Hydrogen as an intermediate energy carrier: deep integration unlocks the path to decarbonization of our society

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Hydrogen recently emerged as a game changer for the decarbonization of our society. However, its future role needs to be properly defined to avoid both glorification by stakeholders and the perception of it being a 'golden bullet' capable of solving all energy issues forever. The use of renewable energies for the 'green' power generation is pivotal for the transformation process, yet there are multiple fields incompatible with electrification, such as heavy-duty transport, the maritime sector and aviation, which require hydrogen as either an intermediate energy carrier or for the production of derived fuels. In the chemical industry, water-splitting electrolysis can substitute hydrogen today produced by natural gas reforming and coal in steelmaking as well as other raw material processes.

In the power sector, it offers a solution for three critical issues: long-term energy storage, bypassing of the bottlenecks of the electrical grid via the natural gas network or dedicated pipelines, and avoiding long-distance transport from overseas. Nevertheless, a long list of technical issues remains: water electrolysis is a technology which has proven its worth for decades, for example for the production of fertilizer in the Egyptian green revolution powered from the Aswan High Dam. Today, the challenge lies in enhancing electrolysis in order to minimize the wear & tear of equipment resulting from the technically unavoidable dynamic operation with the variable load from temporally fluctuating power generation from renewable sources like wind and photovoltaics (PV).

Other challenges include the availability of vast amounts of pure water. Many areas with promising characteristics for renewable energy production are associated with fresh water supply difficulties, for example the offshore wind farm sites at sea and the arid areas where PV systems are often installed. Environmental protection and consumer concerns are strong drivers towards advanced desalination technologies or the direct use of seawater.

The picture is completed by the slow ramping up of production due to scaling issues, lacking standards, high service and maintenance costs, limited production capacities and a still high degree of manufacturing and assembly by hand in contrast to the rapid automatization observed in other emerging technologies.

The signing of the Paris Agreement aimed at keeping global warming below 2°C, ever more common heat waves, floods and other natural disasters, and political movements demanding immediate climate action as opposed to long-term policies with distant targets finally culminated in two remarkable court rulings: in April 2021, the German Federal Constitutional Court ruled that the German Federal Climate Change Act had to be amended. The law stated that climate neutrality has to be achieved, but respective emission-reduction steps had foreseen moderate savings in the first few years and drastic reductions in the years thereafter. This distribution would have overly impacted citizens' chances for prosperity in the future. The law was amended by setting intermediate targets more evenly and bringing forward the date of climate neutrality from 2050 to 2045. In May 2021, the District Court of The Hague, the Netherlands, ordered that Shell must reduce its global net carbon emissions by 45% by 2030 compared to 2019 levels. This explicitly covers not only the emissions from oil production refining and logistics but also those from the use of the products, e.g., as transport fuel.

Somewhat earlier, the new European Commission had presented the European Green Deal, a trillion euro 10-year plan to tackle climate change. One element of this deal is public support for the introduction of the hydrogen economy via Important Projects of Common European Interest (IPCEI) thus allowing state aid for close-to-market hydrogen projects. Another element is the proposed Carbon Border Adjustment Mechanism (CBAM). If adopted, imports would require CBAM certificates, similar to those of the EU emission trading scheme for domestic products. First sectors are steel, cement, and fertilizers as of 2026, but there are concerns that there will be a marginal guiding effect limited to certain countries due to clerical decarbonization.

There is a more solid footing this time compared to past 'hydrogen waves':

today we have a policy with specific targets instead of vague activities which will trigger strong industrial commitment and advance projects formerly stopped due to a lack of competitiveness.

However, cost effectiveness remains a critical issue:

Power price

The 'feedstock cost' accounts for 65 to 90% of hydrogen production costs. Of that, 1 to 57% can be unrecoverable taxes and duties in the EU Member States, with an average of 28% for the EU 27. The German renewable energy charge (EEG levy) is among the non-deductible duties. Initially, generous funding rates led to a rapid increase in renewable power production at a cost of €67.5 per MWh in 2020, a considerable share of the orange bar in the chart below.

However, exported power is not subject to this charge, and an electrolyzer operator in the neighboring Netherlands would have had a good competitive edge because of negligible non-refundable duties and a higher base price for energy. As such, the German Renewable Energy Act and its equivalents in other countries were an excellent measure for bringing renewables onto the market[1] but

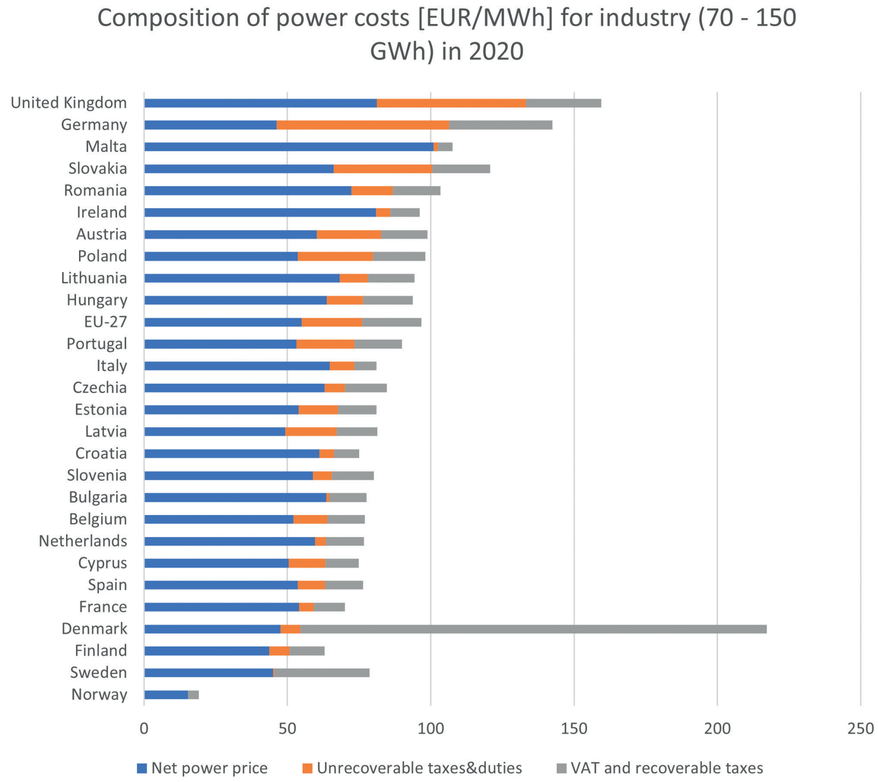


Figure 1 Composition of power costs for industry consumers, relating to 14 to 30 MW electrolysis capacity at 5000 full-load hour per year. Data source © Eurostat

now have to be replaced with other measures better adapted to the market situation. EU Member States should agree on a set tax rate for renewable power for hydrogen production to level the playing field within the European Single Market.

Grid charges

These can account for up to one third of power generation costs. In some countries, the network costs are averaged but the power is produced and consumed in different regions. Regional schemes would lower grid charges in surplus regions, eventually leading to a shift in consumption and a subsequent drop in efforts for grid enhancement[2].

Capacity factor

The Renewable Energy Directive and respective delegated acts set several provisions for the classification of hydrogen as 'green' i.e., sustainable, in order to prevent double funding, stranded investments in the grid and threats to grid stability. It should be produced exclusively from an unsubsidized, preferably newly built renewable power generation capacity. Only the hydrogen from the first 5,000 full-load hours of an electrolyzer are covered – justifiable provisions to keep the fierce competition for renewable power at bay. However, a reduction of full-load hours might increase the production costs. RE systems differ in capacity factor (availability) and production costs.

With directly coupled systems, generation costs can be optimized by saving investment costs in the electrolyzer. This is achieved as the renewable energy source (photovoltaic or wind) has a higher generation capacity and some of the electricity is not used during peak periods. For PV the ratio is 350 kW of electrolyzer capacity per MW of photovoltaic installed capacity, for wind it is 750 kW electrolysis capacity per MW wind turbine generator rated power.

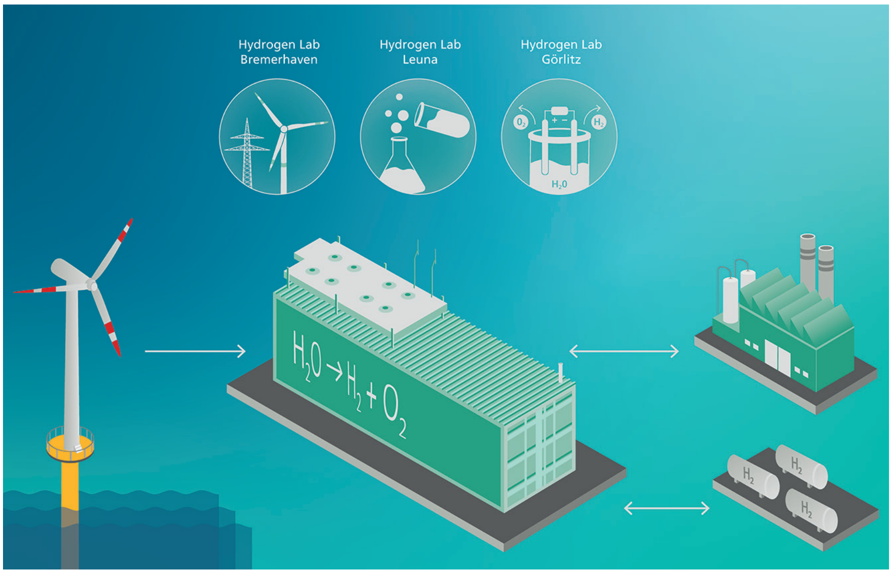
The operating hours of such single-coupled systems might fall into the foreseen bandwidth of electrolyzer full-load hours, which is questionable for projects combining PV and wind power as the energy source. Hydro-based systems would need to throttle generation artificially (or install 1.75 MW electrolyzer per MW hydro) to ensure the hydrogen was classified as green.

Conversion efficiency

This remains a critical issue for applications with competing technologies. In energy applications such as power storage, mobility,

1 The EEG was so successful in driving down the power price initially that a private venture considered connection of a chemical industry site in Delfzijl, the Netherlands, to the German grid via a private cable under the Ems estuary in 2014.

2 and might mitigate the NIMBY effect by creation of high-value industry jobs in the often less developed areas



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and heating, the competition with sector coupling by direct power applications like battery electric vehicles and heat pumps will be hard, with conversion efficiency being an important factor.

The round-trip electrolysis – storage – power generation is plagued by high losses of 50 to 80% in the case of hydrogen pathways compared to 20 to 40% for pumped-storage hydropower or redox flow batteries, for example. The big advantage of hydrogen and its derivatives remains their transportability and long-term storability. These compelling points create the, mainly politically driven, idea of large-scale energy import from remote sunny or windy areas of the world. Doubts about the feasibility are justified as:

- The time for energy return on investment becomes long with low overall efficiency.
- Production costs should not be confused with the price of a product. The production costs of fuel are at less than €0.10 per liter for good oil fields, which hardly reflects the price at the filling station.
- Massive implementation of hydrogen production may impact developing economies, for example as a result of water scarcity or land grabbing. Social and environmental standards are often lower elsewhere, and societies may be impacted by such 'cash crop' approaches. Only embedded systems with local value generation and the possible export of surplus energy in the form of hydrogen are sustainable in the long term.

Deep integration

The renewable energy deep integration processes, is the venture we regard as being most promising and sustainable in the long term. Threats to electrolysis efficiency can be mediated by implementation in an environment with a demand for off-heat, even coping with the dynamic load of sources like PV or wind power. An obvious example is the deep integration of electrolysis in sewage treatment plants. Sewage treatment is an energy-intensive process accounting for 3 to 5% of power consumption in the EU.

Larger plants have an anaerobic digestion stage, and the gas produced is used on-site in a co-generation plant for heating the fermenter and covering the blower load, venting air into the activated sludge tanks. Setting up electrolyzers for hydrogen production on-site enables several options for power system optimization:

- When the wind blows, the sun shines, or in other times of low energy prices, the electrolyzers are operated producing hydrogen and off-heat, which is not a waste but rather used for heating the anaerobic digester. The blower is operated with grid power, too. The co-generation doesn't run and the sewage gas is collected. Similar to modern biogas plants, the co-generation of an integrated plant has several times the capacity of the gas production and is operated in times of high power prices. This turns the integrated plant into a provider of positive and negative balancing power.
- Electrolysis also produces oxygen, a neglected by-product, which is vented off in most projects. Sewage treatment relies on the oxidizing power of approximately 20% O_2 in air. Substitution with technical oxygen reduces the blower load by up to 80%, which would halve the energy demand taking the electrolyzer operating hours into account. Although just one of many applications, it could reduce the EU's power consumption by some 2% – that is 2% of nearly 3,000 TWh!
- Several energy applications such as aviation and heavy-duty transport are expected to rely on liquid hydrocarbon fuels for a long time to come, but carbon will become scarce in decarbonized economies. Sewage will always be there, and respective treatment plants are a reliable source of CO_2. Several power-to-X applications are feasible, ranging from jet fuel to base chemicals for industry and synthetic natural gas.
- This decentral application brings electrolysis to communities, stabilizes local grids, and supports the further increase of local renewable energy generation via roof-top PV systems, for example[3].

Fraunhofer promotes and supports such concepts by two means, namely technology development and technology validation. For the latter, several 'Hydrogen Labs' are constructed for process demonstration in industrial environments. These also serve as multifunctional test sites for optimization and validation of the underlying base technologies e.g., electrolyzers.

Specifically, the Fraunhofer Hydrogen Lab Bremerhaven investigates deep integration of renewable energy systems, comprising the whole process chain from directly coupled PV systems and wind power generators, different electrolyzer systems, the balance of plant processes: water purification, hydrogen compression, storage, heat integration and the use of oxygen.

The focus of the Leuna Fraunhofer Hydrogen Lab, is on the integration of electrolysis systems into the chemical industry and the development of power-to-X processes as well as the improvement of materials and components for this technology. In the third Fraunhofer Hydrogen Lab Görlitz, the whole hydrogen value chain will be established with a focus on reconversion to power.

In all of these three labs, there are test benches for electrolyzer stacks, up to multi-MW, hydrogen storage tanks, fuel cells, and other hydrogen components/ equipment installed for detailed investigations by Fraunhofer.

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3 The first steps in that direction have been taken successfully, for example in the German project LocalHy at the Sonneberg-Heubisch sewage treatment plant in Thuringia.