Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen

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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 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, electrolytic hydrogen can be considered to be green. At the same time, electrolysers can help integrate renewable electricity into power systems, as their electricity consumption can be adjusted to follow wind and solar power generation. Green hydrogen then also becomes a carrier for renewable electricity. Key green hydrogen production technologies, mostly PEM and alkaline electrolysers, are still further maturing, both in technical (efficiency), economical (CAPEX) and durability (lifetime) performance. Nonetheless, we will show in this contribution how fossil parity for green hydrogen, i.e. a Total Cost of Ownership (TCO) similar to grey H_2 coming from todays CO_2 intensive SMR processes, can already be achieved today. Moreover, this can be realised at a scale which corresponds to the basic units of renewable electricity generation, i.e. a few MW.

Keywords

power-to-hydrogen, electrolyser, renewable electricity, fossil parity

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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 4% in 2015) to achieve the decarbonised energy world envisaged by the agreement [1]. 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 [2]. However, the total decarbonisation of certain sectors, such as transport, industry and applications that require high-grade heat, may be difficult purely by means of electrification. This challenge could be addressed by green hydrogen produced electrochemically from renewables (so-called Power-to-Hydrogen or P2H [3]), allowing large amounts of renewable electricity to be channeled from the power sector into these end-use sectors [4]. Renewable electricity can be used to produce green hydrogen via water electrolysis, a well-known process splitting acidified or alkalised water into ultrapure (upto 99.998%) H_2 and O_2 [5]. Such electrolytic H_2 can then further be used downstream as a green and clean chemical feedstock material in sectors otherwise difficult to decarbonise through electrification. The latter include both the chemical industry itself, as well as new applications in the transport sector [6]. As to the first, hydrogen is currently already widely used in several industrial sectors (refineries, ammonia production, bulk chemicals, etc.), with the majority of it being produced from natural gas by steam-methane reforming (SMR), a vast CO_2-intensive process [7]. Green hydrogen from renewables could replace such fossil fuel-based feedstocks in high-emission applications. For the transport sector, fuel cell electric vehicles (mainly cars and busses) provide already today an attractive 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 also replace fossil fuels in the freight sector (including aviation and heavy-duty rail and trucks), without the need to change end-use technologies [8].

Although water electrolysis is already a well-established H_2 production technology for almost a century [9], its large-scale implementation for the production of green H_2 has been hampered mainly by cost issues. In a recent review [10], the production cost of hydrogen from electrolysis has been extracted from a large amount of litterature data, resulting in a very wide range of cost values, ranging from about 2 €/kg to 20 €/kg. This was attributed to the large variability of the underlying assumptions and working parameters of the different sources, the production scale being the most important one [11]. Moreover, when evaluating the potential and economic viability of such green hydrogen production by water electrolysis, the current price of fossil SMR-based H_2 often appears as a rather challenging benchmark [12]. For a fair comparison though, it was recently pointed out [13] that one should always keep in mind that the industrial SMR production price is usually considered for immediate use, while often additional storage is necessary to meet fluctuations in demand and delivery as well. On top of that, hydrogen from SMR still needs to be purified for most applications in order to reach the same grade as electrolytic one. Moreover, in such cost comparisons, the potential valorisation of ultra-pure electrolytic oxygen (8 kg for each kg of H_2) is totally neglected. In any case, on a macro-economical level, according to [14], the global hydrogen feedstock market represented in 2015 a total estimated value of 115 billion €, corresponding to a hydrogen demand of about 56 Mton/yr. By dividing the total estimated market value by the total worlwide hydrogen demand at the same year, a reasonable first-order estimation of the "average" market price for fossil H_2 can then be obained as 115/56 ≅ 2,0 €/kg. In the current paper, we aim at critically assessing the production scale that would be required to reach such fossil parity using electrolytic hydrogen.

While doing so, it is important to acknowledge that significant regional differences may still exist on a micro-economical level. This is not only due to geographical variations in the production price of SMR H_2, but also depending on the availability of sufficient and low-cost renewable electricity. It is for instance well-known that the production cost of hydrogen from SMR is significantly influenced by natural gas prices, which account for 45% to 75% of the total SMR production cost. As a result, the low gas prices in the Middle East, the Russian Federation, and North America give rise to some of the lowest hydrogen SMR production costs, sometimes even down to 1.5 €/kg [15]. On the other hand, gas importers such as Japan, Korea, China and India have to contend with higher gas import prices, which inevitably results in higher hydrogen production costs. As a result, it will be much more feasible for electrolytic hydrogen produced from renewable electricity to compete effectively with SMR in countries relying on natural gas imports and characterised by good renewable resources.

2. Hydrogen production

2.1. Hydrogen production today

As of today, hydrogen is being used as a specialty chemical in a number of applications. These are generally classified into 4 main categories [14], as illustrated in Table I : (1) the chemical industry, where H_2 is a basic building block for the synthesis of ammonia, methanol and a number of technical polymers; (2) a number of downstream refining processes, like hydro-cracking and hydro-treating; (3) iron, steel and glass manufacturing, where H_2 is the preferred reducing gas during annealing, blanketing and forming processes ; (4) other specialty applications, like the semiconductor industry, the use as a propellant fuel or the cooling of generators. The first two categories represent 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 the remaining 10% for the other specialty applications.

An important difference between each of these 4 categories is the scale of the so-called unit process or production size, i.e. the typical individual plant or reactor capacity required to generate the appropriate amount of H_2 feedstock in each application. Table I gives in this respect some indicative numbers (in Nm^3/h of H_2 demand) for each of these 4 categories. In its last column, it also provides the equivalent electrolyser capacity that would be required to satisfy these unit size H_2 feedstock demands by on-site electrolytic H_2 production (assuming a state-of-the art electrolyser efficiency of 70% [16], corresponding to a renewable electricity need of 47,1 kWh/kg H_2). Large variations in production scale can be noticed across the different sectors, ranging from about 250 kW at the low-end (typical for float glass production) to a few GW at the high-end (typical for H_2 demand in refineries).

As of today, the great majority of all of the above H_2 is being delivered by a centralised, off-site hydrogen production, dominated by 2 large-scale chemical processes : steam methane reforming (SMR) and coal gasification. According to [15], these processes made up about 76% and 23% respectively of the total H_2 production in 2018. Unfortunately, as shown in Figure 1, both of these processes are heavily CO_2 intensive, SMR emitting upto 8 tons of CO_2 per ton of H_2 produced. Therefore, with the objective of reaching the CO_2 emission targets in todays fossil-based H_2 production, the part of green electrolytic hydrogen production from renewable electricity (which represents less than 4% today) can be expected to significantly increase over the coming years. In order to meet the current global H_2 demand of around 60 Mton/year, a total of 300 GW installed electrolyser capacity would be needed. As this represents today about 20% of the total installed renewable power capacity, such massive electrolyser deployment is currently not very realistic. As a result, a selection of technologically feasible market penetrations for electrolytic H_2 needs to be made. Such selection also implies that todays local H_2 consumers, besides becoming local (on-site) producers of renewable electricity, also need to become local (on-site) producers of electrolytic H_2, at a production scale which still allows to meet the stringent requirement of fossil parity at about 2,0 €/kg. On the longer run, with the projected 10-fold increase in renewable power to 15.000 GW in 2050, a mere 2% use of this capacity would be required to satisfy the equivalent 300 GW water electrolysis demand. This can be considered to be within the range of grid balancing services, making such green electrolytic hydrogen production on the long run an even more viable and attractive alternative hydrogen production technology.

The above suggested transformation from centralised (off-site) fossil-based H_2 production to a decentralised (on-site) green electrolytic H_2 production provides a significant paradigm shift, allowing local consumers to become local producers as well. Upto now, in an industry largely governed by CO_2-intensive chemical processes, such a local H_2 production in line with the local H_2 consumption was simply not feasible, because of the minimum production scale required for both SMR and coal or oil gasification. The latter typically starts at a few 10.000 Nm^3/hr (about 8000 ton/yr) for the smallest unit size installations, equivalent to a 50 MW electrolyser. As can be seen in Table I, this largely exceeds the industry needs in a number of applications (iron & steel, as well as general industry). Moreover, additional CO_2-intensive logistics (incl. transport, compression and storage) are required in these applications as well.

2.2. Green hydrogen production scale-up

Contrary to the intrinsically large-scale SMR, water electrolysis is intrinsically small-scale, as illustrated in Figure 2. Both the geometrical area of the electrodes (a few m^2 at most) and the number of electrodes that can be compiled in series in a single stack is relatively limited. As a result, the unit size of water electrolysers has long been limited to the kW-range, a typical on-site containerised production unit being a few 100 kW at most. However, in order to be able to realize the mandatory coupling to renewables, mainly wind and solar, the power scale of water electrolysers needs to become of the same order of magnitude as the renewable electricity source itself. As illustrated in Figure 3 (reproduced from ref. [17]), this 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 on-shore wind turbines today. Fig. 3 also shows that this mandatory scale-up has the potential to significantly reduce the investment cost (CAPEX) of electrolysers, potentially reaching the same order of magnitude as small-scale SMR installations from the MW-level onwards.

Such an electrolyser scale-up has initially been realised by increasing the number of cells per stack, as illustrated in Fig. 2. However, from the state-of-the-art data that we recently collected from a number of electrolyser manufacturers, such a "keep-on-stacking" approach seems to have a practical limit at around 100 cells/stack [18]. Beyond that number, other balance-of-plant issues come into play, including the risk of electrical shorts [19] and the technological complexity of a safe large-scale gas collection [20]. There are also a number of specific issues related to electrochemical reactor design, like the increased risk of a non-homogenous electrolyte distribution when pumped through a larger stack [21], and a non-homogeneous current distribution within the different cells [22]. Note that this apparant 100-cell limitation is by no means a stringent intrinsic limitation, but rather an empirical observation based on the above cited industrial data. In other words, it appears that for a number of electrochemical and/or technical reasons, electrolyser manufacturers are currently preferring to upscale production capacity modularly, rather than increasing the capacity of a single stack.
As a result, for (multi-)MW applications, multi-stack electrolyser systems are typically being used. As an example, Figure 4 shows both an iconic historical illustration of a 135 MW alkaline electrolyser plant dating back already from 1953 [23], and a number of today's multi-MW plant designs from a major electrolyser manufacturer, based on a single stack electrolyser of 2,2 MW [24].

3. Fossil parity for green hydrogen

3.1. The cost of electrolytic hydrogen

While Fig. 5 shows that it is technically feasible to produce green electrolytic hydrogen at the multi-MW scale (even > 100MW), the critical question still remains at what price/cost. Clearly, if green H_2 is to become competitive with today's "grey" SMR H_2, it should be made available at its current market price, i.e. around 2,0 €/kg. In this respect, Figure 5 illustrates the effect of the 3 major parameters affecting the electrolytic H_2 production cost : the operational time of the electrolyser (in full load hours or FLH), the cost of renewable electricity (ELCTR, in €/MWh), and the electrolyser CAPEX (CPX, in €/kW). The basic equation used for this first-order cost simulation is as follows

$$H_2 \text{ cost (€/kg)} = \left(\frac{ELCTR}{1000} + \frac{CPX}{10} \cdot \frac{1}{FLH}\right) \cdot \epsilon \qquad (1)$$

where ε represents the electrolyser power consumption (in kWh/kg). With respect to the latter, the theoretical minimum value ε_{th} for obtaining H_2 through electrochemical water splitting can simply be calculated based on a 2 electron reduction step

$$2H^+ + 2e^- = H_2 \text{ (acid)} \qquad (2)$$
$$2H_2O + 2e^- = H_2 + OH^- \text{ (alkaline)}$$

With 1 kg of H_2 requiring $10^3 \cdot F$ Coulomb (F being Faraday's constant), 1 kg/hr of H_2 then corresponds to an electrical current of $(96487 \cdot 10^3)/3600 = 26802$ A. Multiplied by the theoretical water decomposition potential of 1.23 V, this then gives a theoretical minimum power consumption ε_{th} = 33 kWh/kg. A typical electrolyser efficiency being 70% [16], a typical ε-value to be used in eq. (1) is therefore 33/0.7 = 47.1 kWh/kg. Also note that in eq. (1), the factor 1/1000 in the first term serves to convert MWh into kWh, while the factor 1/10 in the second term comes from a linear depreciation for a 10 years electrolyser operation.
First of all, for the red set of parameters in Fig. 5, i.e. a CAPEX of 1000 €/kW and a renewable electricity cost of 70 €/MWh (as taken form [25], a reference which dates back already from 2014), it is clear that producing H_2 from water electrolysis is not always economically viable with respect to the current SMR benchmark price of 2 €/kg. In particular, before becoming a realistic alternative production technology, there is a need for cheap(er) renewable electricity (well below 70 €/MWh), the investment cost of electrolysers needs to be brought down (well below 1000 €/kWh), and there should preferably also be a clear industrial commitment to CO_2 reduction. The latter might notably impose an additional tax/cost to SMR H_2, helping to further close the gap with electrolytic H_2.

Luckily, with respect to the red parametric values used in Fig. 5, 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 6, taken from a recent study from the International

Energy Agency (IEA) [26], shows the projected reduction in average auction prices for renewable electricity from both solar PV and on-shore wind. Clearly, prices on the order of 30 €/MWh can be expected to be realistic already as of 2020. At the same time, this very study also projects load factors of combined wind and solar power to exceed 50% in vast areas. A recent German field study reporting on the operational experience of a 6 MW Power-to-Hydrogen demonstration plant seems to confirm these promising numbers [27]. During its initial testing phase, when operation time was limited to 8h during working days, the electrolyser load demand curve led to an average electricity cost (as purchased from the EPEX SPOT day-ahead auction market) of about 36 €/MWh. After full automation of the plant to a 24/7 operation so that electricity could be bought in times of low spot prices, additional cost savings of more than 15 €/MWh could be realised.

Secondly, as to the electrolyser CAPEX, Figure 7 shows state-of-the-art data from NEL, one of the world's largest alkaline electrolyser manufacturers. They clearly show a significant decrease well below the value of 1000 €/kW used for the red data set in Fig. 5. In particular, a CAPEX value of 750 €/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. Moreover, a significant further reduction in CAPEX as low as 500 €/kW is projected for multi-stack systems when scaling up to 50-100 MW. Also note from Fig. 7 that single stack electrolysers are much more susceptible to CAPEX reduction than multi-stack systems when upscaled.

Based on the above updated numbers, the green data set in Figure 5 then allows to anticipate a significant reduction in the electrolytic H_2 production cost. Indeed, assuming the most favorable but still realistic CAPEX value of 500 €/kW in combination with an electricity cost of 30 €/MWh and a state-of-the-art electrolyser efficiency of 70% (i.e. 47,1 kWh/kg), green electrolytic H_2 can indeed start competing with SMR from 4500 operating hours onwards (i.e. a load factor of about 50%). Note that under these conditions, the total H_2 cost calculated from eq. (1) comes down to 1,95 €/kg and is mainly determined by the electricity cost, which represents 47,1*0.03 = 1,41 €/kg or 72%. One should therefore be aware that any efforts to further reduce the CAPEX of alkaline water electrolysers below 500 €/kW will only have a minor overall effect. For instance, for a CAPEX of 250 €/kW, Figure 8(a) shows that the total H_2 cost goes down to 1,68 €/kg, of which only 15% would come from the very stringent techno-economical measures needed to reach such low CAPEX value.

Instead, eq. (1) indicates that it will be much more effective to focus technological efforts on improving the electrolyser's electrochemical efficiency, since the related power consumption ε

is a common factor to both the OPEX and CAPEX part. The main effect of an efficiency increase, which is equivalent to a lower kWh/kg H_2 electricity consumption, is that it allows to relax the sometimes rather stringent conditions on the renewable electricity price needed to reach fossil parity. In this respect, Figure 8(b) shows, as a function of electrolyser efficiency, the renewable electricity price (in €/MWh) that would be needed to arrive at an electrolytic H_2 cost of 2.0 €/kg for three different CAPEX values : 500, 1000 and 2800 €/kW. The last one can be considered, according to ref. [15], to be a realistic CAPEX target value by 2030 for solid oxide electrolysers (SOE). These are especially known for their high intrinsic efficieny (upto 90%) resulting from high temperature operation (650-1000°C). Nonetheless, from the negative red data in Fig. 9(b), it can be seen that even in that case the higher SOE efficiency will still not be able to provide electrolytic H_2 at fossil parity. This would require SOE CAPEX values to decrease even further, down to a level of 1000 €/kW.

We do acknowledge that the trends presented in Figures 5 and 8 should be considered to be a first-order cost simulation, based on the rather basic eq. (1). For instance, most other economic analyses tend to add a yearly interest rate (typically 7-10%) and in some cases an additional OPEX contribution on top of electricity cost (upto 30% of CAPEX). We have decided here not to do so, as the exact numbers are often rather arbitrary chosen. Moreover, they barely change the principal trends induced by varying the major parameters (i.e. electricity price, capacity factor, CAPEX and efficiency), which are already included in our basic eq. (1). This has been explicitely illustrated in Fig. 5 by the two additional dashed trendlines, which include an additional fixed OPEX cost equal to 30% of CAPEX.

Finally, for a fair comparison, an additional CO_2 price for SMR H_2 should be taken into account as well [28]. In this respect, the seminal IEA report *"The Future of Hydrogen"* [15] predicts an average increase of 50% in the hydrogen production cost from SMR when imposing a carbon price of 100\$/tCO_2. This might even trigger the large-scale implementation of CCUS, which would become economically attractive if CO_2 prices were above 50\$/tCO_2. Adding CCUS to SMR plants would then lead in turn to cost increases of about 50% in terms of CAPEX and 10% for fuel, the exact amounts depending on the plant design. It also leads on average to a doubling of OPEX as a result of CO_2 transport and storage costs [15]. Nonetheless, our above projections, without considering any carbon price, are sufficiently promisingas such to stimulate already today a further penetration of water electrolyser technology for renewable energy storage purposes. At the same time, 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 chemical feedstock industry.

3.2. The scale of fossil parity for green hydrogen

A final issue then relates to the production scale that is required for obtaining such fossil parity with electrolytic H_2. Indeed, from the data in Fig. 7, one could wrongly conclude that reaching the required reduction in electrolyser CAPEX down to 500 €/kW would require very large-scale electrolytic H_2 production units, on the order of 100 MW. In that case, the minimum scale for economically viable electrolytic H_2 production would need to become similar to current SMR installations (cfr. Fig. 3). As already suggested from Table I, for some feedstock applications, like ammonia or methanol production, such a large unit size can be relevant even for an on-site, decentralised green H_2 production. However, Figure 7 indicates that there might still be a much smaller production scale for reaching such low CAPEX values. Indeed, when extrapolating the CAPEX data of single-stack alkaline electrolysers in Fig. 7, the level of 500 €/kW (dashed horizontal green line) can already be reached around 3-4 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. A straightforward consequence of the above observation is that the minimum investment cost needed to install electrolytic hydrogen production units capable of delivering green H_2 at fossil parity goes down significantly as well : from about $100 \cdot 10^3 * 500$ = 50 M€ to a mere 200 k€, a very realistic number in view of a local, decentralised production.

Even more direct corroborating evidence for this relatively small-scale fossil parity for green electrolytic H_2 is provided in Figure 9. The latter presents state-of-the-art industrial data for the Total Cost of Ownership (TCO) of electrolytic H_2 as a function of power input, as obtained from GreenHydrogen, a Danish electrolyser manufacturer who produces pressurized stacks. Values are based on a 10 year operation, including a 10 years' service and maintenance agreement, for a complete turn-key, containerized alkaline electrolyzer unit (including inverter and water treatment), delivered and installed in Europe. The electrolyser power consumption is guaranteed at 46.7 kW/kg, and delivers H_2 at 35 bar. The hydrogen production cost in Figure 9 also takes into account the OPEX part, including the use of water, nitrogen (for purge) and electricity, assuming a renewable electricity price of 40 and 45 €/MWh, respectively. A number of striking observations can be made from this figure. First of all, these TCO data confirm the trend already observed in Fig. 7, namely the much steeper decrease in unit price for hydrogen delivered from a single stack vs. a multi-stack system. Secondly, until now, it was commonly agreed that the only option to decrease the electrolytic H_2 production cost towards fossil parity was to increase the capacity of the (multi-stack) system upto 50-100 MW, as already discussed with Fig. 7. Fig. 9 now clearly shows that in that case, even a decrease in renewable electricity cost (from 45 to 40 €/MWh) only slightly affects the scale of fossil parity, due to the relatively small decrease in TCO with power typical for such multi-stack systems. As a result, large-scale electrolyser systems would still be necessary to reach fossil parity. However, as suggested by the dashed red line in Fig. 9 through the TCO data for single stack systems, there is another technological alternative. It consists of extending the power input that can be taken up by a single-stack electrolyser upto a few MW, the exact power depending on the electrolyser technical characteristics. This then also corresponds to the scale of the basic units of renewable electricity generation. Also note that when considering an even more stringent SMR price level of 1.5 €/kg (corresponding in Fig. 9 to the horizonal axis rather than the dashed green line at 2.0 €/kg), our conclusions on the required scale for reaching fossil parity do not fundamentally change. Indeed, in that case, extrapolation of the single-stack TCO data would arrive at 3 MW, instead of 1.5 MW for 2.0 Euro/kg.

Note that at this stage, there is not really a rigorous scientific reasoning behind the single-stack cost line extrapolations in Fig. 7 and 9. It is a mere empirical observation, but still a rather reliable one since based on two independent industrial data sets over a relatively large power scale. It is also important to realise that the obtained extrapolated single-stack power for fossil parity is not a unique number, but something that is specific to each stack geometry (e.g. the number and area of electrodes used). For instance, the Norwegian HydrogenPro already has a 3.7 MW single-stack alkaline electrolyser on the market, while the Belgian-Chinese Cockerill Jingli Hydrogen even sells 7.5 MW single-stacks, to the best of our knowledge the largest single-stack on the market.

The challenge on the electrolyser level is then to try to technologically implement this single-stack extrapolation in order to arrive at higher single-stack power levels. As the number of cells/stack seems to have reached its limit [18], an alternative option is to increase the specific area of each individual electrode, e.g. by replacing classical 2-D plates by 3-D foams [29,30] hence allowing for a higher current density operation [31]. Incidentally, a recent European demonstration project (Demo4Grid) showing the technical feasibility and greening potential of a single-stack 4 MW alkaline electrolyser has been launched in that sense [32]. Such small-scale fossil parity has the important advantage of allowing a decentralised local H_2 production. Renewables can then be harvested anywhere, and used directly for the local production and consumption of green electrolytic hydrogen. This will not only allow to open up todays market to electrolytic H_2 in a number of small unit scale segments (like iron & steel and glass manufacturing, cfr. Table I), but also to widen the use of green electrolytic H_2 to a number of new small-scale markets (like the food industry targeted in ref. [32]). This is a significant paradigm shift with respect to the current large-scale fossil fuels (SMR) based centralised hydrogen production, the latter also requiring an additional cost to transport the H_2, both in terms of €/kg and CO_2 footprint.

4. Conclusion

In this paper, we have addressed the question what would be an economically viable (minimum) production scale for green hydrogen, produced from water electrolysis using renewable electricity. A realistic benchmark to do so is the current price of grey hydrogen produced by fossil-based and thus CO_2 intensive processes (the so-called fossil parity), currently estimated at 2,0 €/kg. Firstly, we acknowledged the promising market opportunities for such green hydrogen in todays H_2 markets. The latter represent about 60 Mt/yr, and can be classified in 4 major applications, all of them having their own typical unit size in terms of equivalent H_2 demand, ranging from a few hundreds of kW upto several GW. Secondly, it was shown how, based on current state-of-the-art CAPEX data for todays multi-stack electrolysers and using a renewable electricity price of 30 €/MWh, such fossil parity can be reached already today at 50-100 MW. This is about the same scale as the smallest SMR installations. Finally, using the most recent TCO values for electrolytic hydrogen, it was concluded that fossil parity could potentially also be reached at a much smaller production scale, on the order of a few MW. Although this still requires a further intensification of the water electrolysis process, e.g. by extending the power range of a single-stack electrolyser, such small-scale fossil parity provides an important paradigm shift. Indeed, with respect to the current, large-scale fossil fuels (SMR) based centralised hydrogen production, it has the important advantage of allowing a decentralised local H_2 production. Renewables can then be harvested anywhere, and used directly for the local production and consumption of green electrolytic hydrogen, in line with the small-scale local H_2 demand.

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Figure legends

Figure 1 Summary of today's main hydrogen production technologies.

Figure 2 A typical unit size configuration for an industrial alkaline water electrolyser.

Figure 3 Projected cost reduction associated with a scale-up of green electrolytic hydrogen production. The blue diamonds represent real CAPEX data for PEM electrolysers, except for the ones between 100 and 1000 Nm^3/hr, which are cost projections. The red squares and green triangles are real SMR CAPEX data for small-scale (on-site) and large-scale (centralized) reformers, respectively. Taken from ref. [17].

Figure 4 Examples of multi-stack alkaline electrolyser systems : (a) a 135 MW electrolyser plant from 1953 [23] ; (b) current multi-MW plant designs from a major electrolyser manufacturer, based on a single stack electrolyser capacity of 2,2 MW [24]

Figure 5 Electrolytic H_2 production cost as function of electrolyser's annual operating time (1 yr = 8760 hrs), simulated according to eq. (1) for two different CAPEX/electricity cost combinations. The electrolyser's efficiency was fixed at 70%, corresponding to 47,1 kWh/kg. The additional dashed trendlines for the 2 data sets include, besides the electricity cost, also an additional fixed OPEX cost equal to 30% of CAPEX.

Figure 6 Documented and extrapolated decrease in average auction prices for renewable electricity from solar PV and on-shore wind (from ref. [26]).

Figure 7 State-of-the-art CAPEX data for alkaline electrolysers as a function of power input. The change in slope for alkaline electrolysers corresponds to the use of multi-stack systems.

Figure 8 (a) Simulated electrolytic H_2 production cost as a function of electrolyser CAPEX, assuming a 70% efficiency (i.e. 47,1 kWh/kg) and a 50% load factor (i.e. 4380 hr/year). Renewable electricity price was fixed at 30 €/MWh, corresponding to

47,1* 0.03 = 1,41 €/kg. The right axis gives the resulting % contribution of the electrolyser CAPEX to the total H_2 cost ; (b) Renewable electricity price (in €/MWh) as a function of electrolyser efficiency to arrive at an electrolytic H_2 cost of 2.0 €/kg for three different CAPEX values (500, 1000 and 2800 €/kW).

Figure 9 Total Cost of Ownership (TCO) of electrolytic H_2 (delivered at 35 bar) as a function of power input, obtained from the Danish electrolyser manufacturer GreenHydrogen. Prices are based on a 10 years operation (including a 10 year's service and maintenance agreement) for a complete turnkey, containerized alkaline electrolyzer unit (including inverter and water treatment), delivered and installed in Europe. OPEX includes the use of electricity, water and nitrogen (for purge), assuming a renewable electricity price of 40 and 45 €/MWh, respectively.

Table I : Today's major industrial sectors using H_2. For each sector, a typical unit plant size is given (in Nm^3/h H_2 demand), as well as the corresponding equivalent electrolyser power.

Industry Sector	Key Applications	Unit plant size (in Nm^3/h H_2 demand)	Equivalent electrolyser power
Chemical	Ammonia (NH_3) Methanol (CH_3OH)	80.000 10.000	400 MW 50 MW
Refining	Hydrocracking Hydrotreating	400.000	2.000 MW
Iron & Steel	Annealing Blanketing gas Forming gas	400	2 MW
General	Semiconductor Float glass production Propellant fuel Cooling of generators	50	0,25 MW

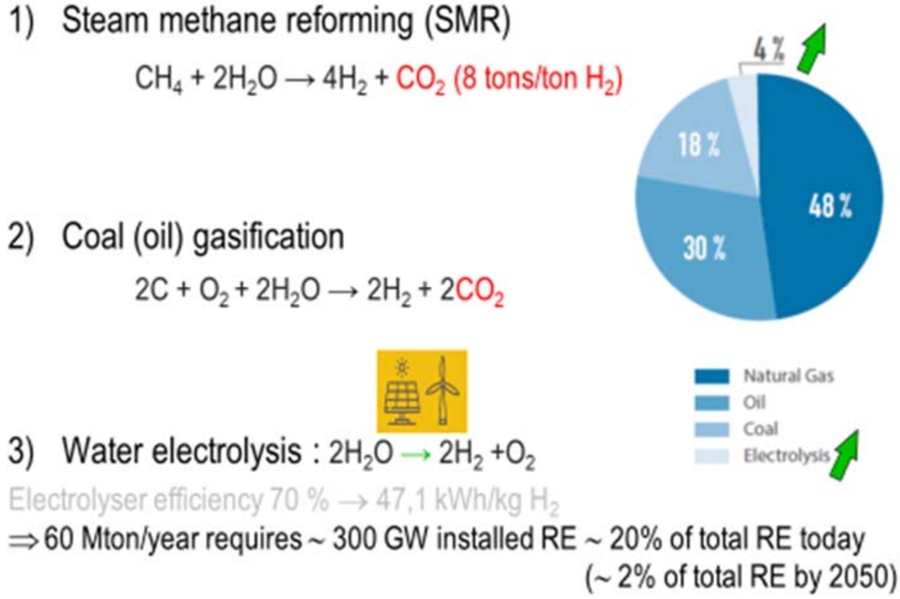

1) Steam methane reforming (SMR)
$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$ (8 tons/ton H_2)
2) Coal (oil) gasification
$2C + O_2 + 2H_2O \rightarrow 2H_2 + 2CO_2$
3) Water electrolysis : $2H_2O \rightarrow 2H_2 + O_2$
Electrolyser efficiency 70 % → 47,1 kWh/kg H_2
⇒ 60 Mton/year requires ~ 300 GW installed RE ~ 20% of total RE today
(~ 2% of total RE by 2050)
4 %
18 %
48 %
30 %
Natural Gas
Oil
Coal
Electrolysis

Figure 1

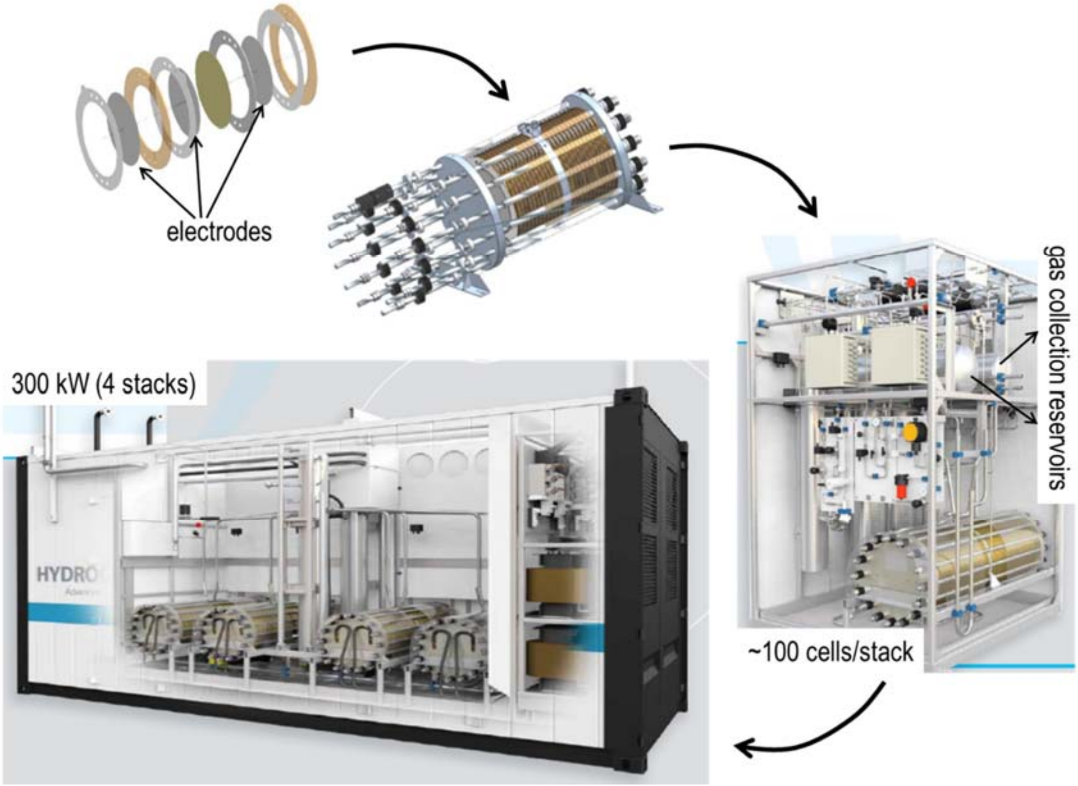

electrodes
gas collection reservoirs
300 kW (4 stacks)
~100 cells/stack

Figure 2

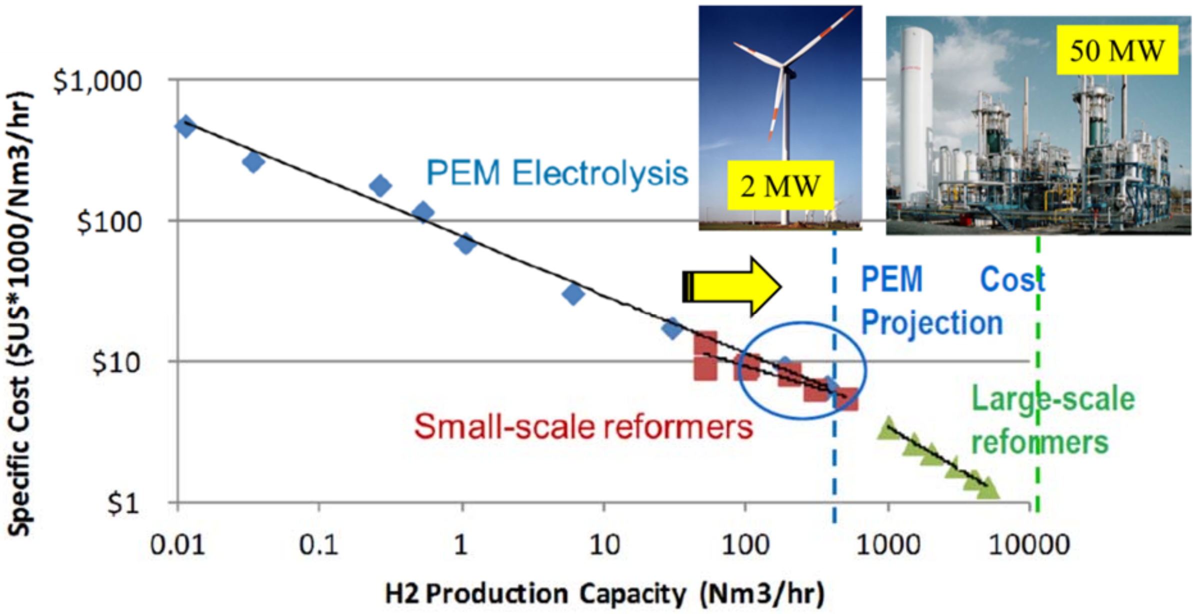

2 MW
50 MW
$1,000
$100
$10
$1
Specific Cost ($US*1000/Nm3/hr)
PEM Electrolysis
PEM Cost Projection
Small-scale reformers
Large-scale reformers
0.01
0.1
1
10
100
1000
10000
H2 Production Capacity (Nm3/hr)

Figure 3

a)


135 MW
30,000 Nm³/hr
(1953)

b)

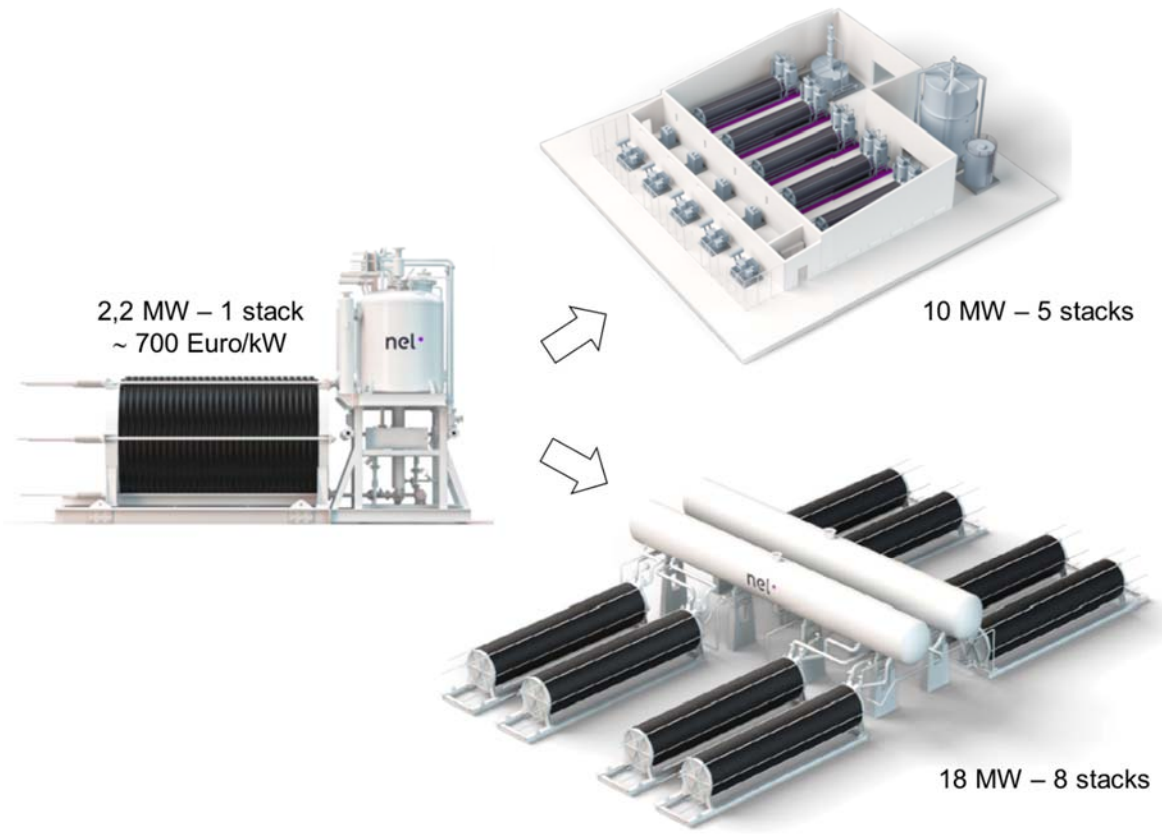

2,2 MW – 1 stack
~ 700 Euro/kW
nel
10 MW – 5 stacks
nel
18 MW – 8 stacks

Figure 4

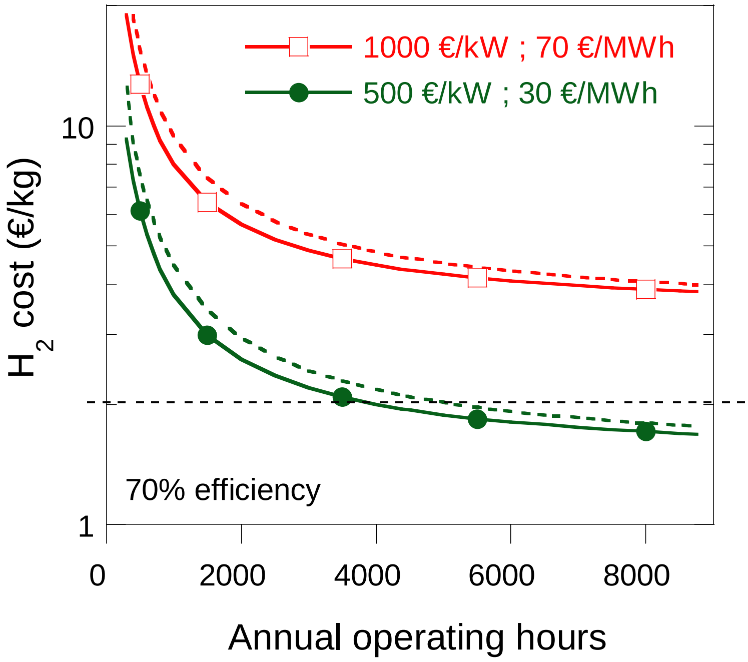

1000 €/kW ; 70 €/MWh
500 €/kW ; 30 €/MWh
10
1
70% efficiency
0
2000
4000
6000
8000
H_2 cost (€/kg)
Annual operating hours

Figure 5

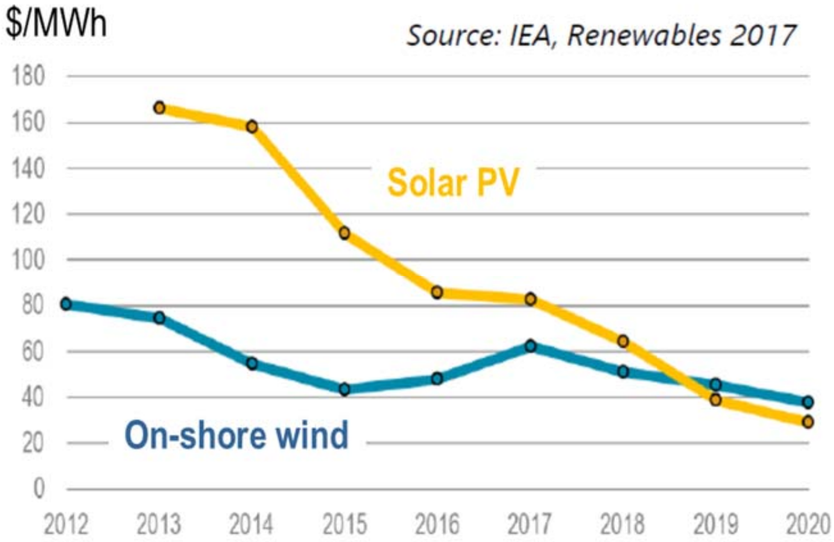

$/MWh
Source: IEA, Renewables 2017
180
160
140
120
100
80
60
40
20
0
Solar PV
On-shore wind
2012
2013
2014
2015
2016
2017
2018
2019
2020

Figure 6

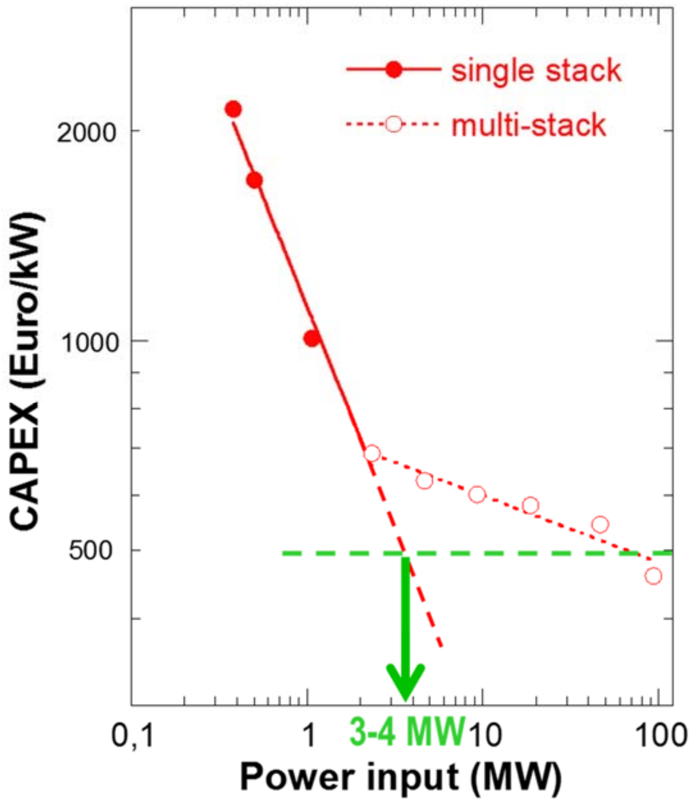
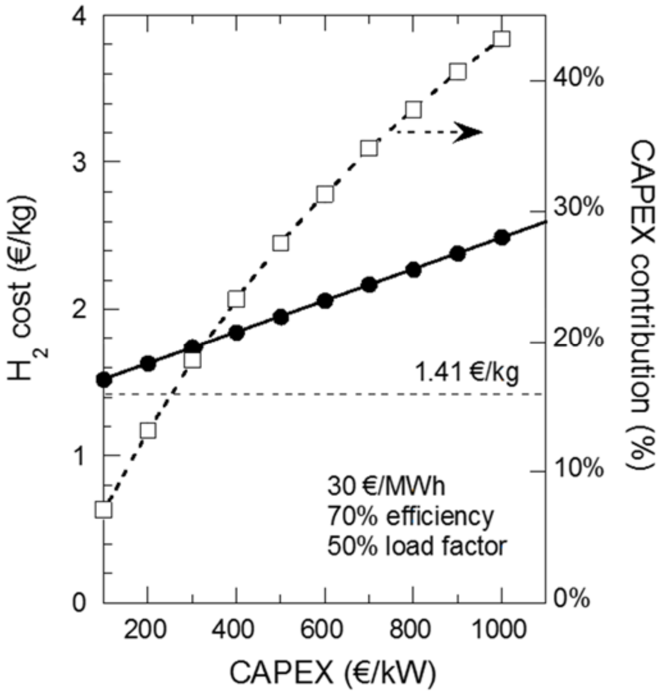
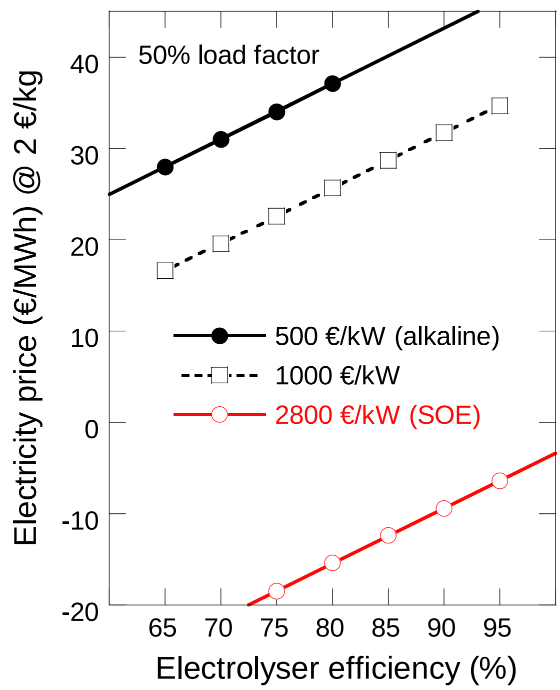

single stack
multi-stack
2000
1000
500
CAPEX (Euro/kW)
0,1
1
3-4 MW
10
100
Power input (MW)

Figure 7


4
3
2
1
0
H_2 cost (€/kg)
40%
30%
20%
10%
0%
CAPEX contribution (%)
1.41 €/kg
30 €/MWh
70% efficiency
50% load factor
200
400
600
800
1000
CAPEX (€/kW)

(a)


50% load factor
40
30
20
10
0
-10
-20
Electricity price (€/MWh) @ 2 €/kg
500 €/kW (alkaline)
1000 €/kW
2800 €/kW (SOE)
65
70
75
80
85
90
95
Electrolyser efficiency (%)

(b)

Figure 8

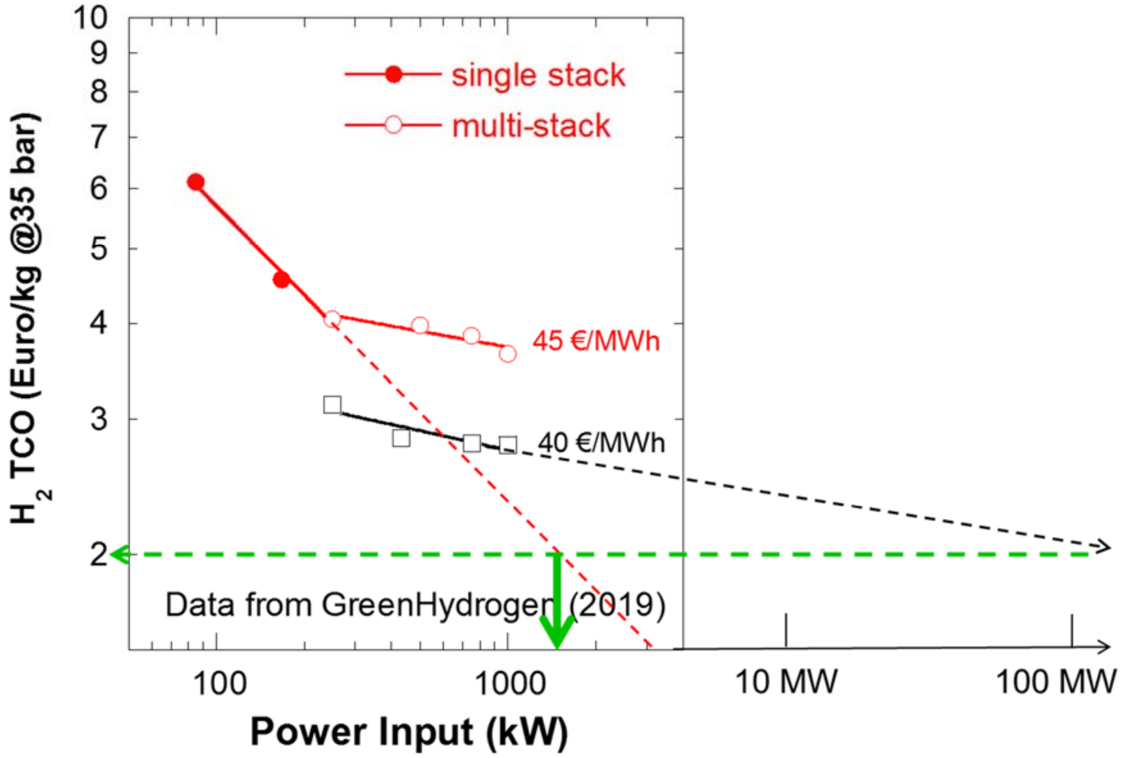

single stack
multi-stack
45 €/MWh
40 €/MWh
Data from GreenHydrogen (2019)
H_2 TCO (Euro/kg @35 bar)
Power Input (kW)
10
9
8
7
6
5
4
3
2
100
1000
10 MW
100 MW

Figure 9