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## **Technology data for high temperature solid oxide electrolyser cells, alkali and PEM electrolyzers**

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**TECHNOLOGY DATA FOR HIGH TEMPERATURE SOLID OXIDE ELECTROLYSER CELLS,  
ALKALI AND PEM ELECTROLYSERS**



**AALBORG UNIVERSITY**

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## 1. Introduction

One of the challenges in a future 100 % sustainable energy system is how to realise sustainable transport. A promising option to this end is production of synthetic fuels using electrolysis. Solid oxide electrolysis cells (SOEC) are still at the research and development stage whereas alkaline and PEM electrolyzers are today commercially available. However, with the current price and scale of these technologies they have not up to now found widespread use in the energy system. It is anticipated that the first commercial high temperature electrolysis plants will be available around 2020-2025. The motivation for creating this report is the need for fossil free fuels for the transport sector. Electrolyzers are one of the key components for the production of these fuels. Therefore, this report was developed to create an overview of recommendations regarding achievable efficiencies and projected costs for the three electrolysis technologies, a more clear understanding of the characteristics of these technologies and what data should be used in feasibility studies and energy systems scenarios for the future, where a larger role and deployment of electrolyzers is expected.

Two sets of data are presented for high temperature SOEC, one representing the theoretical maximum efficiency with ideal conditions and the other with 10% losses included, as an approximation for including balance of plant consumption and losses. The second set of data which includes losses is recommended where analysis is carried out for assessing the integration of electrolyzers in energy systems in combination with other power plants. Values on the efficiency of the cells are presented for both the lower and higher heating value (LHV, HHV). Data is presented for steam-, CO<sub>2</sub>-, and co-electrolysis.

The available data for alkali and PEM electrolyzers presented here is based on the literature and shows the current status and future predictions of the technology. The results for all technologies are listed in Tables 2 - 5. The main focus in this report is SOECs because these are expected to have the highest efficiency and lowest costs in the future, although they are still not commercially available.

It should be noted that future cost and performance estimates are encompassed with some uncertainty due to the long term predictions.

## 2. Definitions

Throughout this report some common terminology is used to assess these technologies.

**ELECTROLYSER EFFICIENCY** represents the total energy to fuel efficiency of the electrolysis system. In the case of high temperature steam and co-electrolysis represents the efficiency of the system excluding the availability of surplus heat for preheating and vaporising the water, i.e. all the heat needed to run the electrolysis process (to produce steam) is generated by input electricity.

**THE LOWER HEATING VALUE (LHV)** accounts for the energy content of a compound assuming that the latent heat of condensation of steam is not recovered. It is useful when comparing fuels where condensation of the combustion products is impractical. For instance, if the flue gas contains sulphur then condensation would cause corrosion in the system or if the heat at a temperature below 150°C cannot be put to use.

**THE HIGHER HEATING VALUE (HHV)** accounts for the energy content of a compound (the energy released on combusting the compound) plus the latent heat of condensing steam produced in the combustion process. It is used in cases where condensation of the reaction products is practical.

Difference between HHV and LHV depends on the chemical composition of the fuel and in the case of hydrogen, the difference is more significant than with other types of fuels due to the steam condensation. LHV is chosen here as it is customarily used in energy system analyses and thus it is recommended because all the technologies in the energy sector are typically compared using the LHV.

### 3. High temperature steam electrolysis - SOEC

#### 3.1. Theoretical maximum and potential future operation

The advantage of the electrolyzers is the possibility to choose the operation efficiency based on their polarization curves. The efficiency of electrolyzers is inversely proportional to the cell voltage while the current density is inversely proportional to their capital costs [1]. Therefore the SOECs have an advantage over alkaline and PEM because they can achieve a higher efficiency and lower capital costs in a wider range of current densities and cell voltages. However to reach the thermoneutral operation for water electrolysis, the cell voltage needs to be above 1.3 V.

An energy balance for SOEC operating under ideal theoretical conditions based on the production of one mole of hydrogen is illustrated in Fig 1 where one mole of hydrogen represents in terms of lower heating value 242 kJ [2]. The input energy is used to heat and evaporate water (44 kJ/mole) to “drive” the electrochemical conversion in the cells (242 kJ/mole). Part of the input energy, specifically the energy needed to heat and vaporize the water could be supplied as heat from an external source.

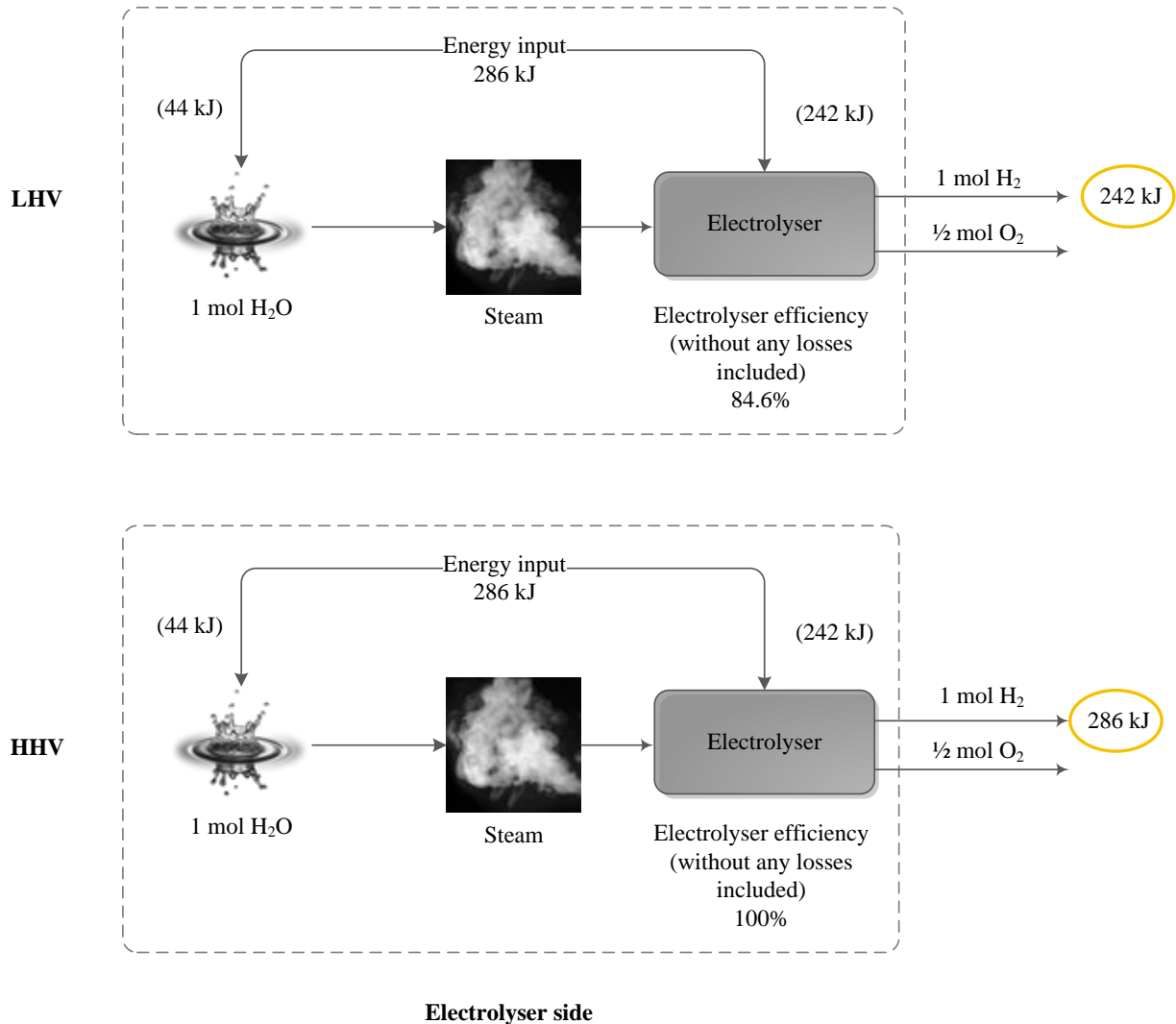
Assuming an operating pressure of 40 bars, the inlet heat should be delivered at ~250 °C. Assuming that there is no waste heat available in the energy system for heating and vaporising the water and assuming no losses in the electrolysis system (ideal operation), the maximum theoretical energy efficiency of water electrolysis based on the LHV is 84.6% [3] and 100% based on the HHV (see eq.1 and 2). To achieve these efficiencies every kJ of input energy must be converted into hydrogen. Ideal operating conditions refer to operation at the thermo neutral voltage (i.e. no excess heat is produced).

$$\eta_{LHV} = \frac{\text{Energy output}}{\text{Energy input}} = \frac{242}{242+44} = 84.6\% \quad (\text{eq.1})$$

$$\eta_{HHV} = \frac{\text{Energy output}}{\text{Energy input}} = \frac{286}{242+44} = 100\% \quad (\text{eq.2})$$

High temperature electrolyses cannot be expected to operate under ideal operating conditions. For energy system analyses it is recommended to include a certain percentage of loss to account for losses in the blowers, dryers, inverters and heat losses (see Fig 2). The magnitude of these losses will depend on the maturity of auxiliary components and on the size of the system. Here, it is suggested to include ~10% losses to the electrolyser system. This is rather optimistic for small scale plants but can be considered a realistic estimate for future large scale mature systems (> 250 KW). In such systems inverter losses could be ~3-5%, surface heat losses 1-3% and losses

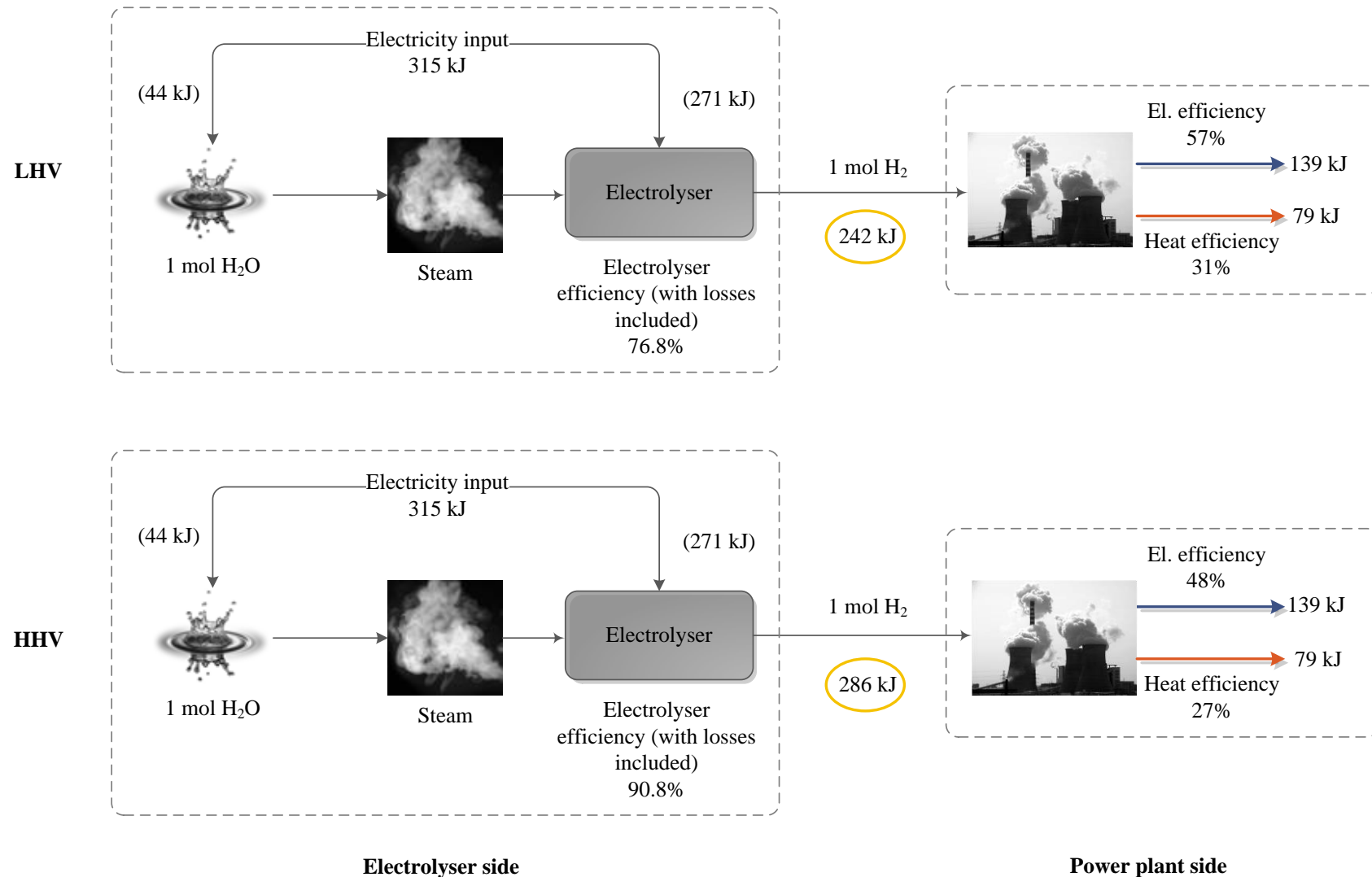
due to auxiliary heating to minimize heat exchange costs could be ~2%. In the future with optimised module designs, the total losses may be lower than 10%. A part of the heat loss may be recovered and used e.g. for district heating. As no large scale SOEC plants exist today, there is no empirical data on the amount of excess available for district heating purposes. Here, it is suggested to count half of the “loss” as retrievable for district heating purposes, i.e. 5%.



**Fig 1. Illustration of the energy flows in ideal steam electrolysis (without auxiliary losses) representing the energy flow of the produced hydrogen with its lower heating value or higher heating value**

If we consider the overall energy input and output of the system it makes no difference whether you present energy flows in the energy system in terms of their LHV or HHV. However, the relative efficiencies of the various parts of the system appear differently as illustrated in Fig 2. When based on the LHV the thermal plants appear “effective” and electrolysis “ineffective” and vice versa if based on the HHV. It is important to recognise that normally, LHV is used when performing energy system analysis.



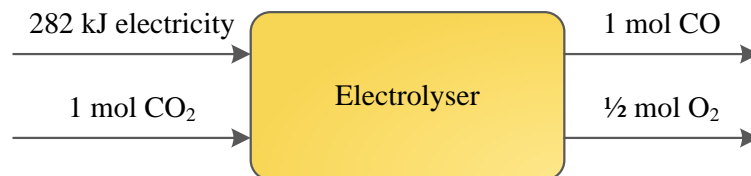


**Fig 2. Illustration of energy flows in a simple system including steam electrolysis and down-stream turbine cycle (including auxiliary losses) representing the energy flow of the produced hydrogen with its lower heating value or higher heating value (efficiencies on the power plant side represent a large-scale combined cycle gas turbine with steam extraction according to [4])**

## 4. CO<sub>2</sub> and co-electrolysis

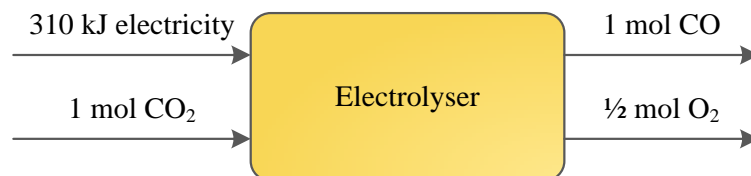
### 4.1. Theoretical maximum and potential future operation

The ideal theoretical condition for CO<sub>2</sub> electrolysis is illustrated in Fig 3. The electricity to fuel efficiency is 100 % in the ideal operation conditions because there is not condensation of CO<sub>2</sub> and CO.



**Fig 3. Theoretical optimal operation conditions of high temperature CO<sub>2</sub> electrolysis**

Energy flow illustrating high temperature CO<sub>2</sub> electrolysis taking in the account 10% of the auxiliary losses is presented in Fig 4. Here, losses are assumed to be the same as in the case of steam electrolysis



**Fig 4. Potential future operation conditions of high temperature CO<sub>2</sub> electrolysis with included 10% of auxiliary losses**

The H<sub>2</sub>O and CO<sub>2</sub> electrolyses can be combined in a process called co-electrolysis. The product of co-electrolysis is synthetic gas (mixture of carbon monoxide and hydrogen) which can be catalyzed into various types of synthetic fuel. The co-electrolysis process is rather complicated compared to separate steam and CO<sub>2</sub> electrolysis because it involves three main reactions that occur simultaneously, the electrolysis of CO<sub>2</sub> to CO, the electrolysis of water and the reverse water gas shift reaction (RWGS). Even though the main reactions of the process are known, there are uncertainties in relation to how this is taking place [5].

The electricity and heat consumption needed, can be calculated combining linearly the efficiencies and energy streams presented for steam and CO<sub>2</sub> electrolysis. Co-electrolysis has been documented at DTU Energy Conversion at different range of temperatures up to 850 °C.

CO<sub>2</sub> might need some purification treatment before electrolysis. This can be done via absorption of impurities using specific materials that can be regenerated. Hence, the related expenses are expected to be small.

## 5. Regulation abilities of SOEC

The cells have fast regulation abilities (from 0% to 100% power in few seconds) if the cell temperature is kept at the operating temperature. If the cell is operated below the thermo neutral



voltage, a heat supply is needed to keep the cell temperature at the operation temperature. The heat-supply device can be fairly simple and is not considered a significant cost component.

If the SOEC is cold in idle state, the start-up time could be several hours depending on the design and fabrication of cell and stack. However different operation and insulation strategies can be applied in the SOEC-plant in order to keep the plant close to operation temperature also when idle.

## 6. The costs of future high temperature electrolysers - SOEC

The cost calculations for technologies that are still at the R&D level are very uncertain and highly dependent on the technological development. A development of the SOEC is reliant on financial supports for R&D and supports in the initial phase of commercialisation.

The costs calculated in this report are based on the assumption that the costs goal for SOFC stack modules which are factory assembled and at atmospheric pressure are achieved [6]. The prices are based on the stack module costs of 175 \$/kW (for annual production volume of 250 MW) in 2007 dollars converted with an inflation factor to 2012 dollars. These are recalculated for SOEC by using scaling factor. This factor is the product of the power ratio between typical SOFC and SOEC operation (the power density in the SOFC is only 0.25 times that expected in the SOEC) and a scaling factor reflects an expected cost reduction with increasing production. The scaling factor of SOEC costs is assumed to scale with production volume as SOFC (defined from Figure 4-7 in [7]), and projected production volumes are assumed to be 10 MW in 2020, 100 MW in 2030 and >1000 MW towards 2050. The BoP costs are added-on the SOEC module costs as a percentage of the module costs (75% in 2020 and 50% in 2030 and 2050). Transaction costs such as development and sales were also added (50% in 2020, 45% in 2030 and 40% in 2050). The calculated costs are in this case connected to the highest achievable efficiency of the technology. However, the highest achievable efficiency is not necessarily the optimum efficiency from the economy point of view.

The calculated costs of SOEC are 0.86 M€/MW (MW electricity in) for 2020, 0.28 M€/MW for 2030 and 0.21 M€/MW in 2050, with an assumed lifetime of 10-20 years. However there are extra costs associated when connecting electrolysers to the grid. The electrolysers use significant amounts of electricity therefore these expenses need to be included. Large electric boilers between 8-15 MW have additional grid costs between €530,000 and €800,000 based on initial Danish experiences. Smaller electric boilers are considered to be too expensive due to their high cost of grid connection that is between €260,000 and €1,000,000 depending on the location and local connection possibilities. Based on that data, the grid connection costs for electrolysis units are estimated to be 66,000 €/MW the same as for electric boilers. These costs refer to a local grid reinforcement to connect electrolysers to the transmission system. These costs do not account for the reinforcement of the distribution grid. The lifetime of the grid connection is assumed to be 30 years for the grid connection. The total investment costs of grid connected electrolysers are thus estimated to be 0.93 M€/MW in 2020, 0.35 M€/MW in 2030 and 0.28 M€/MW in 2050.

The fixed operation and maintenance (O&M) costs are assumed to be approximately 3% of the initial investment annually which in 2020 is 25,800 €/MW/year<sup>1</sup>, in 2030 equals 8,400 €/MW/year and in the case of 2050 6,200 €/MW/year. The replacement of stack modules in the lifetime of

<sup>1</sup> Unit used according to [4] as a term for the annual fixed operation and maintenance costs

these electrolyzers is included in the estimated fixed O&M costs. The one third of the investment is the electrolyzer cells, which has a projected lifetime of 10 years. With such assumptions the total annual O&M costs using a socio-economic interest rate of 3% are 0.101 M€/MW in 2020, 0.033 M€/MW in 2030 and 0.025 M€/MW in 2050.

These cost estimates are based on future large-scale production of electrolyzers for 2020, 2030 and 2050. For comparison according to [8] the costs for small scale SOEC is 0.71 M€/MW and for the large scale 0.28 M€/MW.

## 7. System integration with other technologies

System integration of SOEC can enable maximizing the synergies of different technologies. Electrolyzers can achieve a theoretical maximum of 100% HHV efficiency which corresponds to 84.6% LHV. When operating at thermo neutral voltage a 100% HHV efficiency is one that has electricity as only energy input. If heat from other technologies is available (e.g. thermal energy), part of this electricity input can be replaced: this means that the electric energy required for water evaporation can be replaced with excess heat from other processes. This however does not increase the efficiency of the electrolysis process, but reduces the electricity consumption. An example of the synergy between the potentially heat consuming electrolysis process and an exothermic processes, specifically biomass gasification, is outlined in GreenSynFuel report [9].

## 8. Current and future alkaline electrolyzers

Alkaline electrolysis has been available technology for more than 100 year primarily in the chemical and metallurgic industry and for the production of fertilizer in the form of ammonia ( $\text{NH}_3$ ). Therefore it is the most established electrolysis technology commercially available. A drawback of alkaline electrolysis is the corrosive character of its electrolyte. The purity level of hydrogen can reach 99.9 vol.%. However this requires high purity of water fed to electrolyser.

Alkaline electrolyzers usually operate in temperature ranges between 50 and 80°C and current densities of 200 to 400 mA/cm<sup>2</sup>. Commercially available alkaline electrolysis systems have a production capacity in the range between 1-760 Nm<sup>3</sup>/h which corresponds to an electrical input of 5 kW to 3.4 MW per module [10]. For a bigger range in plants, alkaline electrolyzers can be connected in parallel. The largest existing alkaline electrolysis plants are: KIMA fertilizer plant in Aswan, Egypt with a capacity of 160 MW and 132 modules, and a 7 module 22 MW plant in Peru (pressurized operation) [10].

The data listed in Table 2 is based on state-of-the art atmospheric pressure alkaline electrolyzers and in Table 3 the future possible development of the technology. Some operate at atmospheric pressure, and some with pressurised operation between 4 and 30 bar. New pressurized electrolyzers have exceptional dynamic range and operating flexibility, with the response time in the range of milliseconds, allowing production down to 10% of the capacity. With a high outlet pressure of 15 bar, electrolyzers can have a response time <1second with automatic continuous stand-by operation [11]. The advantage of operating at high pressure is that gas output can be directly stored as compressed gas. The operating temperature for atmospheric pressure alkaline electrolyzers goes up to 90°C, but there are experimental concepts that can reach 400°C [12].

The efficiency of alkaline electrolyzers like SOEC and PEM will depend on the chosen point of operation. Alkaline electrolysis plants are today typically operated to maximize economic competitiveness of the process in which the produced hydrogen is used and not to maximize energy efficiency. To increase energy efficiency voltage has to be lowered close to thermoneutral point which would increase costs significantly. The costs can vary from 0.74 up to 3.7 M€/MW depending on the production capacity and operating pressure with a reported efficiency range of around 38-70% (LHV) [12].

The cost of alkaline electrolyzers is dependent on the size of the plant. The state of the art costs are adapted from [10] representing data for plants 3.4 MWe. The costs are estimated to be at least 1.07 M€/MW with fixed O&M costs of 4% of the initial investment including insurance. The lifetime is 20–30 years with assumed major services every 6 years. The costs for future alkaline electrolyzers are also taken from [10] where the predictions are rather conservative compared to the Roadmap for alkaline electrolysis [13]. The Danish Partnership for Hydrogen and Fuel Cells have predicted development of alkaline electrolysis from 2011 to 2020 in their roadmap, predicting 500 times bigger units in 2020 compared to 2011. The unit size varies from 8 Nm<sup>3</sup>/h in 2011 to 4000 Nm<sup>3</sup>/h in 2020, which together with reduction in costs results in low system cost of just 0.36 M€/MW in 2020 which is competitive with SOEC costs. The costs used in this report [10] do not predict development of higher than 1500 Nm<sup>3</sup>/h before 2020 which is approximately 2.5 times lower than the one predicted in [13].

There are several companies manufacturing alkaline electrolyzers. An overview of manufacturers given in Table 1 (adapted from [12]).

**Table 1. Main electrolyser manufacturers and performance data. Adapted from [12]**

| Manufacturer                     | Configuration of technology | Rated production (Nm <sup>3</sup> /h) | Efficiency % (LHV) | Location    |
|----------------------------------|-----------------------------|---------------------------------------|--------------------|-------------|
| AccaGen                          | alkaline (bipolar)          | 1-100                                 | 44.7-61.5          | Switzerland |
| Avalence                         | alkaline (monopolar)        | 0.4-4.6                               | 55.2-59.9          | USA         |
| Claiud                           | alkaline (bipolar)          | 0.5-30                                | -                  | Italy       |
| ELT                              | alkaline (bipolar)          | 3-330                                 | 65.1-69.6          | Germany     |
| ELT                              | alkaline (bipolar)          | 100-760                               | 64.4-69.6          | Germany     |
| Erredue                          | alkaline (bipolar)          | 0.6-21.3                              | 49.9-59.1          | Italy       |
| NEL Hydrogen <sup>2</sup>        | alkaline (bipolar)          | 10-500                                | 59.6               | Norway      |
| Hydrogenics                      | alkaline (bipolar)          | 10-60                                 | 55.4-57.6          | Canada      |
| H2 Logic                         | alkaline (bipolar)          | 0.66-42.62                            | 54.9-59.9          | Denmark     |
| Idroenergy                       | alkaline (bipolar)          | 0.4-80                                | 39.9-63.6          | Italy       |
| Industrie Haute Technologie      | alkaline (bipolar)          | 110-760                               | 64.4-69.6          | Switzerland |
| Linde                            | alkaline (bipolar)          | 5-250                                 |                    | Germany     |
| PIEL, division of ILT Technology | alkaline (bipolar)          | 0.4-16                                | 42.8-59.9          | Italy       |
| Sagim                            | alkaline (monopolar)        | 1-5                                   | 59.9               | France      |
| Teledyne Energy Systems          | alkaline (bipolar)          | 2.8-56                                | -                  | USA         |

<sup>2</sup> NEL Hydrogen has announced its bankruptcy in June 2013.

## 9. Current and future PEM electrolyzers

The present commercially available PEM electrolyzers are well-suited only for decentralized hydrogen production due to their limited capacities. Commercially available PEM electrolyzers produce high purity hydrogen, typically above 99.99 vol.% with some cases even above 99.999 vol.% [14]. The solid electrolyte used in PEM allows simple compact design and a high operation pressure [15].

The operation temperature is between 50-80°C which enables a fast start-up. An increase in the temperature of operation is not expected due to the character of the membrane; however Danish energy agency [4] expects temperature range up to 200°C based on other proton conducting materials. Some models reach high pressures of 85 bar [16], with one exception reaching up to 350 bar [17]. Pressures above 100 bar require thick membranes and special membrane support structures enabling the high differential pressures [18].

The range of efficiencies reported in the literature for PEM electrolysis vary, 48-65% [12], 55-70% [19] and 68-72% [4] (all based on hydrogen LHV). According to [20] the biggest demonstrated stack size is 45 kW. Currently available PEMEL systems have a hydrogen production rate that varies from 0.06 to 30 Nm<sup>3</sup>/h, with a maximum electrical power up to 150 kW per module according to [10]. This is very low in comparison to alkaline production rates that have already reached 500 Nm<sup>3</sup>/h.

With regard to the lifetime, the membrane represents the critical component of PEM system [21]. Even though the lifetime of PEM electrolysis systems were significantly improved in the last 10 years, it is still limited due to the nature of solid polymer electrolyte membrane, and it is below 20,000 h [10]. PEM electrolyzers are less mature, produced in smaller quantities, and therefore more expensive than alkali electrolyzers. It is expected that the lifetime will be prolonged up to 60,000h in the long term predictions [10] which is twice as the prediction of [4]. Even though there is no clear relation between operating conditions and degradation processes of the stack, in some cases operating conditions can lead to membrane perforation [22].

The fast dynamic response is seen as a major advantage of the PEM electrolyzer. At the cellular level, transients are followed in the electrical power almost instantly. PEM electrolyzers have wide operational range from 5-100%, which enables dynamic operation with fluctuating intermittent sources, and a quick start-up compared to alkaline electrolyzers [23].

According to [10], there are ten existing manufactures that produce PEM electrolyzers. However, alkaline electrolyzers are still dominating the market due to the limited lifetime and low capacities of PEM electrolyzers.

## 10. Technology data for electrolyzers

**Table 2. State of the art characteristics of alkaline and PEM electrolysis [10]**

|   |                       | Alkaline electrolyzers                           | PEM electrolyzers                                |
|---|-----------------------|--|--|
| Production of                                     |                       | Hydrogen   | Hydrogen   |
| <b>Available from</b>                             |                       | State of the art                                 | State of the art                                 |
| <b>Capacity for one unit</b>                      | <i>MW</i>             | 3.4 <sup>3,4</sup>                               | 0.15 <sup>5</sup>                                |
| <b>Output</b>                                     | <i>Bar</i>            | <30  | <30  |
| <b>Operating temp.</b>                            | <i>°C</i>             | 60-80  | 50-80  |
| <b>System efficiency</b>                          | <i>% (LHV)</i>        | 67   | 54   |
| <b>Electricity to heat efficiency<sup>6</sup></b> | <i>% (LHV)</i>        | 5  | 5  |
| <b>Other input</b>                                |                       | Ambient air, water                               | Ambient air, water -                             |
| <b>Start-up time</b>                              | <i>Hours</i>          | Depends on the system<br>Can have rapid response | Depends on the system<br>Can have rapid response |
| <b>Regulation ability</b>                         |                       |  |  |
| <b>Fast reserves</b>                              | <i>MW per 15 min.</i> | Full capacity                                    | Full capacity                                    |
| <b>Regulation speed</b>                           | <i>% per second</i>   | 0.001  | 0.001  |
| <b>Minimum load</b>                               | <i>% of full load</i> | 10-20  | 0-10   |
| <b>Economy (2012-prices)</b>                      |                       |  |  |
| <b>Investment costs<sup>7</sup></b>               | <i>M€/MW</i>          | 1.07-  | 2.55   |
| <b>Fixed O&amp;M costs<sup>8</sup></b>            | <i>% of inv./year</i> | 4  | 4  |
| <b>Variable O&amp;M cost<sup>9</sup></b>          | <i>€/MWh</i>          | -  | -  |
| <b>Lifetime</b>                                   | <i>Years</i>          | 20-30  | 10   |

<sup>3</sup> The largest alkaline electrolyser plant in operation is 160 MW, with average module size of 1.2 MW [10]

<sup>4</sup> Represents a large alkaline electrolyser with pressure of 30 bar, capacity of 500 Nm<sup>3</sup>/h. The electrolyser is turned off only for maintenance purposes and therefore has a load factor of 98%.

<sup>5</sup> Electrolyser capacity of 30 Nm<sup>3</sup>/h, pressure (25 bar). Electrolyser is used for the on-site generation for a small hydrogen fuelling station with a capacity utilization of 75%.

<sup>6</sup> There are no empirical data on available waste heat that can be utilised for district heating purposes

<sup>7</sup> Including costs associated with grid connection (66,000 €/MW for large plants).

<sup>8</sup> Including insurance for alkaline and PEM electrolyzers

<sup>9</sup> No variable costs assumed other than electricity cost which can be identified elsewhere.

Table 3. Potential operation characteristics of alkaline and PEM electrolyzers

|   |                       | Alkaline electrolyzers <sup>10</sup> | PEM electrolyzers <sup>7</sup>                |
|---|-----------------------|--------------------------------------|---|
| Production of                               |                       | Hydrogen                             | Hydrogen                                      |
| Available from                              |                       | 2020-2030                            | 2020-2030                                     |
| Capacity for one unit                       | <i>MW</i>             | >3.4                                 | 1   |
| Output                                      | <i>Bar</i>            | 4-30                                 | <100  |
| Operating temp.                             | <i>°C</i>             | 60-90                                | 60-80 <sup>11</sup> (100-200) <sup>12</sup>   |
| Electricity to fuel efficiency              | <i>% (LHV)</i>        | 50-70                                | 68-72   |
| Electricity to heat efficiency <sup>5</sup> | <i>% (LHV)</i>        | 5                                    | 5   |
| Other input                                 |                       | Ambient air, water                   | Ambient air, water -<br>Depends on the system |
| Start-up time                               | <i>Hours</i>          | 0.01                                 | Can have rapid response                       |
| <b>Regulation ability</b>                   |                       |                                      |   |
| Fast reserves                               | <i>MW per 15 min.</i> | Full capacity (in 10 min)            | Full capacity                                 |
| Regulation speed                            | <i>% per second</i>   | 0.004                                | 0.001   |
| Minimum load                                | <i>% of full load</i> | 10-20                                | 0-5   |
| <b>Economy (2012-prices)</b>                |                       |                                      |   |
| Investment costs <sup>13</sup>              | <i>M€/MW</i>          | 0.87 <sup>14</sup>                   | 1.27 <sup>15</sup>                            |
| Fixed O&M costs <sup>16</sup>               | <i>% of inv./year</i> | 4                                    | 4   |
| Variable O&M cost <sup>17</sup>             | <i>€/MWh</i>          | -                                    | -   |
| Lifetime stack                              | <i>h</i>              | <90,000                              | <60,000                                       |
| Lifetime system                             | <i>Years</i>          | 25-30                                | 30  |

<sup>10</sup> The alkaline and PEM electrolyser data are modified from [4], and [10].

<sup>11</sup> According to [10] – depending on the operating pressure.

<sup>12</sup> According to [4] – depending on operating pressure.

<sup>13</sup> Including costs associated with grid connection (66,000 €/MW for large plants).

<sup>14</sup> Cost for large alkaline pressure electrolyzer with a capacity of 1500 Nm<sup>3</sup>/h.

<sup>15</sup> Cost for PEM electrolyser with a capacity of 250 Nm<sup>3</sup>/h

<sup>16</sup> Including insurance for alkaline and PEM electrolyzers

<sup>17</sup> No variable costs assumed other than electricity cost which can be identified elsewhere.

Table 4. Potential operation characteristics of high temperature electrolysis

| High temperature electrolyzers (SOEC)        |                |                     |                      |                                |
|--|----------------|---------------------|----------------------|--------------------------------|
| Production of                                |                | Hydrogen            | CO                   | Syngas                         |
| Available from                               | years          | 2020-2050           | 2020-2050            | 2020-2050                      |
| Capacity for one unit                        | MW             | 0.5-50              | 0.5-50               | 0.5-50                         |
| Output                                       | Bar            | 40                  | 40                   | 40                             |
| Operating temp.                              | °C             | 800                 | 800                  | 800                            |
| Electricity to fuel efficiency <sup>18</sup> | % (LHV)        | 76.8                | 90                   | 81                             |
| Electricity to heat efficiency <sup>5</sup>  | % (LHV)        | 5                   | 5                    | -                              |
| Other input                                  |                | Steam <sup>19</sup> | Pure CO <sub>2</sub> | Steam and pure CO <sub>2</sub> |
| Start-up time <sup>20</sup>                  | Hours          | 0.2                 | 0.2                  | 0.2                            |
| <b>Regulation ability</b>                    |                |                     |                      |                                |
| Fast reserves                                | MW per 15 min. | Full capacity       | Full capacity        | Full capacity                  |
| Regulation speed                             | % per second   | 3 down / 0.1 up     | 3 down / 0.1 up      | 3 down / 0.1 up                |
| Minimum load                                 | % of full load | 3                   | 3                    | 3                              |

Table 5. SOEC cost data for 2020, 2030 and 2050

| SOEC economy (2012 - prices)   |                |         |         |         |
|--------------------------------|----------------|---------|---------|---------|
|                                |                | 2020    | 2030    | 2050    |
| Investment costs <sup>21</sup> | M€/MW          | 0.93    | 0.35    | 0.28    |
| Fixed O&M costs                | % of inv./year | 3       | 3       | 3       |
| Variable O&M cost              | €/MWh          | -       | -       | -       |
| Lifetime stack                 | h              | <90,000 | <90,000 | <90,000 |
| Lifetime system                | Years          | 10-20   | 10-20   | 10-20   |

<sup>18</sup> Including 10 % of losses for SOEC steam and CO<sub>2</sub> electrolysis

<sup>19</sup> The energy consumption for steam is included in the efficiency.

<sup>20</sup> The start-up time is several hours if started from cold.

<sup>21</sup> Average cost for period of 2030-2050, including improvements in grid connection of 66,000 €/MW for large plants.



## References

- [1] Graves C, Ebbesen SD, Mogensen M, Lackner KS. Sustainable hydrocarbon fuels by recycling CO<sub>2</sub> and H<sub>2</sub>O with renewable or nuclear energy. *Renewable and Sustainable Energy Reviews* 2011. 15, pp.1-23.
- [2] National Academies Press. Michael P. Ramage, National Academy of Engineering (NAE), Board on Energy and Environmental Systems (BEES). *The hydrogen economy: opportunities, costs, barriers, and R&D needs*. 0309091632. Washington, D.C., 2004. Available from: [http://www.nap.edu/openbook.php?record\\_id=10922&page=R1](http://www.nap.edu/openbook.php?record_id=10922&page=R1).
- [3] No. NREL/MP-560-36734, National Renewable Energy Laboratory. J. Ivy. *Summary of Electrolytic Hydrogen Production - Milestone Completion Report*. Colorado, USA, 2004. Available from: <http://www.nrel.gov/hydrogen/pdfs/36734.pdf>.
- [4] Danish Energy Agency, Energinet. *Technology data for energy plants. Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion*. Maj 2012.
- [5] Stoots CM, O'Brien JE, Condie KG, Hartvigsen JJ. High-temperature electrolysis for large-scale hydrogen production from nuclear energy – Experimental investigations. *Int J Hydrogen Energy* 2010. 35, pp.4861-70.
- [6] National Energy Technology Laboratory. *Analysis of Integrated Gasification Fuel Cell Plant Configurations*. February 25, 2011.
- [7] Thijssen J. *The impact of scale-up and production volume on SOFC manufacturing cost*. National Energy Technology Laboratory 2007.
- [8] Topsoe Fuel Cell A/S, H<sub>2</sub> Logic A/S, RISØ DTU Fuel Cells and Solid State Chemistry Division. *planSOEC R&D and commercialization roadmap for SOEC electrolysis. R&D of SOEC stacks with improved durability. SOEC-roadmap steam electrolysis- version 0.5 September 2012*. Available from: [http://www.hydrogennet.dk/fileadmin/user\\_upload/PDF-filer/Partnerskabet/Strategier/SOEC-roadmap\\_steam\\_electrolysis\\_Final1.pdf](http://www.hydrogennet.dk/fileadmin/user_upload/PDF-filer/Partnerskabet/Strategier/SOEC-roadmap_steam_electrolysis_Final1.pdf) [Accessed: 6/18/2013].
- [9] Hansen JB, Petersen AS, Loncarevic I, Torbensen C, Koustrup PS, Korsgaard A et al. *GreenSynFuels: Economical and Technological Statement regarding Integration and Storage of Renewable Energy in the Energy Sector by Production of Green Synthetic Fuels for Utilization in Fuel Cells*. Danish Technological Institute. 2011. Available from: <http://www.risoe.dtu.dk/>.
- [10] T. Smolinka, M. Gunther, J. Garcke. *NOW-Studie: Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien*. Technical report. 2011.
- [11] NEL Hydrogen. *Product leaflet – NEL P60 Pressurized electrolyser*. Available from: [http://www.nel-hydrogen.com/docs/P60\\_product\\_leaflet.pdf](http://www.nel-hydrogen.com/docs/P60_product_leaflet.pdf) [Accessed: 6/18/2013].

- [12] Ursua A, Gandia LM, Sanchis P. Hydrogen Production From Water Electrolysis: Current Status and Future Trends. Proceedings of the IEEE 2012. 100, pp.410-26.
- [13] Partnerskabet for Brint og Brændselsceller. Roadmap for MW alkaline electrolysis. Available from: [http://www.hydrogennet.dk/fileadmin/user\\_upload/PDF-filer/Partnerskabet/Strategier/Roadmap\\_AEC\\_2012\\_Final\\_rev3.pdf](http://www.hydrogennet.dk/fileadmin/user_upload/PDF-filer/Partnerskabet/Strategier/Roadmap_AEC_2012_Final_rev3.pdf) [Accessed: 7/11/2013].
- [14] Barbir F. PEM electrolysis for production of hydrogen from renewable energy sources. Solar Energy 2005. 78, pp.661-9.
- [15] Medina P, Santarelli M. Analysis of water transport in a high pressure PEM electrolyzer. Int J Hydrogen Energy 2010. 35, pp.5173-86.
- [16] Inc Giner. Giner — Products, High Pressure Hydrogen Generators<br /> . Available from: <http://www.ginerinc.com/products.php?a=HPH2> [Accessed: 6/18/2013].
- [17] Katherine E. Ayers, Everett B. Anderson, Christopher Capuano, et al. Research Advances towards Low Cost, High Efficiency PEM Electrolysis. 19385862 <series\_title> ECS Transactions. 2010. Available from: <http://dx.doi.org/10.1149/1.3484496>.
- [18] Millet P, Ngameni R, Grigoriev SA, Fateev VN. Scientific and engineering issues related to PEM technology: Water electrolyzers, fuel cells and unitized regenerative systems. Int J Hydrogen Energy 2011. 36, pp.4156-63.
- [19] Gahleitner G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. Int J Hydrogen Energy 2013. 38, pp.2039-61.
- [20] [www.hydrogennet.dk](http://www.hydrogennet.dk). Partnerskabet for Brint og Brændselsceller (Partnership Hydrogen and Fuel Cells). Elektrolyse i Danmark, Strategi for F, U & D 2010-2018. Electrolysis in Denmark, Strategy for R, D & D 2010-2018. Denmark, August, 2009. Available from: [http://www.hydrogennet.dk/fileadmin/user\\_upload/PDF-filer/Partnerskabet/Strategier/Elektrolysestrategi.pdf](http://www.hydrogennet.dk/fileadmin/user_upload/PDF-filer/Partnerskabet/Strategier/Elektrolysestrategi.pdf).
- [21] Gazey R, Salman SK, Aklil-D'Halluin DD. A field application experience of integrating hydrogen technology with wind power in a remote island location. J Power Sources 2006. 157, pp.841-7.
- [22] Millet P, Ranjbari A, de Guglielmo F, Grigoriev SA, Auprêtre F. Cell failure mechanisms in PEM water electrolyzers. Int J Hydrogen Energy 2012. 37, pp.17478-87.
- [23] R. Glöckner, C. Kloed, F. Nyhammer and Ø Ulleberg. Wind/hydrogen systems for remote areas - A Norwegian case study. In: WHEC 2002 - 14th World Hydrogen Energy Conference. Montreal, Canada, 2002.