

THE GREEN HYDROGEN REVOLUTION – INTEGRATING HYDROGEN INTO INDUSTRIAL APPLICATIONS

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Abstract – The application and use of green hydrogen is expected to have significant potential to decarbonize industrial sectors and lead these sectors in energy transition towards a carbon neutral future. The primary hydrogen production methods are known as grey, blue, and green hydrogen, and are compared. An overview of the hydrogen electrolysis process, and a review of commercially available hydrogen electrolyzer technologies is provided. The key considerations for evaluating hydrogen electrolyzer modules are discussed. The Power-to-X industrial applications where hydrogen is used as either an intermediate or end product are discussed. Finally, the integration of electrolyzer module arrays into an industrial electrical distribution system, and the key electric power requirements and considerations are reviewed.

Index Terms — Hydrogen, electrolysis, green hydrogen, renewable energy, energy transition, Power-to-X, harmonics, power factor, Giga-Watt, Paris Agreement

I. INTRODUCTION

Hydrogen has been produced since the 17th century when Theodore Turquet de Mayrne and Nicolas Lemery poured dilute sulfuric acid on iron and produced a gas of “inflammable air”. At that time, they did not realize that the resulting gas was a standalone element, and they recorded their scientific finding as a “burnable form of sulfur” [1]. In late 18th century the French inventor Jacques Charles made a hydrogen balloon to carry him and another person over a distance of 36 km at a height of up to 550 m. In late 18th century it was discovered that hydrogen had practical uses. Three subsequent discoveries in late 19th and early 20th century opened the possibilities to use hydrogen in industrial applications. The three discoveries were: hydrogenation, the Haber-Bosch process to make ammonia, and hydrocracking [1].

Today, the primary demand for hydrogen is for petroleum refining and ammonia production [2]. As industrial-scale electrolysis becomes commercially viable, hydrogen has significant potential to decarbonize industrial sectors and lead these sectors in energy transition towards a carbon neutral future. These sectors include chemical processes, industrial applications, steel manufacturing, clean transportation fuels (eFuel or hydrogen), etc. This transformation will rely upon the

production of clean hydrogen from green energy sources that have a carbon neutral footprint.

Recognizing this opportunity, the Department of Energy (DOE) has launched the Hydrogen Energy Earthshot initiative on June 7, 2021. This initiative strives to reduce the cost of hydrogen to \$1 per 1 kilogram in one decade. This reflects approximately an 80% reduction in the cost of producing clean hydrogen.

II. PRODUCTION OF HYDROGEN

A. Methods of Production

Most hydrogen produced in the North America is produced using a process called the steam-methane reforming (SMR) process followed by a water-gas shift reaction. In the SMR process, high-temperature steam reacts with methane gas (typically from a pipeline) to produce primarily hydrogen and carbon monoxide. Subsequently, the water-gas shift reaction produces carbon dioxide and additional hydrogen by reacting the carbon monoxide from the SMR process with additional steam. The carbon dioxide can either be released or captured.

When carbon dioxide from the SMR process and water-gas shift reaction is released into the atmosphere, this method of hydrogen production is known as “Grey Hydrogen”. While this is currently the most common method of hydrogen production, releasing the carbon dioxide to the atmosphere will not support the goals of the Paris Agreement (to reduce greenhouse gas (GHG) emissions to limit global temperature rise and support development of low GHG emissions).

The carbon dioxide from the SMR process and water-gas shift reaction can be captured using an amine absorption process or a pressure swing absorption process. Once the carbon dioxide has been captured, it can be compressed and either, utilized or sequestered. Using carbon capture, utilization, sequestration (CCUS) does not release the excess carbon dioxide into the atmosphere. When carbon dioxide from the SMR process and water-gas shift reaction is captured, utilized or sequestered, this method of hydrogen production is known as “Blue Hydrogen” [3].

“Green Hydrogen” refers to utilizing solar energy and wind energy to power electrolyzers to split water into oxygen gas and hydrogen gas by hydrogen electrolysis. The hydrogen gas is

utilized in Power-to-X industrial processes, and the oxygen gas is either released to atmosphere or utilized in other industrial processes.

To produce the same volume of hydrogen as is produced by Grey or Blue methods of hydrogen production, a significant amount of energy is required for the electrolyzers used in Green method of hydrogen production. Due to this, renewable solar and wind energy are considered ideal sources of power for electrolysis.

Grey, Blue, and Green are the primary colors of hydrogen production. The other colors of hydrogen production have more narrow sources power for the electrolysis process and/or different types of CCUS and are beyond the scope of this paper. While this paper will focus on Green Hydrogen; the concept applies to utility connected industrial facilities producing hydrogen using all sources of energy (wind, solar, hydroelectric, nuclear, etc.) that provide a pathway to a carbon neutral future.

Power-to-X refers to the various pathways for the conversion, storage, and reversion of electrical power which is typically generated by renewable energy [4]. Power-to-X is a generic term where X can be hydrogen, ammonia, methanol, syngas, or eFuels. Green Hydrogen is a Power-to-X application.

B. Electrolysis of Water

Hydrogen electrolysis is the decomposition of water (H_2O) into hydrogen (H_2) gas and oxygen (O_2) gas. To understand the basics of hydrogen electrolysis, it will be useful to recall the experiment (refer to Figure 1) conducted in secondary school chemistry or science classes. Two electrodes are inserted into water – one electrode is connected to the battery's positive terminal (the anode) and the other electrode is connected to the battery's negative terminal (the cathode). A minimum DC voltage is required to initiate the electrolysis process. With this DC voltage applied, DC current flows into the water and the water molecules are split into oxygen molecules forming at the anode and the hydrogen molecules forming at the cathode. These gases then bubble to the surface and can either be released to the atmosphere or captured.

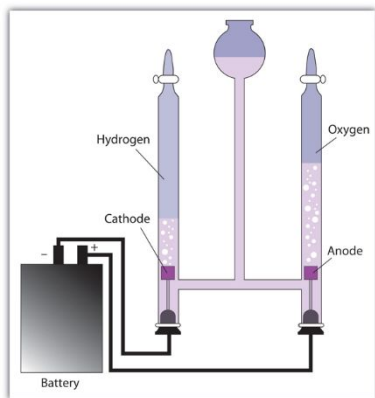


Figure 1 – Electrolysis of Water

This experiment illustrates the principals of water electrolysis and forms the foundation for industrial scale hydrogen production using electrolysis.

III. ELECTROLYZERS

A. Types of Electrolyzers

Whether used for direct industrial processing, as an energy source, or as a basis for synthetic e-fuels, sustainably produced hydrogen is considered a key technology for the energy transition. Thus, green hydrogen plays a central role in the successful decarbonization of complex energy systems. Basic research on hydrogen technologies in the energy sector is well advanced. It is now a matter of quickly making these technologies competitive. Electrolyzers are differentiated by the electrolyte materials and the temperature at which they operate, which consist of four main technologies [5]:

- Alkaline Electrolyzer (AEL) uses a Sodium or Potassium Hydroxide or solid alkaline electrolyte at 70-90°C;
- Proton Exchange Membrane (PEM) is based on a solid polymer electrolyte operating at 50-80°C;
- Anion Exchange Membrane (AEM) is based on a solid polymer membrane operating at 40-60°C;
- Solid Oxide Electrolyzer (SOE) uses a solid ceramic electrolyte operating at about 700-800°C.

In the Alkaline Electrolyzer (AEL), the electrolyte responsible for transporting the hydroxide anions (OH^-) is typically a highly concentrated potassium hydroxide (KOH) solution. The electrodes and produced gases are physically separated by a porous inorganic diaphragm (also called a separator) that is permeable to the KOH solution. Alkaline technology has high commercial maturity and operational experience.

In the Proton Exchange Membrane (PEM) Electrolyzer, the membrane is permeable to hydrogen ion (or proton) (H^+) but impermeable for gases. In other words, this kind of membrane acts as an electrical isolator between anode and cathode side as well as a physical separator, preventing hydrogen and oxygen from remixing.

In the Anion Exchange Membrane (AEM) Electrolyzer, the membrane is permeable to hydroxide anions (OH^-) and utilizes a high-pressure half-cell, and low-pressure half-cell. This pressure difference prevents remixing of gases and results in very high purity hydrogen.

In the Solid Oxide Electrolyzer (SOE), the cell consists of an oxygen electrode (anode) and a hydrogen electrode (cathode) separated by an ionic conducting electrolyte. Oxygen ions (O^{2-}) cross the electrolyte layer from cathode to anode. Due to its high temperature operation, this technology has the potential to significantly increase the power-to-hydrogen efficiency.

Anion Exchange Membrane (AEM) Electrolyzers and Solid Oxide Electrolyzers (SOE) have high potential but are much less mature technologies.

Compared to Alkaline Electrolyzers, Proton Exchange Membrane (PEM) technology is ideal for working with fluctuating wind and solar power sources, as it allows a highly dynamic mode of operation and can be rapidly turned on and off without preheating. This method allows optimum efficiency at high power densities and good product gas quality even at partial loads. The

operation is low-maintenance and reliable without the use of chemicals or foreign substances.

Figure 2 depicts the principles of these four technologies. Common to each of these more complex electrolysis technologies is a DC voltage applied resulting in the production of oxygen at the anode and hydrogen at the cathode, just like the simple experiment shown in Figure 1.

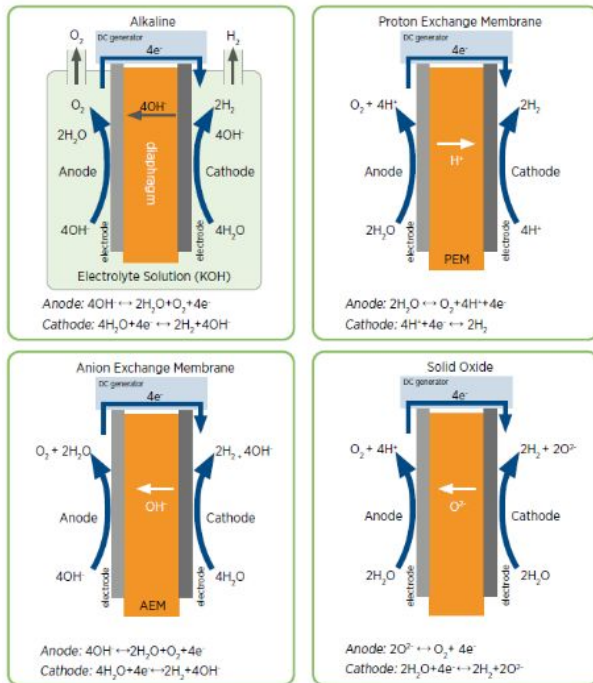


Figure 2 – Types of commercially available electrolysis technologies [6]

B. Electrolyzer Module

In an electrolyzer, the electrochemical process takes place within the cell, which is composed of the anode (+) and cathode (-). The module, also known as stack, is composed of several electrolysis cells connected in series, where the electrolytic production of hydrogen and oxygen takes place. The stack also contains spacers to insulate opposite electrodes, seals, frames for mechanical support, and end plates to prevent leaks and collect the gases, as shown in Figure 3.

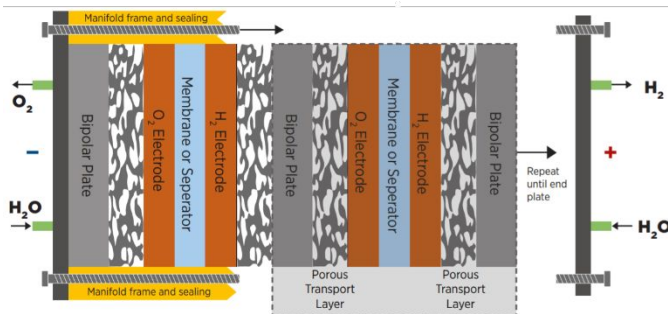


Figure 3 – Representation of Electrolyzer Module [6]

C. Electrolyzer Module Array

Electrolyzer manufacturers have created vendor-specific assemblies which consist of multiple electrolyzer modules connected in series to achieve a rated power and rated hydrogen production. An input transformer and rectifiers are added to create a vendor-specific standard solution. These solutions, known as electrolyzer module arrays, enable use of their standard design. To achieve a desired hydrogen production, multiple standard electrolyzer module arrays are used.

Presently, electrolyzer module arrays are commercially available up to 20MW. In the near term, electrolyzer module arrays up to 100MW are expected [6]. In the future and with continued technological advancements, electrolyzer module arrays rated more than 100MW will be possible. As electrolyzer module arrays grow larger, higher hydrogen production will be achieved. This will reduce the total investment costs for large-scale industrial electrolysis plants.

A typical power supply configuration to the Electrolyzer Module Array consists of the following components:

- Rectifier transformer with MV primary winding and four LV secondary windings to generate a 24-pulse system on the MV side using a 15-degree phase shift between LV windings.
- Thyristor based 6-pulse rectifiers, one per module string, to convert AC power into DC and adjust DC voltage and current to achieve the required hydrogen production rate. Other rectifier topologies are available in the industry.
- Interconnecting busbars and cables, control cabinets, miscellaneous equipment.

The rectifiers isolate the AC power system from the DC system required for the operation of the electrolyzer and splits them into defined subsystems that are ungrounded. The ungrounded system allows to continue operation after a single ground fault permitting a coordinated shutdown instead of a trip.

The thyristor-based rectifiers allow smooth adjustment of the DC voltage over a wide range at the cost of a deteriorating power factor. The active power of each rectifier is constantly adjusted so that the load of each rectifier is identical, and harmonics are reduced to a minimum. The high number of cells are connected in series which results in a typical operation voltage of 500-700 V DC. This comparably high voltage enables a DC supply with high efficiencies.

On-load circuit breaking on the DC side is achieved via firing impulse inhibition of the thyristor rectifiers. For complete separation of the electrolyzer module array from the grid, two off-load DC disconnectors are installed per module series, one on each pole from the rectifier. As a back-up, the MV circuit breaker can be tripped.

Thyristor based rectifiers create significant harmonic content in the feeding power system. The first step to mitigate these is to increase the pulse number. The rectifier transformer creates a 24-pulse system that shows a significant improvement over the individual 6-pulse rectifiers. Evaluation and mitigation of harmonics is further discussed in Section V of this document.

D. Key characteristics of Electrolyzer Module Array

i. Rated Plant Power - MW (BoL/EoL)

Power consumption throughout the lifecycle of the plant is an important design consideration, electrolyzer cells would typically have a Beginning of Life (BoL) stack voltage level and a higher End of Life (EoL) stack voltage level derived from the aging of the cell. Based on this, two different design philosophies can be considered: the plant can be designed on the basis that hydrogen output is maintained at nominal level over the entire lifetime of the PEM module arrays. This is achieved by increasing the power fed to the electrolyzer in order to compensate the effect of membrane degradation. If this approach is selected, the EoL power demand must be used to size the electrical power system. Another approach is to design for constant power consumption, which would mean that hydrogen output would decrease over time.

ii. AC System Efficiency

The efficiency of electrolysis is determined by the amount of electricity used to produce an amount of hydrogen. Depending on the electrolyzer technology used, the efficiency of water electrolyzers is currently in the region of 60 to 80 % [7]. The system efficiency of a green hydrogen production facility, when measured in units of kilowatt hours consumed per kilograms of hydrogen produced (kWh AC / kg H₂), is a result of the individual efficiencies of the cell, stack, and balance of plant [8]. Innovation will be critical to improve efficiency of an electrolyzer system to reduce the amount of electricity required to produce one kilogram of hydrogen.

iii. Hydrogen Pressure

The hydrogen pressure output from the Electrolyzer Module Array is a characteristic that must be evaluated. Electrolyzer Module Arrays from various suppliers can have a hydrogen delivery pressure that varies from <1 barg to 30 barg. Depending on the output delivery pressure and the downstream process needs, additional hydrogen compression may be required to increase the hydrogen header pressure to a usable pressure for industrial applications.

iv. Cooling Requirements

Alkaline Electrolyzers and PEM Electrolyzers have an operating temperature of 50-90°C. This results in a significant amount of heat that must be removed from the Electrolyzer Module Arrays. This may require additional cooling system consisting of cooling water pumps, cooling water pond, air-cooled heat exchangers, cooling tower, etc.

v. Harmonics and Power Factor

Industrial scale applications for hydrogen electrolyzers are expected to be connected to a utility power system or a captive renewable power source. The DC rectifiers will produce harmonic distortions at the PCC that must be evaluated for compliance to IEEE 519 [9]. If the produced harmonic distortions exceed the allowable harmonic limits, then a harmonics filter will be required to bring the harmonics into compliance.

Additionally, the utility may impose a minimum power factor, e.g. 0.95 [10], that the facility must comply with. To meet this requirement, power factor correction capacitors (PFCC) will likely be required. The harmonic filters, if used, already include capacitance that can, at least partially, correct the power factor. If additional PFCC is required, they should be placed in the power system at the MV buses to minimize amount of PFCC that are required.

IV. INDUSTRIAL APPLICATIONS OF HYDROGEN

Today, hydrogen is recognized as a premium product produced with purities reaching near 100%. This section discusses some of the common industrial applications of hydrogen.

A. Hydrogen as Fuel

Hydrogen can be used in fuel cells to generate power using a chemical reaction instead of combustion, producing only water and heat as byproducts. It can be used in cars, in houses, for portable power, and in many other applications.

Fuel cells take the chemical energy contained within a fuel and transform the chemical energy into electricity and by-products [11]. Fuel cells can be considered as energy storage devices, where energy can be used to create hydrogen and oxygen, which can remain in the cell until its use is needed at a later time. There are multiple types of fuel cells, two common types are the solid oxide fuel cell (SOFC) and the polymer electrolyte membrane fuel cell (PEMFC) [11]. Principle of solid oxide fuel cell is shown in Figure 4.

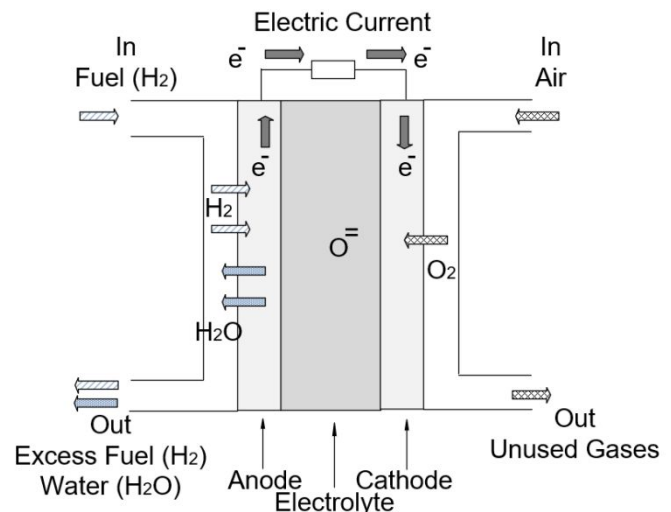


Figure 4 – Fuel cell principle of operation – Solid Oxide Fuel Cell (SOFC)

To produce electricity in a solid oxide fuel cell, oxygen in the air combines with free electrons to form oxide ions. The oxide ions pass through a ceramic electrolyte and react with molecular hydrogen to form water. The reaction that makes water, also releases electrons which pass through an external electrical circuit, producing electricity [11].

The use of hydrogen as fuel is actively being researched and developed. There are two main reasons for using hydrogen as fuel: 1) hydrogen has high energy density, and 2) the only by-product aside from electricity is water.

B. Hydrogen to Methanol

One increasingly popular industrial method of using hydrogen is in methanol production by the direct combination of hydrogen and carbon dioxide, as shown in Figure 5: This method offers a possibility of turning atmospheric CO₂ from carbon capture, or CO₂ from fuel gas extraction, and hydrogen produced from electrolysis of water, and synthesizing the two basic components into methanol. Subsequently, the methanol can be refined into a fossil-fuel substitute. After refinery processing is complete, the eFuels can be produced. The production of eFuels is based on the extraction of hydrogen using an electrolysis process which required the supplied of electricity [12]. These eFuels can be used as eGasoline, eDiesel, eHeating-oil and eKerosene and can completely replace conventional fuels. The eFuels can also be blended with conventional fuels in any desired ratio. The existing logistics, distribution and tank infrastructure, pipelines and filling stations can stay in place – there is no need for an expensive change of technologies.

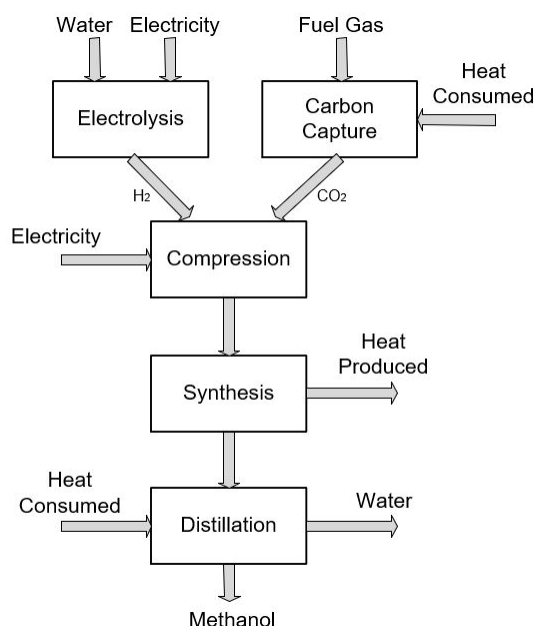


Figure 5 – Methanol production by direct combination of hydrogen and carbon dioxide

The main challenge is to make the process thermodynamically and commercially efficient, i.e. to produce more useful energy in the methanol and eFuel than the total process energy that it takes to produce it, and to sell eFuel at economically viable price.

Like any other fuels in combustion process, eFuels release CO₂. The carbon footprint neutral impact of eFuels is based on the concept that only as much CO₂ is emitted during use of eFuels as was previously captured during production, and electricity from renewable sources can be used in the production. Since electricity is used to produce eFuels, the procedure is also known as a Power-to-X process: electricity is converted into a

eFuels that are easy to store and simple to transport. eFuels can solve challenges of storing and transporting the renewable energy. At normal ambient temperature and atmospheric pressure, renewable energy can be stored easily and transported to any region in the world by using existing technologies.

C. Hydrogen to Ammonia

The Haber-Bosch process is the main industrial processes to produce ammonia. It involves the direct combination of hydrogen and nitrogen under pressure and temperature in the presence of a metal catalyst [1]. The diagram in Figure 6 represents the basics of Haber-Bosch process.

Ammonia NH₃ is used to produce fertilizers based on ammonia nitrate. Ammonia is also part of household cleaning products. Producing ammonia from hydrogen is one of the oldest industrial applications of hydrogen originating from early 20th century. Even today, ammonia represents one of the largest and most common uses and applications of hydrogen.

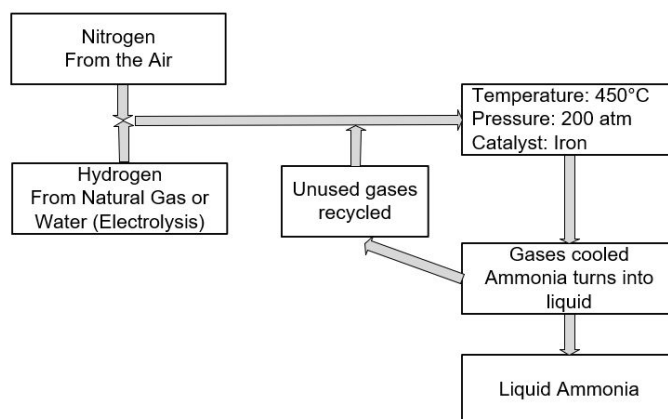


Figure 6 – Ammonia production from hydrogen and nitrogen

Nitrogen is typically extracted from air, and hydrogen is produced either from water by electrolysis, or extracted from the natural gas. The process requires nitrogen and hydrogen gases, mixed in a 1 to 3 ratio, to be placed under pressure and temperature in a vessel containing a catalyst. As the mixed gases are passed over multiple catalyst beds, the cooling between each pass maintains the equilibrium constant for the reactions. On each pass only about 15% of the gas is converted to ammonia. The liquid ammonia is stripped out and the unreacted gases are recycled. In modern plants, overall conversion rates are approximately 97%.

The potential to use ammonia to transport hydrogen is worth noting. One of the major challenges in developing the hydrogen-based approach to energy transition comes from the high cost of hydrogen transportation, which could be even multiple times higher than the cost of production itself. Methods of storing hydrogen for transportation include conversion into pressurized and liquefied form, or conversion to methanol or other types of inorganic compounds like metal hydrides. Ammonia is the desirable medium for hydrogen transportation because it is much easier and simpler to liquefy than pure hydrogen. Ammonia also

contains 1.7 times more hydrogen per cubic meter than liquefied hydrogen. Ammonia can be used directly as a fuel in some applications, or it can be reconverted back into hydrogen.

V. POWER SYSTEM INTEGRATION

Designing the electrical power system in an industrial plant that produces hydrogen requires consideration of the following key parameters:

- 1) total power requirements (which can be Giga-Watt scale),
- 2) individual electrolyzer module array power demand,
- 3) hydrogen compression to achieve suitable operating pressures,
- 4) balance of plant loads including electrolyzer cooling requirements,
- 5) harmonic profile at the utility point of common coupling,
- 6) compliance with the power factor requirements at the utility point of common coupling.

A. Power System Architecture

First, a suitable power source must be identified to supply the large Giga-Watt power consumption required. Green hydrogen projects are expected to be supplied by utility connected renewable power sources. Power purchasing agreements are usually arranged between the utility and the power consumer. The power, typically at 132 kV and higher, will be transmitted via overhead transmission lines to the facility. Redundant power feeds are preferred for increased reliability.

When the transmission lines reach the plant, they are connected to a HV outdoor switchyard, or to a HV gas insulated switchgear within the plant, either directly or via underground cable transition. From the HV switchyard or gas insulated switchgear, the voltage is then stepped down by transformers for further distribution within the facility.

It is important to recognize that a large plant with hydrogen production by water electrolysis can have dozens or hundreds of electrolyzer arrays, with each array in the range of 20 MW. There is a perfect opportunity to standardize power distribution within the facility by developing a medium voltage distribution template configuration to feed standardized clusters of electrolyzer module arrays. The balance of plant (e.g. compression services; electrolyzer cooling; hydrogen processing to methanol, ammonia, etc.) can be designed separately according to the unique features of plant's process requirements and conditions.

Figure 7 shows an example of a power system architecture in a plant that produces hydrogen by electrolysis.

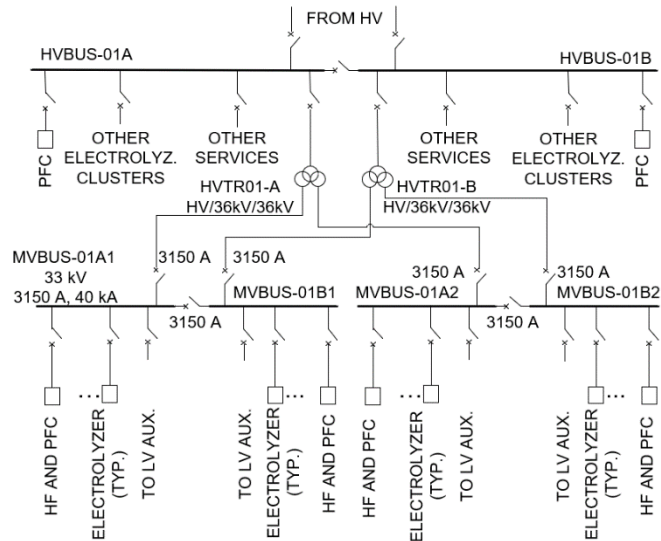


Figure 7 – Example of plant's power system architecture

The power is received from high voltage source at HVBUS-01 within the plant, and then stepped down to medium voltage distribution to feed clusters of electrolyzer arrays and other services. The high voltage level (132kV and higher) selected depends on the available plant voltages from the utility and the total load requirements. The choice of medium voltage level depends on number of electrolyzer arrays and capacity of medium voltage busbar. If 33 kV (IEC) or 34.5 kV (ANSI), gas insulated switchgear should be considered instead of air insulated switchgear to reduce the footprint. At voltages higher than 66 kV level, gas insulated switchgear should be used since air insulated switchgear is typically not available for these voltage levels and using an outdoor switchyard would require excessive space.

The example in Figure 7 shows two main-tie-main 33kV gas insulated switchgear buses (MVBUS-01xx). With 3,150 A rated busbar and circuit breaker at 33 kV level, the bus can take up to 180 MVA load. One 33 kV gas insulated switchgear arrangement with 180 MVA capacity can supply eight (8) electrolyzer module arrays of approximately 20 MW per array, low voltage auxiliaries, and can connect harmonic filters and power factor compensation equipment (HF AND PFC).

The electrolyzer module arrays are connected to the medium voltage 33kV bus using transformers with a single medium voltage input and multiple LV secondary windings. The rectifiers are supplied from these LV secondary windings and provide DC power required by the electrolyzer module arrays. In Figure 7, the typical block ELECTROLYZER (TYP.) represents electrolyzer module array with rectifiers and multi-winding input transformer to connect to medium voltage at a single point. The power factor at the input of this block is typically around 0.9 lagging.

To minimize the number (and associated cost) of HV circuit breakers, the HV feeder supply a three-winding transformer, with one primary HV winding rated 360 MVA and two 33kV secondary windings at 33 kV rated 180 MVA, making the total capacity of

this single three-winding circuit equal to 360 MVA. Figure 7 shows redundant configuration of two three winding transformers HVTR-01A and HVTR-01B, feeding two 33 kV switchgear lineups MVBUS-01A/B1 and MVBUS-01A/B2. A hydrogen production plant with many electrolyzer module arrays and a repeatable configuration is a perfect example where three-winding transformers can be used to optimize the power distribution system and reduce the electrical system cost. By using three-winding transformers, the number of HV breakers feeding electrolyzer areas and the number of transformers feeding electrolyzer areas can be reduced by half. Further details about application, selection and design of three-winding transformers is given in [13].

B. Hydrogen Compression

Hydrogen is typically produced at relatively low pressures between 20 and 30 bars and must be compressed prior to transport [14]. Most compressors used for gaseous hydrogen compression are either positive displacement compressors or centrifugal compressors. Positive displacement compressors can be reciprocating or rotary.

On projects where conventional centrifugal compressors are used, electrical motors would typically be used driven by the compressors. In a large plant with hydrogen produced by electrolysis, there are likely to be multiple hydrogen compressors and associated compressor motors to compress the hydrogen produced by groups of electrolyzer module arrays. Since hydrogen compression can be split to serve groups of electrolyzer module arrays, the rating of electric motors in hydrogen compressor service can be kept within the range of 10,000 HP to 15,000 HP. If electric network short circuit capacity is high enough, motors of those power ratings can be started direct on-line, one by one. In addition, induction motors can be used instead of synchronous, which simplifies the application.

C. Cooling

Cooling loads associated with electrolyzers are a significant energy consumer. The process of water electrolysis generates heat during the dissociation of water into oxygen and hydrogen. Compact cooling systems for the large electrolyzer module arrays are available; however, chilled water systems are very costly and cooling tower systems have too much water loss associated with drift. As an alternative, an open loop pond water circulation system can be implemented. The pond cooling is simple, but the plot restrictions may not allow large enough pond for the full cooling loads. The pond system can also be supplemented by a bank of air coolers. It should be noted that Alkaline and PEM electrolyzers produce a large amount of heat removal at temperatures too low to generate steam and/or power.

On projects involving electrolyzers in hydrogen production, the cooling system requires thorough consideration and may have significant impacts on the project.

D. Harmonics

The rectifiers utilized in the electrolyzer module array are a non-linear load and are a source of harmonics. The harmonics

at the input of the rectifiers impact the electrical network the rectifiers are connected. The harmonic distortions generated depend on the system impedance at the point of common coupling and the amount of harmonic current distortion (THDI) injected into the system. A harmonic voltage distortion (THDU) also occurs as a result.

The typical “not-to-exceed” harmonic level requirements at the point of grid interface, point of common coupling (PCC), are given in IEEE 519 [9] but some utility companies may have their own requirements. The more stringent of IEEE 519 or the utility company’s requirements will be the maximum permitted harmonic values for the project.

On a project with large electrolyzer module arrays with rectifiers, a harmonics study is required to determine THDI and THDU at the point of common coupling with the utility. When the calculated values exceed the maximum permitted harmonic values, harmonic filter(s) will be needed to reduce the harmonic distortions at the point of common coupling with the utility.

After identifying which harmonic orders are contributing most to the harmonic distortion, the harmonic filter can be designed with stages to specifically filter these harmonic orders and reduce the individual and overall harmonic distortion. The harmonic study requires actual equipment data and detailed representation of the components of the electrical system. The final filter design should include margins and provisions for future changes in the electrical system. The harmonic filters should be installed nearest to the source of the harmonics which, in this case, is the MV voltage level.

Figure 8 shows an example of current waveform and current harmonics spectrum of an electrolyzer array at the primary medium voltage side of the input transformer. Input transformer is a five-winding transformer, e.g. one primary medium voltage winding and four low voltage windings to four individual rectifiers, each rectifier feeding its section of electrolyzer array.

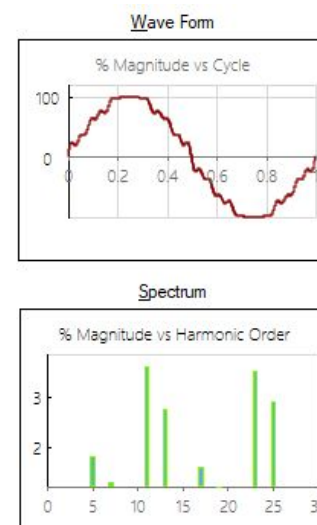


Figure 8 – Example of 4 parallel 6-pulse (24-pulse equivalent) rectifier current harmonics

Four secondary windings connected to four individual rectifiers are phase shifted. Since individual rectifier is a 6-pulse device, connecting four rectifiers through four phase shifted low voltage windings makes the entire assembly effectively a 24-pulse. Figure 8 demonstrates a fairly “smooth” sinusoidal waveform, which is expected from an equivalent 24-pulse harmonic.

The medium voltage 35 kV busbar total voltage harmonics distortion is 7.57 %, and at the point of common coupling (PCC), the HV bus 345 kV, the total voltage harmonic distortion is 4.26%.

The maximum permitted voltage distortion limits from IEEE 519 are shown in Table I.

Table I – Voltage Distortion Limits Per IEEE 519 [9]

Bus Voltage V at PCC	Individual Harmonic (%)	Total harmonic Distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq 69$ kV	3.0	5.0
69 kV $< V \leq 161$ kV	1.5	2.5
161 kV $< V$	1.0	1.5

At the point of common coupling at 345 kV, if no filters are used, the total harmonic distortion of 4.26% is higher than the maximum allowed 1.5% per Table I. Even though 24-pulse waveform is fairly smooth, harmonic filters are required. This clearly illustrates that the decision whether harmonic filters are required should not be solely based on the number of pulses of the rectifier system. Instead, a harmonic study must be performed to evaluate the harmonics at the PCC.

After the harmonics study was done, it was determined that three-stage filters on each 35 kV bus was adequate to address the harmonics. Stages were tuned at 5th, 11th and 23rd harmonic, with damping. With filters, the medium voltage 35 kV busbar total voltage harmonics distortion is 2.68 %, and at the point of common coupling (PCC), the HV bus 345 kV, the total voltage harmonic distortion is 1.48%. Figure 9 shows voltage waveform at the point of common coupling 345 kV bus without filters and with filters.

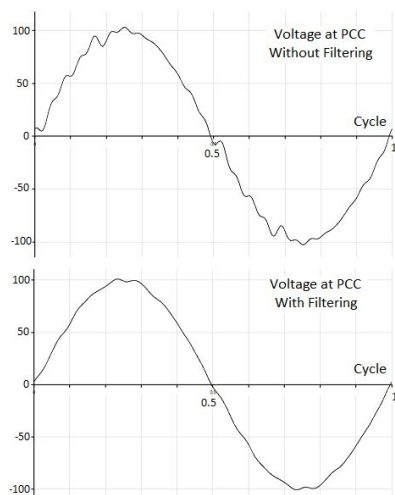


Figure 9 – Voltage waveform at the HV point of common coupling (PCC) without and with filtering

To model for the harmonic analysis studies, it is important to determine sources of current harmonics, model components of the electrical system, select location of harmonic filter, and define criteria and scenarios for harmonic filter sizing. Many scenarios need to be evaluated to consider different load conditions in the plant, capacitors and filters stages, and different electrical system configurations.

E. Power Factor

Large industrial plants with hydrogen production by electrolyzers usually connect to an electric utility grid. Power factor demand at the grid interface is specified by Utility Company and it is often stringent, e.g. higher than 0.95 [10]. The main building block of the power consumption structure in the hydrogen production plant, the electrolyzer array, at the medium voltage primary side of its input transformer, has power factor typically around 0.9 lagging. Also, another side effect of using thyristor-based rectifiers is that control of the DC voltage requires an adjustment of the firing angle, which will cause an increased reactive power draw of the rectifier. Between the high voltage, where point of interface with the utility is, and medium voltage, where inputs to electrolyzer systems are, there is at least one more set of transformers, with reactive power losses, so total power factor is significantly lower than 0.9. To meet a utility requirement of 0.95, power factor compensation will be required.

Harmonic filters are usually connected on medium voltage, where they are most effective because electrolyzer arrays with rectifiers as sources of harmonics are connected to medium voltage through input transformers. Harmonic filters have capacitances as part of filter units and help compensate reactive power and improve the power factor.

In example in Figure 9, if harmonic filters are not used, and there are no other capacitors, power factor at the medium voltage bus would be 89.9% and power factor at the high voltage bus, the point of common coupling (PCC) bus is 81.3%. If filters are included on medium voltage to address harmonics, power factor improves, and in the example, medium voltage bus power factor is 96.77%, and at the PCC on the HV bus the power factor is 90.72%. Typically, additional power factor compensation equipment (PFC) is needed to regulate power factor to acceptable level, in this example above 95%.

VI. CONCLUSIONS

There are significant challenges ahead to meet the target reducing the cost of hydrogen to \$1 per 1 kilogram in one decade outlined by the Hydrogen Energy Earthshot initiative.

However, continued development of large-scale hydrogen electrolyzers will create the opportunities for Giga-Watt scale hydrogen production facilities utilizing clean renewable power. These Giga-Watt scale hydrogen production facilities will be complementary to the continued development of green energy (wind and solar) sources by providing a large but dispatchable load that will allow increased capacity factor for these renewable energy sources.

Integrating large-scale hydrogen electrolyzers in an industrial application creates many challenges in the design of the electric power system. These challenges include obtaining and distributing large scale electric power, designing the system to align with power rating of electrolyzer module arrays, tradeoff of keeping the power demand constant resulting in a reduction of electrolyzer production rate over the lifetime or increased power demand over time to keep the constant production, as well as the challenges with hydrogen compression, electrolyzer cooling, and harmonics and power factor impact on the power supply grid.

Even with these significant challenges, green hydrogen has significant potential to decarbonize industrial sectors and lead these sectors in energy transition towards a carbon neutral future.

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IX. VITAE

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