Opinion piece by Prof Dmitri Bessarabov

Hydrogen production by water electrolysis: Challenges and opportunities

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Water electrolysis in simple terms

In simple terms, water electrolysis is a process that results in the splitting of water into its components, i.e., oxygen and hydrogen, upon the action of electrical current. As simple as it sounds, it is a rather complex process and requires many special components with functional attributes that could increase the efficiency of the process and reduce costs of the electrolysis systems.

Currently, there are four main technologies for hydrogen production by means of water electrolysis (WE). These include alkaline (AWE), proton-exchange membrane (PEM), solid oxide electrolysis cell (SOEC), and anion-exchange membrane (AEM) technologies. All these technologies, known as common world "electrolysers", require components that may be very different in their chemical nature, but their key functional attributes remain similar. The key components of electrolysers must provide good ionic conductivity for various charge carriers and functionality for the separation of oxygen and hydrogen, act as catalyst support, and provide electrical insulation between anode and cathode compartments of the electrolysis cell.

Water electrolysers today play a role of strategic importance for the deployment of green hydrogen as an energy carrier. If electrolysers are integrated with intermittent renewable energy sources with the electrical grid at scale, they can provide renewable hydrogen and stabilise electrical grids. Targets for the total cost of ownership of hydrogen have been constantly revised, but values around $1 to $2 per kilogram of H_2 are generally accepted to reach parity with other energy conversion and storage strategies.

In this paper we briefly discuss PEM technology for water electrolysis.

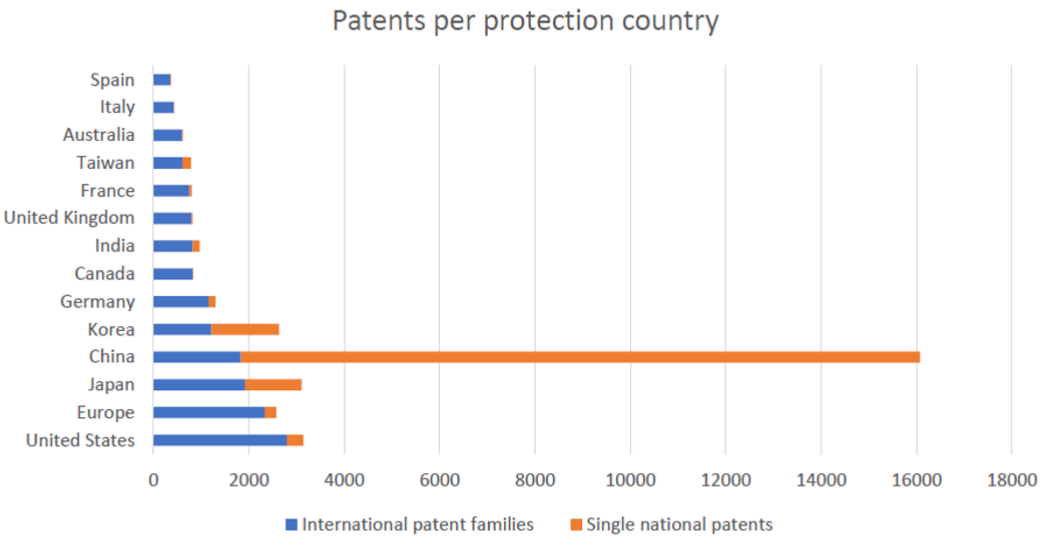
Brief historical view

For decades, proton-exchange membrane (PEM) water electrolysis has been mainly used for oxygen generation for various applications, for example, life support systems. Over the past two decades, however, it has been increasingly used for hydrogen generation in the industrial sector. The technology is also considered as key in the ongoing low carbon energy transition, for sustainable mobility applications, and large-scale energy storage applications.

For these reasons, the technology is increasingly attracting attention. A growing number of research groups are starting to participate in this development with key contributions in the form of fundamental and material advances. It is exciting to see how many research groups are now working on the subject, both experimentally and theoretically: in materials science, electrochemical and process engineering, etc. Many research articles, reviews, and books have already been published on the subject. Several national and international funding agencies are actively supporting R&D in this area. Several companies have already put 1–10th MW-scale systems on the market and new announcements have recently been made for the next generation of 10–100 MW systems.

Intellectual property race by countries

In terms of the involvement of various countries in the development of PEM water electrolysis technologies, the picture below shows related patent activities in some of them (Source: IRENA).



Year after year, new materials become available, new designs are proposed, basic physical phenomena that underline the multidisciplinary nature of the PEM systems are better understood, performance and durability improve, systems are customised for new applications, capital expenditure is decreasing, and demonstration projects as well as the market size of applications are increasing. All these activities demonstrate that this topic is an intense field of research.

More specifically, the PEM water electrolysis technology for hydrogen generation has the following advantages:

- Higher current density operation that results in a smaller footprint of the technology in comparison with other water electrolysis (WE) technologies.
- Easy to scale up due to the technology being modular. Scalability also addresses various demands for energy storage.
- Usage of corrosion-free deionised water.
- Higher discharge pressure (practical pressure, typically 30 to 40 bar) of the hydrogen produced.
- Ability to ramp up and slow down the electrolysis process fast. PEM electrolysers are robust and dynamic, they can respond fast to volatile energy sources.

- High platinum group metals (PGMs) content as platform for mineral beneficiation for South Africa. South Africa has the world's largest reserves of the precious metal platinum, which is used in hydrogen related applications, such as fuel cells, electrochemical hydrogen compressors, and in electrolysers. This is the essential technology to produce renewable hydrogen as well as hydrogen storage technologies.
- Proven technology by many OEMs (original equipment manufacturers).

South African content

In terms of the South African content, the following advantages for large-scale deployment of water electrolysis linked to renewable energy (RE) in South Africa is worth mentioning:

- Superior renewable energy (RE) endowment of both wind and solar energy.
- Large electric grid for the wheeling of RE.
- Largest concentration of known platinum group metals (PGM) reserves.
- Advanced geographic position.
- Deep expertise by Petrosa and Sasol of the Fischer-Tropsch process.
- Large tracts of sparsely populated land.
- Large carbon intensive, domestic industrial base.

Long-term challenges

However, it is important to acknowledge long-term challenges of PEM technology for water electrolysis. In this context, the purpose of this opinion piece is to provide a critical overview of potential challenges that may need to be addressed in the near future when dealing with large scale adoption of water electrolysis technology. These issues may require a special strategy and can only be addressed with an additional budget and long-term research and commitment from all stakeholders in South Africa.
If we look at the European Union (EU), it has set a target to produce 10 million tonnes of GREEN hydrogen per year by 2030 (scan for detailed references and entire documentation. Click on the top icon to open (the bottom one opens an advertisement):

Clean Hydrogen Monitor 2022:[1]

This target requires a very large scale-up of the electrolyser manufacturing capacity that is not available yet. More specifically, up to 17.5 GW/year by 2025 and 53 GW/year by 2030 is needed. However, the current electrolyser production capacity is at approximately 3.3 GW/year, with 79% of the planned production being dependent on massive investments and therefore might change significantly. Electrolysers have high upfront capital costs due to the use of expensive materials like platinum-group metals and specialised components,

[1] "PFASs are, or ultimately transform into, persistent substances, leading to irreversible environmental exposure and accumulation. Due to their water solubility and mobility, contamination of surface, ground- and drinking water and soil has occurred in the EU as well as globally and will continue. It has been proven very difficult and extremely costly to remove PFASs when released to the environment. In addition, some PFASs have been documented as toxic and/or bioaccumulative substances, both with respect to human health as well as the environment. Without taking action, their concentrations will continue to increase, and their toxic and polluting effects will be difficult to reverse."

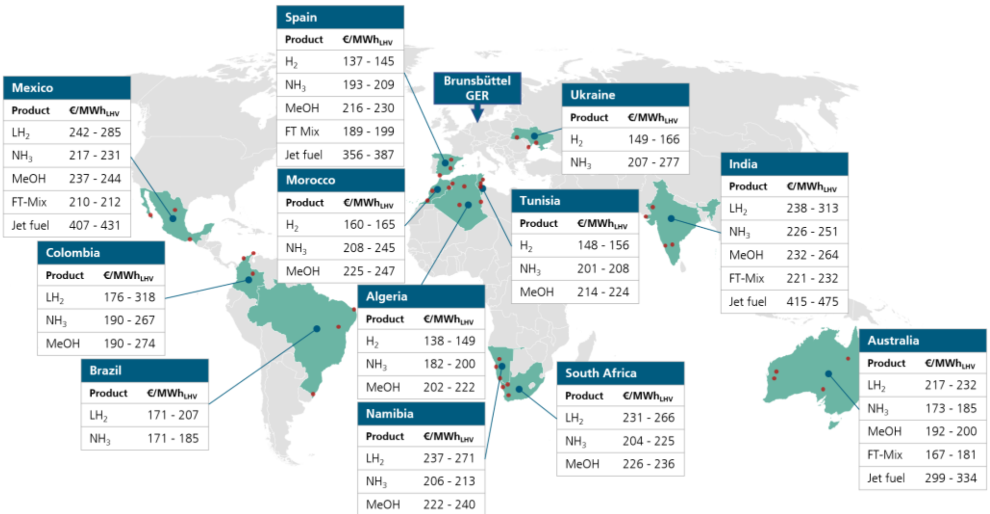
making it challenging to scale up. The production process for electrolysers involves precise and complex manufacturing techniques. Scaling up this production requires significant investments in facilities, workforce training, and quality control.

Targeted hydrogen production in the EU will require 500 TWh of green electricity per year, which is approximately half of what the EU is producing at the moment. To put this into perspective, Africa's entire electricity demand in 2019, according to the International Energy Agency (IEA), was about 700 TWh. According to IRENA studies, in South Africa, in 2017, generation from solar PV was around 3.3 TWh; wind, 5 TWh; and CSP: 0.7 TWh. We observe a sharp increase in PV plants' capacity in recent years, yet larger investments are required.

Implementation described above will require a massive expansion of the existing power grid as well, which presents a problem, since the process for permission and construction permits is very slow.

The production of PEM electrolysers requires specialised materials, such as platinum-group metals, iridium, and other rare-earth elements The other potential challenge for PEM WE scale-up that is not obvious is the limited production of iridium, which is seen as the key catalytic material for the PEM WE technology. The limited availability of these materials constrains the scaling of electrolyser manufacturing. It presents the following challenges. One is technical: the amount of iridium catalyst needs to be reduced that likely will result in compromised durability. Another challenge is the potential loss of confidence of investors in the PEM WE technology due to the above-mentioned risk.

As for the supply of green electrolytic hydrogen to EU (or other countries) in a form of liquid hydrogen (LH2) – a challenge associated with the transportation of hydrogen is becoming a key one. Overview of the countries analysed with regard to hydrogen and its derivatives (e.g. ammonia) and their provision costs, including transport to Germany was recently reported by Fraunhofer ISE. The calculation of the costs for the production of liquid hydrogen (LH_2), ammonia (NH_3), and methanol (MeOH), as well as kerosene (jet fuel) and Fischer-Tropsch products (FT-Mix) was based on the assumption of additional renewable energy plants having been built in the respective export countries. According to these calculations South Africa is not scoring high in comparison with other countries:



Source: Fraunhofer ISE, 2023

In addition to the challenges listed above, there seems to be a new challenge that is applied to all PEM WE systems. It is a possible restriction or a complete ban of the usage of all PFSA (perfluorinated materials) membrane materials, e.g. PEM membranes. Restrictions propose a comprehensive ban of the entire substance class of PFAS (per- and polyfluoroalkyl substances), of which PFSA membranes in WE are one of the key components.

European Chemical Agency (ECHA) notice:

Another point to be noted is the proposal to define "green" hydrogen as GREEN if it meets certain requirements, including the following: 1) If the electrolyser is operated solely with renewable energy sources; 2) If the electrolyser that is connected to the grid is located in a bidding zone where the average share of renewable electricity exceeded 90% in the previous calendar year, AND production does not exceed a maximal number of hours set in relation to the proportion of renewable electricity in the bidding zone; And 3) If additionally, the conditions of temporal correlation and geographical correlation are fulfilled.

European Commission: Questions and Answers on the EU Delegated Acts on Renewable Hydrogen:

Conclusion

In the context of a rapidly increasing urgency to identify adequate solutions for decarbonising the so-called hard-to-abate sectors, the demand for "green" hydrogen, which refers to hydrogen produced using renewable energy sources via electrolysis and renewable hydrogen-based products (PtX) such as ammonia and synthetic jet fuels, is steadily increasing. Many off-takers (e.g., Germany, the EU, Japan) are willing to pay a premium price and to sign long-term supply agreements to stimulate the renewable H_2 market development.

Renewable electrolytic hydrogen (i.e., hydrogen produced via water electrolysis), also offers domestic use opportunities to countries like South Africa, characterised by favourable solar and wind energy conditions, sufficient mineral resources and existing hydrogen value chains and industries.

However, there are still technical, political, and regulatory challenges that need to be addressed. For South Africa to contribute to green hydrogen electrolytic production for domestic use and export, a joint force of many stakeholders will be required. HySA Centre at NWU is the leader in PEM water electrolysis research and development in South Africa and also supports the implementation of the South African Hydrogen Society Road Map recently published by the Department of Science and Innovation (DSI).

Further advancement of electrolysers while maintaining the durability and robustness of its cell/stack components is still needed. This can only be accomplished through focused research and development efforts that address the efficiency, degradation, and cost aspects of the technology.

Prof Dmitri Bessarabov was recruited for the position from Canada in 2010. He obtained his doctoral degree from the University of Stellenbosch, South Africa in 1996. He worked in the Industrial R&D sector in Canada for Kvaerner Group, Ballard Power Systems and AFCC (a Daimler and Ford JV). He is an internationally recognised visionary with extensive industrial and academic decision-making experience. Current responsibilities include, among many other things, providing leadership and management in the National Hydrogen and Fuel Cell Programme (HySA). He is also involved in contributing to the South African National Society Hydrogen Road Map, has co-authored more than 180 publications, including books and book chapters and serves on boards of various scientific committees locally and internationally. He is a world recognised expert in fuel cells and electrolysis for energy applications. He has recently been appointed as PI (Principal Investigator) for South Africa within the SA-Japan SATREPS project for the green H2 and Ammonia project.

The opinions expressed above are those of Prof Dmitri Bessarabov, and do not necessarily reflect the views of the Executive Committee or members of the NSTF.