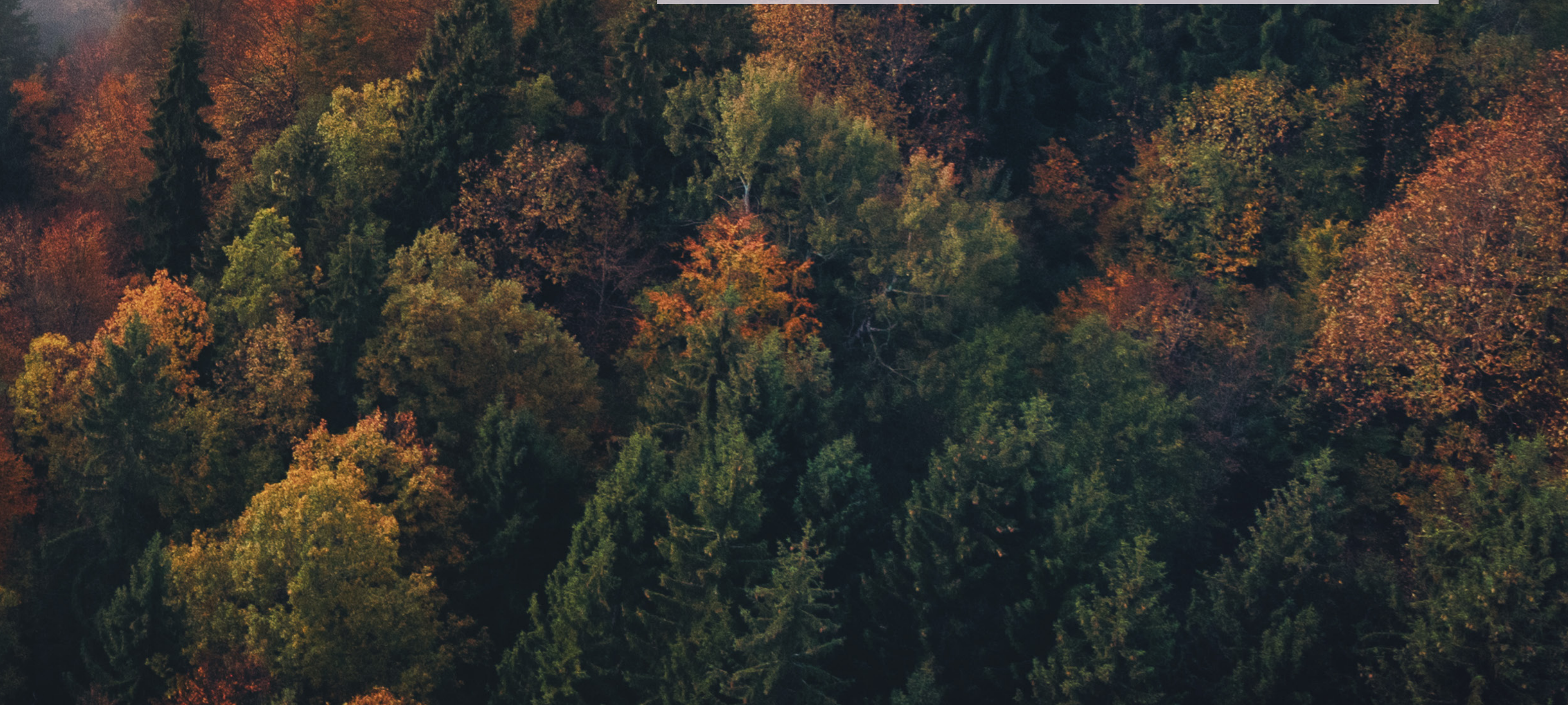
CLEARING THE FOG



Dinesh Pattabiraman and Manish Verma, TMEIC Corp. Americas, USA, address the impact that power supply can have on the cost and efficiency of electrolytic hydrogen production.

One of the biggest challenges with the hydrogen economy is replacing fossil-derived hydrogen with clean hydrogen, a product that has zero impact on the environment. Among the various pathways to produce clean hydrogen, electrolysis is a powerful catalyst for achieving a low-to-no-carbon hydrogen supply. The prevailing idea is that by harnessing excess renewable electricity and transforming it into hydrogen, we have the potential to decarbonise stalwart industries like steel, refining, and fertilizers, and unlock new use applications for hydrogen; replacing traditional energy sources with a clean one. While electrolysers receive much attention as a crucial component in electrolysis, the technology selection for the power supply unit is equally vital. This power supply unit (PSU) is critical in converting alternating current (AC) power to direct current (DC) power, ensuring optimal performance. Its significance lies in its impact on the project's overall capital cost and operating expenses, which has a material effect on the levelised cost of hydrogen (LCOH). This article will outline the importance of the PSU, as well as factors which drive the cost of the PSU, and finally, what types of PSU technologies are available, along with crucial advantages and disadvantages. Ultimately, understanding the PSU and its nuances will help the cost, performance, and scalability of electrolytic hydrogen as one of the most cost-effective vectors for energy transition paths for hydrogen.

Regulatory background

The US government has sent a clear signal to develop the nascent hydrogen industry by passing two pieces of legislation:

- The Infrastructure and Investment Jobs Act (IIJA) of 2021 pledges US$8 billion in funding to de-risk and develop promising hydrogen hubs nationwide, regardless of the hydrogen production technology used. The overarching goal is to demonstrate that for every 1 kg of hydrogen produced, no more than 2 kg of carbon dioxide equivalent (CO_2e) are emitted on-site.
- The Inflation Reduction Act (IRA) of 2022, under Section 26 USC 45V of the tax code, provides a production tax credit (PTC) based on the lifecycle carbon emissions, on a well-to-gate basis, for every kilogram of hydrogen. Table 1 summarises the amount of PTC.

In perspective, current methods of producing hydrogen through the conventional steam methane reforming (SMR) process emit around 8 - 12 kg of CO_2e / kg of hydrogen. Therefore, to qualify for the statutory allowable maximum tax credit of US$3/kg of hydrogen, the carbon intensity should be between 0 – 0.45 kg of CO_2e / kg of hydrogen.

These two pieces of legislation are helping with investment decisions in the hydrogen industry and will accelerate the development of related technologies.

Producing electrolytic hydrogen

Over the past year, hydrogen's role in the energy transition has been widely discussed. Regarding electrolytic hydrogen, the talk has been exclusively focused on the electrolyser itself, focusing on novel materials. There is indeed lots to talk about when it comes to novel materials, coatings, costs, and overall project economics. However, the discussion has not detailed the upstream DC power supply unit, the PSU. This is understandable, as most professionals in this industry are chemical or electrochemical engineers. DC power supplies are viewed as a mature technology relative to electrolysers. However, this is not so. Megawatt (MW) scale DC supplies can vary significantly in cost and performance depending on the technology and topology. A wholistic approach is therefore required to safely, cost-effectively and reliably deploy electrolytic hydrogen.

Figure 1 shows the typical cost structure of an electrolyser system and the component disaggregation for the balance of plant services. The PSU constitutes approximately one-third of the total cost of the electrolyser system, and it should not be overlooked.

Figure 2 provides an illustration of a typical electrolysis process. Three major factors affect the cost structure of the PSU:

- Step-down transformer.
- Grid-side and electrolyser-side performance requirements of the rectifier.
- Electrolyser DC current rating.

The step-down transformer reduces the voltage level available from the utility service (typically 34.5 kV) to a voltage level used by the rectifier itself. In power electronics, the basic building blocks of a circuit form what is known as a topology.

The power conversion topology determines the grid-side and load-side (electrolyser) performance. The DC current rating determines the size and number of PSUs necessary to satisfy the current rating at the electrolyser's beginning and end of life.

It is critical to note that rectifiers are primarily sized and priced based on their DC current rating rather than the power rating, which is a product of voltage and current. A higher current requires more semiconductor devices, more copper and more thermal cooling, which drives up cost. Rectifier cost strongly, positively, and directly correlates with the current they have to deliver. While there is some correlation of cost with operating voltage due to the choice of semiconductor devices, the impact is much stronger with current. Transformer cost is also affected by the stack current rating, since the low voltage winding would require more copper to deliver a higher current, therefore increasing its cost.

Figure 3 shows how DC amps vary as a function of DC volts for a 20 MW, 10 MW and 5 MW electrolyser stack size. Holding DC volts constant, the electrolyser watts directly determine the amps that are required from the rectifier. In addition, as the electrolyser stack voltage is increased, the DC amps are lower in order to hold the stack power constant. This can be leveraged in the electrolyser design to reduce the PSU cost, by lowering the current (amps) that a particular stack requires. A rectifier that needs to deliver 25 MW at 500 V is a quite different rectifier (in terms of size, cost, and configuration) than one that needs to deliver 25 MW at 1500 V. The number of amps necessary is reduced by almost 66%.

Table 1. 45V tax credit structure for hydrogen production

Life cycle emissions (kg of CO_2e/kg of hydrogen)	PTC value (US$/kg of hydrogen)
4 – 2.5	0.60
2.5 – 1.5	0.75
1.5 – 0.45	1.00
0.45 – 0	3.00

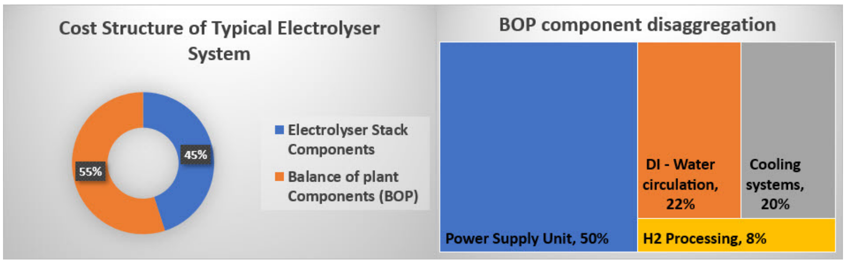


Figure 1. Cost structure of typical electrolyser system and balance of plant (BOP) component disaggregation.[1]

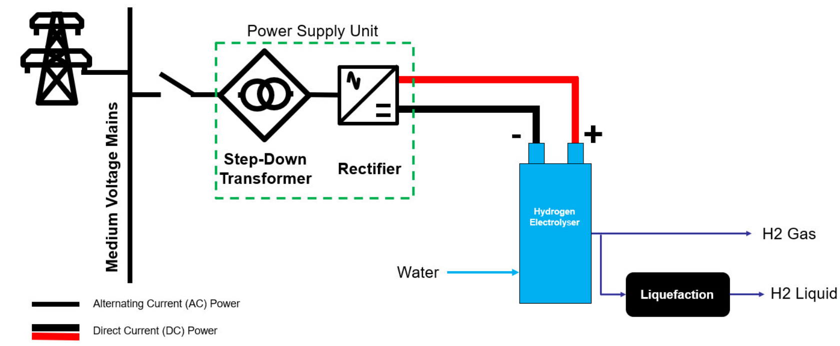


Figure 2. Electrical illustration of an electrolyser.

Major topologies available for PSUs

Historically, thyristor devices such as the silicon-controlled rectifier (SCR) have been used for AC to DC power conversion. Power-intensive processes such as chlor-alkali, electrowinning, and aluminium smelting use these devices. SCRs continue to serve the industry with their robustness and low cost. However, they have application considerations that need to be accounted for in project design. The advent of fast switching transistor devices known as insulated gate bipolar junction transistors (IGBTs), and continuous improvements in their performance, have led to their widespread adoption in many applications such as electric motor adjustable speed drives, traction systems and, more recently, in solar and energy storage inverters. Due to the economies of scale and the nature of their voltage and current characteristics, IGBT-based rectifiers present a unique value proposition for their applicability in electrolytic hydrogen production. These characteristics are summarised in Figure 4.

Two crucial application considerations are highlighted here: harmonics and power factor. AC to DC power conversion inherently introduces non-linearities, generating electrical harmonics on the grid. This can be likened to 'electrical pollution' in simple terms and utility standards necessitate these harmonic levels to be within acceptable limits.

In the case of thyristor-based technology, additional harmonic filters are required at the electrical substation. These passive filters introduce extra costs, occupy physical space, have power losses, and control flexibility comes at a high cost. These filters are hard to design to accommodate the variable electrolyser load which may fluctuate based on available renewable power. Additionally, thyristor-based rectifiers exhibit a low power factor load to the utility, as the line-side power factor is dependent on the electrolyser load. Many utilities worldwide are imposing mandates on their customers, requiring a minimum power factor of 0.95 or even higher. Failure to meet this requirement may result in penalties. Transistor-based rectification technology such as IGBTs mitigate these two issues, providing greater certainty in electrical performance. Furthermore, due to their widespread adoption in the renewables industry, these systems have become cost-effective in terms of manufacturing and installation.

By transitioning to transistor-based rectifiers, the harmonic pollution and power factor challenges can be significantly reduced or eliminated. This alternative technology offers improved electrical performance, cost-effectiveness, and operational flexibility, making it an attractive choice for electrolysis systems seeking optimal efficiency and compliance with utility requirements.

Comparing IGBT-based power conversion topologies

IGBT-based conversion topologies can utilise a single stage or a multi-stage conversion with each topology possessing its own application considerations. A single-stage AC-DC power conversion is typically achieved through a 3-phase converter, which is widely applied in solar photovoltaic inverters, energy storage inverters, etc. This topology offers acceptable harmonic pollution and allows for active control of reactive power, which eliminates the need for any additional harmonic filter or power factor compensation equipment in the plant. The operating principle of this topology is a voltage boost

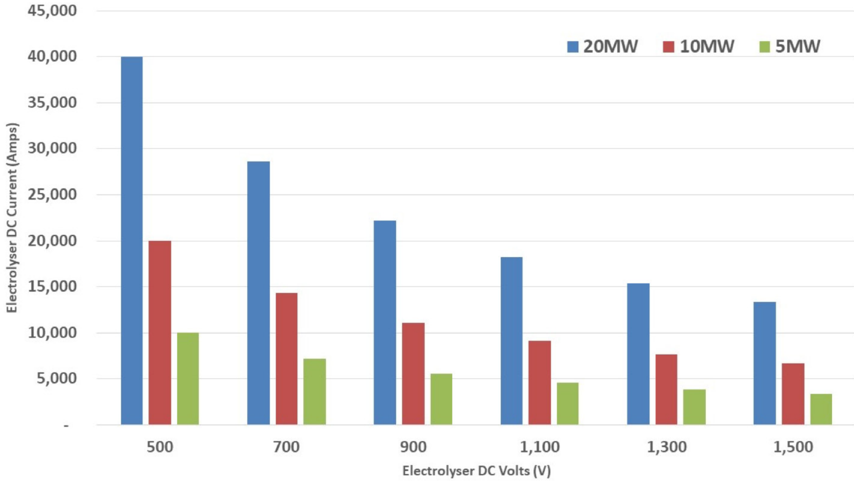


Figure 3. DC current (amps) as a function of DC volts (V) for 20 MW, 10 MW and 5 MW electrolyser stack.

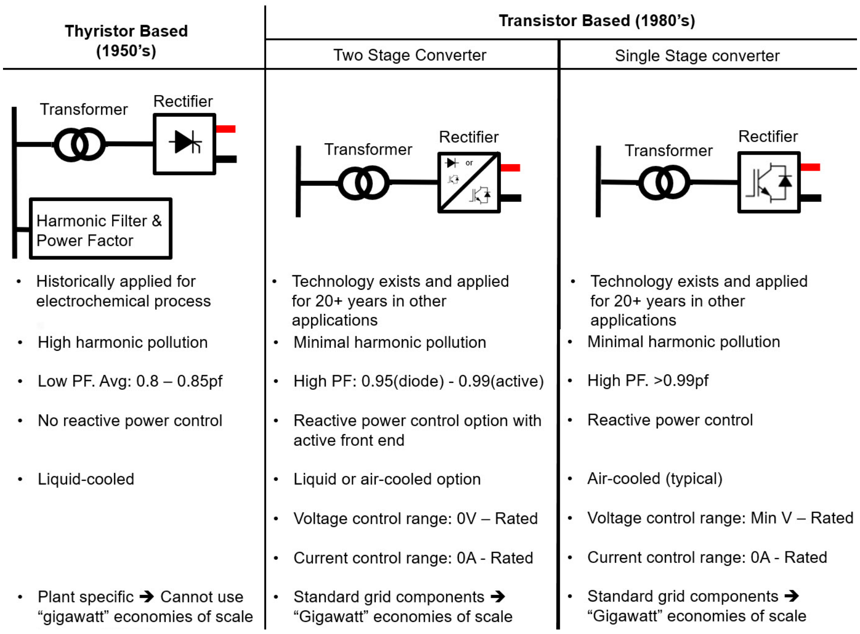


Figure 4. Summary of major rectification topologies for electrolytic hydrogen.

which delivers a higher DC voltage than the AC voltage and therefore necessitates a minimum DC voltage for operation based on a fixed AC voltage. Since the minimum stack voltage is affected by the beginning of life operation at the lowest possible current, the AC voltage must be lowered to match this voltage. A lower AC voltage increases the current capability required and would drive up the cost. In addition, the minimum DC voltage required can complicate pre-charging requirements for the electrolyser.

A two-stage conversion utilises a front-end to rectify the AC voltage to DC as well as a separate DC-DC stage to match the electrolyser demand and overcome the minimum DC voltage requirement. The front-end can be diode-based in order to reduce cost and increase conversion efficiency. Even though active reactive power control is not possible, the topology can deliver at least 0.95 power factor. Harmonic pollution can be lowered to acceptable levels by using a multi-pulse, phase-shift transformer. Using an active front-end instead helps achieve unity power factor and compliance with harmonic limits without using phase-shifted transformers. The active front-end and DC-DC stages can be coordinated to achieve good overall efficiency. Further, the active front-end can boost the DC voltage above the nominal voltage produced by a diode rectifier, which enables operation at higher DC voltages. Overall, the topology offers a broad control range from 0 V – rated DC voltage, which increases its flexibility to match the electrolyser performance.

Conclusion

Hydrogen is poised to revolutionise decarbonisation efforts across major sectors of the economy, and electrolytic hydrogen production stands out as a promising method. While improving electrolyser stack performance and reducing costs remain critical, disregarding the significance of the DC power supply would be a costly mistake. The current flow through the system directly impacts rectifier costs, making it an essential factor to consider. One effective approach to minimise current is by increasing stack voltage. While the average stack voltage hovers around 700 V, the industry is witnessing a trend toward stack voltages in the 1000 - 1500 V range. Standardising the volts and amps within the electrolyser industry would unlock economies of scale and lead to cost reduction, mirroring the success achieved in the solar industry in the last decade. Regarding CAPEX in hydrogen production facilities, the rectifier's cost, performance, and scalability play a crucial role.

Conversely, OPEX is driven by safety, efficiency, and reliability considerations. In the short-term, aligning stack volts and amps with the PSU capability proves to be the most effective means of reducing CAPEX. However, eventually, the OPEX truly matters. The industry must actively engage with both balance of plant (BOP) scope suppliers and, more importantly, DC power supply unit manufacturers at the preliminary stages of design. Collaboration between these stakeholders will enable mutual support and pave the way for widespread adoption of hydrogen, driving the industry toward a cleaner and more sustainable future.

Reference

1. 'Harnessing green Hydrogen in India,' adapted for IRENA report 2020, https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf.