# State-of-the art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings

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## Abstract

Within the framework of the Hydrogen Implementing Agreement (HIA) of the International Energy Agency (IEA), a new Task 38 was started early 2016, entitled "Power-to-Hydrogen and Hydrogen-to-X : System Analysis of techno-economic, legal and regulatory conditions". Within this framework, a specific task force was set-up for the compilation of state-of-the-art technical and economical data on large-scale water electrolyser systems, both based on PEM and alkaline technology. The objectives set forward have been twofold. Firstly, to offer policy makers and industry with comprehensive trends and guidelines for further electrolyser cost reduction (CAPEX, in Euro/kW) into the MW-scale. Secondly, to provide objective technological & economic arguments for converging towards a realistic electrolytic (and hence renewable) $H_2$ market price (in Euro/kg). This should help water electrolysis to become competitive with SMR technology for (local) $H_2$ production, and hence to start making $H_2$ a competitive fuel.

*Key words : electrolyser; CAPEX; $H_2$ price; alkaline; PEM*

## 1. Introduction

Hydrogen is currently considered to be one of the key enabling technologies allowing future large-scale and long-term storage of renewable electricity production through the now well-established Power-to-Gas concept [1,2]. Such chemical storage is based on the direct electrochemical splitting of water into hydrogen and oxygen ($2H_2O = 2H_2 + O_2$), using renewable electricity to power the water electrolyser system. A number of encouraging reports have recently been published on the technological and economical viability of the P2G concept, based on running or past large-scale demonstration projects, especially in Europa [3-5]. Independent of its recognised potential for storage purposes of electricity "upstream", there is still a vast range of opportunities to be explored "downstream" with respect to the use of such electrolytic (and hence renewable) $H_2$. Indeed, with the different rather ambitious roll-out scenarios for renewable electricity worldwide by 2020 and beyond, a vast amount of "green and clean" $H_2$ can be expected to become available on the market on a relatively short term [6,7]. For this very reason, water electrolysis is currently being considered as well to be the only viable route towards large-scale $CO_2$-free $H_2$ production. In this respect, it can be expected at some point in time to become competitive with steam methane reforming (SMR). The latter is still the main $H_2$ production technology used today, but intinsically suffers from significant $CO_2$ emissions ($CH_4 + 2H_2O = 4H_2 + CO_2$). In order for such a technological revolution to become feasible, the investment cost of industrial water electrolysers (CAPEX, in Euro/kW) first needs to become sufficiently low in order to guarantee the electrolytic $H_2$ production cost (in Euro/kg), to become competitive to SMR $H_2$.

One of the first relevant studies in this respect is the industry technical report by Stoll and van Linde, originally published in 2000 in Hydrocarbon Processing Magazine [8]. The authors provided a number of cost comparisons amongst the 3 main production technologies for providing $H_2$ in sufficiently large quantities (50 to 4000 $Nm^3/hr$) : water electrolysis, steam reforming and methanol cracking. In their estimations, they included both capital investments (CAPEX), but also primary energy requirements and operational expenses (OPEX), like depreciation and interest on capital investment, utilities and feedstock costs, manpower and maintenance. Although this report might have become a bit dated as of today, especially in terms of the projected investment cost for large-scale electrolysers, it does have the generic merit of pointing out the relative importance of operational costs. For instance, based on the numbers relevant for the year 2000, it appeared that in only one year, the difference in production costs of the different $H_2$ technologies can in some cases exceed the total investment cost. In our current paper, essentially because of the lack of reliable OPEX data on operating large-scale electrolysers, we will only concentrate on their CAPEX. Moreover, the projected production cost of electrolytic $H_2$ today is dominated by the cost of electricity [9], which can therefore still be considered to be the dominant OPEX parameter.

Rather recently, literature studies have been dedicated to summarize both historical trends [10] and short- and long-term projections [11] of investment cost (CAPEX) and performance data for two of the most common water electrolysers technologies being used today, namely alkaline and Proton Exchange Membrane (PEM) systems. However, such literature reports are often only able to generate a relative wide range of CAPEX data, depending on the exact performance (e.g. input power) of the system being considered. For instance, Figure 1 summarizes CAPEX data from the available literature reports reviewed in ref. [10]. It can be observed that the spread of the CAPEX estimations in the 1990s was in the range 870-2350 Euro/kW and 310-4750 Euro/kW for alkaline and PEM technology, respectively. At the same time, estimations for the future investment costs by the year 2030 are reported to be in the range 790-910 Euro/kW and 400-960 Euro/kW, respectively.

When it comes to the short- and long-term projections reported in the expert elicitation study on future cost and performance of water electrolysers of ref. [11], capital costs by 2020 are predicted to lie between 800 and 1300 Euro/kW for alkaline, and between 1000 and 1950 Euro/kW for PEM systems (all $50^{th}$ percentile estimates, at current R&D funding and without production scale-up). By 2030, these costs are estimated in the same report to be only slightly lower than in 2020, being in the range 700-1000 Euro/kW and 850-1650 Euro for alkaline and PEM, respectively.

Although such ranges can be useful to have a first qualitative idea of cost orders and projected improvements, much more concise CAPEX values for electrolyser systems are needed for a more quantitative modeling of specific business case studies, especially when it comes down to predicting a realistic electrolytic $H_2$ production cost. Therefore, there is still an emerging need for "real-life" cost data coming from the electrolyser manufacturers themselves, based on actual electrolyser systems already on the market today. For this very reason, within the Hydrogen Implementing Agreement (HIA) of the International Energy Agency (IEA), a new Task 38 was set-up early 2016, entitled "Power-to-Hydrogen and Hydrogen-to-X : System Analysis of the techno-economic, legal and regulatory conditions". In particular, a specific task force was asked to collect techno-economical data on commercially available water electrolyser systems directly from the major electrolyser manufactures involved in the Task 38 effort.

## 2. Results & Discussion

2.1. Comparing CAPEX for electrolytic and SMR $H_2$ production systems

As a starting point, Figure 2 (re-)considers published data [12,13] already available from the previous IEA/HIA Task 33 on Local hydrogen production for energy applications (2013-2015), this task being itself a continuation of both Task 23 on Small scale reformers for on-site hydrogen supply (2006-2011) and Annex 16 Subtask C on Small stationary reformers for distributed hydrogen production (2002-2005). Figure 2 shows the actual CAPEX evolution of PEM electrolyser systems, both as a function of $H_2$ production capacity (in $Nm^3$/hr, Fig. 2.a) and as a function of the equivalent electrolyser power input (in kW, Fig. 2.b). The latter graph was derived from the first one, based on data collected separately from the PEM electrolyser manufacturers on the specific electrical energy consumption (in kWh/$Nm^3$ $H_2$) in the range 7-700 kW. Note that the latter refers to the overall energy consumption of the hydrogen plant, including electrolyser, transformer and all auxiliaries (like rectifier losses). These additional data are shown in Fig. 2.c as well, the linear fit resulting in a conversion factor of $5.2 \pm 0.1$ kWh/$Nm^3$ $H_2$, in agreement with published state-of-the-art values for PEM electrolysers [1].

With respect to the first graph (Fig. 2.a), its great merit lies in the fact that it also includes data collected for both small and large scale SMR systems, which is the main $H_2$ production technology used today. Based on these data, it can already be recognised that in order for water electrolysis to become a viable technological choice for $H_2$ production, independent of any storage applications, a process intensification into the MW-range is absolutely mandatory. As a matter of fact, this is not only a necessary condition to become competitive in terms of CAPEX to SMR $H_2$ production technology, but also an inherent prerequisite to be able to couple to the MW-scale renewable electricity production capacities, typical for e.g. today's on-shore wind mills. Moreover, such a coupling to renewables is also an absolute complementary boundary condition for any water electrolyser technology to be able to produce truly green and clean $H_2$.

With respect to this need for a process intensification into the MW-scale, Fig. 2.c also includes additional data on the number of cells/stack needed to comply with a given electrical input. From the collected PEM data for PEM systems, it seems that 100 cells/stack represents some kind of intrinsic upper limit, corresponding to a 1 MW PEM system. Therefore, for Power-to-Gas applications in the multi-MW range, an electrolyser system based on multiple PEM stacks would be required. Such a shift from single to multi-stack systems has so far generally been neglected in the literature when it comes to future CAPEX projections, although it significantly affects the expected decreasing trendline of CAPEX vs. power input, as will be discussed below.

## 2.2. Comparing CAPEX for PEM and alkaline electrolysers

An attempt was then made to complement the previous compilation effort on PEM data from Task 33 with CAPEX data for alkaline water electrolysers. The latter are today still considered to be the most mature and durable technology, especially for large-scale and long-term renewable $H_2$ production [14]. Such a comparison of CAPEX data for both PEM and alkaline electrolysers is shown in Figure 3, again as a function of the overall energy consumption of the hydrogen plant. The latter was explicitly verified with the electrolyser manufacturers to include the following components :

• Transformer(s), rectifier(s), control panel with PLC ;

• Water demineralizer/deionizer ;

• Electrolyser stack(s) ;

• Gas analysers, separators and separating vessels ;

• Scrubber or gas purifier system & recirculating pump ;

• Dry piston compressor @ 15 bar (note that PEM systems are typically self-pressurising upto 20/50 bar).

For the alkaline data, an overall energy consumption of 4.8 kWh/Nm$^3$ was considered in Fig. 3, as specified directly by the manufacturer. Based on a $H_2$ Higher Heating Value (HVV) of 3.54 kWh/Nm$^3$, this corresponds to an efficiency of 80% for the electrolyser itself (4.4 kW/Nm$^3$, DC power), while the overall system would be running at 74% efficiency (at the specified discharge pressure level of 15 bar).

Figure 3 clearly demonstrates that, for single stack systems, alkaline electrolyzers are much more susceptible to CAPEX reduction upon scaling than PEM. 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 cricital CAPEX value should become within reach for 5 MW systems, requiring the use of multi-stack systems.

With respect to the latter, Figure 4 gives some perspectives for further CAPEX reduction upon the use of multi-stack systems, both for PEM (a) and alkaline (b) electrolysers. It can be seen that, contrary to single-stack systems, such a further reduction in CAPEX upon scaling is much more pronounced (on a relative scale) for a multi-stack PEM design than for alkaline. On the other hand, it should be noted that in the above CAPEX estimations, life cycle issues of electrolysers and electrodes have not been taken into account. Clearly, with the durability aspect of alkaline stacks currently still very much in favor in current state-of-the art alkaline vs. PEM technologies, including such lifetime (and hence OPEX) aspects in the calculation can be expected to somewhat flatten out the projected difference in CAPEX reduction between alkaline and PEM for multi-stack systems.

Moreover, in absolute terms, CAPEX values as low as 400 Euro/kW are currently projected by NEL for alkaline systems when scaling up to 100 MW. The latter is based on an intelligent engineering design of a 40 stack system. Moreover, the manufacturer also claims that it would be very feasable to deliver hydrogen at 100 bar for more or less the same CAPEX value as the hydrogen pressure of 15 bar considered as default for alkaline systems in Fig. 3 and 4. This would significantly improve their Power-to-Gas and energy storage business cases, where high pressures are indeed required.

2.3. Impact of CAPEX on electrolytic $H_2$ price settings

Apart from the intrinsic quantitative merit of the above alkaline and PEM electrolyser CAPEX data as such, a major additional asset is that they also allow for a better fine-tuning of projections and simulations regarding price settings for electrolytic (i.e. renewable) $H_2$. In this respect, some simulations from the literature have been reproduced from ref. [15] in Table I, representing a number of relevant production scenario's. This Table, dating back from 2015 and therefore overestimating current available CAPEX values, can still be taken as a useful relative starting point to identify the main additional operational parameters for setting a realistic $H_2$ price. These include, besides electrolyser CAPEX, also electrolyser efficiency, annual operating hours and (renewable) electricity cost. Despite the discrete character of the simulations, and the lack of elementary definitions and explanations in ref. [15], some general relative trends can still be distinguished from the at first sight rather arbitrary parameter combinations. First of all, considering scenario's 5 and 2, it appears that, at a fixed (overestimated) CAPEX of 800 Euro/kW and for a renewable electricity cost on the order of 60-70 Euro/MWh, an electrolytic $H_2$ production cost on the order of 4 Euro/kg is obtained. However, this still requires that the electrolyser can be kept operational for a sufficient amount of time (assumed 7000/8760 ≅ 80% on a yearly basis in scenario 5), which seems as of today not very feasible in view of the relatively weak penetration of $H_2$ for P2G storage purposes. When the electrolyser "up-time" further decreases to 20% (or 2000 hrs/year, cfr. scenario 2), the electrolytic $H_2$ production cost goes up to about 6 Euro/kg. This is clearly not sufficiently competitive, except maybe for $H_2$ mobility applications [16]. Moreover, if at about the same conditions as scenario 2 the electricity price would double to 140 Euro/MWh (cfr. scenario 3), the electrolytic $H_2$ production cost reaches totally inacceptable levels of more than 12 Euro/kg. It appears that in this range of relatively low operational time (< 2000 hrs/year), even a zero renewable electricity cost would still result in unacceptable $H_2$ prices > 10 Euro/kg (cfr. scenario 4).

From Table I, it is obvious that the expected annual operating hours clearly is a critical parameter to consider for electrolytic $H_2$ cost projections. Therefore, it makes much more sence to represent its effect on a continuous rather than a discrete scale. Recent examples from the literature are given in Figure 5 [17,18] and Figure 6 [19] for different CAPEX and renewable electricity prices, respectively. For these simulations, the electrolyser efficiency was kept constant at about 70-80%, which appears to be the limiting value that is being accepted for future electrolyser generations as well [11]. As to the effect of electrolyser CAPEX, both Fig. 5.a [17] and Fig. 5.b [18] quantitatively confirm one of the major conclusions from Table I, namely that for an insufficient electrolyser up-time (< 2000 hrs/year), the cost of electrolytic $H_2$ increases very steeply. Moreover, for an assumed renewable electricity price of 70 Euro/MWh, Fig. 5.a and Table I also appear to be quantitatively coherent in terms of $H_2$ price for a CAPEX of 2000 Euro/kW (scenario 1) and 1000 Euro/kW (scenario 2), respectively. In Fig. 5.b, reproduced from a more recent study [18], a further refinement of price simulations is provided for CAPEX values closer to today's technological reality. This particular study also takes into account more refined assumptions for the (average) electricity price, based on so-called power price duration curves. The latter have been included between brackets under the CAPEX values corresponding to the different curves. These results indicate that, already at current CAPEX values of 700 Euro/kW (considered to be realistic as of today for a 2 MW alkaline electrolyser, cfr. Fig. 3), an electrolytic $H_2$ production cost below 4 Euro/kg can be obtained once an electrolyser uptime > 20% can be guaranteed. Moreover, this cost further decreases to 3 Euro/kg upon a further decrease in CAPEX towards 400 Euro/kW.

Finally, results from a relatively recent IEA study [19], reproduced in Figure 6, allow to anticipate a further evolution in $H_2$ production cost as a function of the available renewable electricity price, assuming the most favorable (but still realistic) CAPEX value of 450 USD/kW. Note that in ref. [19] the default currency was USD, which still entails some uncertainty when comparing to the above CAPEX or $H_2$ prices expressed in Euro's. 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 USD 60 per MWh (cfr. red line in Figure 6). For this combination of onshore wind power and solar PV electricity, the associated load factor will hardly be above 4500 full load hours (FLH), which brings the average electrolytic $H_2$ production cost to 3-4 USD/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 (cfr. blue line in Figure 6), 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 which may take benefit from 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 USD/kg. However, since such small load factors generaly also entail a smaller scale electrolyser, its CAPEX will be significantly higher than the 450 USD/kW assumed in Fig. 11. In that case, as already shown in Table I (cfr. scenario 4), 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 USD/MWh (cfr. green line in Figure 6), would 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. Alternatively, as suggested in ref. [19], areas with abundant hydropower and/or geothermal resources would also be possible choices for siting large-scale electrolysers.

In conclusion, based on all of the above simulations and taking into account our own compiled CAPEX values of Fig. 3 and 4, it appears that an electrolytic $H_2$ production cost on the order of 3-4 Euro/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 $H_2$. As to the latter, it should be noted though that, for a fair comparison, OPEX costs should eventually be taken into account as well, as already pointed out in ref. [8] (e.g. not only electricity price for electrolytic $H_2$, and an additional $CO_2$ tax for SMR). Nonetheless, we believe that these preliminary projections should on the one hand stimulate a further, large-scale penetration of $H_2$ technologies for renewable energy storage purposes. On the other hand, it 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 materials and fuels industry.

## 3. Conclusions

At this stage of the IEA/HIA Task 38 effort, the following major conclusions have been reached :

- for alkaline systems, a CAPEX of 750 Euro/kW, considered to be critical for storage purposes, is already realistic today for a single stack, 2 MW system ;
- for PEM, such CAPEX values come within reach for 5 MW systems, requiring multi-stack systems ;
- CAPEX values on the order of 400 Euro/kW have been projected for alkaline systems, but this will require further upscaling upto 100 MW ;
- from the state-of-the-art CAPEX data collected, an electrolytic $H_2$ production cost on the order of 3 Euro/kg is very realistic by 2020, very much comparable to SMR $H_2$.

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**Table & Figure legends**

**Table I** Electrolytic $H_2$ production cost according to various scenario's (reproduced from ref. [15])

**Figure 1** Compilation of past and expected alkaline (top) and PEM (bottom) electrolysis plant cost in Euro/kW, based on available literature studies (reproduced from ref. [10]).

**Figure 2** CAPEX data for PEM electrolysers, collected from Task 33 [12,13], as a function of $H_2$ production capacity (a) and replotted as a function of equivalent power input (b). The conversion factor corresponds to a specific electrical energy consumption of 5.2 kWh/Nm$^3$ (c). The latter figure also represents the number of cells/stack needed to comply with a given input power in the range 7-700 kW.

**Figure 3** CAPEX data for both PEM and alkaline electrolysers, plotted as a function of power input. Data for alkaline systems are based on a single stack of 2.13 MW consisting of 230 cells, 2.6 m$^2$ in size. The change in slope for alkaline electrolysers corresponds to the use of multi-stack systems.

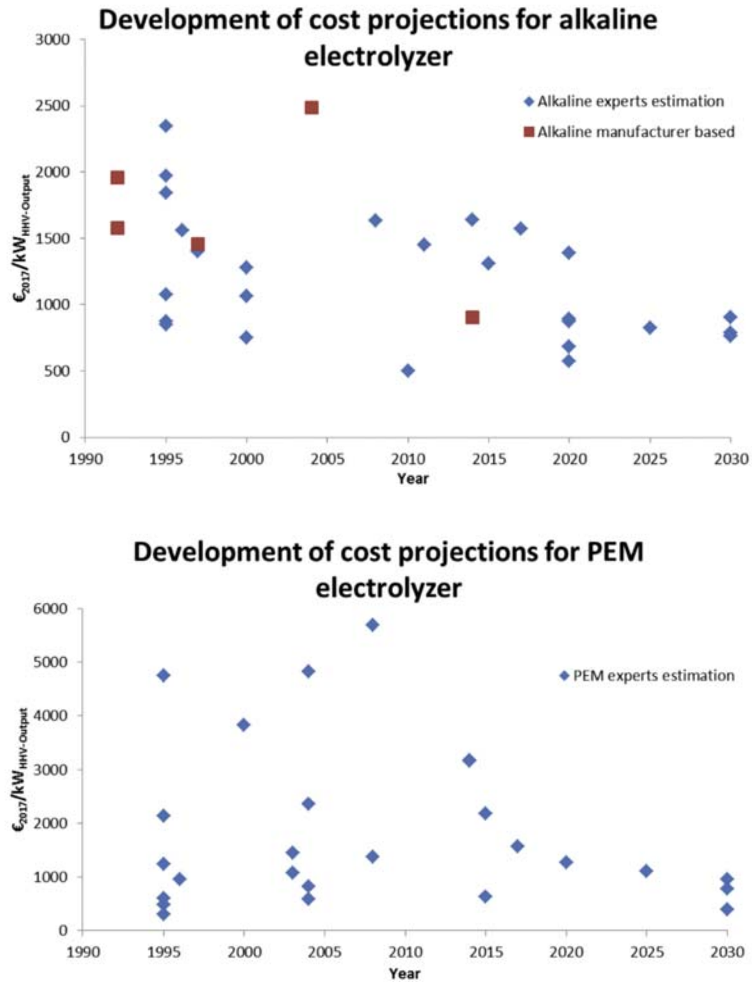
**Figure 4** Reduction in CAPEX upon use of multi-stack systems, both for PEM (a) and alkaline (b) electrolysers.

**Figure 5** Electrolytic $H_2$ production cost (in Euro/kg) as a function of electrolyser operational time for different electroyser CAPEX values ; figures (a) and (b) are reproduced from ref. [17] and ref. [18], respectively

**Figure 6** Electrolytic $H_2$ production cost (in USD/kg) as a function of electrolyser operational time (FLH = full load hours) for different renewable electricity costs (in USD/MWh), reproduced from ref. [19]. Further assumptions are an electrolyser CAPEX of 450 USD/kW, a lifetime 30 years, and a system efficiency of 70%. The cost of hydrogen from SMR (purple area) was estimated at 1-3 USD/kg, depending on regional variations in natural gas prices.

| Scenario | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| CAPEX electrolyser (Euro/kW) | 2000 | 800 | 800 | 800 | 800 |
| Efficiency electrolyser (%) | 60 | 80 | 80 | 80 | 80 |
| Annual operating hours (1 year = 8760 hours) | 7000 | 2000 | 1000 | 500 | 7000 |
| Renewable electricity cost (Euro/MWh) | 70 | 70 | 140 | 0 | 60 |
| Electrolytic $H_2$ production cost (Euro/kg) | 7.0 | 6.1 | 12.2 | 10.5 | 3.7 |

**Table I**



Development of cost projections for alkaline electrolyzer
Alkaline experts estimation
Alkaline manufacturer based
€2017/kWHHV-Output
Year
Development of cost projections for PEM electrolyzer
PEM experts estimation
€2017/kWHHV-Output
Year


**Figure 1**

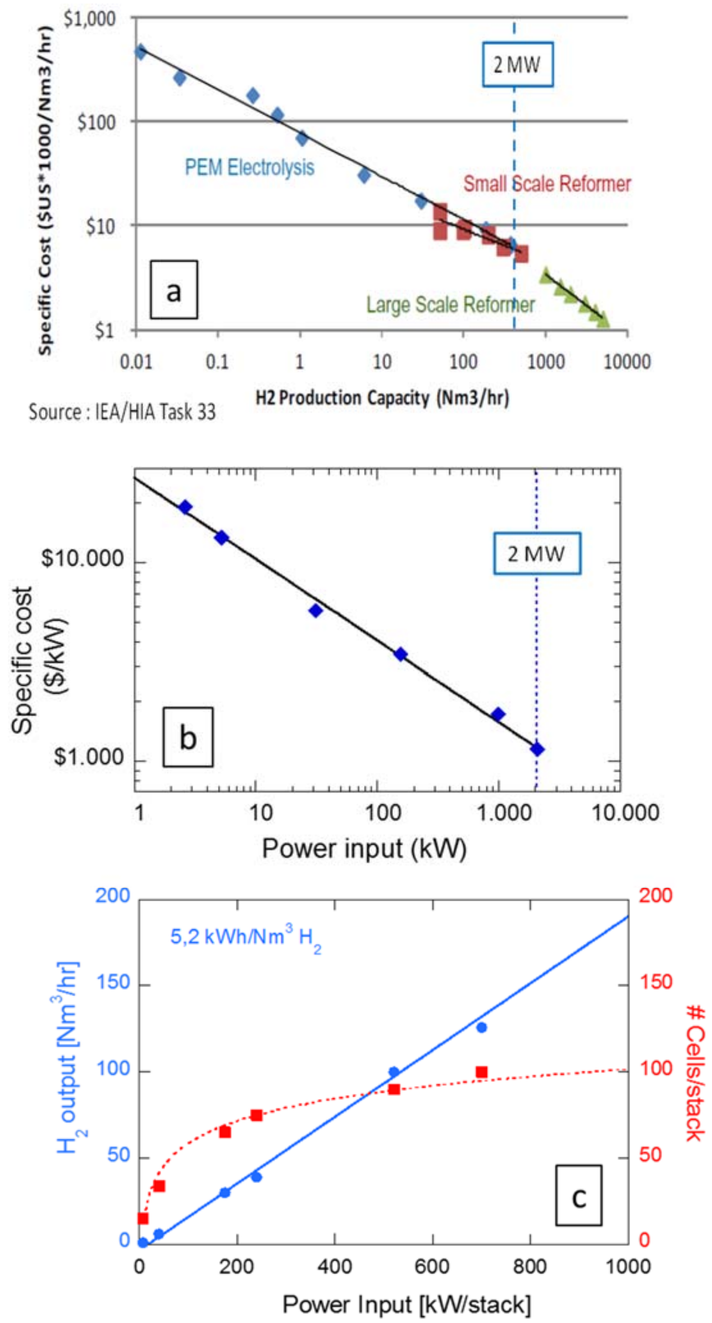
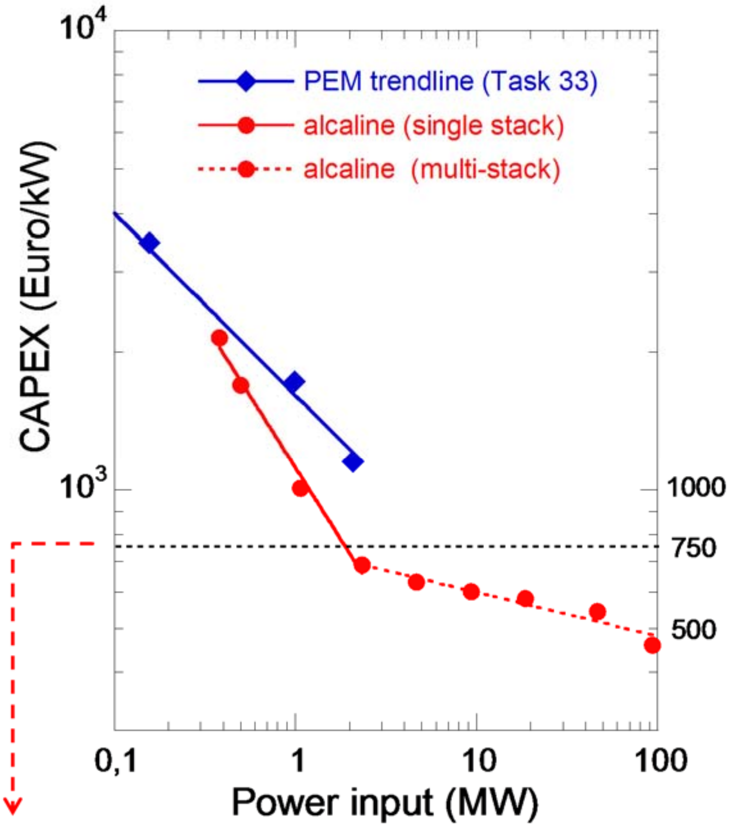

$1,000
$100
$10
$1
Specific Cost ($US*1000/Nm3/hr)
2 MW
PEM Electrolysis
Small Scale Reformer
Large Scale Reformer
a
0.01
0.1
1
10
100
1000
10000
H2 Production Capacity (Nm3/hr)
Source : IEA/HIA Task 33
$10.000
$1.000
Specific cost ($/kW)
2 MW
b
1
10
100
1.000
10.000
Power input (kW)
5,2 kWh/Nm3 H2
H2 output [Nm3/hr]
# Cells/stack
c
0
200
400
600
800
1000
Power Input [kW/stack]

**Figure 2**




Utility providers today have set the capital cost of storing renewable electricity at around 750 €/kW.

**Figure 3**

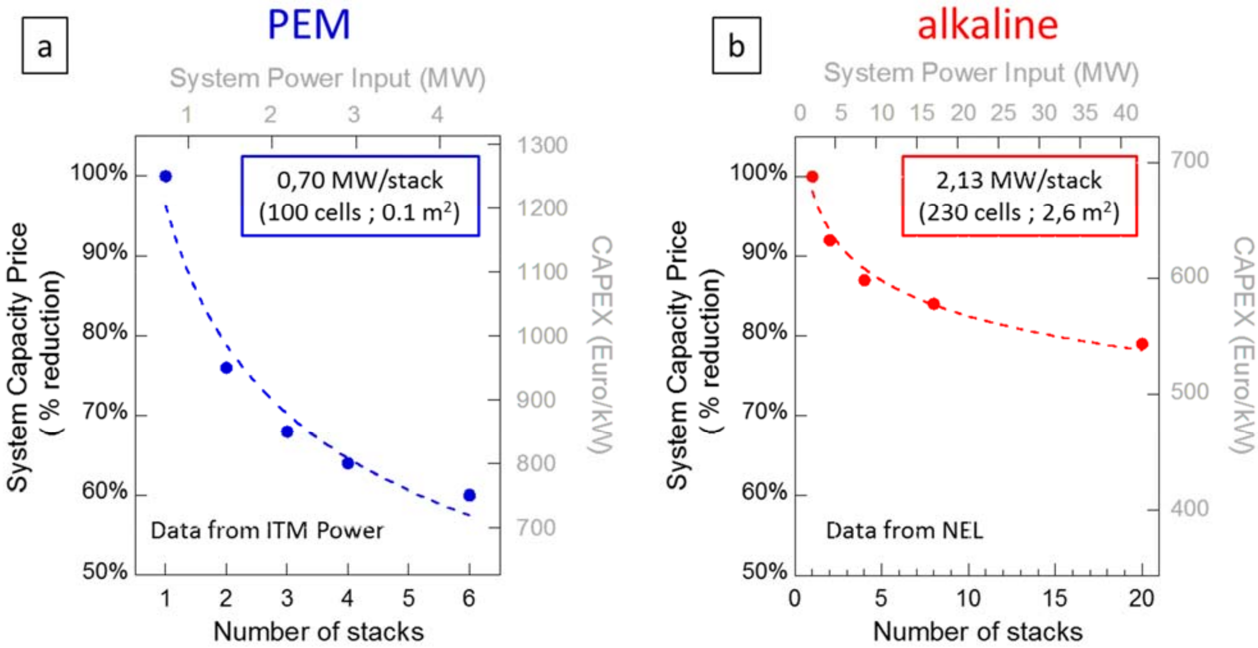

a
PEM
System Power Input (MW)
0,70 MW/stack
(100 cells ; 0.1 m²)
System Capacity Price
( % reduction)
CAPEX (Euro/kW)
Data from ITM Power
Number of stacks
b
alkaline
System Power Input (MW)
2,13 MW/stack
(230 cells ; 2,6 m²)
Data from NEL
Number of stacks

**Figure 4**

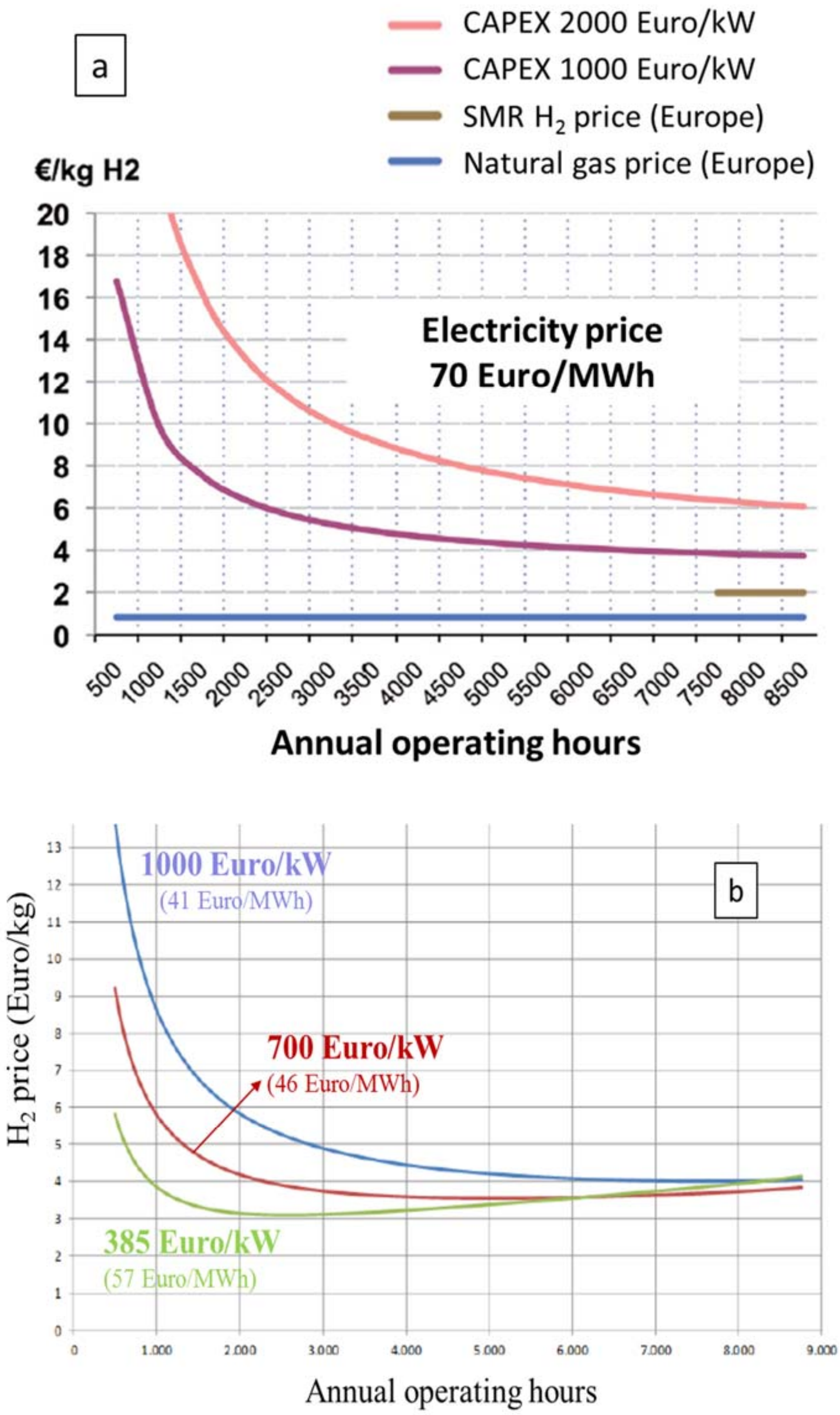
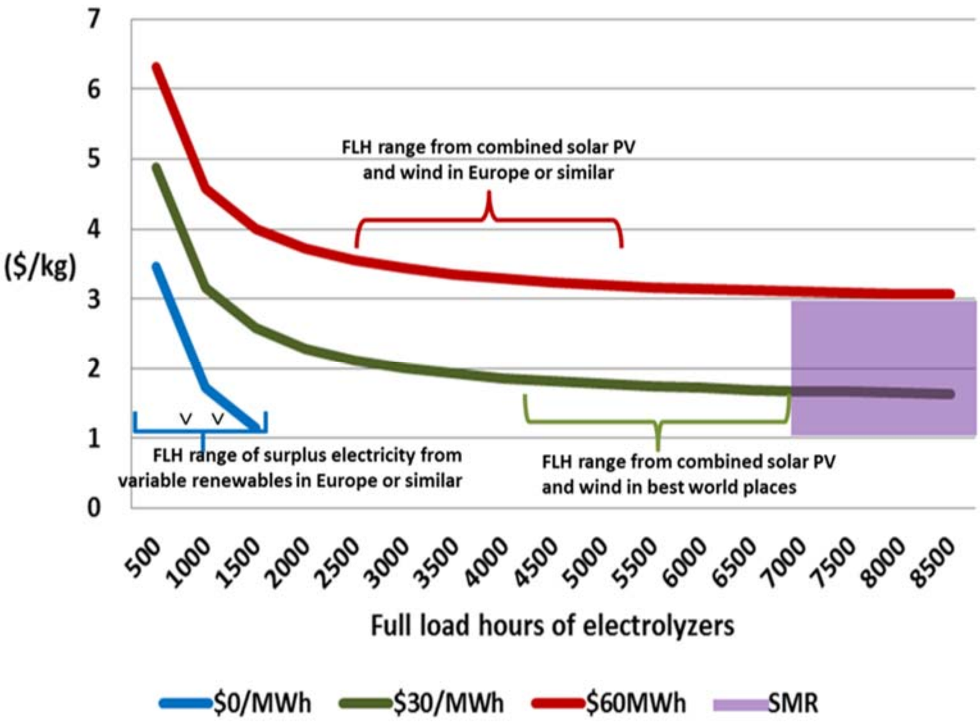

a
CAPEX 2000 Euro/kW
CAPEX 1000 Euro/kW
SMR H2 price (Europe)
Natural gas price (Europe)
€/kg H2
Electricity price
70 Euro/MWh
Annual operating hours
b
1000 Euro/kW
(41 Euro/MWh)
700 Euro/kW
(46 Euro/MWh)
385 Euro/kW
(57 Euro/MWh)
H2 price (Euro/kg)
Annual operating hours

**Figure 5**



7
6
5
4
3
2
1
0
($/kg)
FLH range from combined solar PV
and wind in Europe or similar
FLH range of surplus electricity from
variable renewables in Europe or similar
FLH range from combined solar PV
and wind in best world places
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
Full load hours of electrolyzers
$0/MWh
$30/MWh
$60MWh
SMR


**Figure 6**