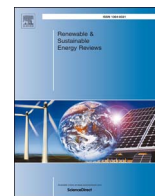




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# Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review

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## ABSTRACT

Water electrolysis has the potential to become a key element in coupling the electricity, mobility, heating and chemical sector via Power-to-Liquids (PtL) or Power-to-Gas (PtG) in a future sustainable energy system. Based on an extensive market survey, discussions with manufacturers, project reports and literature, an overview of the current status of alkaline, PEM and solid oxide electrolysis on the way to large-scale flexible energy storage is presented. These main water electrolysis technologies were compared in terms of available capacity, nominal and part-load performance, flexibility (load range, load gradients, start-up time, stand-by losses) lifetime and investment costs. This review provides a basis of the parameters required and the necessary understanding of electrolysis fundamentals and technologies for a techno-economic analysis of water electrolysis-based concepts and an evaluation of PtG and PtL in energy system studies.

## 1. Introduction

Power-to-Gas (PtG) and Power-to-Liquids (PtL) are often discussed as important elements in a future renewable energy system (e.g. [1–3]). The conversion of electricity via water electrolysis and optionally subsequent synthesis together with CO or CO<sub>2</sub> into a gaseous or liquid energy carrier enables a coupling of the electricity, chemical, mobility and heating sectors. This opens up enormous storage or absorption capacities for excess energy with high electricity generation from renewable energies in excess of demand. It also supports the integration of fluctuating renewables like wind and solar power in the energy system, including the provision of balancing power. By substituting fossil fuels, this can help to reduce greenhouse gas emissions in the mobility or chemical sectors. The future demand for Power-to-Liquids and Power-to-Gas energy storage represents an emerging market for electrolysis systems. Operating strategies such as the absorption of excess energy at limited operating times per year, providing grid services or arbitrage trading (exploitation of highly fluctuating electricity prices) are possible, which also could be combined [4]. This poses new requirements regarding efficiency, flexibility, part-load and stand-by performance, electrolyser capacity (multi MW to GW plants) and capital costs, depending on the specific application and operating strategies.

There have been several excellent reviews on electrolysis technologies in general [4–8] as well as on AEL (alkaline electrolysis) [9,10], PEMEL (proton exchange membrane electrolysis) [11], and SOEL (solid

oxide electrolysis) [12–14]. Moreover, the FCH JU (Fuel Cells and Hydrogen Joint Undertaking) under the EU's funding programme Horizon 2020 has implemented key performance indicators (KPIs) for flexible water electrolysis as a target and for monitoring their multi annual work programme (Table 1) [15].

The scope of this review is on commercial technologies and research related to flexible electrolysis operation and performance relevant for PtG and PtL applications. It provides an overview of the current status of water electrolysis on the way to large-scale flexible energy storage applications. After dealing with the fundamentals of water electrolysis, the major electrolysis technologies (AEL, PEMEL, SOEL) are compared with regard to the available capacity, nominal and part-load performance, flexibility (load range, load gradients, start-up time, stand-by losses) lifetime and investment costs. This comparison is based on the above-mentioned literature reviews, discussions with manufacturers, project reports and an extensive market survey of electrolysis suppliers.

## 2. Fundamentals of water electrolysis

The overall reaction of electrochemical splitting of water into hydrogen and oxygen by supplying electrical (and thermal) energy is given by:



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**Table 1**

State-of-the-art (SoA) and future targets of key performance indicators (KPIs) given by FCH JU [15] for hydrogen production from renewable electricity for energy storage and grid balancing (KPI 1, 2 and 3 are extended by own calculations marked in italics, conversion of values of KPI 2 and 3 are based on energy consumption specified in KPI 1).

	SoA in 2012	2017	2020	2023
KPI 1 Energy consumption @ rated power	57–60 kWh/kg @100 kg/d <i>5.1–5.4 kWh/Nm<sup>3</sup></i>	55 kWh/kg @500 kg/d <i>4.9 kWh/Nm<sup>3</sup></i>	52 kWh/kg @1000 + kg/d <i>4.7 kWh/Nm<sup>3</sup></i>	50 kWh/kg @1000+ kg/d <i>4.5 kWh/Nm<sup>3</sup></i>
KPI 2 CAPEX @ rated power including auxiliary equipment and commissioning	8 M€/(t/d) <i>3400 €/kW<sub>el</sub></i>	3.7 M€/(t/d) <i>1600 €/kW<sub>el</sub></i>	2.0 M€/(t/d) <i>900 €/kW<sub>el</sub></i>	1.5 M€/(t/d) <i>700 €/kW<sub>el</sub></i>
KPI 3 Efficiency degradation @ rated power and 8000 h operation / year	2–4%/year <i>5.4–10.7 μV/h</i>	2%/year <i>5.2 μV/h</i>	1.5%/year <i>3.7 μV/h</i>	< 1%/year <i>&lt; 2.3 μV/h</i>
KPI 4 Flexibility with a degradation < 2% per year (refer to KPI 3)	5–100% of nominal power	5–150% of nominal power	0–200% of nominal power	0–300% of nominal power
KPI 5 Hot start from min to max power (refer to KPI 4)	1 min	10 s	2 s	< 1 s
Cold start	5 min	2 min	30 s	10 s

KPI 4 and KPI 5 shall be considered as optional targets to be fulfilled according to the profitability of the services brought to the grid thanks to the addition of flexibility and (or) reactivity (considering also potential degradation of the efficiency and lifetime duration).

“H2 Production ... @ rated power” – corrected for 30 bar hydrogen output pressure.

The volumetric co-production of oxygen corresponds to half the production of hydrogen. The heat of reaction gives the overall energy demand of reaction  $\Delta H$ , which can be partly supplied by heat ( $\Delta Q$ ) while another part (change in Gibbs energy  $\Delta G$ ), has to be supplied electrically:

$$\Delta H = \Delta G + \Delta Q \quad (2.2)$$

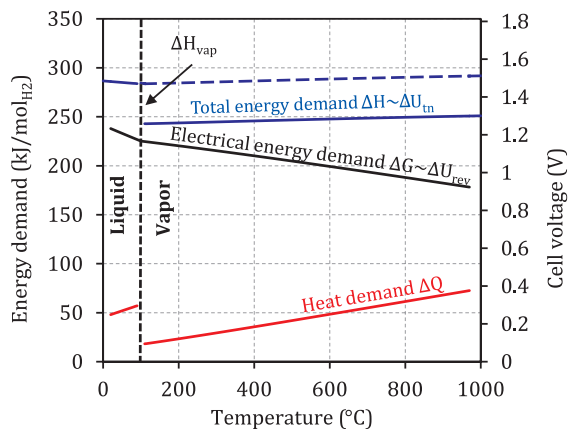
As shown in Fig. 1, the overall energy demand  $\Delta H$  varies only slightly with temperature (between 283.5 and 291.6 kJ/mol H<sub>2</sub> in the illustrated temperature range of 0–1000 °C). However, the share of possible heat integration  $\Delta Q$  rises with temperature, reducing the minimum electrical demand  $\Delta G$ . Beside improved kinetics, the possible high heat utilisation of internal losses is a major motivation of high temperature electrolysis operated at 700–900 °C. Moreover, part of the heat demand corresponding to the latent heat of vapourisation is supplied by feeding water vapour instead of liquid water, as it is the case for low temperature electrolysis (AEL, PEMEL).

The theoretical minimum cell voltage of electrolysis operation, the reversible cell voltage  $U_{rev}$ , is characterised by a necessary external thermal supply of the whole heat demand  $\Delta Q$ . It is directly proportional to the change in Gibbs free energy  $\Delta G$ :

$$U_{rev} = \frac{\Delta G}{zF} \quad (2.3)$$

where  $z$  is the number of electrons transferred per reaction ( $z = 2$ ) and  $F$  represents the Faraday's constant (96 485 C/mol).  $U_{rev}$  decreases with rising temperature. It lies in the range of 1.25–0.91 V in the temperature range of 0–1000 °C (see Fig. 1).

The thermoneutral cell voltage gives the minimum voltage for



**Fig. 1.** Total ( $\Delta H$ ), thermal ( $Q$ ) and electrical ( $\Delta G$ ) energy demand of an ideal electrolysis process as function of the temperature.

electrolysis to take place in an ideal cell without heat integration (but in case of high temperature electrolysis, water is supplied as steam, which means that it had to be evaporated externally):

$$U_m = \frac{\Delta H}{zF} \quad (2.4)$$

This means that the overall energy demand of the electrolysis reaction (including heat) is supplied electrically. The thermoneutral cell voltage is approx. 1.47–1.48 V (284–286 kJ/mol<sub>H<sub>2</sub></sub>) feeding liquid water below 100 °C while it reduces to 1.26–1.29 V (243–249 kJ/mol<sub>H<sub>2</sub></sub>) in the temperature range of 100–1000 °C if steam is supplied (see Fig. 1). This means that the minimum electrical energy consumption of steam electrolysis compared to liquid water electrolysis can be reduced by the heat of evaporation of 41 kJ/mol at ambient pressure. The total energy consumption including evaporation of the water is almost constant from 0 to 1000 °C. However, steam electrolysis offers the possibility to replace high valuable electrical energy in the order of 0.5 kWh/Nm<sup>3</sup> (41 kJ/mol) of hydrogen by low temperature heat for water evaporation. In a real electrolyser the cell voltage for thermoneutral operation is slightly higher than  $U_m$  due to heat losses (non-adiabatic operation) and thermodynamic irreversibilities [5].

Thermoneutral voltage represents the standard operation mode of high temperature electrolyser. The cell is operated at constant temperature as internal heat production by irreversibilities is equalised by heat consumption of the electrolysis reaction. Low temperature electrolyses (AEL, PEMEL) are operated above the thermoneutral voltage due to high internal losses or overvoltages. This results in a heating of the electrolysis cells requiring external cooling of the module. The cell voltage can be expressed as the sum of the reversible cell voltage  $U_{rev}$  and the overvoltages caused by ohmic resistance  $U_{ohm}$ , limitations in electrode kinetics (activation overvoltages  $U_{act}$ ) and mass transport (concentration overvoltages  $U_{con}$ ) [16]:

$$U = U_{rev} + U_{ohm} + U_{act} + U_{con} \quad (2.5)$$

The dependency between cell voltage and current or current density respectively is shown exemplary in Fig. 2. The current-voltage ( $I$ - $U$ ) relationship characterises the electrochemical behaviour of an electrolysis cell. The current density is approximately proportional to the hydrogen production rate according to Faraday's law. However, Faraday's law of an ideal electrolysis cell has to be extended by the Faraday efficiency  $\eta_F$  (or current efficiency) which is defined as the ratio of actual to theoretical hydrogen production rate. This deviation is caused by parasitic current losses along the gas ducts and cross permeation of product gases. Cross permeation of product gases increases with temperature and pressure and this negative effect is higher at low current densities due to lower gas production [17–21]. Parasitic current losses are especially relevant for AEL. The parasitic currents increase at lower

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