IAPE '19, Oxford, United Kingdom
ISBN: 978-1-912532-05-6

Renewables for industry and transport, based on large- and small-scale green hydrogen production

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ABSTRACT

Hydrogen produced from renewable electricity through Power-to-Hydrogen can facilitate the integration of high levels of variable renewable electricity (VRE) into the energy system. An electrolyser is a device that splits water into hydrogen and oxygen using electricity. When electricity is produced from renewable energy sources, the hydrogen becomes a carrier of renewable energy. Electrolysers can help integrate VRE into power systems, as their electricity consumption can be adjusted to follow wind and solar power generation, where hydrogen becomes a source of storage for renewable electricity. Although key hydrogen technologies (especially alkaline and PEM electrolysers) are still further maturing, we will show in this contribution how fossil parity for green hydrogen can already be achieved as of today in a number of sectors where hydrogen from renewables stands out as the best-performing option to meet climate targets and comply with local emissions regulations.

Keywords

power-to-hydrogen, electrolyser, renewables, electrofuels

1. INTRODUCTION

The global energy system has to undergo a profound transformation to achieve the targets of the Paris Agreement. In this context, low-carbon electricity from renewables may become the preferred energy carrier. The share of renewable electricity in all of the energy consumed by end users worldwide would need to increase to 40 % in 2050 (from about half that amount in 2015) to achieve the decarbonised energy world envisaged by the agreement. In absolute terms, this implies that the total installed renewable power capacity should increase from about 1,500 GW in 2015 to more than 15,000 GW in 2050, i.e. a 10-fold increase. However, the total decarbonisation of certain sectors, such as transport, industry and uses that require high-grade heat, may be difficult purely by means of electrification. This challenge could be addressed by hydrogen from renewables, allowing large amounts of renewable electricity to be channeled from the power sector into these end-use sectors. Hydrogen could therefore be the missing link in the energy transition : renewable electricity can be used to produce green hydrogen (via water electrolysis), which can in turn provide a chemical or energetic building block in sectors otherwise difficult to decarbonise through electrification. The latter include :

- Industry: Hydrogen is widely used in several industry sectors (refineries, ammonia production, bulk chemicals, etc.), with the vast majority of it currently being produced from natural gas by steam-methane reforming (SMR). Green hydrogen from renewables could replace such fossil fuel-based feedstocks in high-emission applications.

- Transport: Fuel cell electric vehicles (FCEVs) provide a low-carbon mobility option when the hydrogen is produced from renewable energy sources, and offer driving performances comparable to conventional vehicles. On the longer run, H_2-based electrofuels, i.e. liquid fuels produced from renewable power, can replace fossil fuels without the need to change end-use technologies.

2. HYDROGEN (PRODUCTION) TODAY

As of today, hydrogen is being used as a specialty chemical in a wide variety of applications. These are generally classified into 4 main categories : (1) the chemical industry, where H_2 is a basic building block for the synthesis of ammonia and a number of technical polymers; (2) refining processes, including hydro-cracking and hydro-treating; (3) iron, steel and glass manufacturing, where H_2 is the preferred reducing gas for annealing purposes; (4) other general industrial applications, like the semiconductor industry, the use as a propellant fuel, the hydrogenation of fats or the cooling of generators. The first category represents with 65% by far the largest contribution to the total H_2 demand, followed by refining, iron, steel and glass manufacturing (all together about 25%) and leaving the remaining 10% for the other more general industrial applications. According to [1], this global hydrogen feedstock market represented in 2015 a total estimated value of 115 billion $, with a corresponding hydrogen demand of about 56 Mton/yr. From these numbers, the average hydrogen market price can be estimated as 2.0 $/kg.

Hydrogen production today is dominated by 2 types of chemical processes : about 48% coming from steam methane reforming (SMR), and an equal amount coming from coal or oil gasification. As shown in Figure 1, these processes are heavily CO_2 intensive, SMR emitting upto 8 tons of CO_2 per ton of H_2 produced. Therefore, in view of reaching the CO_2 emission targets in the H_2 production industry, green hydrogen production from renewables has the intrinsic potential to replace these fossil fuel-based feedstocks. Such production is based on using renewable electricity for driving the so-called water electrolysis process. In

DOI: http://dx.doi.org/10.17501..

order to meet the global H_2 demand, a total of 300 GW installed electrolyser capacity would be needed, based on a so-called theoretical lower heating value (LHV) of 33kWH/kg H_2 and a typical electrolyser efficiency of 70%. As this represents already about 20% of the total installed renewable power capacity today, such large-scale electrolyser deployment is currently not very realistic. However, with the projected 10-fold increase to 15,000 GW renewable power in 2050, a 2% use of this capacity for water electrolysis can be considered to be within the range of grid balancing services, making such green hydrogen production a very viable and attractive alternative hydrogen production technology.

1) 48% Steam methane reforming (SMR)

reformer $CH_4 + H_2O \rightarrow 3H_2 + CO$ (endo : T ↗)
water gas shift $CO + H_2O \rightarrow H_2 + CO_2$
$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$ (8 tons/ton H_2)

2) 48% Coal (oil) gasification

gasification $2C + O_2 \rightarrow 2CO$ (exo)
water gas shift $2CO + 2H_2O \rightarrow 2H_2 + 2CO_2$
$2C + O_2 + 2H_2O \rightarrow 2H_2 + 2CO_2$

3) 4% Water electrolysis : $2H_2O \rightarrow 2H_2 + O_2$

Lower Heating Value (LHV) ~ 33 kWh/kg H_2
Electrolyser efficiency 70 % (~ 50 kWh/kg H_2)
⇒ 56 Mton/year requires ~ 300 GW installed RE ~ 20% of total RE today
~ 2% of total RE by 2050

Figure 1. Today's main hydrogen production technologies.

3. GREEN H₂ PRODUCTION SCALE-UP

In order to be able to realize such a coupling with renewable sources, especially wind and solar, it is clear that the power scale of water electrolysers should become of the same order of magnitude as the renewable electricity source. As illustrated in Figure 2, this still requires a major scale-up from the kW-scale typical for state-of-the art electrolysers about a decade ago towards the multi-MW scale typical for state-of-the art current on-shore wind turbines. Fig. 2 also shows that this required scale-up has the potential to significantly reduce the investment cost (CAPEX) of electrolysers, potentially reaching the same order of magnitude of small-scale SMR installations from the MW-level onwards. However, in order to reach similar production capacities as todays large-scale SMR, an electrolyser scale-up towards 50-100 MW would still be required, 50 MW corresponding to about 10,000 Nm^3/hr (equivalent to about 8000 ton/yr).

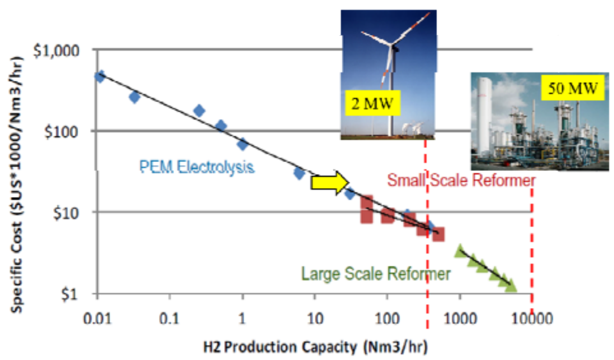

Figure 2. Projected cost reduction upon green (i.e. electrolytic) hydrogen production scale-up (from ref. [2]).

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Such an electrolyser scale-up is typically being realised by increasing the number of cells (i.e. cathode/anode) per stack. However, from the data collected from a number of electrolyser manufacturers and shown in Figure 3 [3], such a "keep-on-stacking" approach seems to have an intrinsic limit at around 100 cells/stack, after which other balance-of-plant issues come into play (risk of electrical shorts, gas collection and safety issues). Therefore, for MW applications, multi-stack systems are typically being used. A typical (historical) example of such a multi-stack configuration is shown in Figure 3 as well.

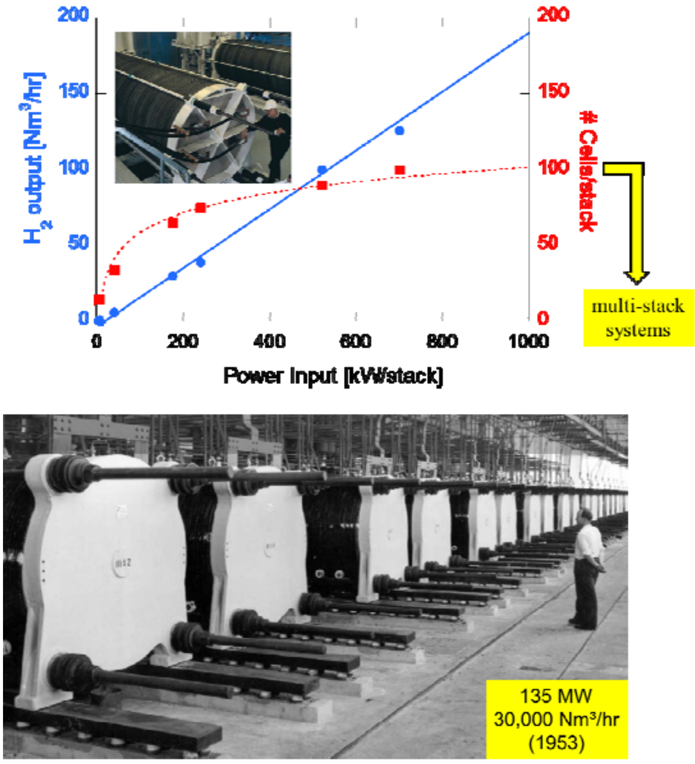

Figure 3. Electrolyser (multi-)stacking scale-up approach (top), with an historical example (bottom).

4. FOSSIL PARITY FOR GREEN H₂

While Fig. 3 shows that in principle, it should be technically feasible to produce green electrolytic hydrogen at the multi-MW scale, the critical question still remains at what price/cost. Clearly, if green H_2 is to become competitive to the state-of-the-art SMR H_2, it should be made available at its current market price, i.e. around 2.0 $/kg. In this respect, Figure 4 illustrates the effect of the 3 major parameters affecting the electrolytic H_2 production cost : the expected operational up-time of the electrolyser, the cost/price of renewable electricity, and the electrolyser CAPEX. From the simulation for the specific set of parameters in Fig. 4 (which dates back already to 2014), it is clear that from an economic point of view, producing H_2 from water electrolysis seems to be a bad idea, unless there is cheap electricity, the investment cost of electrolysers can be brought down, and in case there is also a commitment to CO_2 reduction. The latter might notably impose an additional tax/cost to SMR H_2, helping to close the gap with electrolytic H_2.

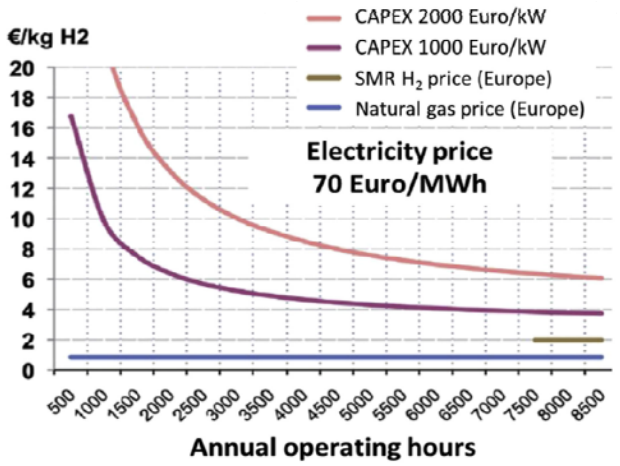

Figure 4. Electrolytic H_2 production cost as function of electrolyser operational time for different electrolyser CAPEX values (1 yr = 8760 hrs). Taken from ref. [4].

Luckily, with respect to the scene set in Fig. 4, significant progress has been made since 2014, both in reducing the price of renewable electricity and in reducing the electrolyser CAPEX. As to the first, Figure 5 shows the projected price reduction for renewable electricity (in $/MWh) for both solar PV and on-shore wind [5]. Clearly, prices on the order or even less than 30 $/MWh can be expected by 2020. At the same time, this very study also projects capacity (load) factors of combined wind and solar power to exceed 50% in vast areas, although the latter are often still relatively remote from large consumption centers.

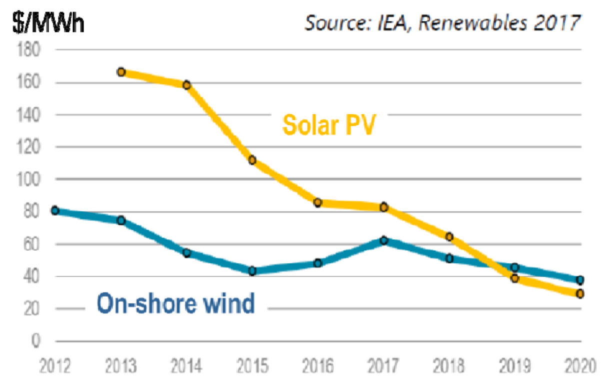

Figure 5. Documented and extrapolated decrease in renewable electricity price for solar PV and on-shore wind (from ref. [5]).

As to the electrolyser CAPEX, Figure 6 [3] indicates a significant evolution with respect to the values used in Fig. 4. In particular, for alkaline systems, a CAPEX of 750 Euro/kW, considered by utility providers to be the capital cost for storing renewable electricity, is already realistic today for a single stack 2 MW system. For PEM, such a critical CAPEX value should become within reach for 5 MW systems, requiring the use of multi-stack systems. Fig. 6 also indicates that for single stack systems, alkaline electrolysers are much more susceptible to CAPEX reduction upon scaling than PEM. And finally, for large-scale applications, CAPEX values as low as 450 Euro/kW are currently projected for alkaline systems when scaling up to 100 MW.

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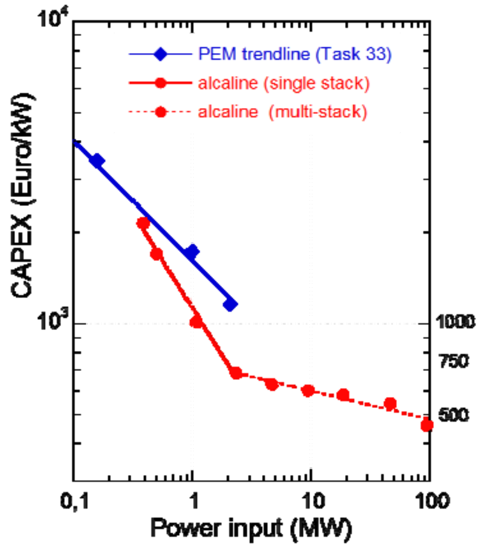

Figure 6. CAPEX data for both PEM and alkaline electrolysers as a function of power input. The change in slope for alkaline electrolysers corresponds to the use of multi-stack systems (from ref. [3].

Based on the above updated numbers, a recent IEA study [5], reproduced in Figure 7, allows to anticipate a further reduction in the electrolytic H_2 production cost as a function of the available renewable electricity price, assuming the most favorable (but still realistic) CAPEX value of 450 Euro/kW. Three different cases have been considered. Firstly, in countries with good but not excellent solar and wind resources, the cost of electricity can be assumed to be about 60 $/MWh (red line). For this combination of onshore wind power and solar PV electricity, the associated load factor can be expected to be around 4500 full load hours (FLH), which brings the average electrolytic H_2 production cost to 3-4 $/kg.

Secondly, at times of excess electricity production from renewables, the market price of electricity can become very low. Assuming a zero renewable electricity price (blue line), it can be seen that the cost of electrolytic hydrogen becomes very dependent on the electrolyser load factor. For instance, if the relevant load factor for such free "dumped" electricity is in the range of 1000 FLH, electrolytic hydrogen can still become very competitive, at a production cost of less than 2 $/kg. However, since such small load factors generally also entail a smaller scale electrolyser, its CAPEX will be significantly higher than the 450 Euro/kW assumed in Fig. 7. In that case, load factor uncertainties can make such an investment quite risky.

Thirdly, a combination of high load factors and a non-zero but relatively low electricity cost, on the order of 30 $/MWh (green line), would still allow electrolytic H_2 production costs to compete with SMR. In this case, both the cost of renewables and the relevant load factors essentially depend upon the quality of the solar and wind resources.

From all of these recently compiled data, it appears that an electrolytic H_2 production cost on the order of 2-3 $/kg is very realistic by 2020, the lower and upper bound limit mainly depending on the best available renewable electricity price. This is very much comparable to SMR H_2. It should be noted though

ISBN: 978-1-912532-05-6

that, for a fair comparison, OPEX costs should eventually be taken into account as well (e.g. not only electricity price for electrolytic H_2, and an additional CO_2 tax for SMR, cfr. [6]). Nonetheless, these projections are sufficiently promising to stimulate a further, large-scale penetration of H_2 technologies for renewable energy storage purposes. On the other hand, they should also provide confidence for the ultimate consideration of electrolytic H_2 as a basic chemical building block, enabling direct coupling to renewable electricity production and hence helping to green the chemicals and fuels (transport) industry.

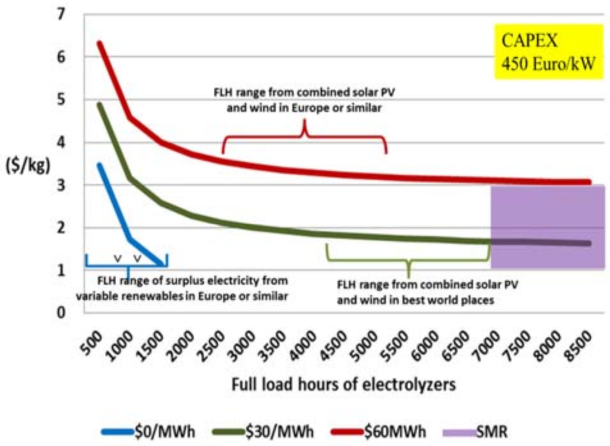

Figure 7. Electrolytic H_2 production cost vs. electrolyser operational time (FLH = full load hours) for different renewable electricity costs and for an electrolyser CAPEX of 450 Euro/kg. SMR H_2 cost (purple area) was estimated at 1-3 \$/kg, depending on regional variations in natural gas prices. Taken from ref. [5].

5. CONCLUSION : THE SCALE OF FOSSIL PARITY

A final more speculative comment then relates to the necessary scale for obtaining such fossil parity. Indeed, from Fig. 6, one could wrongly conclude that reaching the required reduction in electrolyser CAPEX down to 450 Euro/kW would require very large-scale electrolytic H_2 production units, on the order of 100 MW. In that case, the scale of electrolytic H_2 production would be similar to current SMR installations (cfr. Fig. 2). However, as suggested in Figure 8, there might also be an alternative way for reaching such low CAPEX values. Indeed based on the extrapolation of the currently available CAPEX data of single-stack alkaline electrolysers in Fig. 6, the level of 450 Euro/kW (dashed horizontal line) should be reached around 4 MW. Such a significant reduction in the scale required for fossil parity is directly related to the much steeper reduction in CAPEX that can be realised for single-stack as compared to multi-stack systems. The (only) remaining technological challenge to be solved on the electrolyser level would than be to increase the number of cells/stack (cfr. Fig. 3) Incidentally, a recent European research project demonstrating the technical feasibility and potential of a single-stack 4 MW alkaline electrolyser has been launched in that sense [7]. Such small-scale fossil parity has the important advantage of allowing a de-centralised local H_2 production. In that case, renewables can be harvested anywhere, and used directly for the local production and consumption of green, electrolytic hydrogen. This is a significant paradigm shift with respect to the fossil fuels based centralised hydrogen production at refineries, which also requires an additional cost to transport the H_2, both in terms of Euro/kg and CO_2 footprint.

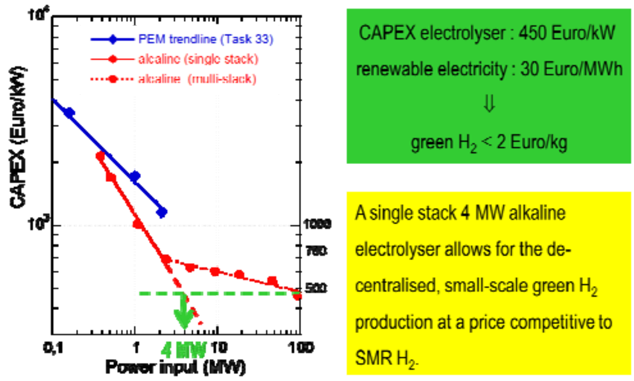

Figure 8. Potential of a 4 MW alkaline water electrolyser for a decentralised small-scale H_2 production at fossil parity.

6. ACKNOWLEDGMENTS

We wish to acknowledge financial support from the Public Service of Wallonia – Dept. of Energy and Sustainable Building.

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