The Role of Green Hydrogen in a Low Carbon Future

An IEEE European Public Policy Committee Position Statement

Adopted 19 August 2022

The IEEE European Public Policy Committee (EPPC), representing a large community of electrical, electronics and computer engineering professionals in Europe, offers specific recommendations on the potential for using green (produced by electrolysis using renewable energy) hydrogen for de-carbonization and as a form of sector coupling - a concept that has been closely examined under the lens of policy makers since the European Commission's Strategy for Energy System Integration.

Potential Benefits of Green Hydrogen for Energy System Integration are Diverse and Include:

1) Ability to convert intermittent renewable energy sources such as sun, wind or hydroelectricity to a flexible form (hydrogen), which can be used as a carbon-neutral energy carrier and as a feedstock for essential industrial and chemical processes.
2) Ability to further transform green hydrogen (Power-to-X) into other stable forms such as methane, methanol or liquid hydrocarbons that have a lower cost of storage and transportation. For reasons of economic efficiency, this process only is practical when there is a concentrated source of CO_2 available nearby. Power-to-X, or e-fuel as it is also called, is not "carbon neutral", unless it takes place in a closed cycle of combustion and capture (for example generating methane for seasonal storage and capturing CO_2 at the output of the gas turbine using that methane, assuming sufficiently high capture rates and/or complementary carbon offsets). Creating ammonia from green hydrogen does not require CO2 and is also a potential end product with many uses.

It is important to realise that there are significant efficiency losses that take place at various stages of all these processes, which must be included in all technical and economic evaluations of the technologies. In light of such challenges, direct electrification in many applications will be more cost-efficient. However, depending on the future regulatory and market situation and future technical developments, the use of green hydrogen and its derivatives may still be technically and economically attractive for certain hard-to-decarbonize sectors, even with the low efficiency of the total process.

Policy Recommendations:

1) The most important application for green hydrogen in the near term is as a replacement for **current** grey (produced by steam reformation of methane) hydrogen use for petrochemical and fertiliser applications. There is no other alternative for these industries to reduce their CO_2 impact. Producing enough green hydrogen for this task is already a mammoth undertaking, in terms of both capital expenditures and the amount of renewable energy required. The need for hydrogen in the petrochemical industry will decrease over the long-term, as less oil is used for transportation, but demand for hydrogen as a chemical feedstock may actually increase. The production of ammonia worldwide is predicted to increase by 1%/year by the UN FAO, based on the need for nitrogen-based fertilisers. These applications of green hydrogen can be classified as "No Regret" measures.

2) The need for green hydrogen production in the future, for grid scale storage, is difficult to predict. Any project should be carefully evaluated with respect to its efficiency, cost and added value to the total energy system. Whether hydrogen will be important for grid scale storage in the future depends on how the power grid develops, how "smart" the grid will be, how many alternative types of grid scale storage will be available and at what cost. Perhaps most importantly, it depends on how the price and volume of "excess" renewable electricity behaves in the future. There are widely conflicting visions of the future need for grid scale storage. There are other energy storage technologies available, which are more mature, and can be widely implemented at scale in the short term (e.g., liquefied air storage, TRL 8[1]).
3) Production of additional green hydrogen for use in the steel industry in place of coke, in the cement industry and other **new** industrial applications is worth studying, but there are other potential alternatives for some of these applications based on direct electrification that need to be evaluated and compared.
4) Production of additional green hydrogen (and e-fuels derived from it) for **new** applications in heavy transportation (trucking, shipping, aviation) is worth studying, but the economics of these applications are at this stage not favourable.
5) A consistent EU policy is needed to guide the application of green hydrogen. In addition to identifying which applications are considered priorities, this policy would also identify which applications are better served with other technologies, based on comparing the reduction in CO_2 emissions, the amount of renewable electricity used and the current and future costs. Several applications for green hydrogen are currently being discussed which would score poorly on such a ranking, such as[2]:
    a. Using green hydrogen to blend in with existing methane streams used for all applications (mainly home heating and cooking) to reduce the carbon intensity of these activities and potentially take advantage of existing infrastructure.
    b. Using green hydrogen in fuel cells in cars for personal transportation

Developing such consistent EU policies requires careful consideration of any interaction that may exist with other key EU climate policies, such as the EU ETS and support mechanisms for other carbon-neutral technologies, in order to safeguard the policy's cost efficiency and effectiveness to reduce European CO_2 emissions.
To achieve the large-scale deployment of green hydrogen envisioned in current EU planning for 2030 and 2050, a significant increase in R&D and field trials are needed. To this end, the IEEE European Public Policy Committee also recommends:

1) The creation of an EU regulatory and economic framework to deal with green hydrogen as a crucial building block of de-carbonization and sector integration within the EU's energy system. This framework needs to include a cost-efficient support mechanism and clear rules for carbon accounting, both for domestic production and imported hydrogen.
2) Support for continued research and development of key technologies needed for hydrogen production and Power-to-X\e-fuels (electrolysers, fuel cells, CO_2 capture, hydrogen storage) to increase capacity and reduce costs. A key factor in choosing which technologies to support is how flexible the technology is in both its implementations and applications, given the significant uncertainty about how the future power\energy system will actually be structured and integrated.
3) The development of a single EU set of "best-practices" to ensure efficient transfer of knowledge and experience for hydrogen applications.

[1] https://www.pv-magazine.com/2021/08/02/a-closer-look-at-liquid-air-energy-storage/
[2] https://www.rechargenews.com/energy-transition/hydrogen-for-heating-and-road-transport-is-not-efficient-and-does-not-make-economic-sense/2-1-1069478

Hydrogen – History, Current Status and EU Plans

In the last few years, the discussion of green hydrogen has become impossible to ignore. In EU documents[3], European government planning[4], corporate reports[5] and in the press[6], green hydrogen is mentioned as a key technology. The EU defines green hydrogen as "*hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources*"[7]. Green hydrogen is being praised as the "solution" to a wide range of problems related to the energy transition, from grid scale energy storage, fuelling heavy goods vehicles and ships, steel making, home heating and even as an aircraft fuel. Interest in using hydrogen for energy storage had a first boom in the 1970's and 1980's, in response to the energy crises of the time. Since then, there have been repeated periods of interest in hydrogen as an energy storage medium, for example with the development of the first fuel cell automobiles. Although the first fuel cell vehicle was developed in 1966 by General Motors (one vehicle was built), various models became available for actual use starting in 2008 (from Honda). Since then, the developments in passenger transportation have been dominated by electric vehicles, not hydrogen.

The concept of using hydrogen for large scale storage of energy has also been around for some time, since the 1970's. The use of salt caverns[8] has been proposed and implemented, but only in a few cases. Most hydrogen used today, in industry, is generated very close to the point of use, using steam reformation of natural gas (methane).

The EU currently uses 10 million tonnes of hydrogen per year, with less than 2% currently being produced from electricity, and less than 1% being produced from renewable sources of electricity. So effectively all hydrogen currently being produced is grey hydrogen, as it is produced from fossil sources using steam methane reformation (SMR), resulting in a large emission of CO_2. The current hydrogen production is used mainly (93% of total) by three industries, for oil refining, for ammonia (fertiliser) and for methanol and other chemical production. Current hydrogen use for transportation is less than 0.1% of the total used. The production of hydrogen is estimated to produce 100 million tonnes of CO_2 per year, or 2% of total EU CO2 emissions, or in other words, 10 kg of CO_2 is produced for every kg of hydrogen produced today from methane.

Goals of current EU hydrogen plan:

- 6 GW of renewable hydrogen electrolysers in the EU by 2024 with production of 1 million tonnes of renewable hydrogen
- 40 GW of renewable hydrogen electrolysers by 2030 producing 10 million tonnes of renewable hydrogen + 40 GW installed outside of the EU transporting hydrogen to the EU
- As of 2030, hydrogen technologies to reach maturity and to be deployed at large scale in all hard-to-decarbonize industries and to play an increasing role in European energy systems, i.e. hydrogen could constitute more than 23% of the European energy mix in 2050

The goals shown here for 2024 are already quite ambitious, given that currently, there is only 1 GW of electrolysis capacity in the EU today. The calculations of how much hydrogen can be produced are also optimistic, as they

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301
[4] https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/uba_position_powertoliquid_engl.pdf
[5] https://renewableh2.eu/
[6] https://spectrum.ieee.org/time-for-utilities-to-learn-to-love-hydrogen
[7] https://ec.europa.eu/commission/presscorner/detail/en/QANDA_20_1257
[8] https://www.osti.gov/biblio/6536941-underground-hydrogen-storage-final-report-salt-caverns-excavated-caverns-aquifers-depleted-fields

assume a 100% electrolyser utilisation rate. This implies that either non-renewable energy would also be used to generate hydrogen, or that there will be sufficient storage capacity (e.g. batteries[9]) and excess renewable energy, as the capacity factors for renewable energy are in the range of 20% to 50%. But, due to the EU ETS, total emissions from, i.e., the power sector and energy-intensive industry are capped, so even if non-renewable electricity is used for generating hydrogen, total CO_2 emissions would not increase, not accounting for the impact of the EU ETS' market stability reserve. The goals for 2030 are even more ambitious, as they assume 100% utilisation and significant improvement in electrolyser efficiency.

Green Hydrogen to Replace Grey Hydrogen

There is a growing realisation that the most important initial use of green hydrogen is to replace current use of grey hydrogen. This position was explained very well in a recent article[10] by the CEO of Enel, Francesco Starace. The essential problem with hydrogen as an energy storage medium is that it is less efficient than the alternatives. For example, one kilogram of hydrogen — produced from 50kWhe — would enable a fuel-cell car to travel 80-90km. "Now I take the 50kWh and I put them in an electric car, that car would drive 250km. It's even worse with heating." A comprehensive chart comparing the efficiency of direct use of electricity, compared to a path using hydrogen, is shown on the next page.

A simple calculation is useful to put in perspective how much electricity would be required just to replace the grey hydrogen now being used with green hydrogen. The energy required to produce one kg of hydrogen from electricity is estimated to be 50 kWhe in the near future (2025). Therefore, just to produce the current amount of hydrogen now obtained from fossil fuel sources would require 500 TWh of renewable electricity per year. Most forecasts of hydrogen production assume an electrolyser load factor of at least 50%to reduce the cost of hydrogen[11]. Even with this optimistic load factor, it would mean that 114 GW of electrolyser capacity would be needed just to produce this, compared to the currently installed 1 GW in the EU. Current production of electricity from wind and sun in the EU is 540 TWh (2020). Thus, generating the amount of hydrogen currently used in the EU would use up all the existing wind and solar capacity available today!

Another way to look at this issue is to compare the amount of CO_2 reduction that is possible from using 1 kg of hydrogen versus other ways of achieving the same result with an electric option, **if** that is possible. For example, comparing the use of green hydrogen to replace grey hydrogen as a feedstock for fertiliser versus in a fuel cell electric vehicle (FCEV):

- 1kg of green hydrogen replacing 1kg grey hydrogen as feedstock -> 10 kg CO_2 reduction
    - There is **no** other option for replacing grey hydrogen as feedstock
- 1kg of green hydrogen in a FCEV gives 80 km of driving, compared to average new gasoline powered vehicle emitting 0.12 kg/km CO_2) -> 9.6 kg CO_2 reduction
    - A battery powered vehicle (0.17 kWhe/km), using current EU electricity mix (0,28 kg/kWhe) is only 4 kg of CO_2

Since the supply of green hydrogen is currently limited, every kilogram of green hydrogen that becomes available that is used to offset the use of grey hydrogen as a feedstock would avoid 10 kg of CO_2 emissions. But using that same kilogram of hydrogen for a FCEV, rather than using an electric car (with current EU electricity generation

[9] https://www.iberdrola.com/about-us/lines-business/flagship-projects/puertollano-green-hydrogen-plant
[10] https://www.rechargenews.com/energy-transition/using-clean-hydrogen-for-domestic-heating-and-transport-is-nonsensical-says-enel-ceo/2-1-1039690
[11] https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf

mix) to drive the same distance only prevents 4 kg of CO_2 emissions. The most effective way to use green hydrogen to reduce CO_2 emissions is therefore to directly replace grey hydrogen made from methane, rather than as an alternative to battery electric vehicles, as seen from this comparison.

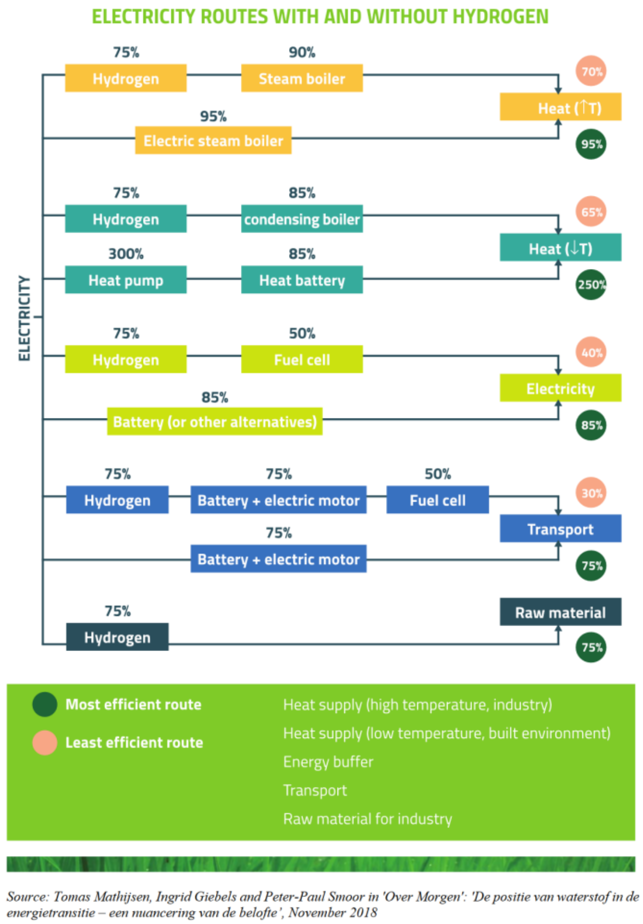

Figure 1: Use of electricity with and without hydrogen[12].

Green Hydrogen for Grid Scale Storage

How much grid scale storage capacity will be needed (hours, days or weeks) in the future and whether green hydrogen can be an economically sustainable option in the long run for grid scale storage and other applications depends on several key assumptions about what the future Renewable Energy System (RES) will look like. There are two main "visions" of what the economic landscape in an RES dominated future will look like in the long-term, which contradict each other in almost every way. The main issue for green hydrogen is what the price of electricity will be[13].

1) There will be large amounts of "excess" green electricity being generated, which will be available for a very low price on a regular basis. This electricity can be used to produce low-cost green hydrogen. The production of green hydrogen will not "compete" with other uses of green electricity and will be cheaper than blue hydrogen at some point in the future.

[12] BELMANS, Ronnie, VINGERHOETS, Pieter, Molecules: indispensable in the decarbonized energy chain, EUI RSCAS PP, 2020/01, Florence School of Regulation, [Energy] Retrieved from Cadmus, European University Institute Research Repository, at: http://hdl.handle.net/1814/66205

[13] D'HAESELEER, William, "Possible Role of Hydrogen-Based Technologies for System Service Assistance in Fully RES-Dominated Energy Systems", Working Paper Series No. ESIM2021-10, KU Leuven

2) There will never be large amounts of “excess” green electricity available for a very low price, as in this situation, no company will build “excess” RES capacity that does not generate income for a significant portion of the time. Producers of green hydrogen will have to pay a “market” rate for electricity, just like all other power users, unless they have their own energy generation\storage capacity.

There are also three main “visions” about the need for grid scale storage in the future:

1) The future grid will be completely free of fossil fuels, so all backup for intermittent RES must come from storage of “extra” electricity produced by additional RES capacity or demand side flexibility. Capacity factors for green hydrogen plants will be high due to large demand for hydrogen for industry and storage. Large amounts of new RES capacity (solar and wind) will be added just to power production of green hydrogen for industrial use.
2) The future grid will include many forms of grid-scale backup power, potentially including natural gas turbines with carbon capture and storage. Due to a combination of demand management, smart grids, flexible pricing etc., the amount of grid scale “backup” power that is needed will be relatively small, so capacity factors for green hydrogen production and related infrastructure will be small, keeping it from being economic. Economics of gas turbine electricity production will be good enough to make it possible to keep current infrastructure viable, even with only a few weeks per year of use.
3) The future grid will not need any grid scale storage. It will be cheaper to construct a huge oversupply of RES capacity over a wide enough geographic region, combined with enough demand side flexibility, that no middle to long-term grid scale storage will be needed. When all RES is operating at peak capacity, there will be much more power available than the grid can accommodate, and this will simply be disconnected at the source. This will be cheaper than creating a huge new infrastructure for grid scale storage.

It is important to note that there is one issue with green hydrogen for energy storage, which must be included in all calculations and scenarios; the energy loss that occurs at each stage of the process. The end-to-end efficiency of turning electricity to hydrogen and back to electricity again could theoretically be as high as 30%, but in practice, it will be much lower[14]. Considering the additional energy for processing, compression and transport of hydrogen, the real end-to-end efficiency could be as low as 20%. When green hydrogen is compared to other options for energy storage, such realistic efficiency numbers must be used for each technology to make a proper economic comparison. When considering the further step of converting hydrogen to methane, the economic analysis must balance the potential savings in infrastructure costs (by using the existing natural gas infrastructure) against the lower end-to-end efficiency. On top of this, the question of how much of the existing natural gas infrastructure can be used for hydrogen and what it would cost to convert the rest for transporting hydrogen is a subject of much debate at the present time. Repurposing of the existing large capacity network for large industrial users (hydrogen clusters) may be attractive[15].

If green hydrogen is to be considered for grid scale storage, it must be compared to the other options that are available. Pumped hydropower is only available in a very limited number of locations and is difficult to expand even in those locations. Liquefied air storage is a mature technology that can be scaled cost effectively, at least for short-term use (e.g. hours). Use of current mature battery technology, like lithium ion (Li-ion) based batteries, is currently only suited to short discharge times at full power (e.g. tens of minutes). Future battery technologies (e.g. flow batteries) could extend this to hours. The choice of the most appropriate technology for grid scale storage in

[14] https://www.linkedin.com/pulse/hydrogen-fuelcell-vehicle-great-idea-theory-paul-martin/
[15] https://www.hyway27.nl/en/latest-news/hyway-27-realisation-of-a-national-hydrogen-network

the future is strongly dependent on the time scale of storage that is actually needed. At the present time, there is no agreement on whether this time scale needs to be minutes, hours, days or even months (seasonal storage). It is also possible that different types of storage will be needed at all of these time scales, working together. With all the uncertainties for this issue, it is impossible to currently make an evaluation of green hydrogen for grid scale storage. At the same time, it is important to consider a wide range of scenarios to account for possible future applications.

Green Hydrogen for Heavy Industry

Green hydrogen has been brought forward as a method to decarbonize various industrial processes that contribute significantly to CO_2 emissions in the EU, such as the steel and cement industries. The fundamental issue with this application is whether there are any alternatives, such as using direct electrification, rather than hydrogen. Since conversion of electricity to hydrogen with electrolysis has a significant energy loss, and storage and transportation of hydrogen also requires significant amounts of energy, direct electrification will in many cases be more efficient than using hydrogen for industrial processes, **if** it is possible to use electricity.

For the steel industry, it is complicated because hydrogen is used in place of coal in the first step of the process. This process has recently been trialled in Sweden[16], however, given the size of the steel industry worldwide, the amount of green hydrogen (and the amount of renewable electricity needed to make it) are comparable to the global renewable energy production today[17]. This is a similar situation as with the generation of hydrogen to replace current grey hydrogen use, which has already been discussed. A significant portion of steel today is made with electric arc furnaces, recycling old steel. Expansion of this type of operation, using new supplies of renewable energy, is a much easier way to displace CO_2 resulting from production of new steel in existing facilities. But this is limited by the potential supply and quality of steel available for recycling. De-carbonization of cement manufacturing is another very difficult problem[18]. Hydrogen has also been suggested here as a fuel for the high temperature operations.

Green Hydrogen for e-fuels (Power-to-X)

Green hydrogen has been suggested as a method to decarbonize heavy transport, shipping and even aviation either by directly using the hydrogen as fuel (with pressurised storage) or by converting the green hydrogen to another form (e-fuel) that is easier to store and transport, such as ammonia, methanol or a synthetic hydrocarbon fuel. Numerous studies have been made on this topic. Studies made by parties directly involved in renewable energy or hydrogen production tend to be quite positive[19]. Studies made by independent\government agencies[20],[21] are in general in agreement that because e-fuels are inherently a very low efficiency solution, they should only be considered when there is no possible alternative based on direct electrification. Therefore, for cars, light trucks and maybe even heavy trucks, e-fuels are not a good solution, as shown in Figure 2. For shipping and aviation, where electrification is impossible for large vessels and planes, e-fuels need to be considered, in spite of the low

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[16] https://www.theguardian.com/science/2021/aug/19/green-steel-swedish-company-ships-first-batch-made-without-using-coal

[17] https://www.carboncommentary.com/blog/2020/11/4/how-much-hydrogen-will-be-needed-to-replace-coal-in-making-steel

[18] https://www.gasworld.com/deep-decarbonisation-of-cement-production/2020509.article

[19] https://orsted.com/en/about-us/whitepapers/decarbonising-society-with-power-to-x

[20] https://www.transportenvironment.org/wp-content/uploads/2021/07/2020_Report_RES_to_decarbonise_transport_in_EU.pdf

[21] https://www.transportenvironment.org/wp-content/uploads/2020/12/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf

efficiency and high cost. But the time frame for the use of such e-fuels will be after 2030, for the first adoption, due to the lack of e-fuel production capacity and green hydrogen supply to feed into e-fuel production.

Another key distinction between e-fuels is that some of them (hydrogen and ammonia) do not require CO_2 to produce, while others, such as methane or liquid e-fuel, require CO_2 to produce and emit CO_2 when used. Unless this CO_2 is captured, these e-fuels are not CO_2 neutral. For example, if captured CO_2 from cement fabrication is used to generate liquid e-fuel, which is then burned in a large oceangoing vessel there are still net CO_2 emissions, unless they are compensated or captured elsewhere. This is an important point which is not always included in discussions of e-fuels.

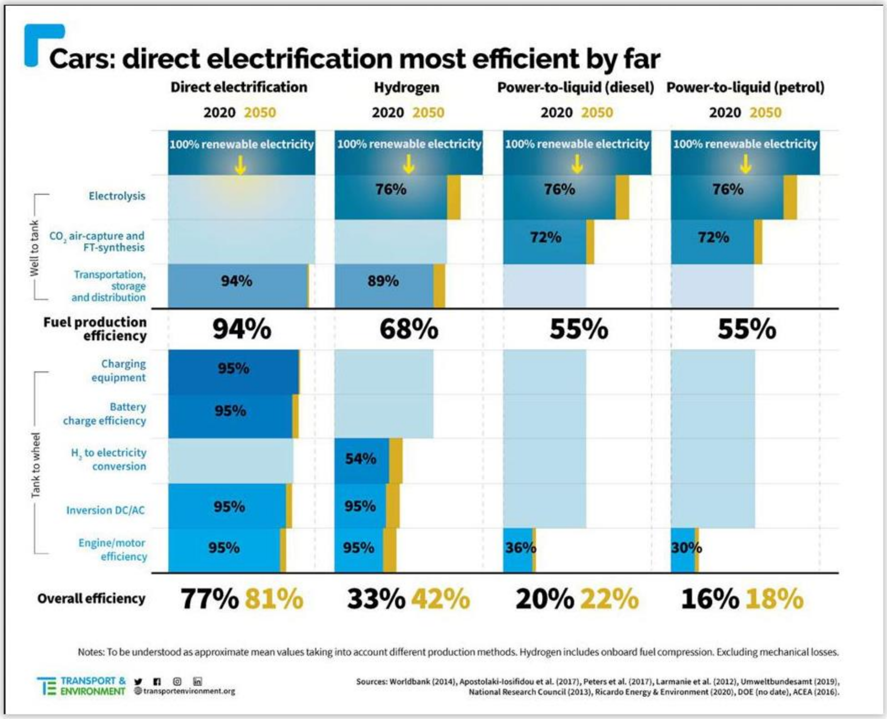

Figure 2: Comparison of electrification and e-fuels.

Consistent EU Policy on Green Hydrogen

In December 2019, the European Council endorsed the EU-wide objective of achieving climate neutrality by 2050, as per the goal set out in the European Green Deal. In order to turn this political commitment into a legal obligation, the European Commission proposed in March 2020 a European Climate Law. This proposal for a Regulation sets a legally binding target of net zero greenhouse gas emissions by 2050 and addresses a few actions necessary to achieve this goal, including a new target for 2030 greenhouse gas emissions reductions. For gas, the Green Deal suggests "*the decarbonisation of the gas sector will be facilitated, including via enhancing support for the development of decarbonised gases, via a forward-looking design for a competitive decarbonised gas market*".

The current cost of green hydrogen is estimated to be about Euro 5/kg based on an average for the entire EU. The current cost of grey hydrogen is about Euro 1.5/kg at a gas price of $3/MM BTU. Adding CCS to make blue hydrogen could increase this cost by 30 to 50%, but currently there is no large-scale CCS capacity in the EU. Various cost estimates have been made based on different assumptions about improvements in technology and reductions in the price of renewable electricity. In the optimistic forecasts, such as in Figure 3, the cost of green hydrogen is predicted to become less than grey hydrogen around 2030. These optimistic forecasts rely on a few optimistic assumptions about reductions in electrolyser costs. The forecasts also assume reductions in renewable electricity costs that may be overly optimistic.

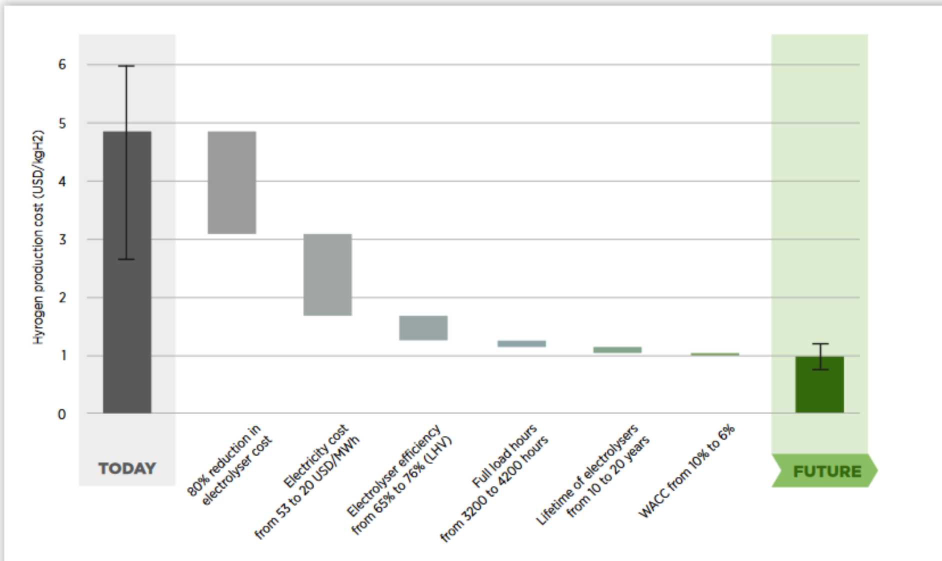

Figure 3: Potential reductions in cost of green hydrogen[22].

EU policy relating to the use of green hydrogen must be made based on realistic future scenarios for hydrogen production, considering a sustainable economic model for the production of renewable energy and increases in energy requirements if hydrogen is actually used in all the potential applications described here.

This statement was developed by the IEEE European Public Policy Committee (EPPC) Working Group on Energy and represents the considered judgment of a broad group of European IEEE members with expertise in the subject field. IEEE has nearly 60,000 members in Europe. The positions taken in this statement do not necessarily reflect the views of IEEE or its other organizational units.

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[22] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf