the 2030 target of 100 GW are within reach under conventional growth rates." They attribute this to the slow, albeit exponential, expansion in the first phase, as a result of which even high annual growth rates don't immediately translate into significant market shares. However, they also note that higher market shares may follow quickly after the breakthrough point.

However, the timing of this breakthrough point – indicated by the largest annual capacity expansions – is at best 25% likely to occur before 2036 in the EU, and before 2043 globally. Luderer's team concludes that there is a substantial risk that a long-term gap will arise between a likely low supply of green hydrogen and a potentially high demand. This risk is due to the substantial uncertainties concerning near-term deployment and feasible growth rates.

Coordination challenge for policymakers

The authors see the crux of the problem in the fact that short-term scarcity creates a three-part coordination challenge, with hydrogen supply, demand, and infrastructure all reluctant to move first without the others in place. The related long-term uncertainties may deter investors from getting on board early; instead, they may prefer to wait until markets consolidate and costs drop.

This uncertainty poses difficulties for policymakers. If hydrogen abundance and affordability fail to materialize while the roll-out of other climate mitigation options such as direct electrification technologies is neglected, societies may be forced to continue using existing fossil fuel infrastructure and end-use applications, having effectively bet on the wrong horse. Without early support from policymakers and investors, green hydrogen might be doomed to fail before it even leaves the gate.

"Unconventional" policy support required to minimize risks

One way to minimize these risks, the authors suggest, is for policymakers and industry to move first and foster rapid investment in green hydrogen supply chains – much more than they did for wind and solar power, which was considered the "conventional" growth scenario by Luderer's team.

In their conventional scenario, growth rates could lead to breakthrough by around 2040 in the EU and 2045 globally, in the median. “Unconventionally” high growth rates, in contrast, would lead to the breakthrough point before 2035 in both cases. To model such unconventional growth, the authors considered historical examples that were observed under exceptional circumstances – such as the production of military machines and nuclear weapons during wartime; the centrally coordinated introduction of nuclear power in France, and of high-speed rail in China; and the market-driven deployment of the internet and smartphones. (The COVID-19 vaccine was excluded as an outlier.)

The authors suggest that this approach could “break the vicious cycle of uncertain supply, insufficient demand, and incomplete infrastructure, and turn it into a positive feedback mechanism.” They underpin this statement with figures. Looking at 2040, they determine the value of the interquartile ranges – a statistical measure of the spread of data and therefore an indicator of uncertainty – to be 3.2–11.2% in the EU and 0.7–3.3% globally for conventional growth. Under unconventional growth, the ranges are much narrower – 11.7–12.9% in the EU and 6.6–7.8% globally – and therefore projections can be expected to be less subject to uncertainties.

In other words, a bold policy move to deploy gigawatt-scale electrolyzers in the next few years could unlock further innovation and scaling effects. Industries could switch to automated production to drive down costs, “which would secure expectations and further accelerate growth.” If that happens, we could see green hydrogen outperform the more conventional growth curves of wind and solar power.

However, the authors warn of a two-fold problem for policymakers. On the one hand, fostering unconventional growth will require accelerated development of technologies throughout the entire supply chain. On the other, it is their responsibility to safeguard against the inevitable risk of limited availability. Therefore, policymakers will need to provide regulatory certainty to encourage green hydrogen investment, while maintaining a realistic view of hydrogen’s long-term prospects and making every effort to scale up critical alternative zero-carbon technologies as well.

Outlook

Future work, the authors note, could include refining their assumptions regarding policy support. At the same time, the authors admit that their focus on the hurdle to upscaling electrolysis capacity disregards other potential obstacles, such as the availability of technologies for the direct capture of atmospheric carbon, which is a basic resource in e-fuel synthesis. Nor did they consider trading in hydrogen: when they estimated the proportion of market share that green hydrogen could achieve in the EU, they only considered hydrogen made within the EU. This is not a major limitation, however, since the global market ramp-up is slower in both the conventional and the unconventional growth scenario.

Going forward, the research community now has the opportunity to build on this work to produce probabilistic decision frameworks that help with difficult policy choices and inform technological deployment pathways while navigating the uncertain feasibility space. ●

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