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Program on Technology Innovation: Prospects for Large-Scale Production of Hydrogen by Water Electrolysis

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ABSTRACT

This study examines the prospects for ongoing development of electrolyzer technology to enable production of hydrogen at the competitive costs projected in some recent forecasts. Information on state-of-the-art, developmental and advanced future technology was solicited through interviews with manufacturers and developers of alkaline and polymer electrolyte membrane (PEM) electrolyzer technologies, and extracted from recent technoeconomic assessments. Data from these various sources was used to project future key performance indicators (KPIs) of electrolyzers: capital cost, efficiency, and operating lifetime. The main factors contributing to cost of product hydrogen were then estimated for future electrolyzer technologies, utilizing published cost factor analyses performed with DOE's H2A hydrogen cost model, and assuming an electricity cost range of 2-5 ¢/kWh. Hydrogen cost sensitivities to the main factors were identified, and prospects were examined for further reductions in the cost of hydrogen produced from electrolysis. Finally, ongoing projects to demonstrate readiness, applications, and benefits of MW-scale electrolyzers were reviewed.

The study finds that electrolyzer manufacturers worldwide are actively developing large-scale alkaline and PEM electrolyzer technologies. Current developmental technologies are already close to meeting the efficiency and lifetime requirements for large-scale hydrogen production. The analysis finds that, given the likely future performance of PEM and alkaline electrolyzers, input electricity costs of 2¢/kWh or less will be required in order to produce hydrogen from electrolysis at a cost $2/kg or less.

Keywords
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KEY RESEARCH QUESTION

This study examines the likely future capital costs for key electrolyzer technologies – one factor influencing the cost of hydrogen produced by electrolysis – based on interviews with major electrolyzer manufacturers. This study then examines the likely future cost of hydrogen produced by electrolysis, and evaluates the sensitivity to several important cost inputs. Electrolysis is the key technology through which electricity (including renewably generated electricity) can be used to produce hydrogen, which is currently being used as a fuel for transportation and for stationary power generation in early deployments. If hydrogen is produced from electrolysis at a cost that is competitive with conventional fossil fuel-based hydrogen production, there may be significant opportunity to cost-efficiently decarbonize a wide range of energy services using renewable electricity together with hydrogen as an energy carrier.

RESEARCH OVERVIEW

Information on state-of-the-art, developmental and advanced future technology was solicited through interviews with manufacturers and developers of alkaline and polymer electrolyte membrane (PEM) electrolyzer technologies, and extracted from recent technoeconomic assessments. Data from these various sources was used to project future key performance indicators (KPIs) of electrolyzers: capital cost, efficiency, and operating lifetime. The main factors contributing to cost of product hydrogen were then estimated for future electrolyzer technologies, utilizing published cost factor analyses performed with DOE's H2A hydrogen cost model, and assuming an electricity cost range of 2-5 ¢/kWh. Hydrogen cost sensitivities to the main factors were identified, and the prospects for further reductions of electrolytic hydrogen costs examined. Finally, ongoing projects to demonstrate readiness, applications, and benefits of MW-scale electrolyzers were reviewed.

The study finds that electrolyzer manufacturers worldwide are actively developing large-scale alkaline and PEM electrolyzer technologies. Current developmental technologies are already close to meeting the efficiency and lifetime requirements for large-scale hydrogen production. The analysis finds that, given the likely future performance of PEM and alkaline electrolyzers, electrolytic hydrogen will only cost $2/kg or less if the input electricity costs 2¢/kWh or less.

KEY FINDINGS

- Water electrolysis is a well-established process for production of hydrogen for specialized industrial applications. State-of-the-art alkaline and PEM electrolyzers are technically mature, but the existing electrolyzer capacity and the electrolyzer manufacturing industry are small, and the amount of electrolytic hydrogen produced is limited.
- The possibility of producing hydrogen on a large scale with electrolyzers powered by renewable electricity has been attracting growing interest as a potential pathway to greatly reduce carbon dioxide emission in the industrial, energy, and transportation sectors. The corresponding growth potential for the electrolyzer industry could become very large if the cost of product electrolytic hydrogen can be reduced to competitive levels, for example $2/kg or less.

- Motivated by this potential, electrolyzer manufacturers worldwide have been advancing the performance, extending the lifetimes and reducing the capital cost of alkaline and, especially, scaled-up PEM EL technologies. Current developmental technologies are already close to meeting the efficiency and lifetime requirements for large-scale hydrogen production.
- Capital costs are projected to be reduced to more competitive levels (e.g. ≤$500/kW) through continuing cost reduction efforts and establishment of volume production methods and facilities for cell components and cells, stacks and the main BoP components over the next 10-20 years.
- The cost factor analysis shows that hydrogen produced by alkaline and PEM electrolyzers with the likely best future KPIs will only cost $2/kg or less if the cost of the input electricity is 2 ¢/kWh or less. Significant reductions of the main electrolyzer-based hydrogen cost factors below projected future levels seem unlikely.
- The prospects for ‘green’ electrolytic hydrogen to compete in future large-scale markets could improve markedly if production and utilization of this hydrogen created benefits and carried credits beyond its direct economic value to users. For example, a carbon credit of $100 per ton of CO_2 emissions avoided could offset a 1.5 ¢/kWh increase in input electricity cost, without increasing product hydrogen net cost.
- Despite the uncertainties about future electrolyzer KPIs and availability of low cost electricity, US, European and Asian manufacturers have been advancing alkaline and PEM electrolyzer technologies toward the performance and cost goals for future large scale market competitiveness of electrolytic hydrogen. Several manufacturers are now, or are planning to become, engaged in MW-scale electrolyzer field test projects to demonstrate the readiness and benefits of their technologies. These projects can be expected to yield valuable information on electrolyzer technology performance and economics, and the costs and value of hydrogen produced by advanced water electrolyzers powered by renewable energy.

WHY THIS MATTERS

There is growing interest in hydrogen as an energy carrier that can integrate renewable electricity generation with transportation, power, and other energy demands (“sector coupling”), with key stakeholders engaging in numerous demonstration projects. The cost of hydrogen produced with electrolyzers using renewable energy is a decisive issue that can enable or impede new business models, and related infrastructure investment, in the power, gas, transportation, and manufacturing sectors. This analysis carefully examines the foreseeable impact of electrolyzer technology development on reducing the cost of electrolytic hydrogen production.

HOW TO APPLY RESULTS

Corporate strategy and emerging technology groups can apply this research to understand the factors that will affect the production cost of renewable hydrogen, and as a critical review of future cost projections for electrolyzer equipment. This may be useful when evaluating engagement with new business models involving hydrogen (such as decarbonizing fuels or alternative fuels for distributed generation) or hydrogen-related technology investments. The compilation of demonstration projects illustrates innovative business models and use cases of hydrogen technology.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- *Program on Technology Innovation: Review of the Uniper Energy Storage GmbH Power-To-Gas (P2G) Demonstration Projects at Falkenhagen and Hamburg-Reitbrook, Germany.* EPRI, Palo Alto, CA: 2017. 3002011519. https://www.epri.com/#/pages/product/000000003002011519/
- *Program on Technology Innovation: Status and Prospects of Automotive Proton Exchange Membrane Fuel Cells: Study Summary.* EPRI, Palo Alto, CA: 2017. 3002010624. https://www.epri.com/#/pages/product/000000003002010624/
- *Program on Technology Innovation: Hydrogen Energy Systems Development in Europe.* EPRI, Palo Alto, CA: 2016. 3002007274. https://www.epri.com/#/pages/ product/000000003002007274/

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PROGRAM: Program on Technology Innovation

ACRONYMS AND SYMBOLS

A	ampere
AEM	alkaline electrolyte membrane
Ah	ampere-hour
atm	atmospheres of pressure
BoP	balance of plant
C_C	electrolyzer capital investment cost factor ($/kg$H_2$)
C_{EE}	electric energy cost factor ($/kg$H_2$)
C_{ER}	electrode replacement and indirect capital cost factors ($/kg$H_2$)
C_{H2}	cost of electrolytic hydrogen ($/kg$H_2$)
$C_{O\&M}$	fixed O&M cost factor ($/kg$H_2$)
DC	direct current
DOE	Department of Energy
g	gram
E_{min}	minimum energy for electrolytic production of 1 kg hydrogen (= 33 kWh/kg [LHV basis])
E_{op}	specific energy for production of 1 kg H_2 (kWh/kgH_2)
EC	electricity cost ($/kWh or ¢/kWh)
EL	electrolyzer
FC	fuel cell
E_{total}	total energy used by the electrolyzer system per kg of product hydrogen (kWh)
i	current (flowing through electrolyzer)
i_{op}	total current flowing through the operating cell and stack (A)
J	current density (A/cm^2)
kg	kilogram
KPI	key performance indicator
kW	kilowatt
kWh	kilowatt-hour
MEA	membrane-electrode assembly
MW	megawatt

MWh	megawatt-hour
O&M	operations and maintenance
P_n	electrolyzer’s nominal system power capacity (the power required for the system’s nominal (rated) hydrogen production rate RHP_n)
P_{op}	stack power requirement
P_{system}	electrolyzer system power requirement
PEM	polymer electrolyte membrane
RHP_m	rate of hydrogen production, mass basis (kg/h)
RHP_v	rate of hydrogen production, volume basis (Nm^3/h)
SC_{ST}	specific costs of electrolyzer stack ($/kW)
SC_{EL}	specific costs of electrolyzer system ($/kW)
SMR	steam methane reforming
SO_x	solid oxide
V	Volt
V_{dv}	decomposition voltage for water electrolysis (V)
V_{op}	electrolyzer cell operating voltage (V)
η	energy efficiency of an electrolyzer cell (and stack of identical cells) (%)
η_i	current efficiency of an electrolyzer cell
η_{system}	efficiency of a complete electrolyzer system (%)
η_v	voltage efficiency of an electrolyzer cell

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1
INTRODUCTION

Electrochemical splitting (electrolysis) of water is a well-established process for production of hydrogen for industrial applications. It is used where the advantages of water electrolysis – simplicity and robustness, ready variability of scale, and high purity of the product hydrogen – outweigh the higher cost compared to hydrogen production by chemical water splitting through steam reformation of natural gas (SMR) and other forms of fossil energy. In the US electrolysis at present accounts for 3-4% of the 10 million metric tons of hydrogen produced annually. At approximately 20 billion kWh, the required electric energy is only around 0.5% of the electricity consumed in the US each year.

Over the past several years, electrolytic hydrogen has been attracting growing interest because of its zero-carbon footprint if the electrolyzers producing it are powered by electricity generated with renewable resources. This interest is encouraged by the expectation that this "green" electricity will become increasingly available at costs that would make electrolytic hydrogen competitive on a large scale in the industrial, transportation and energy markets.

The consequent potential for the growth of water electrolysis is very large, with correspondingly large impacts on electrolyzer markets, electricity consumption, and carbon dioxide emissions. For example, shifting just 20% of the current US industrial hydrogen production to electrolysis with renewables-derived electricity would require at least 10,000 MW of new electrolyzer capacity, increase US annual electricity consumption around 3%, and reduce US annual carbon dioxide emissions by about 15 million tons. If 50 million vehicles (about 20% of the 250 million vehicles with internal combustion engines on U.S. roads today) were fuel cell vehicles using electrolytic hydrogen, at least 60,000 MW new electrolyzer capacity would be required, and annual electricity consumption would increase by 15%. If this additional electricity was provided by renewable generation, annual CO_2 emissions would decrease by about 125 million tons, approximately 8% of transport sector CO_2 emissions. Finally, if renewable-derived electricity in the amount of 5% of current US generation were used to store and utilize energy in form of electrolytic hydrogen, at least 25,000 MW of new capacity would be needed, and the resulting displacement of natural gas by hydrogen combustion would reduce annual carbon dioxide emissions by about 30 million tons.[1]

Whether one or more of these scenarios will develop, and how quickly, depends on a number of economic and institutional factors. Foremost among these is whether the cost of electrolytic hydrogen will be competitive in future industrial, transportation fuel, and energy markets.

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[1] Assumptions made for estimating electrolyzer electricity and capacity requirements and carbon dioxide emission reductions: EL electricity use 50 kWh/kgH2, capacity factor 90%; SMR emissions: 7.3 kg CO_2/kgH_2; annual vehicle mileage: 12,000 miles, average fuel efficiency: gasoline vehicle 40 miles/gallon, fuel cell vehicle 60 mi/kgH_2; US annual electricity consumption: 4×10^{12} kWh.

Most of the hydrogen currently used in the US industrial sector is produced by large-scale steam reforming of natural gas at a cost of around $1-1.5/kgH2 but industrial markets exist also for hydrogen above this cost. In the transportation sector the introduction of cost-competitive fuel cell vehicles would create a future mass market for hydrogen with a production costs of around $2/kg or less. Finally, storing and utilizing electric energy as electrolytic hydrogen added to the natural gas system might become broadly viable at hydrogen costs below approximately $1.5/kg. In all these markets electrolytic hydrogen would become more competitive if it carried a significant credit for reduction of carbon dioxide emissions generated in the production of hydrogen by steam reforming of natural gas (SMR): even the most efficient SMR processes emits at least 7kg of carbon dioxide for each kg of product hydrogen.

Whether the cost of electrolytic hydrogen can be reduced from the currently much higher levels to levels approaching those above will depend critically on the cost of input electricity, the electrolyzer capacity factor, and on the key performance indicators (KPIs) of electrolyzers: efficiency, operating life, and capital specific cost, i.e. the cost of the electrolyzer per kW of its nominal power rating which is directly related to hydrogen production rate. For example, to meet the $2/kg cost target for electrolytic hydrogen production, the US DOE is postulating availability of electricity at ≤3¢/kWh and targeting development of electrolyzer technology with specific capital cost reduced to $300/kW (pre-installation), system efficiency raised to 75%, and operating life increased to 10-20 years.

This study examines the prospects for ongoing electrolyzer developments to reach these targets, and thereby create a techno-economic basis for large-scale production of cost-competitive hydrogen for the prospective mass markets of the future.

2

WATER ELECTROLYSIS: BASICS AND TERMINOLOGY

Electrochemical splitting of water occurs when a DC voltage exceeding the decomposition voltage of water (1.23 Volt at room temperature and atmospheric pressure) is applied between two conducting, chemically inert electrodes inserted in an aqueous electrolyte: water made ionically conducting by addition of an electrolyte. Hydrogen is evolved at the negative electrode (cathode) and oxygen at the positive (anode) at rates directly proportional to the current flowing through the electrolysis cell. Formation of 1 g H_2 requires passage of 26.8 ampere-hours (Ah) of electric charge. The theoretical minimum electric energy required for producing 1 g hydrogen by electrolysis thus is 26.8 Ah × 1.23 V ≈ 33 Wh, or 33 kWh/kgH_2.[2] For the typical 1.7-2 V cell voltage range of commercial electrolyzers the electric energy requirements are approximately 47-52 (kWh/kgH_2).[2] The decomposition voltage, and thus the theoretical as well as the practical electrolysis energy requirements per kg hydrogen, decrease with increasing temperature and increases with increasing product hydrogen pressure.

Electrolyzers (ELs) are electrochemical reactors designed to carry out water electrolysis to produce hydrogen and/or oxygen efficiently and economically. Like fuel cells, ELs are classified by the type of electrolyte they use. Alkaline ELs operate with alkaline electrolyte, proton exchange membrane (PEM) ELs depend on a proton-conducting polymer electrolyte membrane as an electrolyte-separator combination, solid oxide (SO_x) ELs use ceramics that conduct oxide ions at high temperatures, and anion exchange membrane (AEM) ELs use an OH^- ion conducting polymer as electrolyte-separator membrane. Figure 2-1 illustrates these electrolyzer types schematically.

Key features of modern electrolyzers are

- High-performance electrolysis cells, each consisting of:
    - Conducting, non-corroding anode and cathode covered with catalysts to minimize voltage losses caused by electrochemical over-potentials;
    - a thin layer of ion-conducting liquid or solid electrolyte between anode and cathode compartments that allows passage of high electrolysis currents per unit cell area (current densities) with low resistive voltage losses;
    - a separator membrane between anode and cathode that permits ready passage of ions but keeps product hydrogen and oxygen separate. In PEM, SO_x, and AEM cells, the solid electrolyte also serves as a separator that can withstand pressure differences between the cathode and anode compartments;
    - a cell frame for mounting electrodes and membranes that contains passages for supply of reactant water to, and removal of hydrogen and oxygen from, each cell;

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[2] Based on lower heating value (LHV) of hydrogen.

- insulating circumferential seals between adjacent cell components, cell frames and the conducting (“bipolar”) plates bounding each cell and transmitting the electrolysis current to adjacent cells.

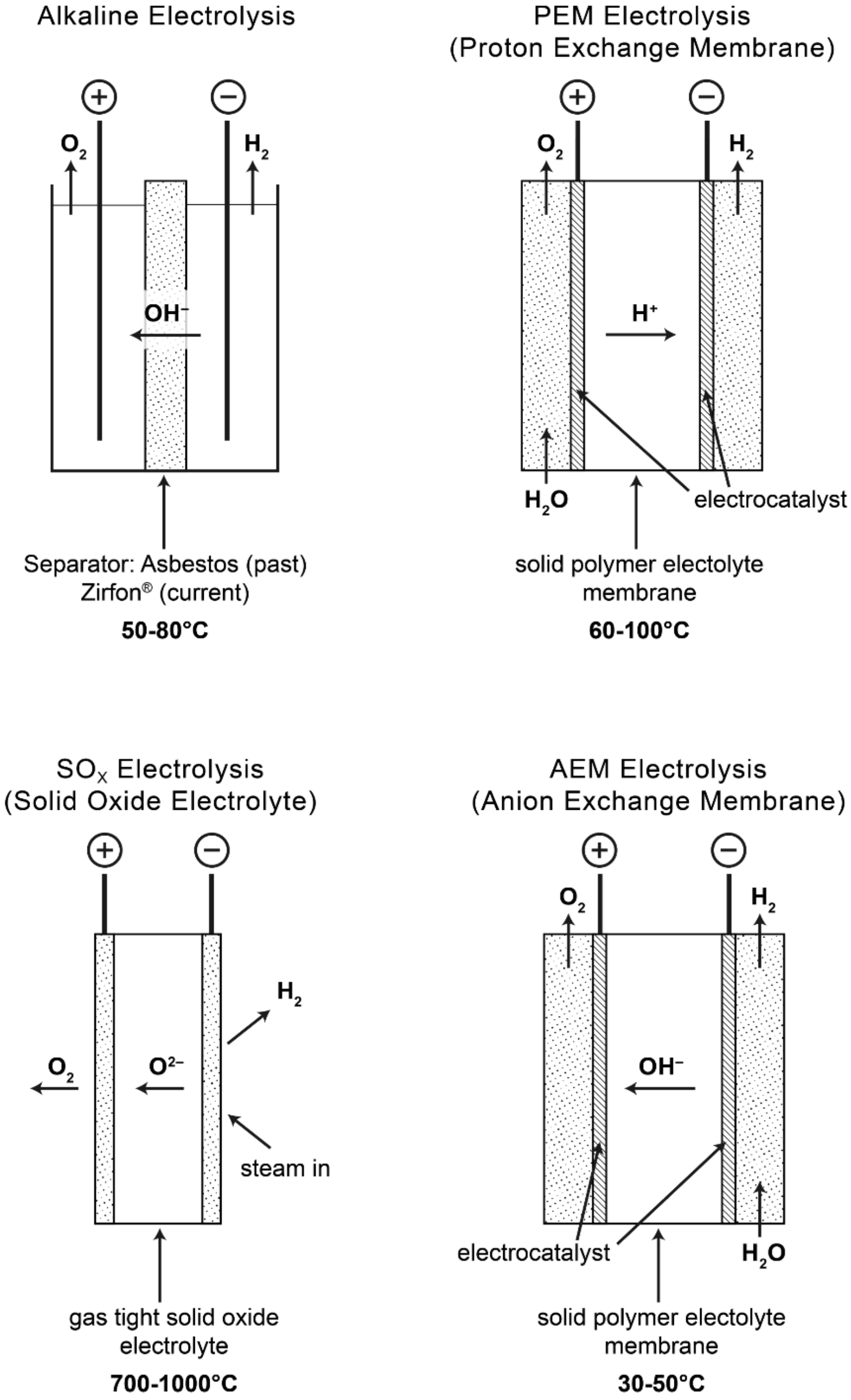

Figure 2-1
Water electrolysis technologies

- Cell stacks that are:
  - assembled from individual cells physically and electrically in series and with end plates that permit compression of the cell stack to insure integrity of seals, thus forming compact multi-kW or even MW-scale electrolysis units (see Fig. 2-2);
  - interfaced with water supply and product gas collection subsystems connected to cells in parallel through passages in the cell frames;
  - supplied with DC power to the two stack terminals.

Figure 2-2
Siemens Silyzer 200 1.25 MW PEM electrolyzer stack

- Balance-of-plant equipment including:
  - DC power supply
  - Water supply
  - Hydrogen purification
  - Piping and instrumentation

A complete PEM electrolyzer with its functional subsystems is shown in Figure 2-3.

Figure 2-3
Nel Proton 2 MW PEM electrolyzer system (capacity ~1000 kgH2/day)

The rate of hydrogen production by an electrolyzer cell can be stated as a hydrogen mass flow rate RHP_m that depends on the electrolysis current as follows:

$$\mathbf{RHP_m\ (kg/h) = 1/26{,}800 \cdot i = 1/26{,}800 \cdot a \cdot J} \qquad \text{(eq. 2-1)}$$

where 1/26,800 (Ah/kg) is the conversion factor for hydrogen production rates expressed as hydrogen mass flow rate (kg/h) and, respectively, as the current i (A) resulting in electrolysis; a (cm^2) is the electrochemically active part of the cell area; and J (A/cm^2) = i/a is the electrolysis current density.

The rate of hydrogen production also is often expressed as a H_2 gas volume flow rate RHP_V:

$$\mathbf{RHP_v\ (Nm^3/h) = 11.2\ (Nm^3/kg) \cdot RHP_m(kg/h)} \qquad \text{(eq. 2-2)}$$

where Nm^3 denotes normal cubic meters of hydrogen.

The voltage efficiency of an electrolyzer cell (as well as a stack of identical cells in series) is:

$$\boldsymbol{\eta_v\ (\%) = 100 \cdot V_{dv}/V_{op} = 123/V_{op}} \qquad \text{(eq. 2-3)}$$

where V_{dv} (V) is the decomposition voltage for water electrolysis (1.23 V at 25°C and 1 atm pressure) and V_{op} (V) the cell operating voltage.

The current efficiency of cell and cell stack is defined as:

$$\boldsymbol{\eta_i\ (\%) = 100 \cdot i/i_{op}} \qquad \text{(eq. 2-4)}$$

where i_{op} is the total current flowing through the operating cell and stack. (For properly designed electrolyzer cells and stacks, and under most operating conditions, essentially all of the current flowing through the cell results in water electrolysis and net production of hydrogen: $i_{op} \approx i$ and $\eta_i = 100 \cdot i/i_{op} \approx 100\%$).

The lower heating value (LHV)-based energy efficiency of an electrolyzer cell (and stack of identical cells) is defined as:

$$\boldsymbol{\eta\ (\%) = 100\ V_{dv} \cdot i/V_{op} \cdot i_{op} = 100 \cdot E_{min}/E_{op} = 3{,}300/E_{op}} \qquad \text{(eq. 2-5)}$$

where E_{min} (= 33 kWh/kg) is the minimum energy (LHV basis) for electrolytic production of 1 kg hydrogen and E_{op} (kWh/kgH_2) the specific energy for production of 1 kg H_2 in electrolyzer cell or stack operation.

For cells and stacks operating at close to 100% current efficiency, $i \approx i_{op}$, and:

$$\boldsymbol{\eta\ (\%) \approx 100 \cdot V_{dv}/V_{op} = \eta_v = 123/V_{op}} \qquad \text{(eq. 2-6)}$$

The LHV-based efficiency of a complete electrolyzer system is defined as:

$$\boldsymbol{\eta_{system}\ (\%) = E_{min}/E_{total}} \qquad \text{(eq. 2-7)}$$

where E_{total} is the total energy used by the electrolyzer system per kg of product hydrogen; E_{total} always exceeds E_{op}, therefore $\eta_{system} < \eta$.

The stack power requirement for a given hydrogen production rate RPH_m is:

$$\mathbf{P_{op}\ (W) = i \cdot V_{op} = 26{,}800 \cdot RHP_m \cdot V_{op}} \qquad \textbf{(eq. 2-8)}$$

or, in kW,

$$\mathbf{P_{op}\ (kW) = 26.8 \cdot RHP_m \cdot V_{op}} \qquad \textbf{(eq. 2-9)}$$

Using (eq. 2-9 above, this power requirement can be expressed as function of EL hydrogen production rate and stack efficiency:

$$\mathbf{P_{op}\ (kW) = 26.8 \cdot RHP_m \cdot 123/\eta} \qquad \textbf{(eq. 2-10)}$$

The electrolyzer system power requirement is:

$$\mathbf{P_{system}\ (kW) = 26.8 \cdot RHP_m \cdot 123/\eta_{system}} \qquad \textbf{(eq. 2-11)}$$

An electrolyzer's nominal system power capacity is the power required for the system's nominal (rated) hydrogen production rate RHP_n (kgH_2/h) at the system's energy efficiency for that rate:

$$\mathbf{P_n\ (kW) = 26.8 \cdot RHP_n \cdot 123/\eta_{system} = 3{,}300\ RHP_n/\eta_{system}} \qquad \textbf{(eq. 2-12)}$$

And

$$\mathbf{P_n\ (MW) = 3.3\ RHP_n/\eta_{system}} \qquad \textbf{(eq. 2-13)}$$

Finally, the specific cost (i.e., cost per kW of EL capacity) of EL stack is defined as

$$\mathbf{SC_{ST}\ (\$/kW) = C_{ST}/P_n} \qquad \textbf{(eq. 2-14)}$$

where C_{ST} is the total EL stack costs.

The specific cost of EL system is

$$\mathbf{SC_{EL}\ (\$/kW) = C_{EL}/P_n} \qquad \textbf{(eq. 2-15)}$$

where C_{EL} is the total EL system cost.

The key performance characteristic of an electrolyzer is the current density (J). Current density capability is a principal driver for the specific costs of EL stacks and a major factor for EL system specific costs: increases in J result in proportionate increases in H_2 production rate (see (eq. 2-1 above), and thus in potentially substantial cost reductions of the hydrogen produced by a given stack and system. However, increasing the current density requires higher cell operating voltage. This leads to lower stack and system efficiencies (see eq. 2-3 above), and thus increases the specific energy consumption and electricity costs per kg of hydrogen.

3

ELECTROLYZER TECHNOLOGY: STATUS AND PROSPECTS

Scope

EL technologies have been developed around all four basic technical concepts mentioned above: alkaline electrolyte (Alkaline EL), proton exchange membrane (PEM EL), solid oxide (SO_x EL) and alkaline (ion) exchange membrane (AEM EL) (Figure 2-1). Alkaline EL technology has been commercial for more than a century and is commercially available at the multi-MW scale. PEM EL technology went commercial in the 1990s with kW-scale installations; it is now being upscaled in stack and system capacities. The first two sections below briefly review the status of alkaline and PEM EL technologies, and discuss ongoing efforts to attain key performance and cost indicators.

Neither SO_x nor AEM EL technologies appear to have reached the combination of key performance indicators needed for commercial competitiveness. R&D efforts are continuing, in the expectation that successful developments would make these technologies competitive with alkaline EL and PEM EL technologies because of several inherent advantages they offer. These advantages, and the prospects for SO_x and AEM EL, are examined briefly further below.

Alkaline Electrolyzer (Alkaline EL) Technology

History

Alkaline EL technology for hydrogen production goes back to 1900 when Oerlikon in Switzerland introduced the first bipolar alkaline electrolyzer. In 1927 Norsk Hydro commissioned the first multi-MW alkaline EL plant in Norway, which used inexpensive hydropower to produce hydrogen for ammonia synthesis. Over the next 50 years, this first large application of electrolytic hydrogen gradually disappeared because of declining availability of inexpensive hydropower and aging of existing EL installations. However, in part enabled by advances in alkaline EL technology, a series of smaller-scale systems were introduced that offered the advantages of electrolysis – reliable, readily scalable production of high-purity hydrogen – for selected petrochemical, food, pharmaceutical, float glass, primary metals, and electronics materials production processes that require hydrogen. Production of hydrogen for turbine generator cooling has become another successful application. The bulk of electrolytic hydrogen is still produced by alkaline ELs today, although many of the smaller new systems are now PEM ELs.

A number of manufacturers worldwide are now offering technically mature alkaline EL systems for these applications, in system capacities ranging from kWs to multi-MWs. The Bibliography references recent reviews of alkaline EL technologies (Marini *et al.*; Zheng and Zhang) and listings of manufacturers (Buttler and Spliethoff).

Status, Challenges, and Prospects

Motivated by the prospects of major new markets for low-cost electrolytic hydrogen, several alkaline EL manufacturers and technology developers are seeking improvements in the key performance indicators (KPIs) of their technologies, especially lower system specific costs.

Development of alkaline EL cells and stacks that permit higher current densities without technology cost or efficiency penalties is pursued by a combination of approaches. Cell impedance (total resistance) is being reduced by decreasing the width of the electrolyte gap, in some developments up to complete elimination ("zero gap" technology) coupled with introduction of porous gas collection cathodes and anodes; by using microporous separators that can withstand pressure differences up to at least 30 atm; and by using electrolyte additives to promote separator wetting by the potassium hydroxide-based electrolyte. Together with increased cell pressure these approaches also reduce the negative effect of hydrogen and oxygen bubbles on cell conductivity. In addition, catalysts with higher activity and improved stability are being applied to anodes and cathodes to reduce the efficiency losses caused by electrochemical overvoltage. Recent reviews (see Bibliography, Schalenbach *et al.*; Phillips *et al.*; Vogt *et al.*) discuss some of the advances achieved in these efforts, and Table 3-1 below shows the alkaline EL performance levels achieved and projected.

Reduction of EL technology specific costs is still being sought on the cell, stack, and system levels by reducing the costs of materials, designs, and fabrication techniques. However, alkaline EL manufacturers expect the largest reductions of their technology costs to come from developing volume manufacturing methods and increasing cell, stack, and system production volumes. Expanding markets for electrolytic hydrogen are expected to provide not only these larger volumes but also financial incentives to continue technology and manufacturing development. The competitive pressures and uncertainties surrounding manufacturing and market developments make it difficult for EL manufacturers to provide specific cost projections for their technologies. The cost data in Table 3-1 below are therefore primarily from engineering cost study projections published by independent experts in recent years (see EL Cost section of the Bibliography), but the data in the table were reviewed also by several alkaline EL manufacturers.

Operating life limitations affect EL reliability and operating costs negatively. However, established alkaline EL products have provided highly reliable service for several decades, with only occasional electrode replacements required due to slowly declining activities of their Raney nickel (high surface area) catalyst coatings. The goal is to increase the typical replacement period from 5 years to at least 10 years – a goal that seems achievable with continued electrode materials development but that will need to be verified through long-term operation of advanced-technology alkaline electrolyzers.

Table 3-1 summarizes the most important characteristics of commercial (state-of-the-art), evolving (developmental), and projected (future) alkaline EL technology. Commercial alkaline ELs are available in kW-scale to multi-MW capacities. For developmental and future alkaline ELs the characteristics apply for MW-scale stacks; KPI data are in bold. DOE targets for future PEM EL technology are included in the table for comparison.

Table 3-1
Key alkaline EL technology characteristics[1]

Characteristic	State-of-the-Art Technology	Developmental Technology	Projections for Future Technology	DOE Targets[2] for \$2/kg hydrogen
Operating temperature (°C)	50-80	50-80	~80	not defined (n.d.)
Operating H_2 pressure (atm)	1-30[3]	≤30	≥30	n.d.
Max. current density (A/cm^2)	<0.5	~1	1.5-2	n.d.
Cell (active) area (m^2)	<2	<3	~3	n.d.
Specific energy use – Stack (kWh/kgH_2)	**47-53**	**48**	**44**	**42**
Specific energy use – System (kWh/kgH_2)	**62-70**	**50-52**	**46**	**44**
Efficiency – Stack (%)	**62-70**	**~64-67**	**75**	**77**
Efficiency – System (%)	**50-60**	**64-67**	**72**	**75**
Stack capacity range (MW)	≤3	~5	5-10+	n.d.
Stack specific cost (\$/kW)	>500	~400	~150	n.d.
System capacity (MW)	up to 400	~100	GWs	~100
System specific cost (\$/kW)	**1,000-2,500[4]**	**~1,000**	**400-500 (300)**	**300**
Operating life	**50k hours (5-7 years)**	**60k-80k hours (10 years)**	**>100k hours (20 years)**	**80k hours[5] (10 years)**

[1] Characteristics data and projections from published engineering analyses (see alkaline EL section of Bibliography) and from leading alkaline EL manufacturers and advanced technology developers.

[2] For PEM EL technology and electricity at 3¢/kWh, based on DOE's H2A hydrogen cost model (Bibliography, James *et al.*).

[3] Large commercial alkaline ELs generally operate at atmospheric pressure; smaller systems at up to 30 atm.

[4] Smaller systems have higher per-kW costs.

[5] Implied by 10-year stack life.

The data in Table 3-1 indicate an approximate doubling of current density in the near term, and the prospect of another 50% increase in the future, while maintaining high stack and system efficiencies. Together with similar increases in cell active area and stack capacity, the increases in current density are expected to reduce stack and system specific costs substantially, as shown in the table. Because much of alkaline EL technology is mature, the KPI increases projected for future technology appear entirely credible. However, reducing capital costs to \$500/kW or less is a challenge that will require maximizing current density as well as substantially reducing balance-of-plant costs. The DC power supply, a major contributor to BoP costs, appears amenable to specific cost reduction in view of continuing advances in power electronics and the progress made in reducing the specific costs of high power inverters for fuel cells. The implications of KPI progress for the cost of electrolytic hydrogen produced on a large scale by future alkaline electrolyzer plants are discussed in Section 4.

Proton Exchange Membrane Electrolyzer (PEM EL) Technology

History

The first PEM electrolyzers were developed in the 1950s by General Electric to generate oxygen for space flight life support. The motivation for developing PEM EL technology for electrolytic hydrogen production derives from the advantages offered by a solid (conducting polymer) membrane electrolyte: no liquid electrolyte is present in the cell, so product hydrogen and oxygen escape separately from the back of the porous cathode and anode structures, respectively. This feature simplifies gas and water flow, and eliminates the cell conductivity reductions and fluctuations caused by gas bubbles in alkaline ELs. Important consequences are that PEM ELs can operate efficiently at substantially higher current densities, produce very high purity hydrogen, and enable pressurized cell operation.

However, the limited lifetime of the PEM materials available before the 1970s, and high costs of early PEM EL cell materials and systems, were barriers to their application for hydrogen production. A major step toward physical realization of the advantages expected for PEM ELs was the introduction of Nafion-type membranes – already well established in the chlor-alkali industry – to provide the separator-electrolyte function in PEM electrolyzer cells. For example, the Swiss company ABB constructed an electrolyzer equipped with a Nafion® 117 membrane electrolyte that produced 20 Nm^3/h (~1.8 kgH_2/h) of high-purity hydrogen for a Swiss metallurgical facility; it operated for 15,000 hours until 1990. Beginning in the 1990s, the development of modern PEM EL technology benefited significantly from advances in the development of solid PEM electrolytes, membrane-electrode-assemblies (MEAs), and cell and stack design and manufacturing techniques achieved in the development of PEM-based fuel cells.

Status, Challenges, and Prospects

One major challenge in developing PEM electrolyzers was to find anode catalysts and materials for the current distribution and gas collection layers that were sufficiently stable at the high positive potentials and acid environment of operating EL anodes. The key step forward was the development of structures consisting of porous titanium layers in contact with highly active, stable catalysts made of Ir (iridium) alloyed with other platinum group metals coated on stable PEMs to form highly active, low-resistance MEAs (see PEM EL section of Bibliography). This advance resulted in PEM EL technology capable of high efficiency at high current densities, as shown in Table 3-2 below. The associated MEA and cell materials and design challenges appear to have been overcome. However, anode catalyst and cell materials cost reduction remain important objectives, as is the development of lower-cost automated processes for manufacturing MEAs, cells, and stacks.

Table 3-2
Key PEM EL technology characteristics[1]

Characteristics		**State-of-the-Art Technology (small systems)**	**Developmental Technology**	**Projections for Future Technology**	**DOE Targets[2] for $2/kg hydrogen**
Operating temperature (°C)		50-80	65-80	80-90	not defined
Operating H_2 pressure (atm)		<50	10-30	30-60	n.d.
Current density (A/cm^2)		1-2	1.5-2	~2 (3-5?)	n.d.
Cell active area (m^2)		0.03-0.07	0.2-1	≥1	n.d.
Specific energy use – Stack (kWh/kgH_2)		**50-60**	**45-48**	**44**	**43**
Specific energy use – System (kWh/kgH_2)		**55-65**	**49-53**	**47**	**45**
Efficiency – Stack [3] (%)		**55-66**	**68-73**	**75**	**77**
Efficiency – System[3] (%)		**50-60**	**62-67**	**71**	**75**
Stack capacity range (MW)		~ 0.001	1-2	3-10	n.d.
Stack specific cost ($/kW)		500-600	300-600	150 (100?)	n.d.
System capacity range (MW)		0.001-2	1-2	MWs to GWs	~3 to ~100
System specific cost[4] ($/kW)		**1,000-1,400**	**750-1,000**	**450-500 (300)**	**300**
Operating life	**Electrode**	**>50k hours**	**80k hours**	**>80k hours**	**>80k hours [5]**
	System	**8 years**	**10 years**	**20 years**	**10 years**

[1] Characteristics data and projections from published engineering analyses (see PEM EL section of Bibliography) and from leading PEM EL manufacturers and advanced technology developers.

[2] For PEM EL technology, and assuming availability of electricity at 3¢/kWh.

[3] LHV basis.

[4] Prior to installation.

[5] Implied by 10-year stack life.

For PEM fuel cells, decades of R&D were needed to attain adequate electrode and cell lifetimes. Achieving the extended operating life needed for practical PEM EL anode catalysts and structures has been similarly challenging, especially since the electrolyzer application is still more demanding: compared to 5,000-20,000 hours required for typical PEM FC applications, PEM EL electrode operating life should be at least 80,000 hours to be competitive with alkaline ELs. Longer operating lifetimes are desirable for PEM ELs because cost of replacing their MEAs is significantly higher than the cost of replacing the electrodes in alkaline ELs. On the other hand, the cost constraints for EL stacks are less severe than for PEM fuel cell stacks, allowing more durable (and costly) electrode compositions and cell components to be used. Table 3-2 notes the progress in PEM EL electrode life achieved to date.

Another important advance was to capture the efficiency of electrochemical hydrogen pressurization through operation at higher cell voltages by developing PEM cells and stacks that can withstand pressure differences between the cathode and anode compartments of cells.

Hydrogen pressures of 30-40 atm are typical for commercial PEM ELs, and pressures well above 30 atm (the approximate current limit for alkaline ELs) are technically feasible. Safe operation at more than 300 atm has been achieved at a small scale by developing suitable membranes, membrane supports, and cell sealing and stack compression techniques, although reductions in their complexity and cost still are desirable and seem possible. It must be recognized, however, that higher hydrogen pressures result in increased diffusion of hydrogen through the PEM electrolyte and recombination with oxygen from the anode compartment. The associated reduction of current efficiency and energy efficiency can reach 5% or more (Bibliography, Fateev).

A number of companies are currently producing kW-scale PEM electrolyzers (see Bibliography, Buttler and Spliethoff), and their products are now competing with alkaline EL systems of smaller capacities in existing specialty applications. Several of these manufacturer – among them Giner Inc., Hydrogenics, ITM Power, Nel/Proton, and Siemens – have been scaling up their PEM technologies to stack and system capacities with cost prospects for capturing wider industrial applications and eventually competing in the production of hydrogen for future, potentially large-scale energy and transportation markets. Ultimately, PEM EL technology is expected by developers/manufacturers to compete in the entire range of EL applications, from small systems to intermediate-capacity dispersed systems where its smaller footprint and operating flexibility are advantages over alkaline ELs, to large multi-MW central plants for electrolytic hydrogen production.

Table 3-2 summarizes the most important characteristics of state-of-the-art (commercial), evolving (developmental), and projected (future) PEM EL technology. The data and projections are from published engineering analyses (see PEM EL section of Bibliography) and from leading PEM EL manufacturers and advanced technology developers. The state-of-the-art technology data in the table apply for kW-scale commercial PEM EL systems. All other data (including the DOE targets) are for the MW-scale stack and system technologies intended for expanding industrial and future energy and transportation applications of electrolytic hydrogen. KPIs are shown in bold.

The data in Table 3-2 indicate a modest increase of already high current densities in the near term and further increases in the future while increasing stack and systems efficiencies, eventually to DOE target levels. Some long-term projections suggest substantially higher current densities but without giving a technology basis. Importantly, cell active area is being upscaled 10- to 30-fold from commercial small-scale PEM EL technology, and with it stack capacity for a given voltage. This scale increase increases the active fraction of a cell's total area, and reduces the cost of cell and stack hardware as a proportion of total system cost.

On this basis, and assuming continuing improvements in cell and stack technology and manufacturing development, major reductions of stack specific costs are projected, as shown in the table. It seems likely that these efforts will continue to benefit from the massive worldwide efforts to reduce PEM fuel cell stack mass production costs. While the PEM FC stack cost goal of $30/kW seems beyond the reach of PEM EL stacks because of their more demanding current density, stability and lifetime requirements, $150/kW appears to be a realistic long-term target for mass-manufactured PEM EL stacks, and $100/kW might be possible.

System cost reductions are likely, as the main balance-of-plant components (DC power supply, hydrogen purification, instrumentation and control, and piping subsystems) are beginning to receive systematic technology improvement and cost reduction efforts. BOP specific costs are likely to decrease also as system capacities increase. For example, the specific costs of DC supplies should decrease, and their efficiencies increase, with increasing stack cell numbers, probably up to stack voltages of around 500 V. Further system cost reductions – possibly even to the very low $300/kW level suggested in Table 3-2 – can be expected once volume production economies are realized not only for stacks but also for critical BoP components.

All in all the projected PEM EL KPIs shown Table 3-2 appear credible, although future system specific costs and electrode/stack life appear more uncertain than those projected for alkaline EL technology. Their implications for the cost of electrolytic hydrogen produced on a large scale by future PEM electrolyzers are discussed in Section 4.

Solid Oxide Electrolyte Electrolyzer (SO_x EL) Technology

The interest in SO_x electrolyzers is driven by two expectations. The first is to realize significantly higher efficiencies than are possible with other EL types. The reason for this potentially achievable higher efficiency is that the water decomposition voltage is substantially lower at typical SO_x EL operating temperatures of 700-900°C: ≤ 1 Volt (compared to 1.23 Volt at 25°C and 1.16 Volt at 80 °C). As a consequence, a good part of the heat required by the endothermal water electrolysis reaction can be provided by the process waste heat, with a corresponding increase in electrolyzer energy efficiency. However, efficient thermal management will be a challenge in the realization of the high efficiencies projected by SO_x EL developers. The other expectation is that SO_x EL technology development and cost reduction will continue to benefit from the progress still being made in SO_x-based high temperature fuel cell materials and fabrication technologies.

To date SO_x development has not yet led to commercial ELs, but the concept has been proven through development and operation of small stacks over limited periods; the current densities achieved are promising. The developmental characteristics of SO_x EL technology in Table 3-3 certainly attest to its lower electric energy requirements per kg of product hydrogen (a more important characteristic than efficiency, which disregards the efficiency gain from utilization of process waste heat). On the other hand, cell areas and stack capacities still are less than 10% of alkaline and PEM technologies. This makes the high efficiencies and low stack costs projected by industry (in response to a recent DOE questionnaire) for developmental and future SO_x EL technology seem rather speculative. Independent engineering system and cost analyses, of the type applied repeatedly to alkaline and PEM EL technologies, should help increase confidence in SO_x EL performance and cost projections.

Table 3-3
SO_x EL and AEM EL technology characteristics

Characteristics	SO_x EL[1]		AEM EL[2]	
	Develop-mental Technology	Future Technology	Develop-mental Technology	Future Technology
Operating temperature (°C)	700-900	700-900	30-50	50-80
Operating H_2 pressure (atm)	20	≤50	7-10	10-30
Current density (A/cm^2)	~1	~3	0.1 – 0.5	0.5-1 (PEM[3])
Cell active area (m^2)	≤0.05	?	lab scale	(PEM)
Specif. energy use (kWh/kg H_2)	**35**	**35**	**~60**	**~50**
Efficiency (%)	**66**	**~70**	**~55**	**~66**
Stack capacity range (MW)	~0.025	?	0.1-0.2	(PEM)
Stack specific cost ($/kW)	~300 (?)	~100	600-800	(PEM)
System capacity range (MW)	0.15	?	test stands	(PEM)
System specific cost ($/kW)	**~800 (?)**	**≤500**	**n.a.**	**300-400 (?)**
Operating life (years)	**4(?)**	**7(?)**	**≤2,000 hours**	**5(?)**

[1] Current density, cost and life data from industry survey, see Table 5 in *Final Report: Hydrogen Production Pathway Cost Analysis (2013-2016),* B.D. James et al., DOE-StrategicAnalysis-6231-1, 30 Sept. 2016; https://www.osti.gov/biblio/1346418

[2] Data from technical experts and publications (see Bibliography, AEM EL section).

[3] PEM EL-level performance and characteristics should be attainable if AEMs with PEM-level conductivity, stability, and cost are developed.

The other issue faced by SO_x EL technology is the limited life of cell and stack materials at the technology's very high operating temperatures. Significant progress has been made, but published performance degradation rates still are impractically high (see Bibliography, *Chen and Jiang*). The 7 years of operating life currently projected for SO_x ELs (see Table 3-3) are likely to be insufficient for competitive EL economics and hydrogen costs, because SO_x cells – perhaps even entire stacks – may need to be replaced as a whole given the monolithic construction of high temperature electrochemical cells. Only if truly long operating lifetimes (e.g. > 80,000 hours) can be attained reliably for stacks of competitive costs (e.g. ≤$150/kW) can SO_x electrolyzers be expected to compete with alkaline and PEM ELs.

Alkaline Polymer Electrolyte Membrane Electrolyzer (AEM EL) Technology

AEM EL technology is conceptually very similar to PEM EL technology, except for the chemical composition and ionic conduction mechanism of the polymer electrolyte: AEM materials conduct alkaline (OH^-) ions rather than protons. Compared to EL technology with liquid alkaline electrolyte, the AEM EL technology has the advantages that make PEM ELs attractive, as noted in the previous section. Compared to PEM EL technology, the alkaline cell chemical environment and electrode potentials present in AEM EL cells are less corrosive than the environment and electrode potentials in PEM EL cells, so lower cost materials can be used for the catalysts, catalyst supports and other cell components of AEM ELs.

In principle, therefore, AEM EL technology should be able to compete successfully with both alkaline EL and PEM EL technologies in electrolytic hydrogen production. In practice, this goal, pursued by a number of AEM membrane and AEM EL technology developers, has not been reached. For one, AEM membranes tend to have substantially lower ionic conductivity due to the lower mobility of OH^- (hydroxide) ions in AEMs compared to (hydrated) H^+ ions (protons) in PEMs. This limitation is likely to restrict AEM ELs to lower current densities than PEM ELs. In recent years, new AEM materials with high conductivities have been developed for possible application in AEM fuel cells but to date the life of these materials is inadequate.

Despite extensive R&D on a variety of alkaline-ion conducting polymers (see AEM EL Bibliography), the stability of OH^--conducting polymer membranes in the alkaline chemical environment of AEM EL cells has not nearly reached the levels required for long term EL operation. As indicated by the data in Table 3-3, AEM-based electrolysis still is in the laboratory R&D stage, and the ultimate prospects of the technology seem uncertain. A genuine breakthrough resulting in highly conducting and stable, affordable AEMs could change this outlook. In that case the transfer of important technology features and solutions from PEM EL could expedite the development of future AEM EL technology with competitive KPIs, as suggested in Table 3-3.

4

COST PROSPECTS FOR ELECTROLYTIC HYDROGEN

Production of hydrogen by water electrolysis is superior to steam reforming of fossil with respect to climate change and environmental impacts, but is currently substantially more expensive. However, electrolyzer technology has progressed to the point where expanded and potentially large-scale applications in the industrial, energy and transportation sectors are technically feasible. This section examines the prospects of future EL technologies to produce hydrogen at competitive costs for these applications.

Electrolytic Hydrogen Cost Factors and Sensitivities

Detailed analyses of current and prospective electrolytic hydrogen production costs have been carried out repeatedly in recent years (Bibliography, Electrolyzer and Electrolytic Hydrogen Costs). The simplified approach below is based on the H2A hydrogen cost analysis model developed for DOE in 2003 and refined periodically since then.

The per-kg cost C_{H2} of electrolytic hydrogen is composed of four main cost factors:

$$C_{H2}\ (\$/kgH_2) = C_C + C_{ER} + C_{O\&M} + C_{EE} \qquad \textbf{(eq. 4-1)}$$

where C_C is the electrolyzer capital investment cost factor, C_{ER} includes the electrode replacement and indirect capital cost factors, $C_{O\&M}$ is the fixed O&M cost factor and C_{EE} the electric energy cost factor, with all cost factors referred to production of 1 kg of hydrogen.

The electric energy cost factor is the cost of electricity per kg product hydrogen:

$$C_{EE}\ (\$/kgH_2) = EC\ (\$/kWh) \cdot E_{op} = 0.01 \cdot EC\ (¢/kWh) \cdot E_{op} \qquad \textbf{(eq. 4-2)}$$

where EC ($/kWh or ¢/kWh) is the electricity cost; and E_{op} (kWh/kgH_2) the EL energy consumption per kg product hydrogen.

The cost data shown in Table 4-1 are for a central alkaline electrolyzer plant with a capacity of 50,000 kg/day operated with a 97% capacity factor, the assumptions for the nominal central electrolyzer plant in DOE-supported cost analyses. The capital cost factors in the table were derived from *James et al.* (see Bibliography, Electrolyzer and Electrolytic Hydrogen Costs section*)* by replacing their capital cost assumptions with the cost range projected in Table 3-1 for future alkaline EL technology. The values for C_{ER} and $C_{O\&M}$ also were taken from *James et al.* The electric energy cost factors C_{EE} were calculated for EL specific energy consumption values of 55, 50, and 45 (kWh/kgH_2), the range likely to cover future alkaline ELs, and for assumed electricity costs of 5, 3.5, and 2¢/kWh, respectively. Hydrogen production costs calculated for the resulting cost factor combinations (eq. 4-1) are presented in the last column of Table 4-1.

Table 4-1
Hydrogen production cost (central alkaline electrolyzer system[1])

Capital Cost Factor C_C (\$/kgH_2)	Replace-ment Cost Factor C_{ER} (\$/kgH_2)	O&M Cost Factor $C_{O\&M}$ (\$/kgH_2)	Electricity Cost Factor C_{EE} (\$/kgH_2) = 0.01· EC (¢/kWh) · E_{op} (kWh/kgH_2)									Hydrogen Production Cost C_{H2} (\$/kgH_2)
			Electricity cost (¢/kWh) // specific electricity consumption E_{op} (kWh/kgH_2)									
Capital Cost[2]												
\$800/kW			**5 // 55**	**5 // 50**	**5 // 45**	**3.5 // 55**	**3.5 // 50**	**3.5 // 45**	**2 // 55**	**2 // 50**	**2 // 45**	
0.86	0.1	0.2	2.75									3.91
0.86	0.1	0.2		2.50								3.66
0.86	0.1	0.2			2.25							3.41
0.86	0.1	0.2				1.93						3.09
0.86	0.1	0.2					1.75					2.91
0.86	0.1	0.2						1.58				2.74
0.86	0.1	0.2							1.10			2.26
0.86	0.1	0.2								1.00		2.16
0.86	0.1	0.2									0.90	2.06
\$500/kW			**5 // 55**	**5 // 50**	**5 // 45**	**3.5 // 55**	**3.5 // 50**	**3.5 // 45**	**2 // 55**	**2 // 50**	**2 // 45**	
0.54	0.1	0.2	2.75									3.59
0.54	0.1	0.2		2.50								3.34
0.54	0.1	0.2			2.25							3.09
0.54	0.1	0.2				1.93						2.77
0.54	0.1	0.2					1.75					2.59
0.54	0.1	0.2						1.58				2.42
0.54	0.1	0.2							1.10			1.94
0.54	0.1	0.2								1.00		1.84
0.54	0.1	0.2									0.90	1.74
\$300/kW			**5 // 55**	**5 // 50**	**5 // 45**	**3.5 // 55**	**3.5 // 50**	**3.5 // 45**	**2 // 55**	**2 // 50**	**2 // 45**	
0.32	0.1	0.2	2.75									3.37
0.32	0.1	0.2		2.50								3.12
0.32	0.1	0.2			2.25							2.87
0.32	0.1	0.2				1.93						2.55
0.32	0.1	0.2					1.75					2.37
0.32	0.1	0.2						1.58				2.20
0.32	0.1	0.2							1.10			1.72
0.32	0.1	0.2								1.00		1.62
0.32	0.1	0.2									0.90	1.52

[1] EL capacity: 50,000kgH_2/day, capacity factor: 97%; [2] not including installation cost.

Hydrogen costs near or below the \$2/kgH_2 target for future large-scale applications are highlighted in the table. To attain this level requires electricity costs below 2¢/kWh for likely electrolyzer capital costs of \$500/kW; or below approximately 3.5¢/kWh if electrolyzer capital costs can be reduced to about \$300/kW. Hydrogen production cost sensitivities (ΔC_{H2}) to key central electrolyzer characteristics derived from the cost factor data in Table 4-1 are shown in Table 4-2.

Table 4-2
Hydrogen cost sensitivities (central alkaline electorlyzer plant)

ΔC_{H2} (\$/kgH_2)			**ΔC_C (\$/kW)**	**ΔE_{op} (kWh/kgH_2)**			**ΔEC (¢/kWh)**		
				5 ¢/kWh	**3.5 ¢/kWh**	**2 ¢/kWh**	**55 kWh/kg**	**50 kWh/kg**	**45 kWh/kg**
0.11 (11¢/ kgH_2)			**100**						
0.25	0.18	0.1		**5**	**5**	**5**			
0.82	0.75	0.67					**1.5**	**1.5**	**1.5**

The first line of the table shows a relatively small hydrogen cost sensitivity of 11 ¢/kgH_2 to a \$100/kW variance in capital costs ΔC_C. The second line shows hydrogen cost sensitivities to a 5 kWh/kg variance in specific energy use (the inverse of efficiency) for three different electricity costs; at 2 ¢/kWh, the 10 ¢/kgH_2 impact of this variance is comparable to that of a \$100/kg capital cost variance. The last line of Table 4-2 illustrates the critical importance of electricity cost for electrolytic hydrogen competitiveness: a 1.5 ¢/kWh cost variance changes hydrogen costs by 67-82 ¢/kgH_2 for EL specific energy uses of 45-55 kWh/kg.

In Table 4-3, prospective hydrogen costs are shown for a PEM electrolyzer system with a capacity of 1,500 kg/day, the assumption for the nominal dispersed ('forecourt') electrolyzer plant in DOE-supported cost analyses. However, instead of the 86% capacity factor used by James *et al.* this study assumes 45%, close to the 4,000 hours of annual operation mentioned by some PEM EL manufactures engaged in EL field demonstrations. The underlying assumption is that smaller PEM EL installations close to hydrogen users can be operated more flexibly than large alkaline EL plants to take advantage of limited periods of low electricity costs. The rapid response and load following capabilities of PEM EL technology enable this flexible operation.

Based on this change, the capital, replacement and O&M cost factors in Table 4-3 were derived from those used by B.D. James *et al.* for the 1,500 kgH_2/day EL by replacing their projected PEM EL capital costs with a range that covers likely future PEM EL technology (see Table 3-2). The same electric energy cost factors C_{EE} as for the central EL plants are assumed. Hydrogen costs calculated for the resulting cost factor combinations are in the last column of Table 4-3.

Table 4-3
Hydrogen Production Cost (dispersed PEM electrolyzer system[1])

Capital Cost Factor $(\$/kgH_2)$ **Capital Cost[2]**	Replacement Cost Factor $(\$/kgH_2)$	O&M Cost Factor $(\$/kgH_2)$	Electricity Cost Factor C_{EE} $(\$/kgH_2)$ $= 0.01 \cdot EC$ (¢/kWh) $\cdot E_{op}$ (kWh/kgH_2) **Electricity cost (¢/kWh) // specific electricity consumption E_{op} (kWh/kgH_2)**									Hydrogen Production Cost $(\$/kgH_2)$
\$750/kW				**5 // 50**	**5 // 45**	**3.5 // 55**	**3.5 // 50**	**3.5 // 45**	**2 // 55**	**2 // 50**	**2 // 45**	
1.74	0.16	0.18	2.75									4.83
1.74	0.16	0.18		2.50								4.58
1.74	0.16	0.18			2.25							4.33
1.74	0.16	0.18				1.93						4.01
1.74	0.16	0.18					1.75					3.83
1.74	0.16	0.18						1.58				3.63
1.74	0.16	0.18							1.10			3.18
1.74	0.16	0.18								1.00		3.08
1.74	0.16	0.18									0.90	2.98
\$500/kW			**5 // 55**	**5 // 50**	**5 // 45**	**3.5 // 55**	**3.5 // 50**	**3.5 // 45**	**2 // 55**	**2 // 50**	**2 // 45**	
1.16	0.16	0.18	2.75									4.25
1.16	0.16	0.18		2.50								4.00
1.16	0.16	0.18			2.25							3.75
1.16	0.16	0.18				1.93						3.43
1.16	0.16	0.18					1.75					3.25
1.16	0.16	0.18						1.58				3.08
1.16	0.16	0.18							1.10			2.60
1.16	0.16	0.18								1.00		2.50
1.16	0.16	0.18									0.90	2.40
\$300/kW			**5 // 55**	**5 // 50**	**5 // 45**	**3.5 // 55**	**3.5 // 50**	**3.5 // 45**	**2 // 55**	**2 // 50**	**2 // 45**	
0.70	0.16	0.18	2.75									3.79
0.70	0.16	0.18		2.50								3.54
0.70	0.16	0.18			2.25							3.29
0.70	0.16	0.18				1.93						2.97
0.70	0.16	0.18					1.75					2.79
0.70	0.16	0.18						1.58				2.62
0.70	0.16	0.18							1.10			2.14
0.70	0.16	0.18								1.00		2.04
0.70	0.16	0.18									0.90	1.94

[1] Plant capacity: 1,500kgH$_2$/day, capacity factor: 45%;

[2] not including installation costs.

Because of the lower capacity factor assumed for the dispersed EL system its capital cost factors are larger, and hydrogen costs near or below \$2/kgH$_2$ are achieved only for capital costs ≤\$300/kW and electricity costs ≤2¢/kWh. Hydrogen cost sensitivities to key characteristics of dispersed PEM electrolyzers are shown in Table 4-4.

Table 4-4
Hydrogen cost sensitivities (dispersed PEM electrolyzer system)

ΔCH_2 (\$/kgH$_2$)			ΔC_C (\$/kW)	ΔE_{op} (kWh/kgH$_2$)			ΔEC (¢/kWh)		
				5 ¢/kWh	3.5 ¢/kWh	2 ¢/kWh	55 kWh/kg	50 kWh/kg	45 kWh/kg
0.23 (23¢/kgH$_2$)			**100**						
0.25	0.18	0.1		**5**	**5**	**5**			
0.82	0.75	0.67					**1.5**	**1.5**	**1.5**

At 23 ¢/kWh, hydrogen cost sensitivity to a \$100/kW EL capital cost variance is doubled for a dispersed EL system operating at an assumed 45% capacity factor (first line of Table 4-4), and with it the hydrogen cost reduction benefit of dispersed EL capital cost reductions. However, the dominant cost factor remains electricity cost: even at the highest likely EL efficiency (specific electricity consumption of 45 kWh/kgH$_2$), a 1.5 ¢/kWh variance in electricity cost changes hydrogen costs by 67 ¢/kg, as shown in the last line of the table.

A comparison of Table 4-1 and Table 4-3 indicates that hydrogen from a \$500/kW dispersed plant operated at 45% capacity would cost nearly 60 ¢/kg more than from a \$500/kW central EL system (alkaline or PEM) operated at 97% capacity. For \$750-800/kW systems, the hydrogen cost difference would increase to approximately \$1/kgH$_2$, for \$300/kW systems it would decrease to 38 ¢/kgH$_2$ – highlighting the greater importance of low capital costs for dispersed ELs operated at lower capacity factors. However, the hydrogen cost advantage of the central EL plant would be more than offset if the electricity available to the dispersed EL system during its operating periods (e.g. 4,000 hours/year) would cost 1.5 ¢/kWh less in the average. Also, hydrogen from a central EL plant to distributed use sites will incur the additional cost of transportation that, in the lowest-cost case (hydrogen pipeline to distribution network), is likely to add at least 50 ¢/kg to hydrogen costs. The economic case for central EL plants depends primarily on the availability of low cost electricity in large amounts nearby, for example close to large renewable installations with collectively good capacity factors. In that case, low electricity distribution losses and costs would help offset the cost of product hydrogen transportation to user sites.

Prospects for Reducing Electrolytic Hydrogen Costs

Future industrial, energy, and transportation fuel market sizes for electrolytic hydrogen as a function of hydrogen cost appear highly uncertain. However, true mass markets seem assured only if hydrogen production costs in the order of \$2/kg or less can be achieved. Attaining this level will continue to put pressure on every electrolytic hydrogen cost factor (see eq. 4-1 above). From the perspective of this study, the prospects for reducing the EL-related specific costs underlying the corresponding cost factors appear limited, as discussed below. However, several manufacturers pointed out that the H2A hydrogen cost model is conservative, and different financing models can result in lower cost factors than those in Table 4-1 and Table 4-3 for the EL-related specific costs shown.

Capital costs

$500/kW is mentioned as an attainable goal for future MW-scale EL systems by a number of alkaline as well as PEM manufactures, and it is projected in published engineering cost analyses. A major new German study projects €450/kW (approx. $510/kW) long term, based on inputs from 12 PEM and alkaline EL and EL component manufacturers and seven EL users (Bibliography, Smolinka, *et al*., 2017). Accordingly, this author considers $500/kW EL capital cost achievable for future centralized (alkaline and PEM) and dispersed PEM electrolyzers if ongoing technology cost reduction efforts are successful and volume production methods and facilities for cells, stacks and the main BoP components are implemented over the next two to three decades. $300/kW should be considered a highly ambitious lower limit.

Replacement costs (including indirect capital costs)

The replacement cost factors in Table 4-1 and Table 4-3 represent US industry projections (Bibliography, James *et al.)* for future centralized and dispersed (PEM) EL technologies meeting 10-year (>80,000 hours) electrode replacement and 20-year plan life requirements. Further large increases in stack and system life not only are unlikely but would have diminishing hydrogen cost reduction benefits. Accordingly, significant reductions in the stack replacement cost contributions, of 10¢/kg (for centralized) and 16¢/kg (for distributed), seem unlikely. (See Table 4-1 and Table 4-3 for future central and dispersed ELs, respectively.)

O&M fixed costs

The information sources for these costs are the same as those for replacement costs, and so is the conclusion: fixed O&M contributions to the cost of hydrogen are unlikely to be reduced much below 20¢/kg and 18¢/kg (see Table 4-1 and Table 4-3) for future central and (reduced capacity factor) dispersed ELs, respectively. Lower O&M costs are considered achievable by some EL manufactures, but because of the low sensitivity to O&M cost, the associated hydrogen cost reductions will be small.

Electricity costs

Even if the KPIs projected for alkaline and PEM ELs are achieved, future costs of electrolytic hydrogen will exceed the $2/kg target for all but the highest EL efficiencies projected and lowest electricity costs assumed in this study. Yet lower electricity costs may well be essential for electrolytic hydrogen to achieve the high levels of industrial, energy, and transportation fuel market penetration needed to result in major CO_2 emission reductions. It is not yet clear, however, under which circumstances, at which rate, and to which extent very low cost electricity – for example, in the 1-2¢/kWh range – will become available in the US for large-scale production of electrolytic hydrogen in the course of the next 2-3 decades.

Other factors affecting electrolytic hydrogen competitiveness

These fall into two broad categories: (1) economic/cost benefits realized by electrolyzer operation beyond the value of product hydrogen to users; and (2) policy measures that provide financial incentives for production and/or utilization of electrolytic hydrogen because of its CO_2 emission reduction potential. The first category involves benefits to electric power producers and/or EL operators from EL operation as an interruptible electric load to balance the grid, or for system regulation, among others. The second includes regulation of CO_2 emissions, imposition of carbon taxes, etc. but also incentives for use of ‘green’ hydrogen such as tax-free sale for fuel cell applications. Quantification of the associated gains in electrolytic hydrogen competitiveness is complex since this involves a number of variables and uncertainties. However, some of these factors could become significant. For example, a carbon tax of $100 per ton CO_2 emitted could translate into a credit of approximately 75 ¢/kgH_2 for ‘green’ electrolytic hydrogen replacing hydrogen from an SMR process. Applying that credit would permit a 1.5 ¢/kWh increase in electricity cost without increasing product hydrogen net cost (see Table 4-2 and Table 4-4).

5

ELECTROLYZER PILOT AND DEMONSTRATION PROJECTS

Despite the uncertainties about future electrolyzer KPIs and the availability of low cost electricity, the expectations for a major future role of electrolytic hydrogen have been growing over the past 3-5 years. Encouraged by these expectations and the perception of expanding markets for electrolytic hydrogen US, European, and Asian manufacturers have continued to advance PEM and alkaline EL technologies toward the KPIs and scale needed for competitiveness in future large-scale markets. Several of them have become engaged in pilot and demonstration projects, working with hydrogen users and other stakeholders (including electric utilities) to demonstrate the readiness and benefits of electrolytic hydrogen production for expanded and new applications. Published information on recent and current projects using electrolyzers with stack capacities ≥ 1 MW is summarized in Table 5-1, presented in the order of project startup dates. The predominance of German and Austrian organizations among these projects may be due to the fact that most of the published projects are receiving substantial public funding from the European Union. EL manufacturers engaged in promotion and planning of privately funded demonstration projects were reluctant to provide information for this study.

All but one of the projects listed in the table involve PEM electrolyzers, attesting to the commitments of their manufacturers to demonstrate the technical readiness of upscaled PEM technology as well as its advantages of operating flexibility and a relatively small footprint. It is noteworthy also that most projects have an electric utility company as a partner.

Besides validating the operation and reliability of upscaled Hydrogenics PEM EL technology, the purpose of the Falkenhagen and Reitbrock near-term pilot projects listed in Table 5-1 is to show the technical feasibility of injecting and storing EL-produced hydrogen in the natural gas pipeline network; both projects are termed successful (Bibliography, EPRI 2017). The Mainz Energiepark project is intended to demonstrate multi-MW Siemens PEM EL technology of high efficiency, rapid dynamic response and part-load operation over a wide range. Product hydrogen can be stored on site, supplied to tube trailers, or injected in the local gas grid.

Table 5-1
Electrolyzer Pilot and Demonstration Projects

Location Project Name (Project Type)	Participants	Period	EL Supplier (Type) Power Rating	Application
Falkenhagen, Germany (Pilot)	Uniper (utility) Swissgas, Hydrogenics	2013-	Hydrogenics (PEM) 2 MW	Windfarm; power-to-gas
Reitbrock, Germany Wind Gas Hamburg (Pilot)	Uniper ES (utility), Hamburg Environmental Agency, Hydrogenics	2015-2016	Hydrogenics (PEM) 1 MW (1.5 MW peak)	Windfarm; power-to-gas
Mainz, Germany Energiepark Mainz (Demo)	Stadtwerke Mainz (utility) Siemens Linde	2015-	Siemens (PEM) 4 MW (6 MW peak)	Windfarm; EL load following and demand response
Innsbruck, Austria Demo4Grid (Demo)	IHT 5 European organizations	2017-2022	IHT (advanced alkaline) 10 MW	Grid balancing; H_2 for food processing
Hamburg, Germany (Demo)	H&R GmbH (Schindler) Hamburg Environmental Agency, Siemens	2018-	Siemens (PEM) 5 MW	H_2 for petroleum processing into high value products
Linz, Austria (Demo)	Voestalpine Siemens Verbund (utility)	2019-	Siemens (PEM) 6 MW	Grid balancing; H_2 for steel making and NH_3 synthesis
Wesseling, Germany (Demo)	Shell SINTEF ITM Power	2020-	ITM Power (PEM) 10 MW	H_2 for petroleum refining processes

The Demo4Grid project in Innsbruck, Austria is a multi-European organizations effort intended to demonstrate advanced, pressurized alkaline IHT EL technology on the 10 MW level. Its power is supplied by a regional hydroelectric plant. Product hydrogen can be stored on site and then used for food processing heat, eventually also supplied to fueling stations for fuel cell vehicles. The project is to provide information on EL technology performance, operating flexibility, and reliability, interface of the system with the electric grid, distribution of product hydrogen to multiple markets, and technoeconomic system characteristics.

Ölwerke Schindler, an industrial company manufacturing specialty products by refining petroleum, is partnering with Siemens to demonstrate a Siemens 5 MW PEM electrolyzer near Hamburg. This project is part of Schindler’s strategic concept of a ‘green’ refinery that uses hydrogen to help achieve very high utilization of heavy petroleum fractions in Schindler’s processes. Power to the EL is primarily from wind-generated excess power available in substantial quantities in the North of Germany. Of the >€10 million (approx. $11.3 million) project cost, €2.5 million (approx. $2.8 million) is provided by the European Union via the Hamburg Environmental Agency.

The Austrian Steel products manufacturer Voestalpine is partnering with Siemens and the Austrian utility Verbund to build and operate a 6 MW Siemens EL system in Linz. Electricity is supplied by Verbund, a leading provider of hydroelectric power. Project goals are to demonstrate flexible EL technology meeting the ~80% efficiency goal of the FCH 2 JU European Union initiative that is funding two-thirds of the €18 million (approx. $20.3 million) project cost, and to explore the use of 'green' product hydrogen in several stages of high-quality steel production, with the ultimate objective to minimize the carbon footprint of steel production that contributes about 4% to CO_2 emissions in the EU. The project partners stress that large-scale applications of electrolytic hydrogen in the steel and other industries will depend on attainment of competitive economics.

Shell and ITM Power will build the 10 MW 'REFHYNE' PEM EL plant in Wesseling, Germany with €10 million (approx. $11.3 million) co-funding by the FCH 2 JU initiative. The business model to be validated by the demonstration is based on supply of electrolytic hydrogen to Shell's oil refinery processes while creating financial benefits through balancing of the refinery's internal electric grid through flexible electrolyzer operation. The business model is based in part on the German regulatory structure, but different models that put value on process carbon footprint reduction will be needed to justify GW-scale industrial applications of electrolytic 'green' hydrogen. The REFHYNE demonstration project is designed as a building block for future EL installations on the 100 MW scale, and it is intended to gather data for models on that scale.

Collectively, the projects listed in Table 5-1 can be expected to generate a wealth of information on every key aspect of MW-scale electrolyzer operation: technology characteristics, especially operating flexibility, efficiency and reliability, but also capital and O&M costs and cost prospects; interfacing electrolyzer plants with the power grid on one hand and with multiple hydrogen uses on the other; value of grid balancing and other grid-beneficial EL operating modes; value of hydrogen in, and size of, hydrogen markets in the industrial, energy, and transportation sectors; and extent and value of the carbon footprint reductions achieved by electrolytic hydrogen applications in these sectors.

6

SUMMARY AND CONCLUSIONS

This study examined the prospects of future water electrolysis technologies to produce hydrogen that will be able to compete in expanding industrial and future large-scale energy and transport markets.

Information on state-of-the-art, developmental, and advanced future technology was solicited through interviews with manufacturers and developers of alkaline and PEM electrolyzer technologies, and extracted from technoeconomic EL assessments published in recent years. Data from these various sources was used to project future key EL performance indicators (KPIs) – capital cost, efficiency, and operating lifetime. The main factors contributing to cost of product hydrogen were then estimated for future EL technologies, utilizing published cost factor analyses performed with DOE's H2A hydrogen cost model, and assuming an electricity cost range of 2-5 ¢/kWh. Hydrogen cost sensitivities to the main factors were identified and the prospects for further reductions of electrolytic hydrogen costs examined. Finally, ongoing projects to demonstrate readiness, applications and benefits of MW-scale electrolyzers were reviewed.

The study's main findings and conclusions are:

- Water electrolysis is a well-established process for production of hydrogen for specialized industrial applications. State-of-the-art alkaline and PEM electrolyzers are technically mature, but the existing electrolyzer capacity and the electrolyzer manufacturing industry are small, and the amount of electrolytic hydrogen produced is limited.
- The possibility of producing hydrogen on a large scale with electrolyzers powered by renewable electricity has been attracting growing interest as a potential future energy pathway and strategy to greatly reduce carbon dioxide emission in the industrial, energy, and transportation sectors. The associated growth potential for electrolysis and the electrolyzer industry could become very large if the cost of product electrolytic hydrogen can be reduced to competitive levels, for example $2/kg or less.
- Motivated by this potential, electrolyzer manufacturers worldwide have been advancing the performance, extending the lifetimes and reducing the capital cost of alkaline and, especially, scaled-up PEM EL technologies. Current developmental technologies are already close to meeting the efficiency and lifetime requirements for large-scale hydrogen production. Capital costs are projected to be reduced to more competitive levels (e.g. ≤$500/kW) through continuing cost reduction efforts and establishment of volume production methods and facilities for cell components and cells, stacks and the main BoP components over the next 10-20 years.
- The cost factor analysis shows that hydrogen produced by alkaline and PEM ELs with the likely best future KPIs will only cost $2/kg or less if the cost of the input electricity is 2 ¢/kWh or less. Significant reductions of the main EL-based hydrogen cost factors below projected future levels seem unlikely.
- The prospects for 'green' electrolytic hydrogen to compete in future large-scale markets could improve markedly if production and utilization of this hydrogen created benefits and

carried credits beyond its direct economic value to users. These include benefits to electric power producers and/or electrolyzer operators from EL operation as an interruptible electric load, as a load usable for system regulation, etc. Credits for the strategic CO_2 emission reduction impact of green hydrogen could be in form of carbon taxes, or incentives such as tax-free sale for use in fuel cells. For example, a carbon credit of $100 per ton of CO_2 emissions avoided could offset a 1.5 ¢/kWh increase in input electricity cost, without increasing product hydrogen net cost.

- Despite the uncertainties about future electrolyzer KPIs and availability of low cost electricity, US, European, and Asian manufacturers have been advancing alkaline and PEM EL technologies toward the performance and cost goals for future large scale market competitiveness of electrolytic hydrogen. Several manufacturers are now, or are planning to become, engaged in MW-scale electrolyzer field test projects to demonstrate the readiness and benefits of their technologies. These projects can be expected to yield valuable information, not only on EL technology performance and economics but on the present and prospective costs and value of hydrogen produced by advanced water electrolyzers powered by renewable energy.

7
BIBLIOGRAPHY

Electrolyzer Overviews and Comparisons

Smolinka, T. et al., *Studie IndWEDe: Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme [Industrialization of Water Electrolysis in Germany: Opportunities and Challenges for Sustainable Hydrogen for Transport, Electricity and Heat],* Berlin: NOW GmbH, 2018.

Butler, A. and H. Spliethoff. "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids. A review." *Renewable and Sustainable Energy Reviews*, 82 (3), February 2018, pp. 2440-2454.

Schalenbach, M., G. Tjarks, M. Carmo, W. Luckea, M. Mueller and D. Stolten. "Acidic or Alkaline? Toward a New Perspective on the Efficiency of Water Electrolysis." *J. Electrochem Soc*. 163 (11) 2016, pp. F3197-F3208; see also http://jes.ecsdl.org/content/163/11/F3197.full

Schmidt, O., A. Gambhir, I. Staffell, A. Hawkes, J. Nelson and S. Few, "Future performance and cost of water electrolysis: an expert elicitation study," *International Journal of Hydrogen Energy* (42) 52, December 2017, pp. 30470-30492; see also https://www.sciencedirect.com/science/article/pii/S0360319917339435

Smolinka, T., *Water Electrolysis: Status and Potential for Development*, Water Electrolysis Day, Brussels (Belgium), April 3, 2014; see also http://www.fch.europa.eu/sites/default/files/2%20Water%20Electrolysis%20Status%20and%20Potential%20for%20Development.pdf

Smolinka, T., Garche, C., Hebling and O. Ehret, *Overview on water electrolysis for hydrogen production and storage*, Symposium – Water electrolysis and hydrogen as part of future Renewable Energy System, Copenhagen (Denmark), May 10, 2012; see also http://www.hs-ansbach.de/uploads/tx_nxlinks/NOW-Studie-Wasserelektrolyse-2011.pdf

Alkaline Electrolyzers

Bertuccioli, L., A. Chan, D. Hart, F. Lehner, B. Madden and B. Standen, *Development of Water Elecrtolysis in the European Union*, Final Report to the European Fuel Cells and Hydrogen Joint Undertaking, February 2014; see also http://www.fch.europa.eu/sites/default/files/study%20electrolyser_0-Logos_0_0.pdf

ELNakajima, Y., N. Fujimoto, S. Hasegawa and T. Usui, "Advanced Alkaline Water Electrolyzer for Renewable Hydrogen Production," presented at the 232nd Meeting of the Electrochem. Society, National Harbor, MD (USA), October 2, 2017; see also https://ecs.confex.com/ecs/232/webprogram/Paper104839.html

Fateev, V., "High pressure PEM electrolyzers: efficiency, life-time and safety issues," First International Workshop Durability and Degradation Issues in PEM Electrolysis Cells and ist

Components, Freiburg (Germany), March 12-13, 2013; see also https://www.sintef.no/globalassets/project/novel/pdf/2-4_nrckurchatov_fateev_public.pdf

Marini, S., P. Salvi, P. Nelli, R. Presnti, M. Villa, M. Berrettoni, G. Zangari and J. Kiros, “Advanced alkaline water electrolysis,” *Electrochimica Acta* 82 (2012), pp. 384-391, see also https://www.researchgate.net/publication/255791873_Advanced_alkaline_water_electrolysis?enrichId=rgreq-70259c18c5cf41874c6b0cf8421f1f32-XXX&enrichSource=Y292ZXJQYWdlOzI1NTc5MTg3MztBUzo1NTc5NDE5NTI4NDM3NzdAMTUxMDAzNTEzNTg5MA%3D%3D&el=1_x_2&_esc=publicationCoverPdf

Millet, P. F. Andolfatto and R. Durand, “Design and performance of a solid polymer water electrolyzer,” *International Journal of Hydrogen Energy* 21 (2), February 1996, pp. 87-93.

Phillips, R., A. Edwards, B. Rome, D.R. Jones and C. W.Dunnill, “Minimising the ohmic resistance of an alkaline electrolysis cell through effective cell design,” *International Journal of Hydrogen Energy* 42 (38), September 2017, pp. 23986-23994.

Vogt, U.F., M. Schlupp, D. Burnat and A.Zuettel, *Novel Developments in Alkaline Water Electrolysis*, 8th International Symposium on Hydrogen & Energy, Zhaoquing (China), February 16-21, 2014; see also http://www.elygrid.com/wp-content/uploads/2015/09/HE8-Zhaoquing-China-022014-Empa-Vg-ex.pdf

Zheng, K. and D. Zhang, “Recent progress in alkaline water electrolysis for hydrogen production and applications,” *Progress in Energy and Combustion Science*, 36 (2010), pp. 307-326.

Solid oxide (SO_x) Electrolyzers

Chen, K. and S.P. Jiang, “Review—Materials Degradation of Solid Oxide Electrolysis Cells.” *J. Electrochemical Soc.* 163 (11) 2016, pp. F3070-F3083, see also http://jes.ecsdl.org/content/163/11/F3070.full

Commissariat a l‘energie atomique et aux energies alternatives, *Final Report Summary - RELHY (Innovative solid oxide electrolyser stacks for efficient and reliable hydrogen production)*, see also https://cordis.europa.eu/result/rcn/57060_en.html

Wood, A., H. He, T. Joia, M. Krivy and D. Steedman, “Electrolysis at high efficiency with remarkable hydrogen production rates,” *J. Electrochem Soc.* 163 (5) 2016, pp. F327-F329, see also http://www.ice2017.net/-/media/Sites/Ice2017/Uploads/ICE2017_012_Kraglund.ashx

Alkaline Electrolyte Membrane (AEM) Electrolyzers

Leng, Y., G. Chen, A. Mendoza, T.B.Tighe and C.-Y. Wang, “Solid-State Water Electrolysis with an Alkaline Membrane,” *J. American Chem. Society* (2012) 134, pp.9054-9057; see also http://ecec.mne.psu.edu/Pubs/2012-Leng-JACS.pdf

Varcoe, J., et al. (11), “Anion-exchange membranes in electrochemical energy systems,” *Energy & Environmental Science* (2014) 7, pp. 3135-3191; see also http://www.ias.surrey.ac.uk/generalimages/Energy%20Environ%20Sci%20vol7%20p3135-3191%20(2014).pdf

Vinvent, E. and D. Bessarabov, “Low cost hydrogen production by anion exchange membrane electrolysis: A review,” *Renewable and Sustainable Energy Reviews* 81 (2018), pp. 1690-1704; see also http://www.sciencedirect.com/science/article/pii/S1364032117309127

Electrolyzer and Electrolytic Hydrogen Costs

Hart, D. and Y Yang, “PEM & Alkaline Electrolyzers Bottom-up Manufacturing Cost Analysis, 2017,” Fuel Cell Seminar & Energy Exposition, Long Beach (USA) November 7-9, 2017; see also http://businessdocbox.com/Green_Solutions/68482103-Pem-alkaline-electrolyzers-bottom-up-manufacturing-cost-analysis.html

James, B.D., D.A. DeSantis and G. Saur, *Final Report: Hydrogen Production Pathways Cost Analysis (2013-2016*), DOE-Strategic-Analysis-6231-1, September 30, 2016; see also https://www.hydrogen.energy.gov/h2a_production.html

Schmidt, O., A. Gambhir, I. Staffell, A. Hawkes, J. Nelson and S. Few, “Future performance and cost of water electrolysis: an expert elicitation study,” *International Journal of Hydrogen Energy* (42) 52, December 2017, pp. 30470-30492, see also https://www.sciencedirect.com/science/article/pii/S0360319917339435

Field Tests and Demonstrations

Program on Technology Innovation: Review of the Uniper Energy Storage GmbH Power-To-Gas (P2G) Demonstration Projects at Falkenhagen and Hamburg-Reitbrook, Germany, EPRI, Palo Alto:CA, 2017. 3002011519.

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