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GREEN HYDROGEN - FUEL OF THE FUTURE

Yashar MUSAYEV[1,a*], Carlo LOCCI[1,b], Nizami YUSUBOV[2,c], Kamran RZAYEV[2,d]

[1]Siemens Energy AG, Freyeslebenstraße 1, 91058 Erlangen, Germany
[2]Department of Machine Building Technology, Azerbaijan Technical University, Baku, Azerbaijan

E-mail: [a]yashar.musayev@siemens-energy.com, [b]carlo.locci@siemens-energy.com, [c]nizami.yusubov@aztu.edu.az, [d]kamran.rzayev@mail.ru*

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Abstract: The critical issue of increase in carbon emissions in the world's atmosphere will have fatal for the stability of the climate. Therefore, increasingly tangible effects of climate change have led the world's economies in recent years to intensify their efforts for a transition away from fossil fuels. An exceptional push for innovation is the development of renewable energy sources. One promising complement to intermittent renewable power generation is the conversion of surplus electricity to energy storing products, like hydrogen. Current industrial supply for hydrogen is derived primarily from a carbon-intensive process based on natural gas (steam reforming). Hydrogen is the lightest and most abundant element in the universe. On Earth, hydrogen is usually present as part of organic compounds such as methane (CH_4), ammonia (NH_3), or water (H_2O) [1, 2]. Siemens Energy is one of the world's leading energy technology companies. An estimated one-sixth of the electricity generated worldwide is based on technologies from Siemens Energy. The portfolio includes conventional and renewable energy technology, such as gas and steam turbines, hybrid power plants operated with green hydrogen, and power generators and transformers. For the development of green energy systems is electrolysis a one of key technology to meet Paris agreement targets. The joint vision of the companies is to advance the technology to produce green hydrogen from innovative PEM (Proton Exchange Membrane, Fig.1) water electrolysis using renewable energy systems. This paper describes how the green hydrogen, produces via electrolysis technology, will play a significant role in satisfying the rising demand of green fuels in the future.

Keywords: *energy transitions, green hydrogen; electrolysis; PEM: Proton Exchange Membrane; MEA: Membrane Electrode Assembly; GDL: Gas-Diffusion-Layer; giga-factory.*

Introduction.

Climate change is widely acknowledged by the largest economies and developing countries as a significant problem that needs to be tackled urgently. A growing number of countries are developing programmes and strategies on greenhouse gas mitigation and decarbonisation roadmaps to overhaul their energy systems and infrastructures within the next decades. Signing states of the Paris agreement are required to cut down emissions by 50% by 2030. The agreement is ratified by the European countries, which engage themselves towards carbon neutrality by 2050. Through a combination of renewables, energy storage, energy efficiency and smart grid technology, a large share of end-use applications will be decarbonised in the coming decades. As more countries foster deep decarbonisation strategies, green hydrogen produced from renewables via water electrolysis is expected to be at the very heart of energy transition as a key piece of the clean energy puzzle. IRENA's 1.5°C scenario projects that hydrogen and derivatives will account for up to 12% of final energy consumption by 2050 [2, 3].

Germany's roadmap towards carbon neutrality puts renewable energies into focus, with wind and solar being the main future energy sources. 80% of gross electricity production must be from renewable by 2030, which is expected to reach 800 TW by the end of the decade [4]. One of the challenges tied to wind and solar renewable resources is the unpredictability which does not optimally follow the energy demand. For this reason, energy storage systems working as an energy buffer are necessary.

Hydrogen is an energy vector. Differently from batteries, hydrogen offers extreme flexibility and can be used in heterogeneous sectors, such as manufacturing, heating, transport and energy. For this reason, Germany plans to install at least 6 GW of hydrogen production capacity by 2030, and an additional 6 GW by 2040 [5]. The Hydrogen Council estimates 232 GW of total electrolysis capacity worldwide, if all the projects announced by manufacturers so far will follow through [6].

Electrolysis is the only way to produce green hydrogen with no CO_2 emissions, but it is still very marginal if compared to hydrogen production from fossil fuels, which represents 96% of hydrogen production nowadays. Mature electrolysis technologies for large scale hydrogen production are two [7]. In alkaline electrolysis, two electrodes operate in potassium hydroxide (KOH). The produced hydrogen and oxygen are separated by a diaphragm. The second one is Proton Exchange Membrane (PEM) electrolysis, in which the catalyst is coated on the membrane (catalyst coated membrane – CCM). In PEM, the protons involved in the catalytic reactions travel efficiently across the membrane. Compared to Alkaline electrolysis, the proton exchange is more efficient for PEM, making this technology more responsive to load fluctuations, hence more suitable for coupling with intermittent technologies such as wind or solar. PEM is however more expensive: the catalytic material for the anode side is Iridium, one of the scarcest materials on earth [8].

Giga Factory: Mass Production of Green Hydrogen via PEM-Technology

PEM electrolysis at industrial scale occurs in a stack made of single cells (Fig. 1): at each side of the membrane, a gas-diffusion-layer (GDL) homogenizes and stabilizes the flow across the membrane and enables the electron flux to the catalytic layers. The core of the cell, defined as membrane electrode assembly (MEA) is then packed between two bipolar plates. Depending on design and hydrogen production requirements, a given number of cells is piled together within two external metal collectors. Such ensemble is defined as stack, whose production ramping up for the Silyzer300® is the main element of this article. A stack for the Silyzer300® is shown in

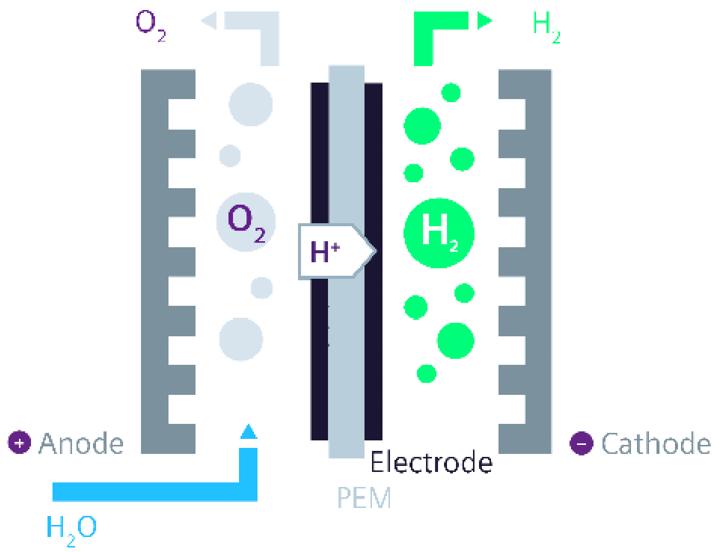
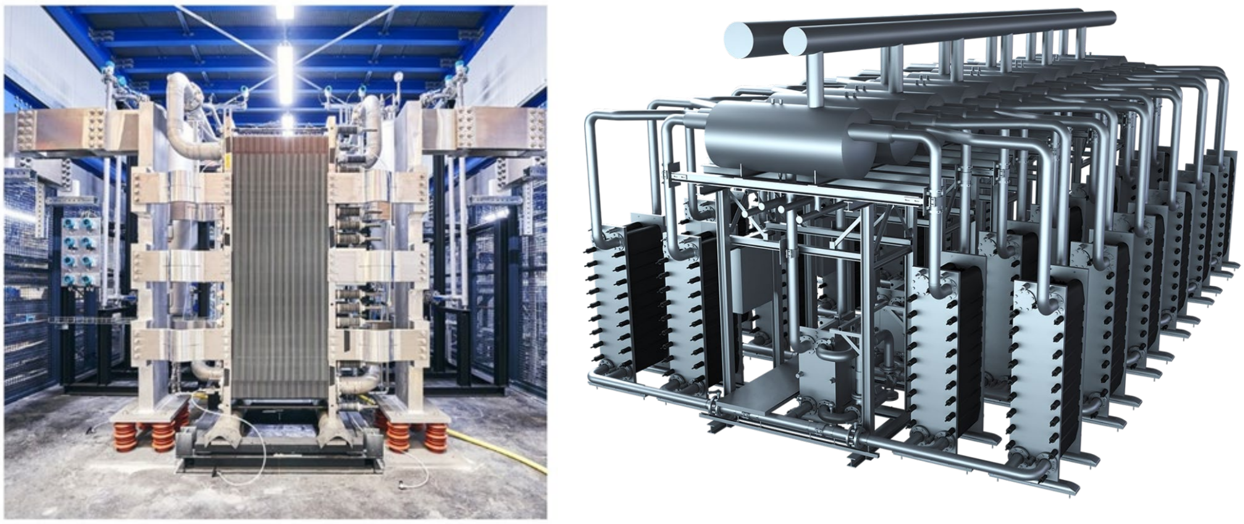


Figure 1. Water Electrolysis process and production of green hydrogen via PEM- Technology

Fig. 2a. In a reference plant configuration, 24 stacks build an array, which is able to produce about 335 Kg/h of hydrogen at full load Fig. 2b. Such production corresponds to 0.55 MW per stack, when the higher heating value of hydrogen is used as a reference.



a) *b)*

Figure 2. Stack (a) & full module array (b) of the Silyzer300® with 24 single module units.

Building a PEM stack for the Silyzer300® is a nearly full automatized process. The way the performance of a module is measured is the polarization curve, which correlates the voltage needed to polarize the cell for a given load of electricity. The stack must be manufactured with a very high level of standardization, from the cells manufacturing up to the module assembly. Slight differences in the process would lead to a modification of the polarization curve, which is an undesired outcome during the quality and testing phase.

Building up a giga-factory for such a highly standardized process, requires then to think thoroughly about the workflow and to find the best optimization between speed of manufacturing and strict control of all the KPIs of the final product.

All the most important elements involved in the cell electrochemical reactions are already involved.

- Coating: the catalytic layers are coated on each side of the membrane, but layering is not done directly on the membrane itself. The first step is to create the layer on carrying foils. This is a very delicate step as imperfect adherence of the catalytic layers might affect the performance of the cell. Here standardization and automation are fundamental and the mechanical and thermal characteristics of the layer are accounted for to regulate the machines;
- Temper: in this step we run a heat treatment to modify and optimize the mechanical characteristics of the coating layer on the foils;
- Cutting machine: up to this phase, the carrying foils are in a roll. In this step, they are cut into sheets of a convenient size for the continuation of the process sequence;
- Sandwich machine: this is the first time the layers enter in contact with the membrane. In a sandwich machine, two foils, one for the anode and one for the cathode side, are attached to the membrane;
- Lamination machine: the sandwich formed in the previous step is then laminated to press the coating onto the membrane;
- Punching machine: the throughput from the lamination machine is cut to obtain the final size corresponding to the active area of the cell. Visual inspection and maneuvering are here

needed, as after this step we finally have the MEA;

- Cell assembly: the cells are now manufactured. This step is fully automated with two robots continuously picking up the cell components and assembling each cell. Each finished cell is then piled one after the other. The need for robots here is fundamental for rapid ramp-up.
- Module pressing: the cells are pressed and screwed. Several screws are used for the operation, which is also fully automated, requiring two additional robots. The modules are finally be tested and shipped to the customer site.

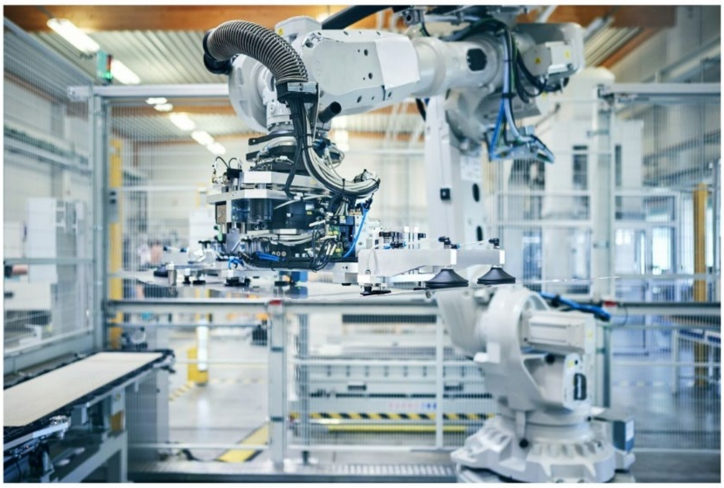


Figure 3. One of the robots involved in the cell manufacturing process

As it can be understood, most of the steps are dedicated to the MEA, and this also had consequence on the way the layout of the giga-factory was architected. Since the target is to produce 3 GW by end of 2025, this is an equivalent of 4 modules per day when the factory will work at full regime.

Such robots need to be continuously monitored to prevent any malfunction and disruption, before any major event occurs. In addition, the machines continuously dialogue together via a cloud network. The coordination of the machine is a fundamental aspect to increase and steer the production efficiency. Only when a given machine is perfectly aligned with the previous step, production times can be highly optimized.

Testing of the modules is fundamental. When the factory will be at full regime, a statistical sample of the modules will be tested. As a reminder, the test consists in running the module at several current loads, and to measure the voltage. The relation between the two provides the polarization curve. The polarization curve is compared to a reference one, which is also reported in the contractual agreements with customers. Any misalignment with the reference polarization curves is a red flag, and the process within the giga-factory needs to be reassessed. To enable fast analysis and process feedback, the giga-factory will continuously store the data from the testing and it will be easier to find discrepancies in the process.

The system coordinating the giga-factory is called manufacturing execution system (MES) which will play a fundamental role during ramping up. From beginning of operations to full regime, the giga-factory will be continuously optimized and the setting up of thousands of parameters will be required. This is the fundamental reason why a central brain is needed, and only a strict monitoring of all the events will allow a satisfactory production. The giga-factory represented a very important investment, from the founding agency up to the industrial actors involved. Hence it is important that its costs will be recovered. It is then highlighted that the giga-factory will also produce potential new products that will be proposed in the market by Siemens Energy. The way the giga-factory was designed was to favor not only automation, but also full flexibility to allow a fast resetting of the machines, dealing with different stack designs and concept. Several possible improvements in future stack designs for PEM manufacturers are discussed, and it is of primary importance for the giga-factory to be able to produce new and more cost competitive stacks. Finally, it can be argued that the giga-factory will be highly demanding in terms of material influx and this might be one of the main challenges for the whole workflow. In the next chapter, such challenges will be detailed and discussed, with potential solutions and perspectives. In particular, poor collaboration within companies might lead to misalignment in the supply chain, potentially delaying further hydrogen market growth and decarbonization targets.

PEM technology will evolve continuously in the next years. New stack designs will appear, new MEAs will be developed and this in very short time ranges. The issue is that recycling techniques optimized for a given stack, might need re-tuning for a different stack, even produced by the same company. If this is true for the MEA for the Iridium recovery process, this is also valid for all the other components, such as GDL, which might not be directly used after refurbishment as incompatible with a new design. Finally, both paths, reduction and recycling have actually to be combined together, posing further challenges to the PEM market for a sustainable supply chain.

Europe puts industrial eco-systems at the center of its economy strategy [9,10]. In total, 14 eco-systems are considered as the main pillar of European transition towards sustainability. Among these 14 eco-systems, “Energy-Renewables” and “Energy-Intensive-Industries” are the main areas in which hydrogen will play a significant role. As a consequence, hydrogen is considered by the European Union as a strategic area among other five. For Europe, strategic areas are industry sectors which need particular attention from European institution due to their strategical importance but also for challenges these areas will face in the future. Raw material supply chain is of concern for PEM technologies. Europe fully acknowledges this challenge and puts the raw material supply chain for hydrogen into focus. In addition, still on a European level, the European Hydrogen Alliance brings European hydrogen actors together, to boost growth and exchange know-how [11,12,13].

It can be argued that without such initiatives, that is government backing up industry, the hydrogen economy could not grow. In [12], it is reported that green hydrogen production has a chicken-egg dilemma. First challenge is the levelized cost of hydrogen, defined as the cost per Kg of hydrogen, accounting for all the costs during production. PEM manufacturers need to invest in R&D to drive cost down, but only if demand grows such investments can happen. However, in order for the demand to grow, the cost of hydrogen must be affordable. As mentioned in the introduction part, 96% of hydrogen nowadays is produced via fossil fuels, with a levelized cost of hydrogen (LCOH) pre-pandemic between USD 0.5 and 1.7 USD [13]. Green hydrogen is nowadays more expensive, with a LCOH between USD 3 and 8. At the moment, it is still uncertain whether the price will reach levels that will trigger enough demand for green hydrogen and for sure, PEM manufacturers will need to rethink and redesign the stacks [14] to increase market attractiveness compared to grey hydrogen. From a technological point of view, immediate measures will be to increase the MEA active area, pressurize the system and finally increase the current density. However, it is also reminded that independently from the measures and the strategies implemented by PEM manufacturers, this always has an effect on long term performance of PEM stacks, also defined as degradation [15], which is a fundamental variable to be taken into account for a sustainable business case. However, the increase in gas prices can still negatively affect the green hydrogen market. In Europe for instance, the merit-order system sets the electricity price as the price coming from the source with the highest marginal costs. Due to high gas prices, this leads Europe, and especially Germany, to high electricity prices, which is a very harsh boundary condition for green hydrogen development as electricity can be considered as the fuel for electrolysis [16].

Another chicken and egg dilemma is how to push companies to invest heavily on hydrogen. We saw above how the giga-factory will need a continuous flux of material to satisfy the ambitious production targets. This means a continuous flux of all the components, from the bipolar plates to the catalytic layers, from the membranes to the external blocks. A disruption of one of these elements would bring to interruption of the factory operations as well as inventory accumulation of idling elements. Such components are built in an eco-system of suppliers and sub-suppliers, which will also need to invest internally to increase their production throughput. In addition, the giga-factory needs reliable and long-term partners. Industrial partnerships will also play a crucial role in this sense, in which big energy players can build joint ventures to enhance specific know-hows. Only with such positive examples, large volume manufacturing will be required more and more.

Conclusion.

Paris agreement represented a strong push for investments into green technologies. Hydrogen is at the center of Europe’s strategy and it is seen as a valid way to store energy from intermittent renewable sources. Only governmental investment and strong commitment to roadmaps will create a favorable environment for the giga-factory to reach its production targets.

PEM electrolysis is a promising technology that holds great potential in the era of sustainable energy production. It can be used to store excess renewable energy, produce high-purity hydrogen for fuel cells, and generate oxygen for various applications. As the demand for renewable energy storage and hydrogen fuel cell technology continues to grow, the use of PEM electrolysis is expected to become more widespread. With further development and investment, PEM electrolysis has the potential to play a critical role in achieving a more sustainable and cleaner.

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