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Email of secretary: jim.ferrero@bnq.qc.ca
Secretariat: SCC (Canada)

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2 The role of electrolysis in the future European energy system

2.1 The role of electrolysis today

Although originally hydrogen was produced by electrolysis, today the majority (48%) comes from reforming natural gas and refinery gas, as a by-product from chemicals production (30%) and from coal gasification (18%). Only about 4% of global hydrogen production (65 million tonnes) comes from electrolysis (IEA, 2007). The largest electrolysis plants (over 30,000 Nm^3/h) have historically been deployed for the fertiliser industry (Statoil, 2008). Apart from this industry, hydrogen from electrolysis is used in making other chemicals, food processing, metallurgy, glass production, electronics manufacturing and power plant generator cooling.

However, industrial hydrogen from electrolysis is not destined for specific industry segments but used where it is cost-effective. For example, hydrogen in the food industry in eastern Canada may come from electrolysis because of the very large plants in Quebec powered by hydroelectricity, but hydrogen for the food industry in Europe will almost certainly come from steam reforming of natural gas.

Today, only small amounts of hydrogen from electrolysis are used in energy applications, in sustainable transport programmes, in renewable energy storage, and in some other cases. These cases often benefit from hydrogen produced near the point of use, which is something that electrolysers can offer. However, these energy uses are geographically fragmented, and largely dependent on policy incentives. An emerging sector is that of 'power to gas', where electrolysers are being tested in pilot stations for integration between renewable electricity generation and the production of alternative energy carriers such as hydrogen or synthetic methane, which ultimately enable greater utilisation of renewable power. Globally about 50 such demo plants have been realised or are in the planning stage, and more recent projects are often larger than one megawatt of electrolyser electrical load (Gahleitner, 2013). Those pilot projects are often driven by the interest of power utilities and other actors in the value chain looking to better understand the potential and challenges of this technology, and who are looking to gain specific experience with electrolyser operation, plant siting, permitting, and regulations, as well as with power and gas grid connections.

2.2 Summary of stakeholder views on the role of electrolysis in the future energy system

Based on the stakeholder consultation there is general agreement that electrolysis will play an important role in the future energy system. New uses of electrolytic hydrogen in transport and energy storage are expected to outgrow traditional industrial use, although there are different views as to when this point will be reached.

The stakeholder consensus is that electrolytic hydrogen use is expected to gradually evolve from limited industrial exploitation today, through early energy and transport uses around 2015, to wide deployment in hydrogen refuelling infrastructure around 2020. Views on energy storage related deployments (e.g., power to gas) and industrial uses vary among stakeholders, but in general energy storage related applications are expected to grow significantly only after 2020. It is widely accepted that this growth will depend on the evolution of the energy system and of regulatory frameworks. The views expressed by stakeholders are synthesised in Figure 1.

	Now to 2015	2015 - 2020	2020 - 2030	Beyond 2030
Hydrogen as an industrial chemical	Existing markets for electrolytic hydrogen expected to grow moderately		Potentially emerging	Energy system and use cases expected to have evolved significantly by this time
Energy storage, grid services & Renew.-heat	Pilot stations in several countries (MW scale)	Deployment of multi MW systems	Cumulative deployments reach GW scale	
Hydrogen refuelling stations	Hundreds of stations (100 kW – 2 MW)		Thousands of stations (1 MW to 5 MW)	

Figure 1: The changing role of electrolysis as reported by stakeholders

Transport-related electrolyser sales are expected to serve as a transition path for the industry to gradually get from the current 'made-to-order' business to a stage where higher volume production is typical. Demand for larger systems, e.g., up to 5 MW at large bus depots, is also expected. This should help to advance technologies such as PEM and AEM, currently not available at this scale.

While there is wide agreement on the importance of hydrogen refuelling in the near future, it is worth noting that views on deployments in energy storage applications vary depending on the group of stakeholders consulted. Research institutes often see more uncertainty in future deployment rates, whereas some electrolyser manufacturers see energy storage as an important market by 2020. One explanation for this discrepancy is simply their viewpoint, given the small size and fragmented nature of the electrolyser industry today. Even if electrolysis for energy storage is still in a (growing) field demonstration phase by 2020, this would likely represent a significant increase in business for the manufacturers. Also consulted were utility companies, currently investing in pilot and demonstration plants for 'energy storage' systems in order to assess the potential of electrolysis to provide services for the future energy system. The continued activity of utilities in this field is expected to depend on the outcomes of those pilot and demonstration projects.

2.2.1 Electrolysis in transport applications

At the European level, the establishment of alternative fuel infrastructure, including hydrogen, is seen as a priority. About 120 hydrogen refuelling points have been deployed across different countries to date (EC, 2013), while several member states have set national targets for the deployment of hydrogen infrastructure. Similar deployment efforts can be observed in parts of the United States (e.g., California) and Japan. The global car industry plans to roll out fuel cell electric vehicles in Europe from 2015 onwards.

It has been proposed to include hydrogen refuelling infrastructure targets for 2020 in the Directive on the deployment of alternative fuels infrastructure (EC, 2013). Although some uncertainty remains, several hundred hydrogen refuelling stations are expected to be deployed between today and 2025[3].

Whether this will create demand for *electrolysers* is not yet clear. Some early hydrogen refuelling stations are equipped with on-site electrolysers for hydrogen production. However, other sources of hydrogen, such as steam methane reforming (SMR) or the off-gases of industrial processes such as chlor-alkali, may be more cost-effective. Which source is better suited or more commercially viable for each refuelling point will depend on the local circumstances.

A number of stakeholders expect that mandates will require a certain share of renewable hydrogen at refuelling stations. Such mandates are currently already in place in California where at least one-third[4] of the hydrogen at refuelling stations is required to be 'green'. Such a mandate would favour the deployment of electrolysis and other low carbon routes to hydrogen (bio-hydrogen, by-product-hydrogen). Similarly, the UK H2 Mobility initiative put forward a roadmap with a 51% share of electrolytic hydrogen by 2030 (UK H2 Mobility, 2013).

2.2.2 Electrolysis for energy storage and grid services

In view of high renewable electricity targets in some regions, electrolysis is seen by many stakeholders as an element to address the potentially increasing challenges of integrating intermittent renewables. Electrolysers would operate when electricity generation is in excess of demand, or available at very low prices (e.g., during periods of high solar irradiation), thereby avoiding or reducing the need to curtail renewable electricity generation. The produced hydrogen could then be stored locally, or fed into the natural gas infrastructure, and be used in transport, heating or for re-electrification in power plants. Hydrogen production via electrolysis is often broadly classed as energy storage, irrespective of the final use of the hydrogen. As no formal definition exists, we have chosen a comparatively narrow definition of energy storage for this report, only covering those applications where the electrolyser usage profile is primarily designed to shift energy system loads in time, often across markets. So, for instance, an electrolyser that is only operated on excess renewable electricity would be considered energy storage, whereas one at a refuelling station nominally operating 8,760 hours per year would not.

Because they will need to respond to intermittent and fluctuating renewable power generation, the ability to operate dynamically is often cited as a key requirement for electrolysers to play the role above in high renewables energy systems.

A number of electrolyser operating strategies can be used to help balance supply and demand. Different strategies, which may be combined, have been suggested by stakeholders:

- *Limiting operation to times of excess or low cost renewable power generation*, which is expected to result in load factors of a maximum between 2,000 and 4,000 hours per year in 2050. This would require a system design optimised for efficient stand-by modes and would favour low capital cost over high efficiency.

[3] The "H2 Mobility" initiative (including Air Liquide, Daimler, Linde, OMV, Shell and Total) plans to deploy 400 stations by 2030 in Germany alone (H2 Mobility Initiative, 2013)
[4] Section 43869 (a)(2)(A) of the California Health and Safety Code

- Taking part in the markets for operational reserves (i.e., load shedding in case of grid incidents). This would require a system design optimised for quick response and start-up times.
- *Taking advantage of highly fluctuating electricity prices*. This would require a system design able to operate at a wide range of part loads, with highest efficiency at low part loads (operating at full load at suboptimal efficiency when electricity prices are low, operating at low part load with highest efficiency when electricity prices are high).
- *Allowing flexibility on very constrained grids*. In regions (such as islands) where high penetration of renewables has already been achieved, the use of hydrogen as an alternative energy vector to electricity may be beneficial.

It is important to note that while these different operating strategies (and the system performance characteristics that they imply) are being looked into by stakeholders and tested at pilot and demonstration plants, the industry is currently rather uncertain as to which of the requirements will ultimately be valuable in a future energy market, and FCHJU support could prove valuable in helping define these characteristics.

2.2.3 Electrolysis in the chemical industry

Consulted stakeholders do not expect hydrogen from electrolysis to compete as a basic industrial chemical with hydrogen produced from SMR. This is simply due to the lower value of base chemicals compared to transport fuels, where significantly higher prices can be achieved.

However, a number of stakeholders mentioned that use of hydrogen in the chemical industry in the near term may present lower barriers (such as the need to deploy infrastructure) than the use of hydrogen in energy-related applications. This may therefore offer opportunities for electrolysers. As an example, a German consortium including the chemical industry has investigated the potential for use of 'wind hydrogen' as a base chemical, and proposed to include this pathway in a strategy to deploy power to gas facilities (ChemCoast, 2013).

3 Status and outlook for electrolysis technology

3.1 Overview of electrolyser technologies

Three different types of electrolyser technology are currently available as commercial products, namely conventional alkaline electrolysers (liquid electrolyte), Proton Exchange Membrane (PEM) electrolysers and most recently also anion exchange membrane (AEM, also known as alkaline PEM[5]) electrolysers. Historically, alkaline electrolysis has dominated the market and accounts for nearly all the installed water electrolysis capacity worldwide. PEM electrolysis has been commercial for close to 10 years, whereas AEM appeared on the market only very recently. In Table 1, the characteristics of the three technologies are summarised.

[5] with PEM standing for Polymer Membrane Electrolyte

		Alkaline	PEM	AEM
Development status		Commercial	Commercial medium and small scale applications (≤ 300 kW)	Commercial in limited applications
System size range	Nm^3_{H2}/h	0.25 – 760	0.01 – 240	0.1 – 1
	kW	1.8 – 5,300	0.2 - 1,150	0.7 – 4.5
Hydrogen purity [6]		99.5% – 99.9998%	99.9% – 99.9999%	99.4%
Indicative system cost	€/kW	1,000-1,200	1,900 – 2,300	N/A

Table 1: Overview of commercially available electrolyser technologies

Although no products based on solid oxide electrolysis (SOE) technology are available, the concept has been proven by development and operation of short stacks[7]. We include this technology with respect to research activities, its claimed potential to significantly reduce costs and increase efficiencies, and its anticipated potential to become commercially available by 2020. Solid oxide electrolysers operate at significantly higher temperatures than alkaline, PEM and AEM electrolysers, typically 500-850 ^oC. As in Solid Oxide Fuel Cells (SOFCs), ceramics are used as a solid electrolyte which is stable at high temperatures. Technical advantages of SOE commonly claimed by researchers and developers are:

- Potentially higher electrical system efficiency compared to low temperature technologies, as (dependent on the temperature) a significant share of the energy input can be provided in the form of heat (e.g., waste heat).
- Potential use for co-electrolysis of both steam and CO_2, producing syngas, from which hydrocarbons such as liquid fuels can be produced.

3.2 Key performance indicators

This section provides an overview of the status and expected development of key performance indicators of electrolysis systems. The data provided is a synthesis of recently (2010-2013) published literature reviews (Smolinka et al., 2011; Mathiesen, 2013; Carmo et al., 2013; planSOEC, 2011), presentations, US DoE progress reports on electrolysis, manufacturers' data sheets, as well as original data gathered from manufacturers. Through stakeholder consultation, we have constructed trend lines to capture the developments broadly expected by experts and manufacturers. We term these key performance indicator-specific trend lines as *central case* KPIs in this report. The range of expected developments is bounded by a more optimistic (*best case* KPIs) and a more conservative (*worst case* KPIs) outlook.

[6] As per manufacturer data sheets, excluding optional (additional) purification stages. Note: This includes any non-optional purification stages within the system boundary described in data sheets.
[7] A stack consisting of a few cells only (typically 5 to 50 stacked cells). Short stacks are often used for testing and demonstration at lab scale.