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How can Hydrogen Electrolysers be Made in India?

A Bottom-up Cost Assessment to Quantify the Indigenisation Potential

Report | September 2024

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How can Hydrogen Electrolysers be Made in India?

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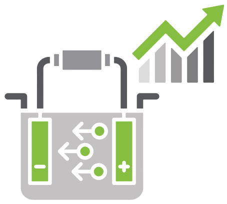
Contents

An electrolyser system comprises an electrolyser stack and balance of plant (BoP) components like power supply unit, pump, compressor, storage, and hydrogen processing unit.

Image: Alamy

Executive summary

India has set an ambitious target of producing 5 million tonnes per annum (MTPA) of green hydrogen by 2030 with an aim to mitigate 50 million tonnes of CO2 and reduce energy imports by INR 1 lakh crore. Electrolysers play a critical role in the green hydrogen production process and constitute 30–50 per cent of the total cost of green hydrogen; the rest is renewable energy (RE) and storage (Biswas, Yadav and Baskar 2020). India has already introduced several policy interventions to scale up domestic production of RE (PIB 2024). Although electrolysers have existed for many decades, the green hydrogen economy has significantly increased demand for them. The electrolyser market in India is expected to grow to 20 GW by 2030, 112 GW by 2040, and 226 GW by 2050 (NITI Aayog 2022). A robust domestic electrolyser manufacturing ecosystem can also help unlock export opportunities, as the global demand for electrolysers is expected to be 590 GW by 2030 and 3,300 GW by 2050 (IEA 2023).



India's electrolyser market is projected to reach 20 GW by 2030. This capacity is expected to increase fivefold to 112 GW by 2040 and double again by 2050, reaching an estimated 226 GW

However, the success of domestic electrolyser manufacturing will depend, to a large extent, on the indigenisation of the overall manufacturing cost. To secure a competitive advantage, India must invest in developing indigenous technologies that increase efficiency and thus the cost of green hydrogen production and proprietary knowledge of various newer electrolysers technologies. A strategic approach to maximising the indigenisation of electrolyser manufacturing will be important for India in the early stages of a green hydrogen economy. A bottom-up cost analysis for electrolyser manufacturing provides insights into potential cost-reduction trajectories and identifies the indigenisation potential for the commercial models – alkaline, proton exchange membrane (PEM), and solid oxide electrolysers (SOEs).

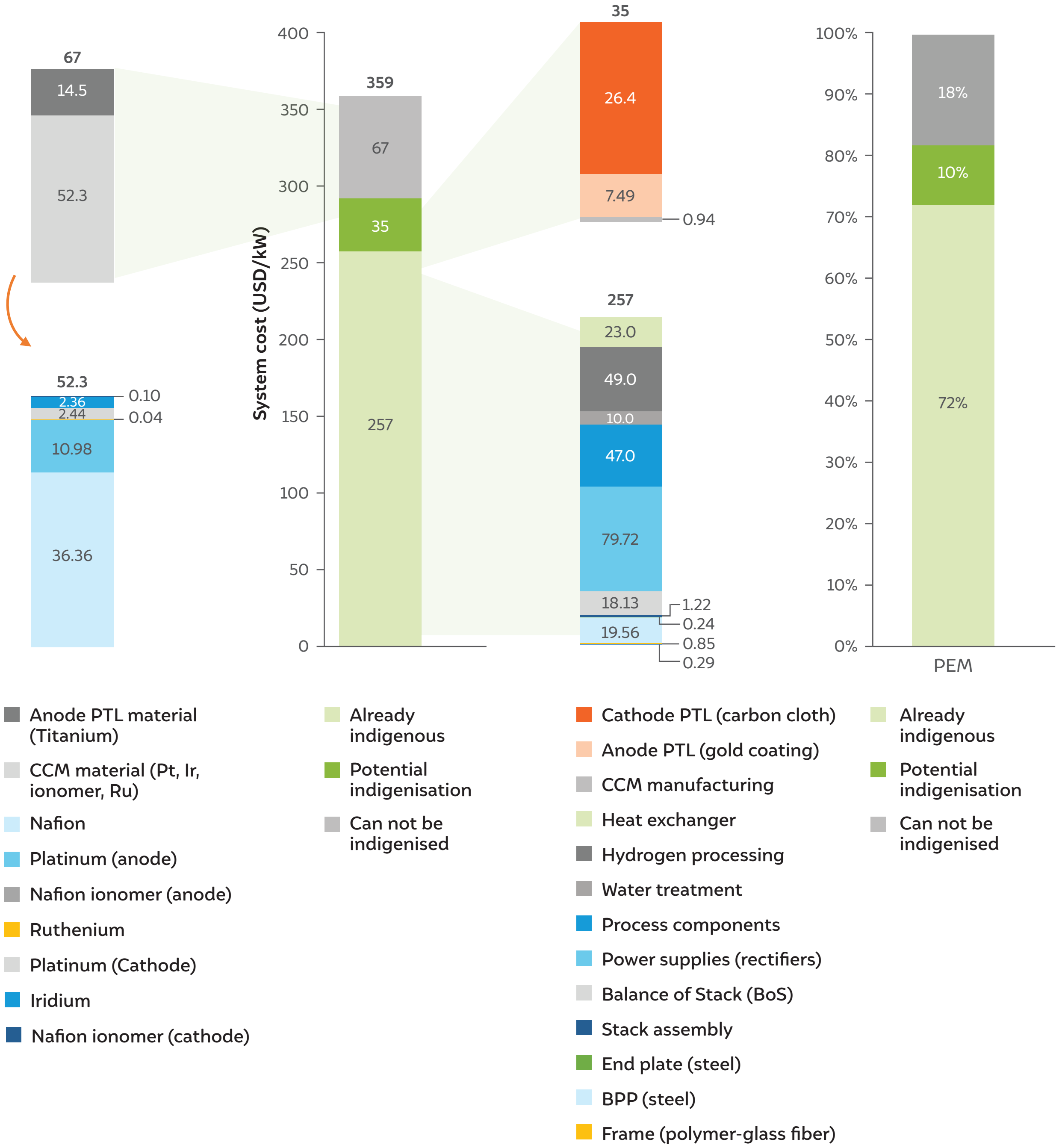
A. Bottom-up manufacturing cost and potential for indigenisation in electrolysers

To assess the potential for indigenisation in electrolyser manufacturing, we categorise the manufacturing cost of electrolysers into three parts: components that are already indigenous, components that can be indigenised with some effort, and components that cannot be indigenised due to technology and material constraints.

Manufacturing costs of PEM electrolysers

As indicated in Figure ES1, our analysis shows that the bottom-up manufacturing cost of a PEM electrolyser is USD 359 per kW. The electrolyser stack constitutes about 40 per cent of the overall manufacturing cost, while the balance of plant (BoP) covers the remaining 60 per cent.

Figure ES1 Around 82% of PEM electrolyser manufacturing can be indigenised



Source: Authors' analysis

Our research indicates that about 72 per cent of the PEM electrolyser manufacturing cost can be readily indigenised. All BoP components, such as power converters and heat exchangers, are already manufactured in India for various other applications and can be readily adapted to electrolyser manufacturing. However, components such as the Nafion membrane[1] have not yet been developed in India. Hence, these components will need to be imported in the initial years. Further, key minerals such as platinum and iridium are not available in India. Thus, indigenous manufacturers will remain dependent on mineral imports unless alternatives are developed. Nonetheless, our study finds that these components contribute to only 18 per cent of the total manufacturing cost.

On a system level, 72% of PEM manufacturing cost, 80% of alkaline manufacturing cost, and 61% of SOE manufacturing cost can be readily indigenised

We found that the indigenisation of a few components can be increased if the raw material is imported, and its processing takes place in India. For example, although titanium powder might have to be imported for meeting our future electrolyser demand, its compacting, sintering, and gold coating can be accomplished in India. Similarly, it may be more efficient to import only key minerals and the Nafion membrane whereas the CCM manufacturing and carbon cloth can be made in India. With such incremental efforts, electrolyser manufacturing processes in India can be indigenised by an additional 10 per cent.

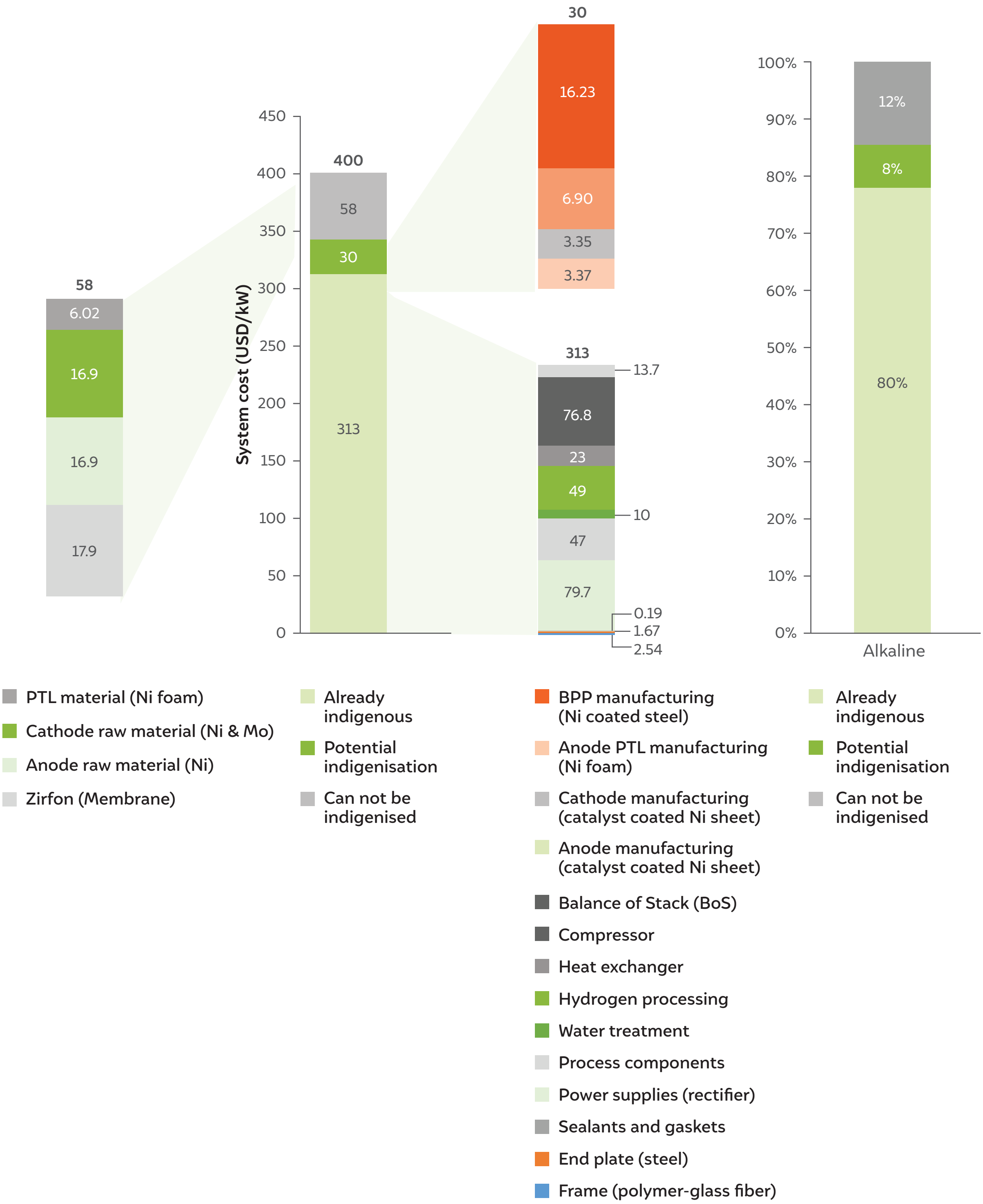
Manufacturing costs of alkaline electrolysers

Figure ES2 shows the bottom-up manufacturing cost of alkaline electrolysers to be USD 400/kW. As with PEM electrolysers, we assume that all BoP components – including the hydrogen compressor – are already manufactured within India. Components such as frames, end plates, and the balance of stacks (BoS) within the electrolyser stack can also be manufactured in India.

Our analysis indicates that around 80 per cent of the total alkaline electrolyser cost can be readily indigenised. While India does not have nickel resources, nickel coating of bipolar plates (BPPs) and electrodes can potentially be done in India, which can further boost the indigenisation of electrolyser manufacturing by around 8 per cent. The current technology uses Zirfon membranes, nickel, and molybdenum as raw materials for electrode manufacturing and coating. Nickel foam might not be indigenised right away and must be imported. Hence, we regard these raw materials and imported commodities as those that cannot be indigenised. While the Zirfon membrane can potentially be manufactured in India, zirconia (ZrO_2) – which costs around USD 10/kW (USD 90/kg)– has to be imported due to limited reserves within India. Therefore, while India should focus on augmenting its capacity to manufacture the membranes used in alkaline electrolysers, attempts should also be made to develop alternatives to zirconia-based technologies or explore zirconia resources in India.

1. Nafion is a sulfonated tetrafluoroethylene-based fluoropolymer-copolymer used as a proton exchange membrane in fuel cells and water electrolysers to separate the anode and cathode which selectively allows only protons to cross the membrane.

Figure ES2 Around 85% of the alkaline electrolyser cost can be indigenised

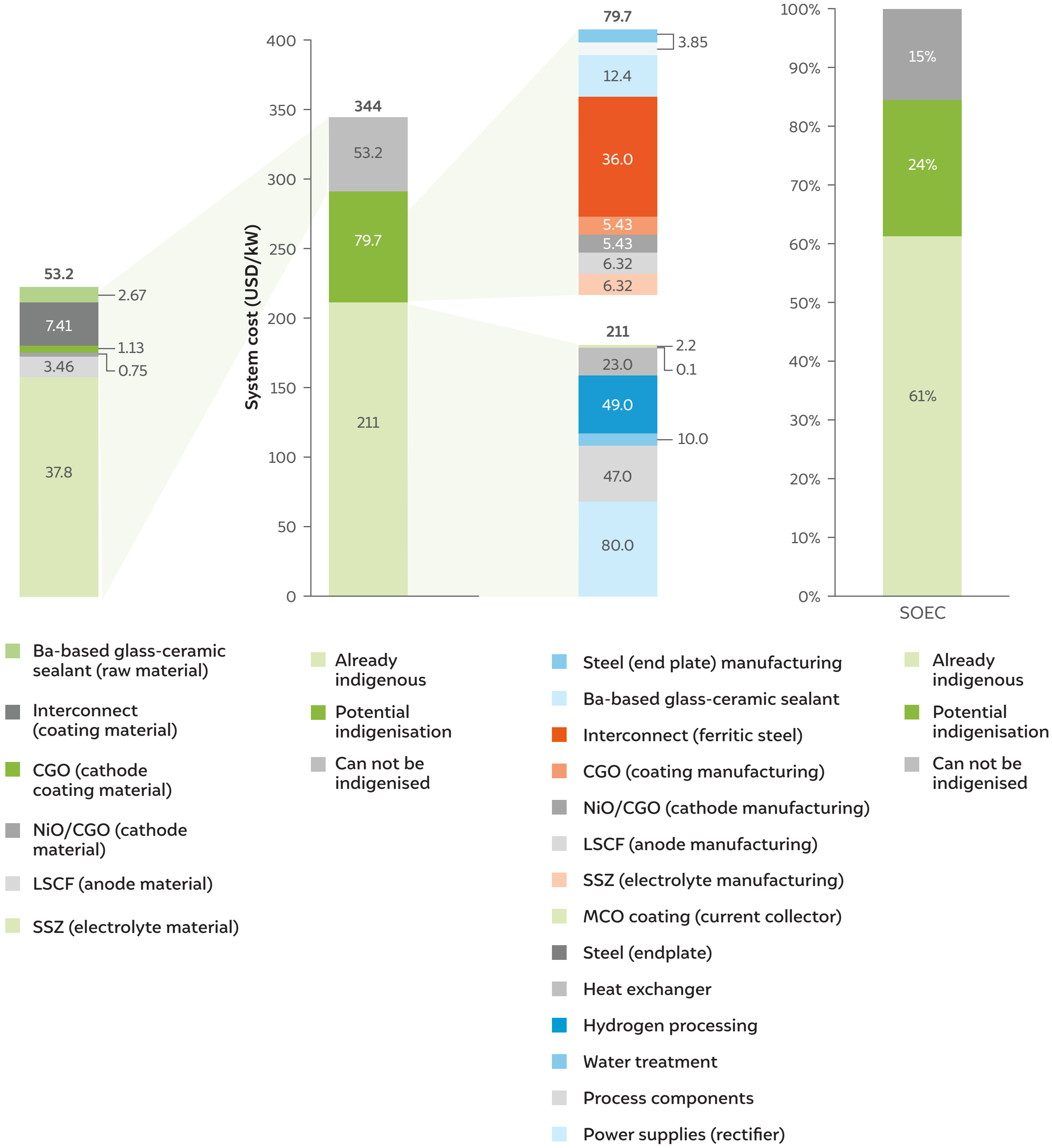


Source: Authors' analysis

Manufacturing costs of solid oxide electrolysers (SOEs)

Figure ES3 shows that the bottom-up manufacturing cost of an SOE system would be around USD 344/kW. We estimate that the BoP constitutes approximately 60 per cent of the total manufacturing cost while the rest are stack material and manufacturing costs. The broad assumptions – that BoP components are already indigenised, that manufacture of finished components can potentially be indigenised, and that critical raw materials with low reserves in India cannot be indigenised – still hold. So we estimate that up to 61 per cent of the total manufacturing cost of SOEs is already indigenised. A further 24 per cent can be indigenised if components such as the interconnect, electrolyte, and electrodes are manufactured in India; however, the raw materials for these might still need to be imported. However, 15 per cent of the manufacturing cost cannot be indigenised, primarily because India lacks reserves for critical minerals such as nickel, molybdenum, and zirconium. Thus, full indigenisation is possible only if alternatives are developed for these minerals.

Figure ES3 Around 85% indigenisation is possible in SOEs



Source: Authors' analysis

B. Technology development targets

Table ES1 lists the technology development targets for PEM and alkaline electrolyser manufacturing in India. A major developmental goal is improving electrolyser performance such that the current density can be increased significantly without any increase in operating voltage. This implies that the electrolyser size (in kW or MW) should be able to increase without resulting in an increase in material consumption.

Further, material consumption can also be reduced through other technological improvements. For example, the consumption of platinum and iridium in PEM electrolysers can potentially be reduced, and the thickness of the membrane in PEM and alkaline electrolysers can be decreased substantially, potentially through the use of nanotechnology. The use of alternative materials can also play a crucial role in reducing electrolyser costs. For example, the titanium used as the porous transport layer (PTL) in PEM electrolysers can be replaced with stainless steel, thus reducing manufacturing costs substantially.

Table ES1 Technology development targets to reduce the manufacturing cost of PEM and alkaline electrolysers

Area	Parameter	Current status	Technology development goals	Reference
PEM electrolyser				
Stack specification improvement	Current density	1.8 A/cm^2	3.5 A/cm^2	(Krishnan, et al. 2023)
	Voltage	1.6 V	1.8 V	(Krishnan, et al. 2023)
	Stack size	0.2 MW	0.44 MW	This study based on (NREL 2019)
CCM	Nafion membrane thickness	183 microns	80 microns	(Krishnan, et al. 2023)
	Pt-Ir loading	Pt: 0.9 mg/cm^2 Ir: 0.2 mg/cm^2	Pt: 0.05 mg/cm^2 Ir: 0.1 mg/cm^2	(Krishnan, et al. 2023)
PTL (anode)	Material	Titanium	Stainless steel	(Daudt, Hackemüller and Bram 2020)
	Coating and thickness	Gold: 100 nm	Niobium: 20 nm	(Kim, et al. 2021)
BPP	Coating and thickness	Gold: 100 nm	Niobium: 20 nm	(Kim, et al. 2021)
Alkaline electrolyser				
Stack specification improvement	Current density	0.2 A/cm^2	1.3 A/cm^2	(Krishnan, et al. 2023)
	Voltage	1.68 V	1.79 V	(Krishnan, et al. 2023)
	Stack size	0.2 MW	0.69 MW	This study based on (NREL 2019)
CCM	Zirfon membrane thickness	500 microns	200 microns	(Krishnan, et al. 2023)
Electrode	Nickel reduction	1,602 kg/kW	800 kg/kW	(IEA 2021)

Source: Authors' compilation

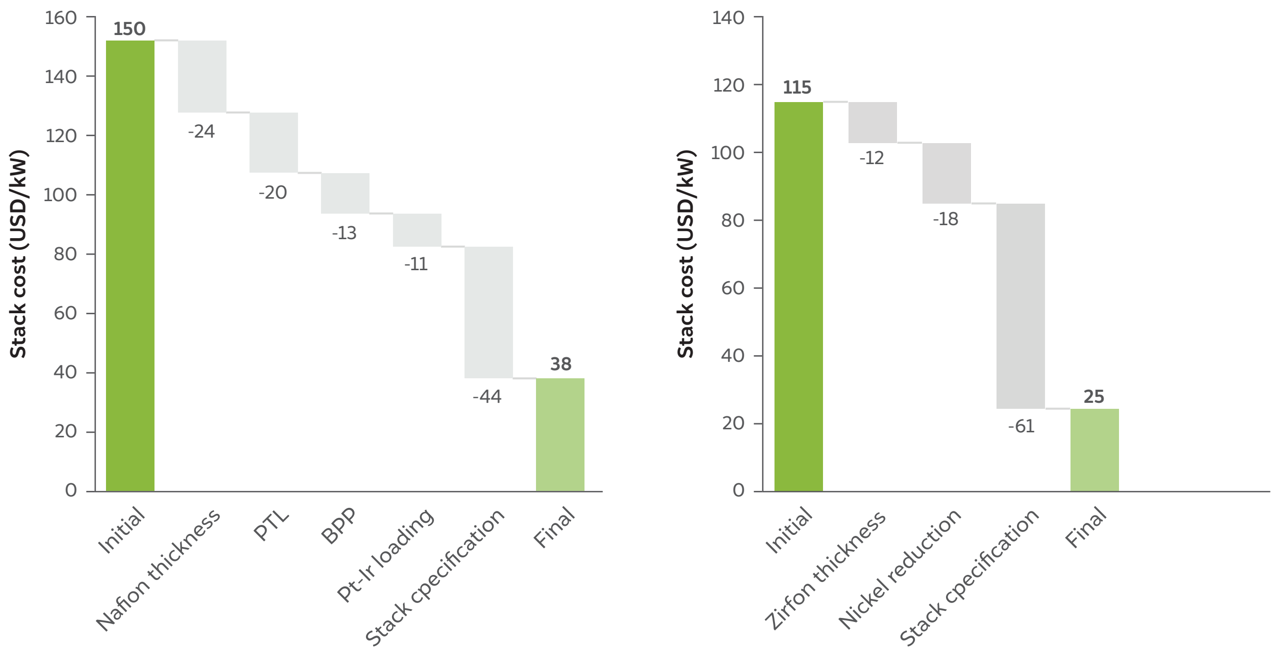
Figures ES4 (a) and (b) show the possible cost reduction in electrolyser manufacturing due to various parameters such as stack specification improvement, reducing catalyst loading, and using alternate material as listed in Table ES1. Reducing Pt–Ir loading and bipolar plate (BPP) coating thickness, using stainless steel as an alternative to titanium for the PTL on the anode side, and reducing the thickness of the membrane can decrease the cost of a PEM electrolyser by 45 per cent. However, the largest reduction in electrolyser cost can be realised by increasing the current density, which increases the stack size by 2.2 times for PEM types and 3.5 times for alkaline electrolysers without any increase in material cost.

These are very ambitious technology development targets, but as indicated in Figure ES4, they can reduce the electrolyser manufacturing cost significantly. Our analysis suggests that the electrolyser stack cost can be reduced from USD 150/kW to USD 38/kW for the PEM electrolyser and from USD 115/kW to USD 25/kW for the alkaline electrolyser.

Figure ES4 **Electrolyser stack cost can be reduced to < USD 40/kW through technological improvements**

a) Stack cost reduction for PEM electrolysers

b) Stack cost reduction for alkaline electrolysers



Source: Authors' analysis

Our findings are consistent with results obtained elsewhere (Krishnan, et al. 2023). While these cost reductions are ambitious, they are essential to reducing the overall cost of electrolysers, given that most components of the BoP are already produced at a commercial scale, which make future cost reductions unlikely. An overall electrolyser system cost lower than USD 200/kW can only be achieved if the stack cost is reduced to below USD 30/kW as indicated in Figure ES4.

C. Policy recommendation and conclusion

Indigenising electrolyser manufacturing will need a strategic approach and support from the Government, innovation from research laboratories and academic institutes and intent from the industry. We recommend the following measures to indigenise electrolyser manufacturing:

1. The Ministry of New and Renewable Energy (MNRE) should adopt a three-pronged strategy to maximise indigenisation of electrolyser manufacturing
   - Ensuring that finished components for electrolysers are made in India even if the raw material are imported due to a lack of domestic availability
   - Focusing on research to reduce the loading of critical minerals not available in India and developing their alternatives, and
   - Prioritising the development of advanced membrane technologies to minimise import dependency.
2. The MNRE should develop a compendium of domestic suppliers for all components – especially those involving low-TRL components like porous transport layer, bipolar plate etc. used for electrolyser manufacturing – and place it in the public domain for easy access to electrolyser manufacturers.
3. Power electronics constitute 15-30 per cent of the total electrolyser cost. The MNRE should provide the necessary support for the manufacture of power electronics for electrolysers through integration with existing Government of India schemes like Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors (SPECS) and Modified Electronics Manufacturing Clusters Scheme (EMC 2.0) for domestic manufacture of electronics.
4. The MNRE should initiate the development of an electrolyser testing facility that will serve as a platform for the development and optimisation of indigenous electrolyser designs, and contribute to the broader goal of achieving cost-effective electrolyser manufacturing.
5. The R&D projects under NGHM should have well-defined technology development targets for reducing the dependency on imported technologies and minerals and also reducing the manufacturing cost. Further, the R&D projects should focus on supporting new technologies like AEM, E-TAC, and capillary-based electrolysers.
6. The MNRE should coordinate with other ministries like Ministry of Mines to develop a resilient supply chain for the minerals used in electrolyser manufacturing for domestic manufacturers.
7. The MNRE should coordinate with Ministry of Commerce to create a new harmonised system (HS) code for monitoring imports of hydrogen-related components in India.

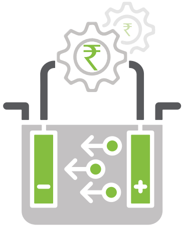
R&D should focus on developing of membrane technologies, reducing loading of critical minerals and developing their alternatives

1. Introduction

Green hydrogen can play a multifaceted role in decarbonising the hard-to-abate industrial and mobility sector.

Climate change is an existential threat to humanity and our planet. The challenges it presents can only be mitigated by reducing the consumption of traditional carbon-intensive fossil fuels and substituting them with renewable and clean energy sources. In this context, green hydrogen is a promising option to reduce our dependency on fossil fuels and has recently sparked remarkable interest as a low-carbon energy vector. As of July 2024, at least 57 countries as well as the European Union (EU) have announced national policies and strategies for hydrogen (CSIRO 2024). India has also announced the *National Green Hydrogen Mission* (NGHM) (Ministry of New and Renewable Energy 2023). Green hydrogen is especially important for India, as it will help achieve our larger climate goals, such as reaching net zero emissions by 2070, and strategic goals, such as achieving energy independence by 2047.

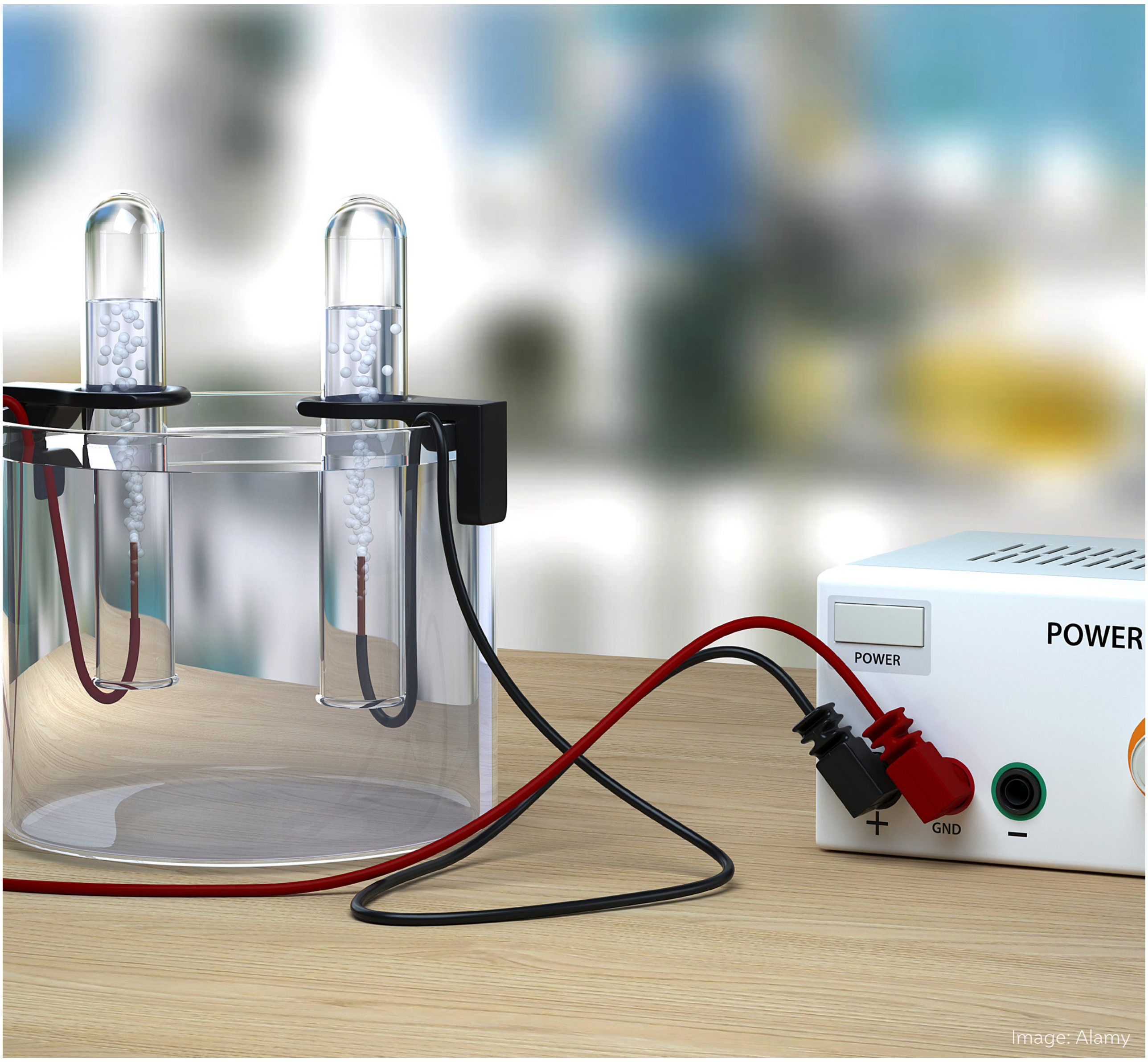
Electrolyser is the heart of the hydrogen production process, utilising electricity to split water into hydrogen and oxygen. If the electricity used in the process is derived from renewable sources – such as wind and solar power – then the hydrogen produced is called 'green hydrogen'. The Government of India has taken significant steps to develop the green hydrogen ecosystem in India. In February 2022, India notified its green hydrogen/ammonia policy, setting itself an annual target of producing 5 million tonnes per annum (MTPA) of green hydrogen. In January 2023, in launching the NGHM, the Ministry of New and Renewable Energy (MNRE) received a significant budgetary allocation of INR 19,750 crore (USD 2.2 billion) to scale up the green hydrogen economy in India (Ministry of New and Renewable Energy 2023). India has also learned from the lessons of solar manufacturing which is why it is focusing on the manufacture of electrolysers in the early phases. Therefore, the NGHM has a budgetary allocation of INR 4,500 crore (approximately USD 550 million) to support the domestic manufacture of electrolysers alone. Further, a fully functional and well-developed electrolyser manufacturing ecosystem in India can also potentially unlock export opportunities for various types of electrolysers.



This report develops a bottom-up manufacturing cost of electrolysers and identifies indigenisation opportunities

In this report, we detail the bottom-up manufacturing costs of electrolysers. First, we briefly discuss various electrolyser types and the status of global and domestic manufacturing ecosystem. Subsequently, we delve deeper into electrolyser manufacturing by detailing it to component-level. We identify and quantify aspects of the indigenisation of electrolyser manufacturing in India, including the mineral requirement to meet our green hydrogen production targets in the short and the long term and the geopolitical factors affecting the availability of these critical minerals. We also briefly discuss a few upcoming electrolyser technologies that appear promising. Finally, we delve into technology development targets that may help reduce electrolyser costs and identify the gains from each technological intervention.

2. Electrolyser technologies



The electrolysis process involves passing electricity through water to produce hydrogen and oxygen.

A schematic of a typical electrolyser cell is shown in Figure 1, wherein electricity is passed through two electrodes dipped in water and separated by a membrane. Based on the nature of the membrane used, electrolysers can be classified into the following categories:

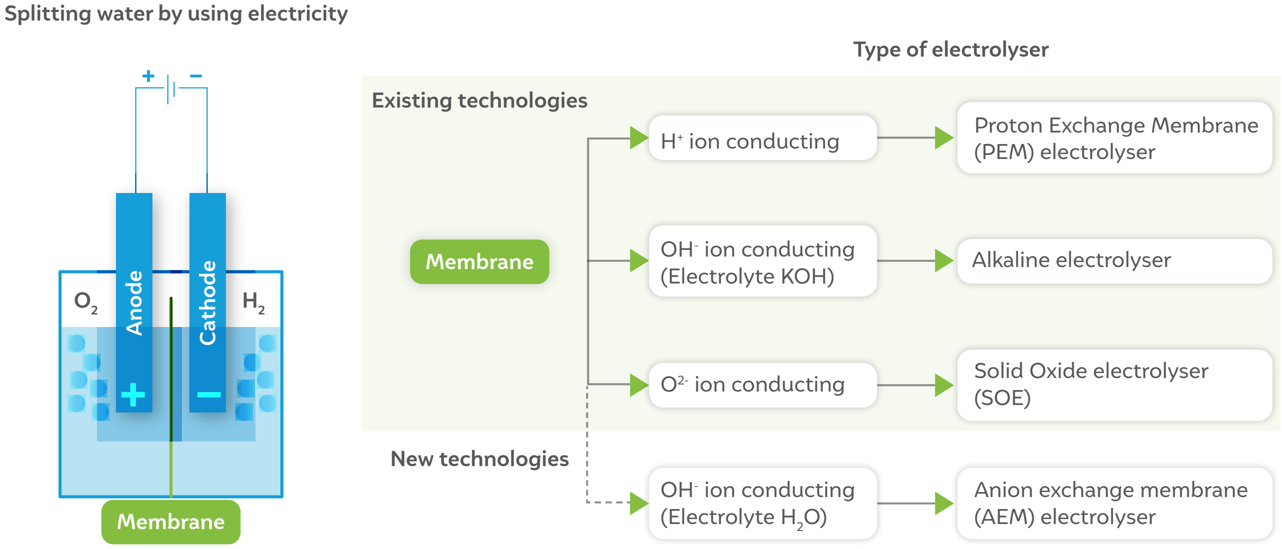
a. **Proton exchange membrane (PEM) electrolyser**: If the membrane conducts H^+ ions (protons), the electrolyser is known as a PEM electrolyser.

b. **Alkaline electrolyser**: If the membrane conducts OH^-, it is termed an alkaline electrolyser. Alkaline electrolysers use an alkaline medium (such as potassium hydroxide or KOH) as the electrolyte.

c. **Solid oxide electrolyser (SOE)**: If the membrane conducts O^{2-} ions, it is termed an SOE.

These three technologies are commercially available in India at present; we offer a detailed, bottom-up cost evaluation of each of them in Section 5. However, electrolyser technology is still evolving, as new technologies are being developed. For instance, an anion exchange membrane (AEM) electrolyser is one such technology that has reached a higher technological readiness level (TRL) and has been deployed commercially. In AEM electrolysers, the membrane conducts OH^- ions but uses water as an electrolyte rather than an alkaline solution. AEM is a relatively new technology, so literature on it remains limited. Since accessibility of data on AEM manufacture poses a significant challenge, especially in the early stages of development, the cost study of AEM manufacturing is outside the scope of this report.

Figure 1 Electrolysers are categorised based on the selective conductivity of the membrane



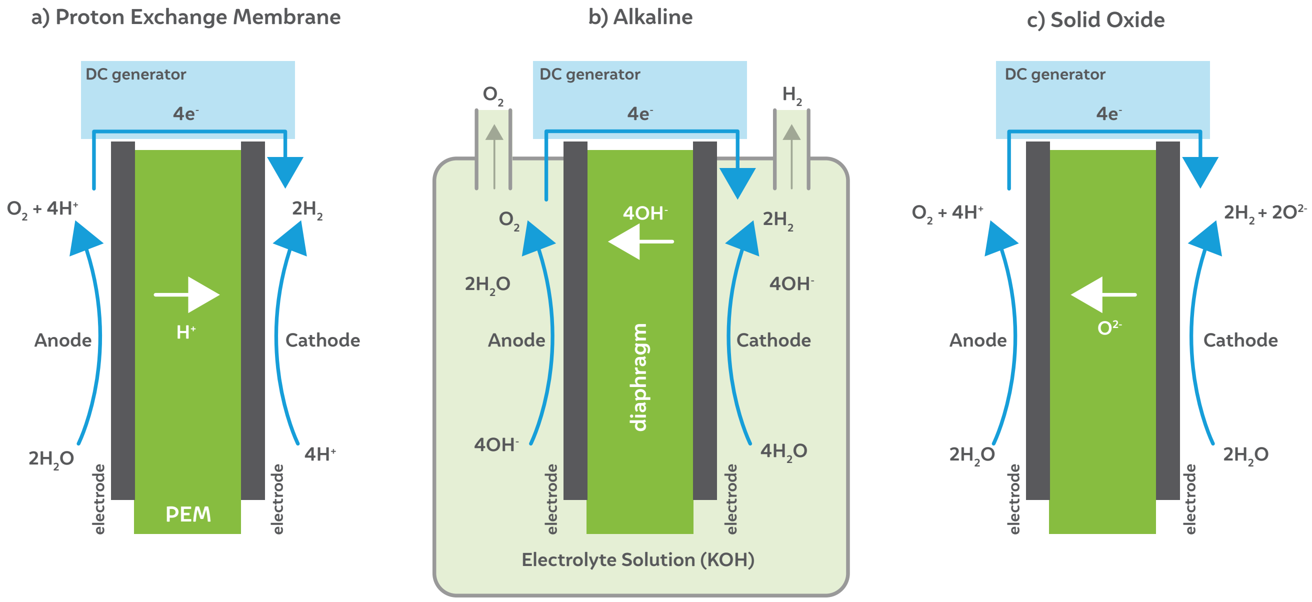
Source: Authors' analysis

The mechanism of hydrogen production in various electrolysers can be explained by two half-cell reactions, as shown in Figure 2. In the PEM electrolyser (Figure 2a), water splits on the anode side, producing oxygen and H^+ ions, thereby generating free electrons. The electrons are transferred to the cathode via a wire completing the circuit, while the H^+ ions are conducted via the membrane and reach the cathode, where they combine with the electrons to produce hydrogen. The membrane thus selectively conducts protons (H^+), making this device a PEM electrolyser.

As the name suggests, alkaline electrolysers (Figure 2b) use a 30–40 per cent solution of KOH as the electrolyte instead of water. The alkaline solution provides excess OH- ions to drive the water-splitting reaction. These OH^- ions are converted into H_2O and generate electrons at the anode while also producing oxygen. Similar to the PEM electrolyser, the electrons move to the cathode side via the circuit. On the cathode side, water splits into hydrogen and OH^- ions. The OH^- ions are transported through the membrane to the anode side, while the hydrogen gas is collected from the cathode for further processing.

Similarly, in the case of solid oxide electrolysing cells (SOECs) (Figure 2c), water is split at the cathode to produce hydrogen and O^{2-} ions. These O^{2-} ions are transported via the electrolyte medium, and then convert into oxygen (O_2), releasing electrons on the anode side to complete the cell reaction.

Figure 2 Mechanism of hydrogen production in PEM, alkaline, and SOEs



Anode: $2H_2O \longleftrightarrow O_2 + 4H^+ + 4e^-$

Cathode: $4H^+ + 4e^- \longleftrightarrow 2H_2$

Anode: $4OH \longleftrightarrow 2H_2O + O_2 + 4e^-$

Cathode: $4H_2O + 4e^- \longleftrightarrow 2H_2 + 4OH^-$

Anode: $2O^{2-} \longleftrightarrow O_2 + 4e^-$

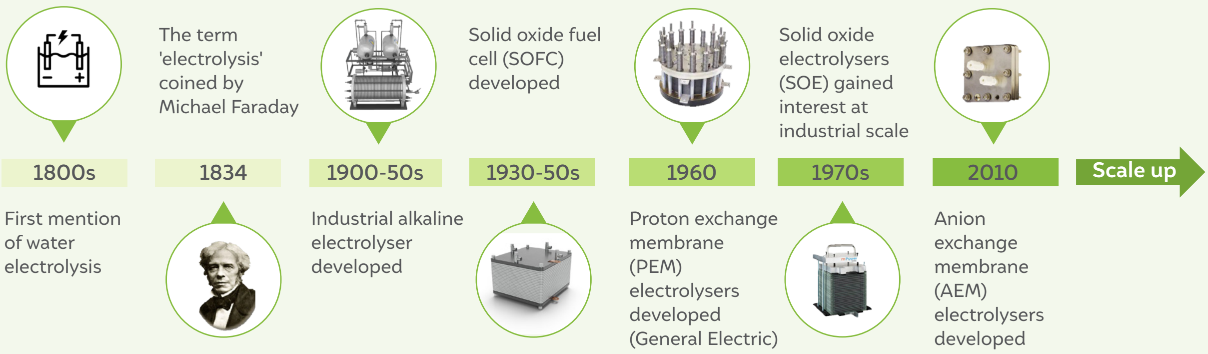
Cathode: $2H_2O + 4e^- \longleftrightarrow 2H_2 + 2O^{2-}$

Source: Authors' compilation from IRENA. 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal. Abu Dhabi: International Renewable Energy Agency.

BOX 1 History of electrolyser technology development

Figure 3 highlights the major milestones in the development of electrolyser technology. Electrolyser technology dates back to the 1800s when the first paper on the phenomena of water splitting was published (Smolinka, et al. 2021). However, the first mention of water electrolysis emerged only in 1834, and the term 'electrolysis' was coined by Michael Faraday. The inception of the chemicals industry ramped up hydrogen demand in the 19th century. Alkaline electrolysers were at the forefront on technological advancement when the first electrolyser was developed in the early 19th century (Diogo, Sequeira and Figueiredo 2013). The earliest version used a simple cell, with a platinum wire as the cathode and carbon as the anode. This design gradually evolved to use larger cells and eventually became the basis for commercial electrolysers.

Figure 3 Timeline for electrolyser development



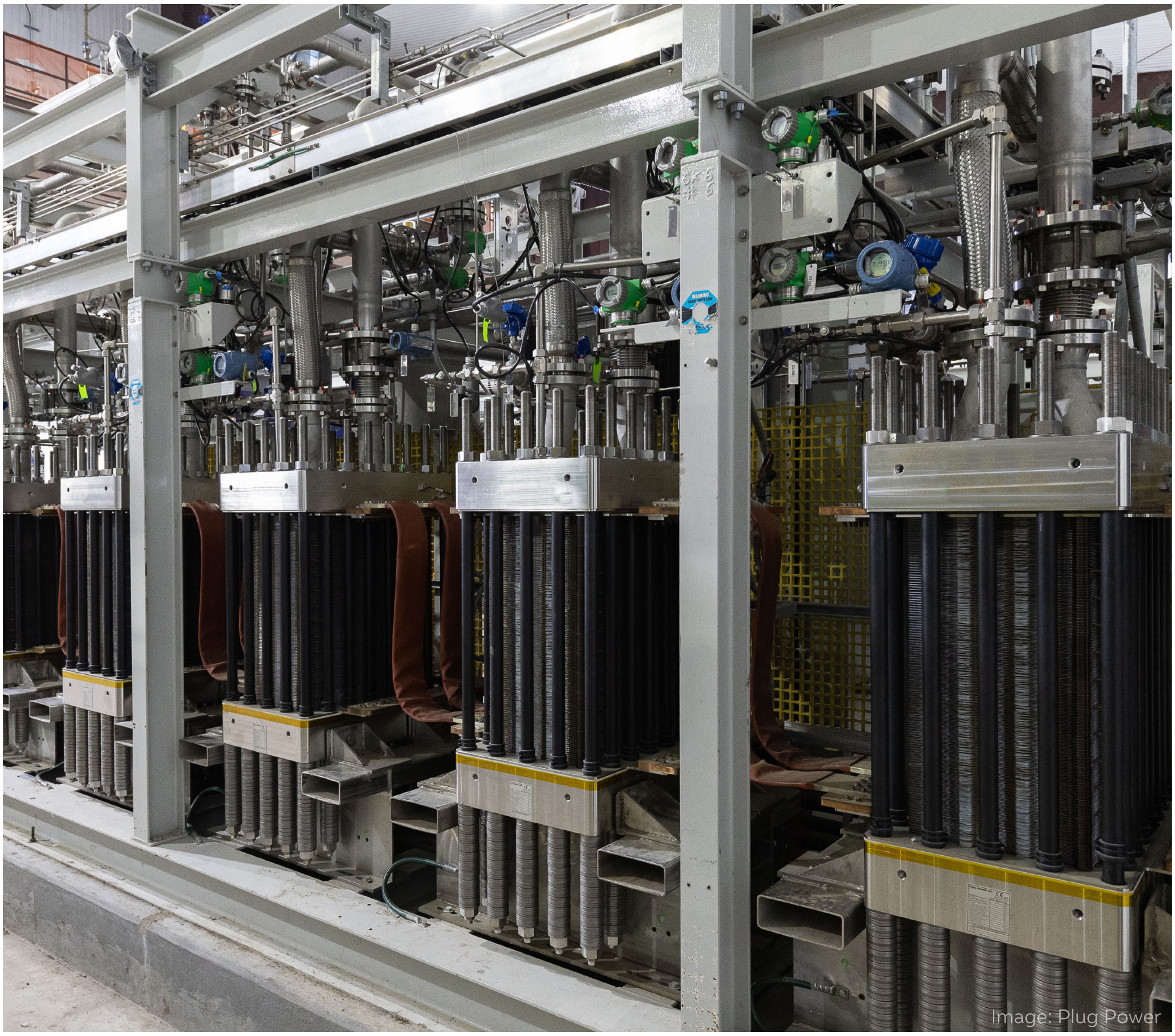
Source: Authors' analysis

Over the next few decades, newer technologies were developed and tested. During the 1960s, PEM electrolysers were first ideated by General Electric (Mardle and Du 2017) and gained popularity due to their high current density. However, the requirement for critical minerals posed a challenge to their widespread adoption. It is believed that the first solid oxide fuel cell (SOFC) experiment was taken up by Nernst in 1899, but the first prototype cell was demonstrated only in 1937 (Baur and Preis 1937). NASA has since used SOFCs in several of its missions. The development of SOEC technology for industrial applications began in the early 1970s. However, prohibitive costs and a lack of commercial applications led to slow growth.

Today, compared to these technologies, which have achieved commercial scale, AEM electrolysers are at a nascent stage. However, they too have gained popularity since 2010 and have a significantly improved design compared to other electrolysers. Other novel designs, such as capillary-fed, electrochemical–thermally activated chemical (E-TAC), and zero-gap electrolysers could further revolutionise the electrolyser market if they can be scaled up.

Source: Authors' analysis

3. Global and domestic status of electrolyser manufacturing



As part of the *National Green Hydrogen Mission*, India is focusing on electrolyser manufacturing from the outset through the *Production-Linked Incentive* scheme.

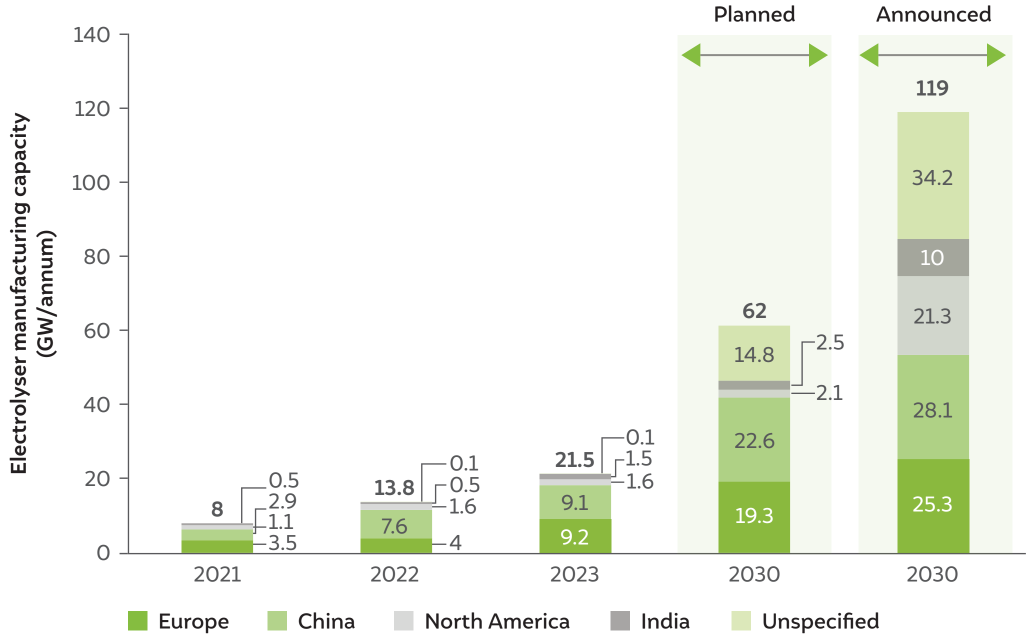
This section summarises the global and domestic status of electrolyser manufacturing, highlighting key players, technological advancements, and capacity expansion plans.

3.1 Global status of electrolyser manufacturing

Globally, electrolyser manufacturing capacity has increased from 8 GW per year in 2021 to 21.5 GW per year in 2023 (IEA 2022) as shown in Figure 4. Country-level commitments and announcements by various companies globally indicate that electrolyser manufacturing capacity is expected to reach 62 GW per year by 2030 (IEA 2022). Another IEA study indicates that 200 GW per year of electrolyser manufacturing capacity is needed by 2030 to achieve the 2050 net-zero emission (IEA 2023). India has already witnessed a threefold increase in electrolyser capacity, rising from 0.5 GW in 2021 to 1.5 GW in 2023. By 2030, it is projected that

China and Europe will dominate around 67 per cent of the global capacity, totalling 42 GW, whereas India's capacity is expected to reach 2.4 GW annually per planned projects and 10 GW annually per announced capacity (IEA 2023).

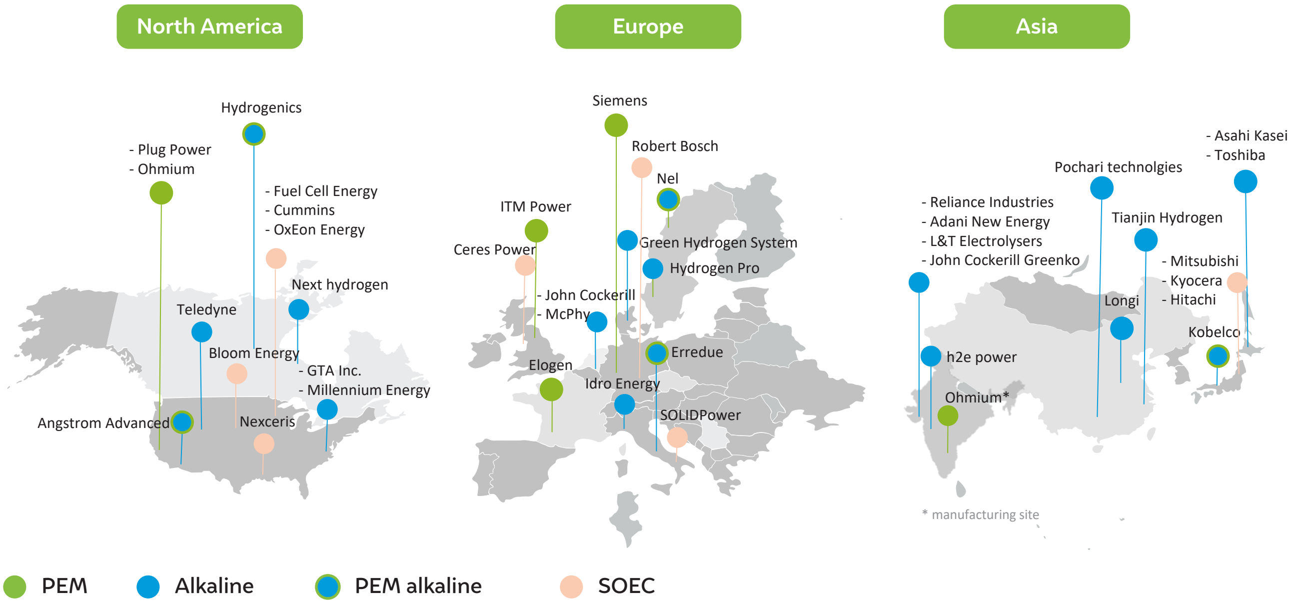
Figure 4 Global electrolyser manufacturing capacity



Source: Authors' compilation from (1) IEA. 2022. Planned electrolyser manufacturing capacity by region, 2021-2030. Paris. International Energy Agency (2) IEA. 2023. Announced electrolyser manufacturing capacity by region and manufacturing capacity needed in the Net Zero Scenario, 2021-2030. Paris. International Energy Agency.

Figure 5 shows the locations of various electrolyser manufacturers worldwide. Most electrolyser manufacturing units are located in developed economies, with only a few situated in Asia (except China). This is because, so far, the technology has only been available to companies based in the EU and North America. However, the number of electrolyser manufacturers is expected to increase in Asia, especially in India and China, in the next few years, thanks to lower costs and proven manufacturing capabilities for the balance of the plant (BoP) components.

Figure 5 Headquarters of major alkaline, PEM, and SOEC manufacturers



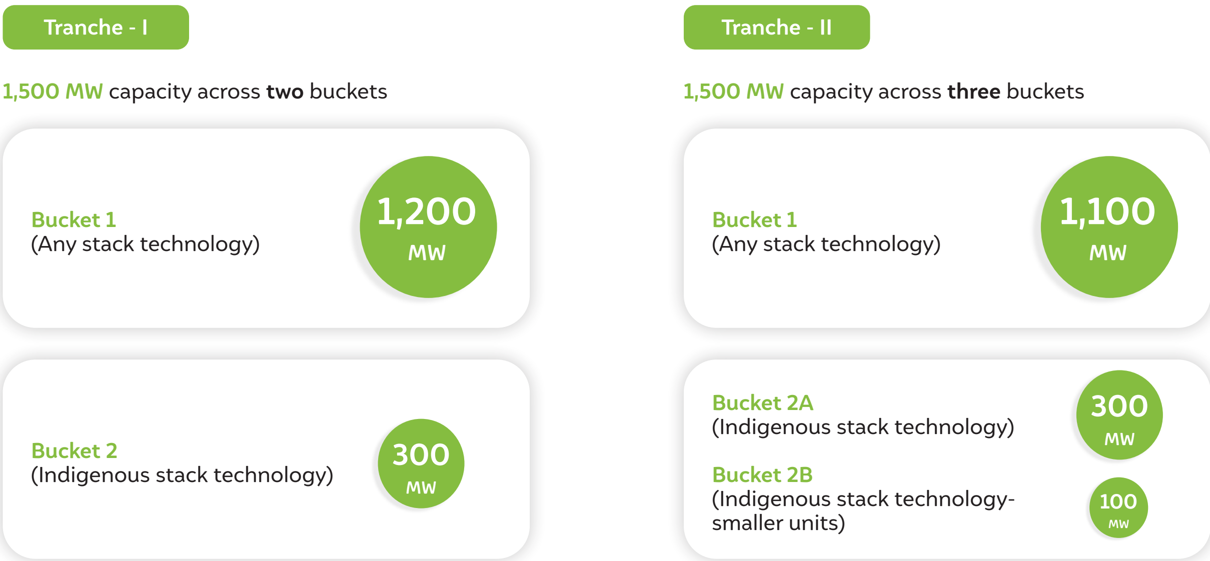
Source: Authors' compilation from (1) Badgett, Alex, Joe Brauch, Kyle Buchheit, Gregory Hackett, Yijin Li, Marc Melaina, Mark Ruth, Debra Sandor, Morgan Summers, and Shubhankar Upasani. 2022. Water Electrolyzers and Fuel Cells Supply Chain: Supply Chain Deep Dive Assessment. United States Department of Energy (2) SECI. 2024. "Request for Selection (RfS) Document for Selection of Electrolyser Manufacturers (EM) for Setting up Manufacturing Capacities for Electrolysers in India under Strategic Interventions for Green Hydrogen Transition (SIGHT) Scheme (Tranche-II)." Tender dated March 16, 2024. New Delhi: Solar Energy Corporation of India Ltd.

3.2 Status of electrolyser manufacturing in India

As we have discussed earlier, India had an electrolyser manufacturing capacity of only 1.5 GW till 2023. This is insufficient to meet our green hydrogen ambitions as envisaged in the NGHM. Further, it is important to develop indigenous capabilities in electrolyser manufacturing to support the *Make in India* initiative. Therefore, the Government of India, through the NGHM, has proposed a production-linked incentive (PLI) scheme for manufacturing electrolysers in India. Under the *Strategic Interventions for Green Hydrogen Transition* (SIGHT) scheme, the NGHM has created a budgetary provision of INR 4,440 crore for a PLI on electrolyser manufacturing to increase India's production capacity by 3 GW.

Figure 6 is an overview of the two tranches released under SIGHT. In the first tranche, bids were invited for 1,500 MW electrolyser production capacity. Of this, 1,200 MW were allocated for electrolyser technologies of any description, whereas bids for 300 MW were reserved for original equipment manufacturers (OEMs) manufacturing electrolysers using indigenously developed stack technology. The second tranche proposes bidding for 1,100 MW from any stack technology, 300 MW from indigenously developed stack technology, and 100 MW from indigenously developed stack technology from smaller players (10–30 MW) (SECI 2024).

Figure 6 SIGHT scheme offers an incentive under two tranches for increasing the national production capacity by 3 GW



Source: Authors' adaptation from MNRE. 2023. Hydrogen Schemes & Guidelines. New Delhi. Ministry of New and Renewable Energy, Government of India

As shown in Table 1, the base incentive for electrolyser manufacturing under the PLI scheme starts at INR 4,440/kW (USD 55/kW) in the first year and will gradually taper down annually. Incentives will be provided for five years from the date of commencement of manufacture. It is expected that the market for green hydrogen will scale up in the next five years; consequently, electrolyser manufacturing will become cost-competitive, and the industry will not need any additional support for investing in gigafactories.

Table 1 Electrolyser incentive will taper down each year (INR/kW)

Year of sales	Year 1	Year 2	Year 3	Year 4	Year 5
Base incentive available (INR/kW)	4,440	3,700	2,960	2,220	1,480

Source: Authors' adaptation from MNRE. 2023. Hydrogen Schemes & Guidelines. New Delhi. Ministry of New and Renewable Energy, Government of India

In the first tranche, bids were received from 21 companies for 3.48 GW/year manufacturing capacity, and 1.5 GW/year manufacturing capacity was awarded. Figure 7 shows the distribution of electrolyser capacity allotment and incentives provided to various companies under SIGHT.

A critical observation is that only one firm bid for the manufacturing of PEM electrolysers. In contrast, seven companies were allocated incentives under SIGHT for the manufacture of alkaline electrolysers. A potential reason for this could be that most manufacturers have the technological know-how for alkaline electrolyser manufacturing rather than for PEM electrolyser manufacturing. This highlights the need for new and advanced indigenous technologies in the manufacturing ecosystem.

Figure 7 Of the 1,500 MW/annum capacity allocated under tranche one, 137 MW capacity was allocated to the only PEM manufacture bidder

Source: Authors' compilation from SECI. 2024. "Request for Selection (RfS) Document for Selection of Electrolyser Manufacturers (EM) for Setting up Manufacturing Capacities for Electrolysers in India under Strategic Interventions for Green Hydrogen Transition (SIGHT) Scheme (Tranche-II)." Tender dated March 16, 2024. New Delhi: Solar Energy Corporation of India Ltd.

BOX 2 Is overcapacity in electrolyser manufacturing a potential risk?

India will need 20 GW of installed electrolyser capacity by 2030 in order to produce 1.65 MTPA of green hydrogen. Further, this installed capacity is expected to increase to 112 GW by 2040 and 226 GW by 2050 (NITI Aayog 2022). The government's PLI has supported the deployment of 3 GW of electrolyser capacity. However, Indian OEMs are also working to set up gigafactories of their own to meet any additional demand within India or from export markets.

Table 2 lists the investment required to set up manufacturing facilities for the various electrolyser types. However, as the industry is still evolving, there is significant uncertainty around securing investments for new electrolyser manufacturing units. In the international context, an electrolyser gigafactory needs an investment of USD 30–45 million/GW of manufacturing capacity. Other studies also indicate an investment of USD 47–71 million/GW for electrolyser manufacturing (IRENA 2020). Industry experts indicate that a plant's CAPEX may not scale linearly with its capacity. Establishing an electrolyser facility from scratch requires approximately ~USD 100-150 million for the first gigawatt, but subsequent expansions can be achieved at a with ~USD 50 million per gigawatt. Further, the CAPEX requirement also significantly depends on the level of manufacturing within the plant. If a few components are a directly bought out item, then the capex requirement for the manufacturing unit will be lower. In the early stages of technology development and manufacturing, research and development (R&D) costs are also expected to be significant that might be reflected in Table 2.

contd...

Table 2 Investment required for setting up electrolyser gigafactories

S. No.	Electrolyser manufacturer	Type of electrolyser	Capacity (GW)	Investment (million USD)	Capital required (USD million/GW)	City/state, country	Reference
Domestic manufacturers							
1.	**Greenko**	Alkaline	2	500	250	Andhra Pradesh, India	(Greenko 2022)
2.	**GreenZo**	Alkaline	0.25	50	200	Gandhinagar, India	(GreenZo Energy 2022)
3.	**homiHydrogen**	Alkaline, PEM, AEM, SOEC	1.5	50	33.3	Pune, India	(homiHydrogen 2022)
4.	**Ohmium**	PEM	2	250	125	Bengaluru, India	(Ohmium 2024)
International manufacturers							
1.	**McPhy**	Alkaline	1	32–42	32–42	Belfort, France	(McPhy 2021)
2.	**ITM Power**	PEM	2.5	68–75	27–30	Sheffield, United Kingdom	(S&P Global 2021)
3.	**Nel**	Alkaline/ PEM	4	400	100	Michigan, United States	(Nel 2023)
4.	**Siemens Energy**	PEM	1	32	32	Germany	(Siemens Energy 2023)
5.	**Fortescue**	PEM	2	114	57	Australia	(Fortescue 2022)
6.	**Bloom Energy**	SOEC	1	200	200	Newark, Delaware, US	(Bloom Energy 2022)

Source: Authors' compilation

The Government of India, through its PLI scheme, has selected bids for setting up an electrolyser manufacturing capacity of 1.5 GW per year and intends to support an additional 1.5 GW per year to achieve a cumulative installed capacity of 3 GW per year. However, electrolyser manufacturers in India will also wish to have significantly higher manufacturing capacity to additionally cater to export markets. Therefore, there is a chance that the electrolyser manufacturing capacity will be significantly higher than the actual demand within India, i.e., an overcapacity.

Figure 8 shows the impact of electrolyser manufacturing capacity utilisation on the cost of electrolysers for a range of capital investments. In this figure, we assume that the maintenance cost of the electrolyser gigafactory is 5 per cent of the capital cost. We can see that the capital and maintenance cost of the gigafactory becomes significant only for a capacity utilisation factor lower than 20–25 per cent. Even in the worst-case scenario, where the capacity utilisation factor is 20 per cent, the capital required for setting up an electrolyser gigafactory only constitutes USD 15–35/kW of the electrolyser cost. Therefore, we conclude that the overcapacity of electrolyser gigafactories will not significantly impact the competitiveness of OEMs, since it will not lead to a huge increase in electrolyser cost. We believe that an overcapacity will imply a competitive market for electrolysers, which will reduce the cost of green hydrogen further and help achieve parity with incumbent production processes.

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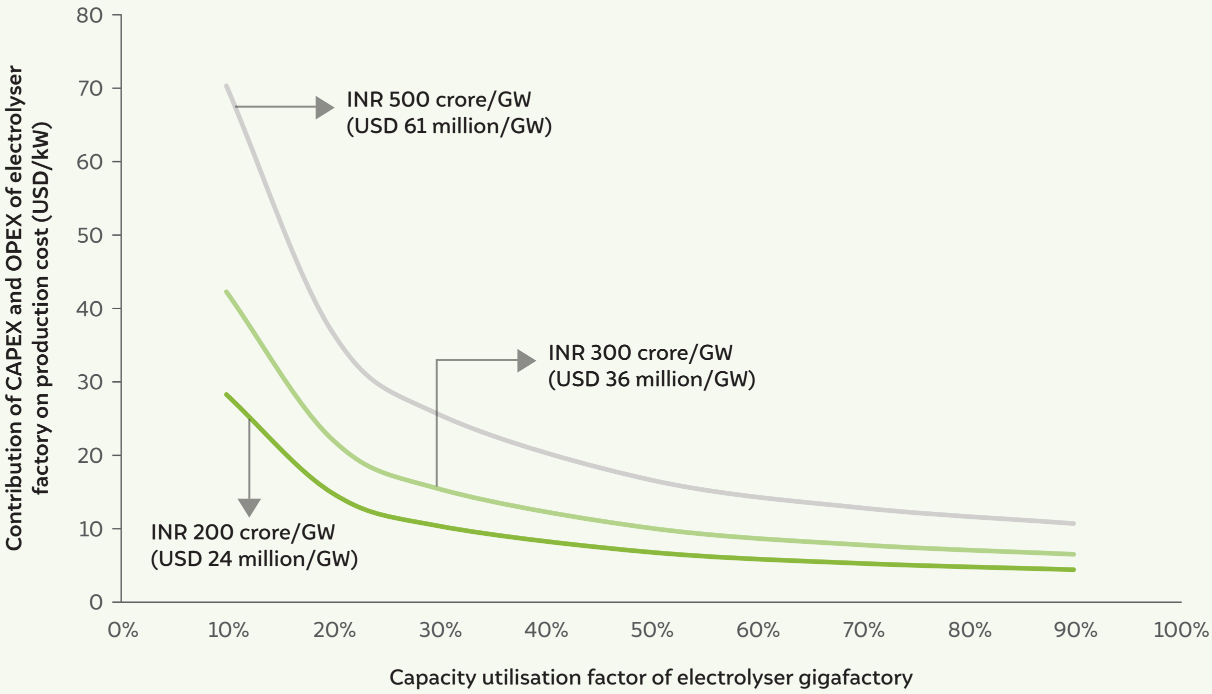
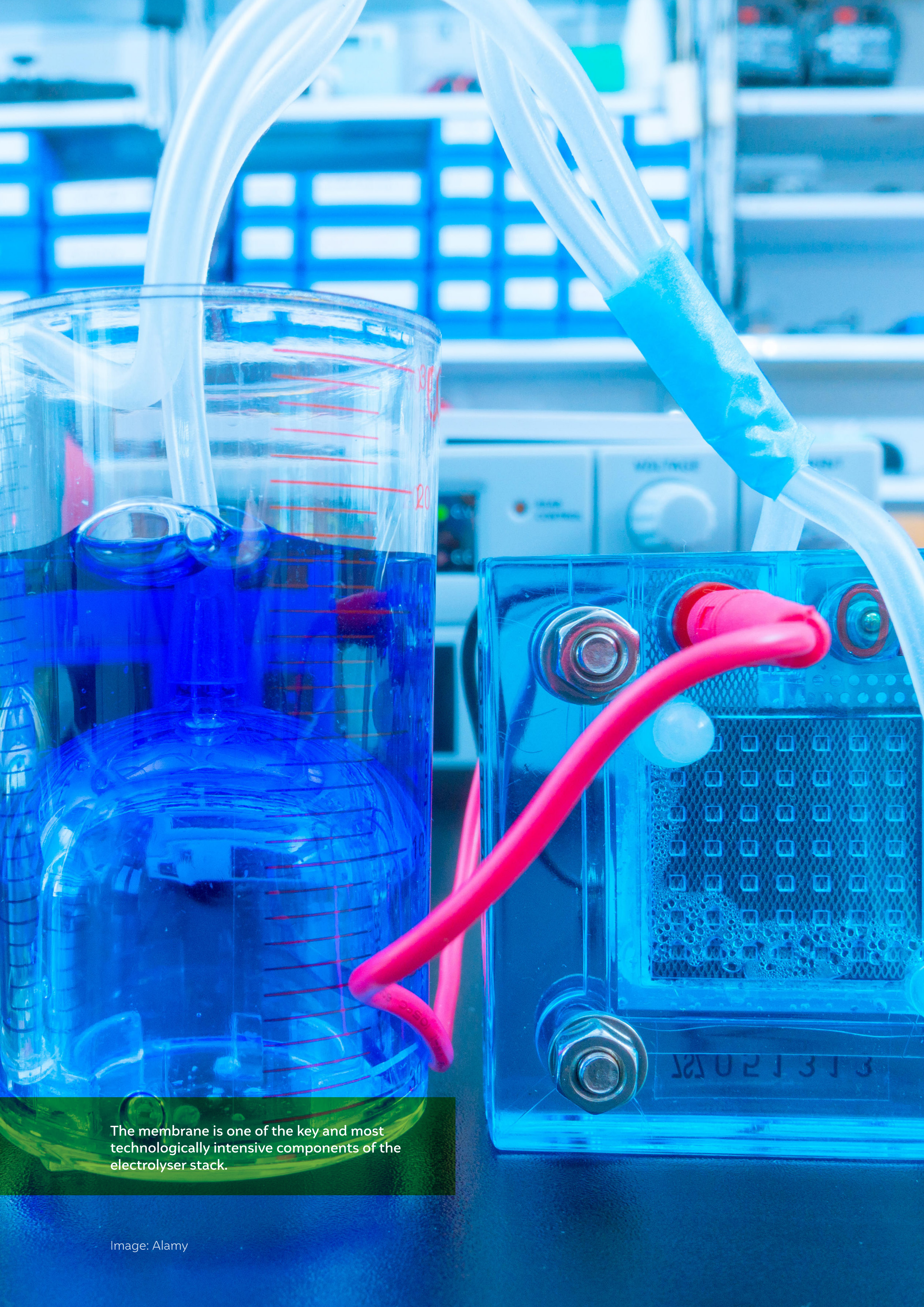
Figure 8 **Capital required for setting up an electrolyser gigafactory has limited impact on the overall electrolyser manufacturing cost**



Source: Authors' analysis

Source: Authors' analysis

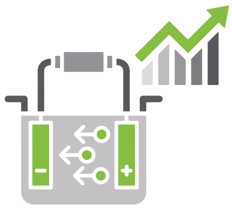


The membrane is one of the key and most technologically intensive components of the electrolyser stack.

Image: Alamy

4. Electrolyser components

In the earlier section, we shared a brief history of electrolyser development and manufacturing status globally and within India. This section deep-dives into the technical aspects of electrolysers. Typically, an electrolyser consists of a single repeating unit (SRU) integrated into an electrolyser stack. The electrolyser stack and the BoP together constitute an electrolyser system.



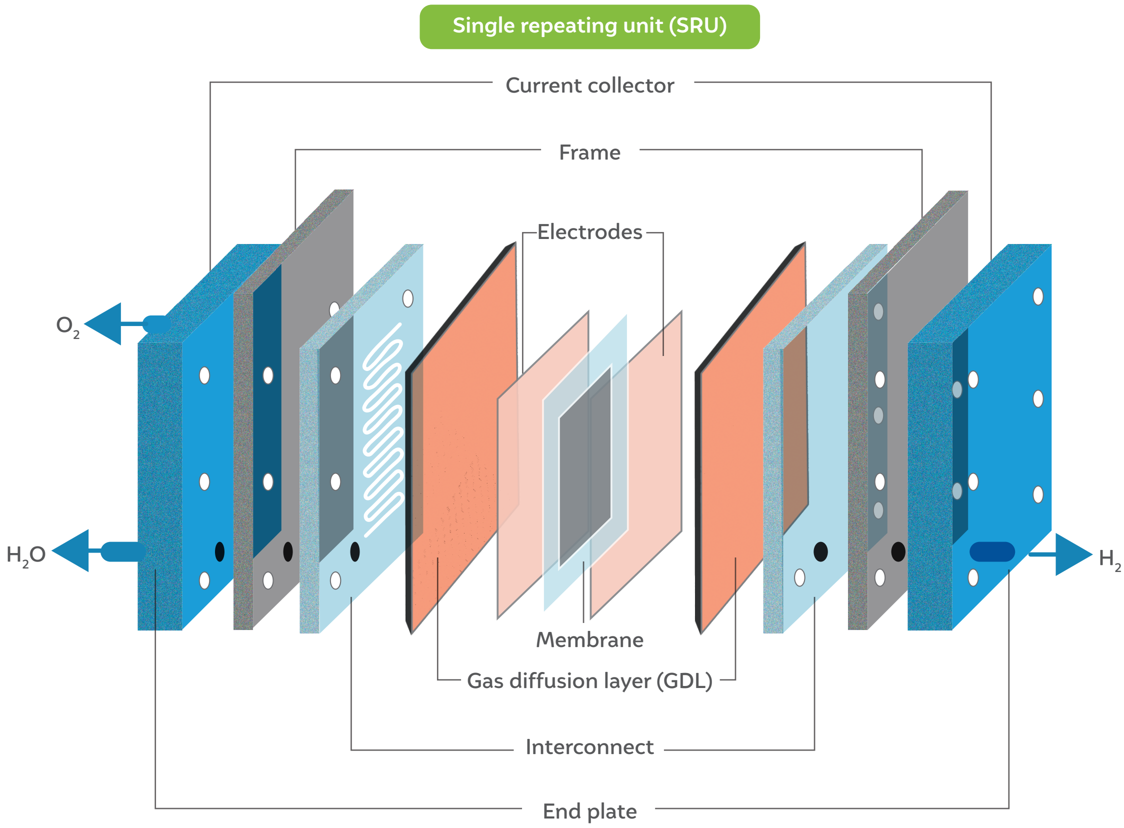
India's electrolyser market is projected to reach 20 GW by 2030. This capacity is expected to increase fivefold to 112 GW by 2040 and double again by 2050, reaching an estimated 226 GW

4.1 Single repeating unit (SRU)

A typical electrolytic cell design has certain key components (Figure 9) that form the SRU – the building block of an electrolyser stack. An SRU has the following components:

- **Membrane**: The membrane separates the anode and cathode sides of the electrolyser. Broadly, the membrane is a porous diaphragm that allows the selective transport of ions and prevents the flow of electrons from completing the water-splitting process. The membrane is the most technology-intensive component of an electrolyser.
- **Electrodes**: Electrodes are conducting metals that are usually coated with catalysts to enhance current conduction. The anode and cathode are coated or tape-cast on either side of the membrane. This arrangement of the electrodes and the membrane is together known as a membrane electrode assembly (MEA). If the electrodes are coated on the membrane, which is the case with PEM electrolysers, the assembly is known as a catalyst-coated membrane (CCM).
- **Porous transport layer (PTL)**: This is made of an electrically conductive material, usually gold or platinum, coated onto a steel or titanium substrate. It covers the MEA and is responsible for transporting the generated hydrogen and oxygen away from the electrode. In some cases, such as in SOEs, the PTL also acts as a current collector.
- **Current collector**: This plate or foil accumulates the current and passes it to the electrode to ensure that equipotential is maintained at each electrode. Maintaining equipotential allows a steady flow of current, and avoids short circuits.

Figure 9 Electrolyser cell consists of multiple components



Source: Authors' analysis

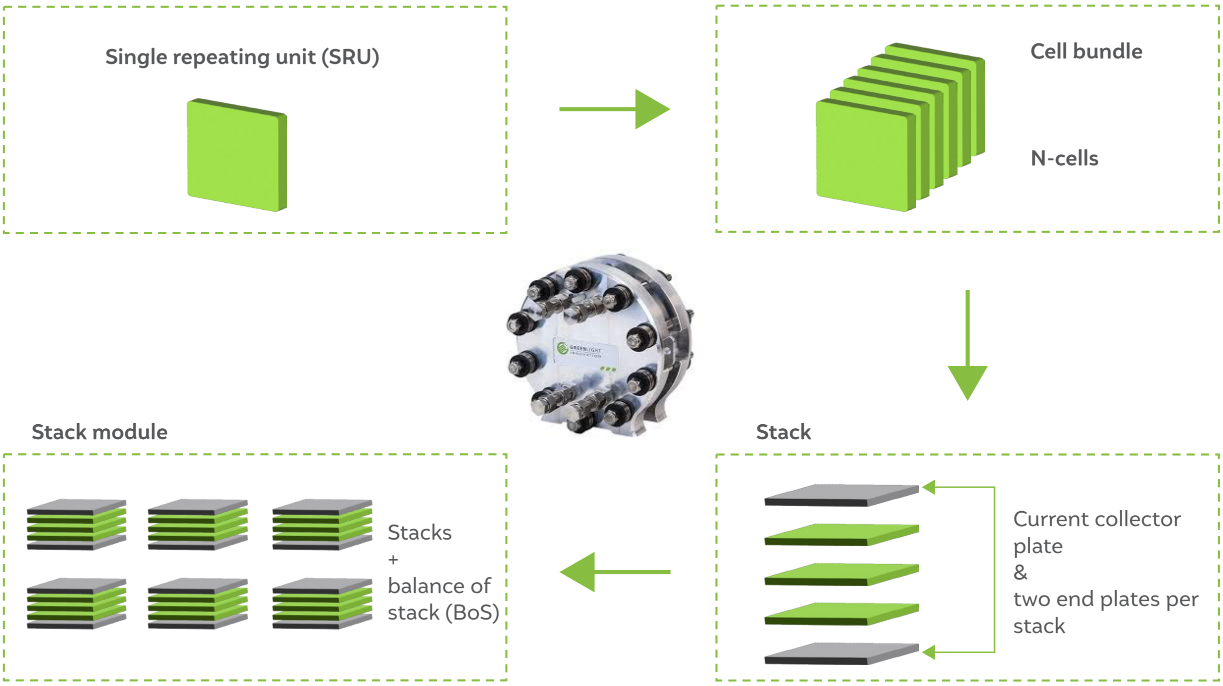
- **Bipolar plate (BPP):** This component has a multifunctional role. First, as seen in Figure 9, the grooves on a BPP assist in the uniform distribution of water over the entire active surface area of the MEA. Secondly, the BPP conducts electrical current from the anode of one cell to the cathode of the next cell. Finally, it supports the thin membranes and electrodes and applies the clamping forces necessary for the stack assembly[2].
- **Frame:** The frame supports the cell structure, holding the stack together. It is made up of thermoplastics such as polyether ether ketone (PEEK) or polyphenylene sulphide glass fibre (PPS-40GF).
- **End plates:** These are needed at both ends of the stack to apply pressure on the cells and provide structural strength, thereby preventing gases from escaping between the plates. End plates are bolted and have holes for the inlet and outlet manifolds through which water and hydrogen and oxygen gases may flow.
- **Stack assembly:** All the components discussed above together constitute the stack assembly.

2. While the bipolar plate is responsible for electrical conduction and the distribution of reactants and products within the cells, as well as maintaining the integrity of the membrane and electrodes, the frame provides structural integrity and support to the overall stack.

4.2 Electrolyser stack

Figure 10 shows the construction of a typical electrolyser stack. While Figure 9 shows the structure of an SRU, here multiple SRUs are assembled to form a cell bundle. This cell bundle is then enclosed within two thick plates. The entire assembly of SRU and end plates is termed an electrolyser stack. The electrolyser stack is assembled and fixed using seals, gaskets, wiring, and insulation. Together these components are termed the 'balance of stack' (BoS). The electrolyser stack and the BoS make up a stack module.

Figure 10 An SRU is the building block of a stack module



Source: Authors' analysis

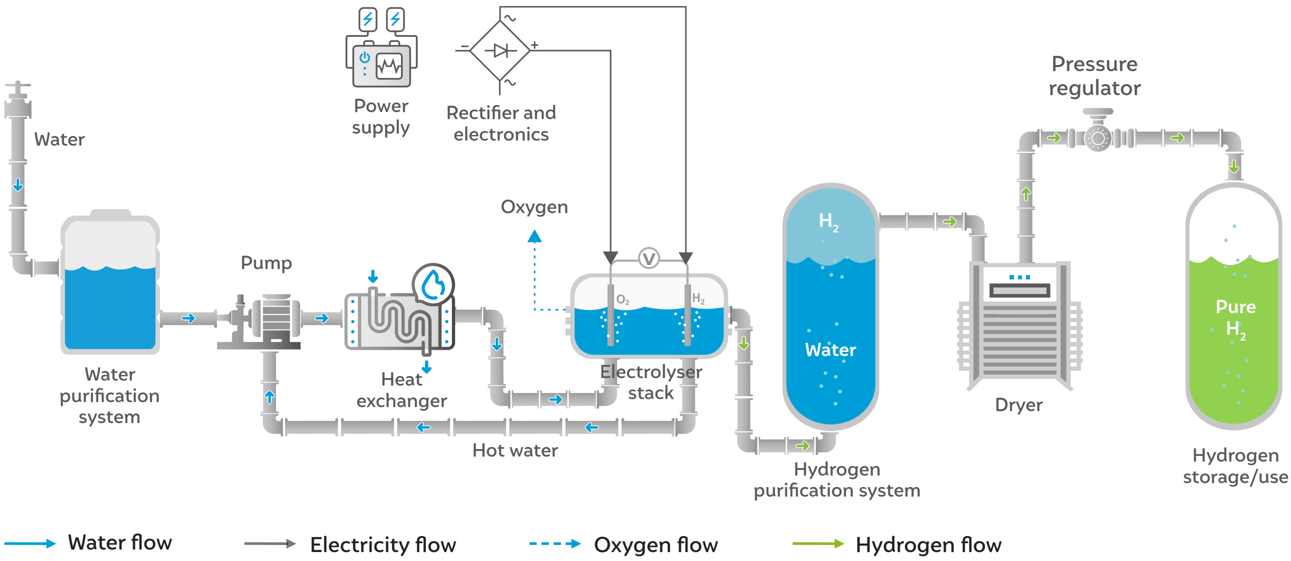
4.3 Balance of plant (BoP)

An electrolyser system consists of the electrolyser stack and the BoP components (Figure 11). These include:

- **Power supply system**: This converts the input AC power to DC power at the desired voltage level and provides it to the electrolyser stack. The power supply system typically consists of an AC/DC rectifier, a DC voltage transducer, and a DC transducer.
- **Process components**: These include tanks, circulation pumps, piping, valves, instrumentation, and controls, which help ensure the safe and seamless operation of the electrolyser.
- **Water treatment**: The water purification system typically consists of a demineralisation or reverse osmosis plant to maintain the required water purity and prevent membrane blockage and degradation.

- **Hydrogen processing**: The hydrogen obtained from the electrolyser contains moisture, which must be removed. The hydrogen processing plant has a dryer bed and a hydrogen–water separator unit that helps achieve the desired hydrogen purity.
- **Heat exchanger**: Heating and cooling units are needed to maintain the water temperature at the inlet and the outlet of the electrolyser stack to ensure optimal functioning.
- **Compressor**: The main function of a compressor is to store hydrogen at a pressure usually higher than 30 bar. In general, PEM and high-pressure alkaline electrolysers have an operating pressure of 25–30 bar. Therefore, these units do not need external compressors. However, low-pressure alkaline electrolysers, depending on the application, might need external compressors to meet the desired pressure levels.

Figure 11 **Balance of plant comprises ancillary equipment that are already commercially available**



Source: Authors' analysis

5. Bottom-up evaluation of electrolyser manufacturing costs in India

The bottom-up electrolyser manufacturing cost modelling includes the cost of cell components, stack components, and the balance of plant.

In this section, we report the bottom-up manufacturing costs of PEM, alkaline, and SOEs in India. We also briefly discuss the indigenisation potential for these electrolyser types and estimate the critical mineral requirements to meet electrolyser demand in India till 2050.

5.1 Proton exchange membrane (PEM) electrolyser

In PEM electrolysers, water splitting is achieved by the selective transfer of protons (i.e., H^+ ions) across the membrane. Figure 12 shows the construction of a typical PEM electrolyser. Hydrogen is obtained at the cathode, while oxygen is produced at the anode. A PEM – usually Nafion (a brand name for a sulfonated tetrafluoroethylene–based fluoropolymer by DuPont) – separates the anode and the cathode. Alternatives to Nafion include sulfonated poly(ether ether ketone) (SPEEK) and polybenzimidazole-based membranes. However, these are reported to be less efficient and have lower performance (Fernández, et al. 2021). The electrodes are made of platinum-group materials – platinum on the anode and platinum–iridium/iridium oxide and ruthenium on the cathode – as catalysts. Since the material is coated on the membrane, it is known as a catalyst-coated membrane or a membrane electrode assembly. The availability of these minerals presents challenges; therefore, several platinum alloys (Pt-Co, Pt-Ni, Pt-Fe, Pt-V, Pt-Mn, and Pt-Cr) are being tested as alternatives (Wang, et al. 2020).

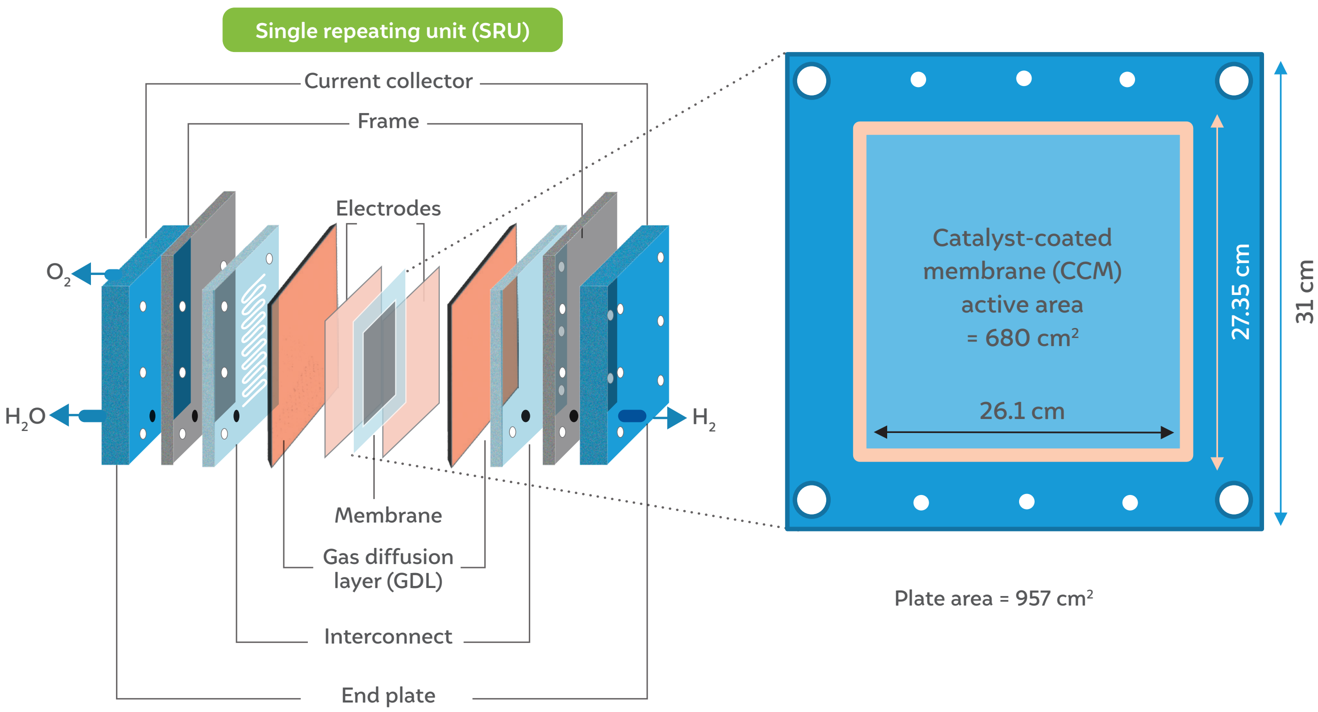
The PTL is made of an electrically conductive material – usually gold or platinum coated on a titanium felt – that covers the CCM and is responsible for transporting hydrogen and oxygen away from the electrode. It also acts as a current collector in PEM electrolysers. Alternatively, graphite plates can be used instead. As discussed in Section 4.1, the BPP assists in uniformly distributing the water over the entire active surface area of the MEA. The frame keeps the internal components of the cell together and provides the flexibility required to hold the stack; it is made of PPS-40GF thermoplastic. Finally, end plates seal the whole stack. Table 3 lists the advantages and challenges of the PEM electrolyser.

Table 3 Advantages and disadvantages of PEM electrolysers

Advantages	Challenges
• Compact in size due to high current density • High purity of hydrogen produced without an additional purification process • No additional compressor required (operating pressure of ~30 bar) • Corrosion-resistant; no electrolyte refilling • Can be used with intermittent RE	• Expensive catalysts such as platinum and iridium • Ultrapure feed water is required • Alternative to expensive catalysts is a challenge

Source: Authors' adaptation from Scottish Government. 2022. Assessment of Electrolysers: Final Report. September 23, 2022. Edinburgh: Arup.

Figure 12 Components within a PEM cell



Source: Authors' analysis

PEM cell specifications assumed for this study

The bottom-up cost analysis we conducted used the electrolytic cell arrangement shown in Figure 12. Table 4 details the cell specifications. Our bottom-up analysis assumes these cells are part of an electrolyser gigafactory facility. Further, we assume an electrolyser stack size of 1 MW. As Table 4 indicates, each stack consists of 252 cells with an active CCM area and a plate area of 680 cm2 and 957 cm^2, respectively. While there are significant uncertainties in the consumption of critical minerals, we assume catalyst loading of 7 grams/m^2 and 4 grams/m^2 on the anode and cathode side, respectively (NREL 2019). Table A1 (Annexure) details other assumptions in the bottom-up cost analysis.

Table 4 Electrolyser cell parameters considered for the bottom-up cost analysis

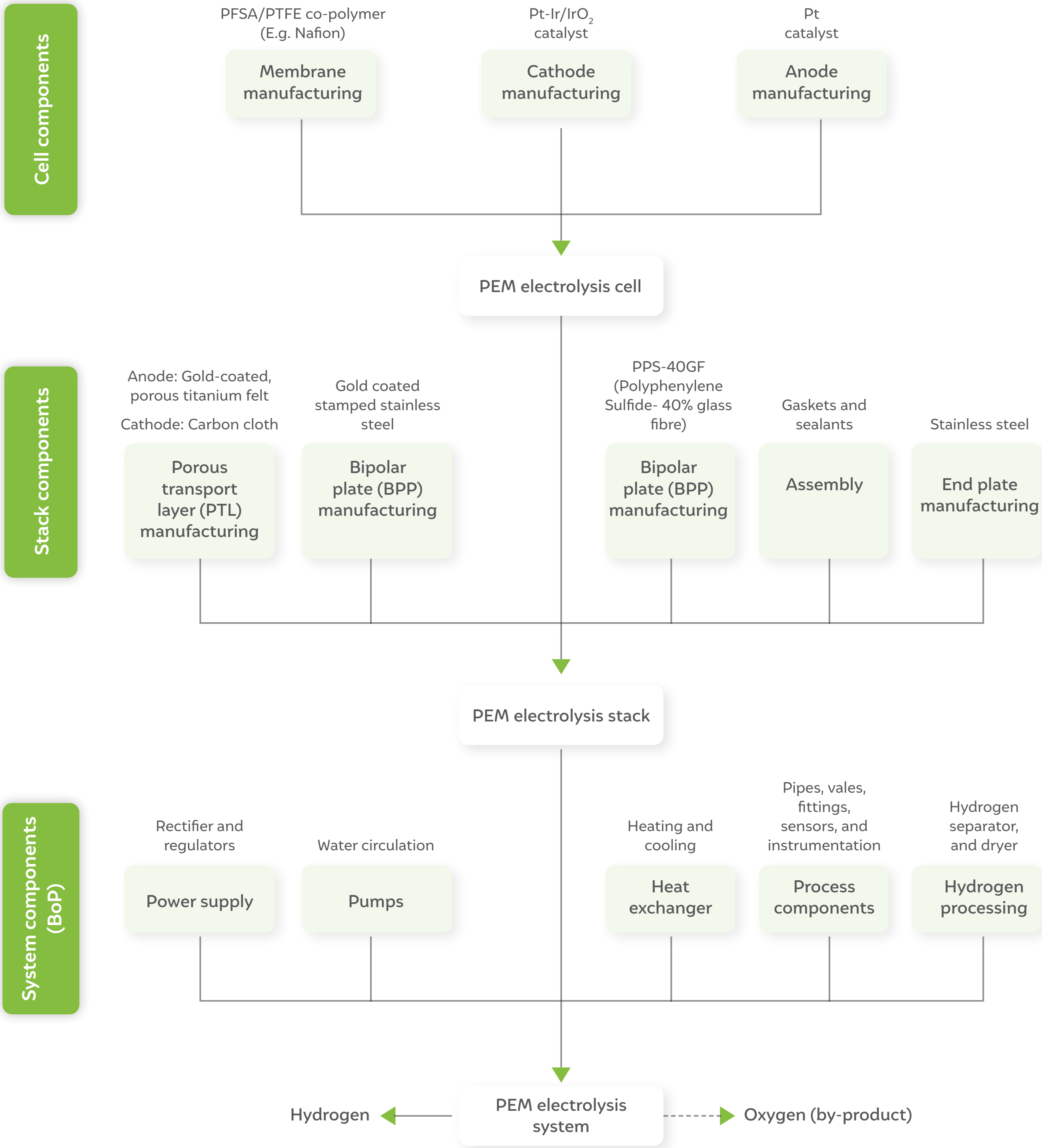
S. No.	Parameter	Value	Units	Formula
1.	Stack power	1,000	kW	a
2.	Single-cell amps	1,224	A	b
3.	Current density	1.8	A/cm^2	c = b/m
4.	Reference voltage	1.619	V	d
5.	Power density	2.913	W/cm^2	e = c × d
6.	Pt-Ir-loading anode	7	g/m^2	f
7.	Pt group material-loading cathode	4	g/m^2	g
8.	Single-cell power	1.981	kW	h = e × m/1000
9.	Cells per system	505	cells	i = a/h
10.	Stacks per system	2	stacks	j = a/i
11.	Cells per stack	252	cells	k = i/j
12.	Total plate area	957 (31 x 31)	cm^2	l
13.	CCM active area	680 (26.1 x 26.1)	cm^2	m
14.	CCM coated area	748 (27.35 x 27.35)	cm^2	n

Source: Authors' adaptation from Mayyas, Ahmad, Mark Ruth, Keith Wipke, Bryan Pivovar, and Guido Bender. 2019. Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers. Golden, Colorado: National Renewable Energy Laboratory.

Manufacturing levels of PEM electrolyser

The manufacturing of PEM electrolysers can be divided into three levels: cell components, stack components, and system components. Figure 13 lists the components and the key sub-components across the three levels. Notably, cell and stack manufacturing needs a dedicated facility, whereas BoP manufacturing is already commercialised and can be a direct buy-out item for the electrolyser manufacturer. Therefore, in this study, we have limited the detailed description of the electrolyser manufacturing process to stack components.

Figure 13 PEM electrolyser manufacturing levels



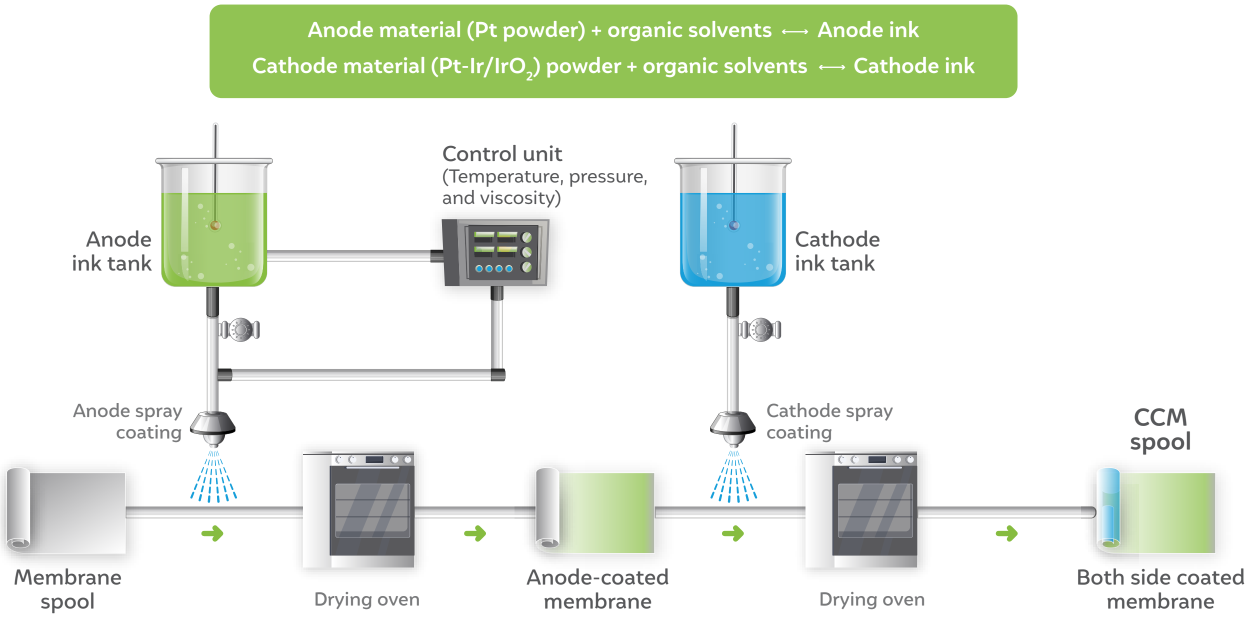
Source: Authors' analysis

a. **Cell components**: As discussed above, the electrolyser cell consists of a membrane and electrodes called an MEA. Here, we discuss the manufacturing of cell components in the context of an integrated MEA without getting into details of membrane, anode, and cathode manufacturing separately.

i. **Membrane electrode assembly (MEA):** Given the lack of clarity on membrane manufacturing and it being a proprietary technology with limited technical know-how in public domain, we assume the membrane is a direct bought-out item in our bottom-up cost analysis of PEM electrolysers. Therefore, the discussion is limited to only MEA manufacturing. Figure 14 shows the schematics of the process.

The first step involves the preparation of catalyst ink by mixing catalyst powder with organic solvents such as isopropyl alcohol (IPA) and dimethylformamide (DMF) (Therdthianwong, Ekdharmasuit and Therdthianwong 2010). Platinum powder is mixed with organic solvents to prepare the anode-side ink, while Pt-Ir/IrO2-Ru powder is mixed with the organic solvent to prepare the cathode-side ink. The anode and cathode inks are then sprayed on the respective sides of the membrane using a spray-coating method to create the CCM spool (NREL 2019).

Figure 14 The CCM manufacturing process

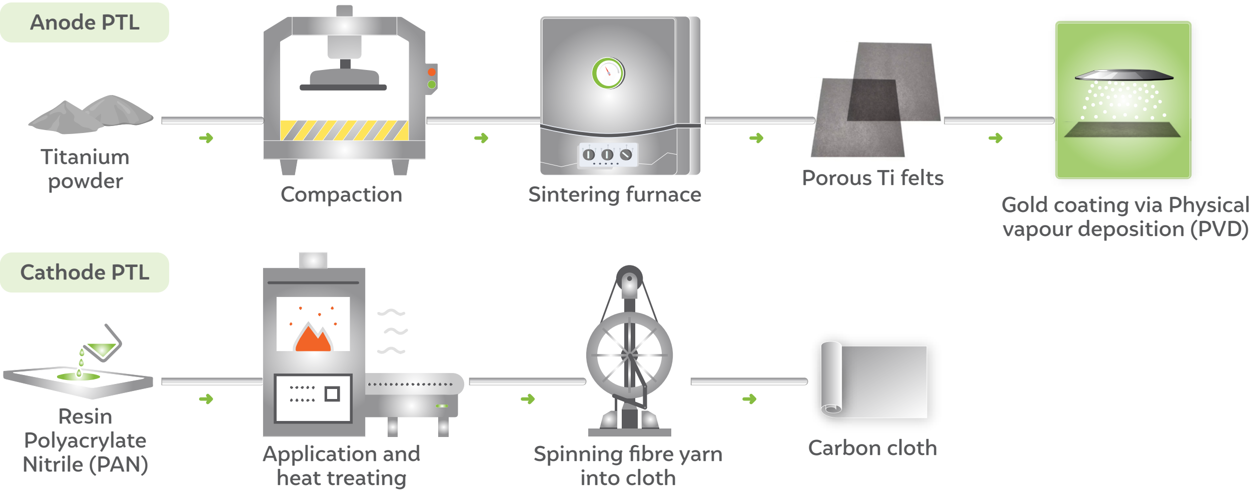


Source: Authors' analysis

b. **Stack components**: An electrolyser stack consists of several key components that work together to facilitate the electrolysis process. These components are discussed below:

i. **Porous transport layer (PTL):** The anode-side PTL is made of titanium felt coated with gold while the cathode side is a carbon cloth. The anode-side PTL is manufactured by compacting titanium powder into a plate shape, which is sintered in a furnace. Subsequently, the plate is coated with gold via a physical vapour deposition (PVD) technique. Although, some designs may use only Titanium without gold coating. The cathode-side PTL is a carbon cloth made of polyacrylate nitrile resin woven into fabric after heat treatment. The process of producing PTL is shown in Figure 15.

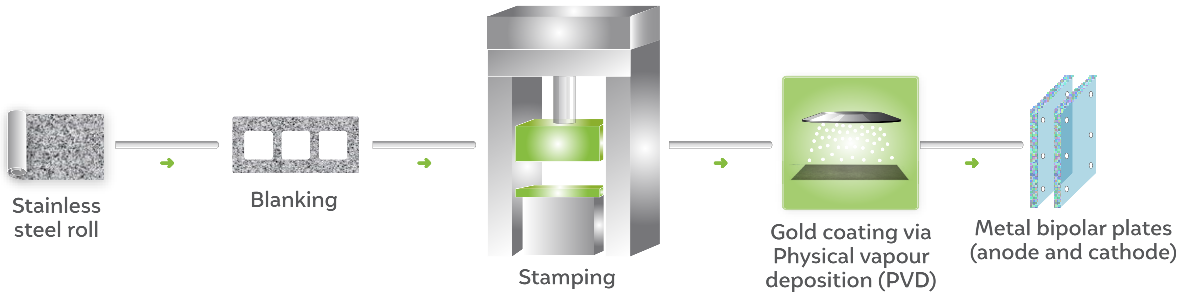
Figure 15 The PTL manufacturing process



Source: Authors' analysis

ii. **Bipolar plate (BPP)**: The choice of material for BPP can be metals with good corrosion resistance, such as stainless steel, titanium or carbon composites made through injection molding or powder metallurgy (NREL 2019). Our study considered gold-coated stainless steel (SS) for bipolar plates. In the manufacturing process (Figure 16), the stainless steel plate is blanked and stamped to inscribe flow fields that transport water to the electrodes. In the final stage, the plate is coated with gold to prevent corrosion.

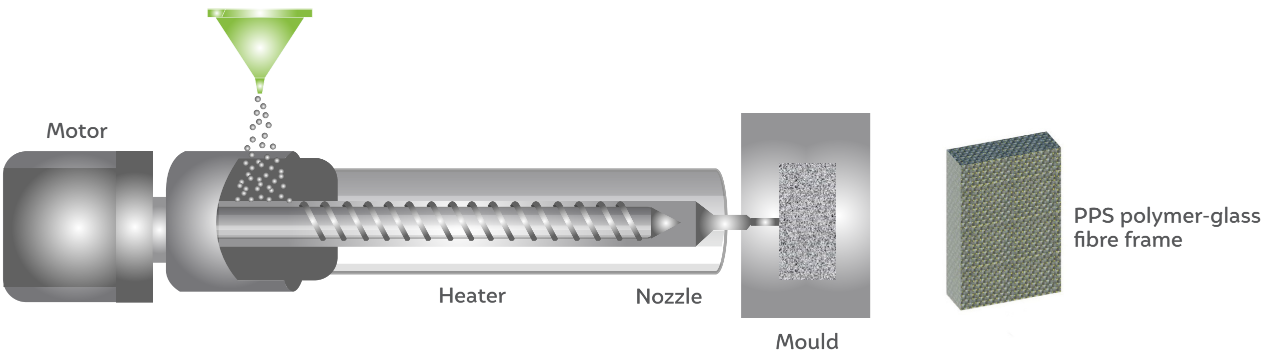
Figure 16 The bipolar plates manufacturing process



Source: Authors' analysis

iii. **Frame**: The frames provide structural support to the stack assembly. A frame is made by injection moulding as depicted in Figure 17. A PPS polymer pellet is heated via a heater and moulded in the required shape and size.

Figure 17 Frame manufacturing process



Source: Authors' analysis

iv. **End plates**: The end plates are made of stainless steel. Holes are drilled into the end plates for the bolts and the inlet and outlet manifolds.

v. **Stack assembly**: The stack assembly process involves stacking together the various components of the electrolyser. Typically, this process is conducted manually in small-scale manufacturing. However, it can be fully automated in electrolyser gigafactories, which will reduce the production cost.

c. **Balance of plant (BoP)**
Please see Section 3.3 for a detailed discussion on BoP components.

Materials required in PEM electrolyser manufacturing

The materials used in PEM electrolyser manufacturing can be broadly classified into critical and non-critical minerals. Non-critical minerals include stainless steel, while critical minerals include platinum, iridium, titanium, and gold. Table 5 indicates the mineral requirements for manufacturing PEM electrolysers and provides a comparison between the values derived in the various studies. The literature shows a significant discrepancy in the consumption of critical minerals. There is considerable uncertainty around the consumption of platinum and iridium across various publications, primarily due to differences in catalyst loading. Nevertheless, we have indicated the range of materials required for electrolyser manufacturing in India in order to highlight the challenges associated with mineral availability.

Notably, the iridium consumption we estimate is almost tenfold less than in other studies, as the reference study (NREL 2019) considers the possibility of potential reductions in iridium loading based on industry expertise. We estimate stainless steel and polymer consumption for electrolysers to be 15,459 kg/MW and 247 kg/MW, respectively. The availability of these materials is not a challenge for electrolyser manufacturing; hence, we do not include them in Table 5.

Table 5 Significant discrepancies exist in the loading of critical minerals for PEM electrolyser manufacturing

S. No.	Reference	Platinum loading (mg/cm^2)	Iridium loading (mg/cm^2)	Platinum (kg/MW)	Iridium (kg/MW)	Titanium (kg/MW)
1.	This study based on (NREL 2019)	0.9	0.2	0.340	0.076	414
2.	(IEA 2021)	–	–	0.3	0.7	–
3.	(Bareiß, et al. 2019)	0.2	2	0.075	0.75	528
4.	(IRENA 2020)	2	5	0.5	1–2.5	–
5.	(Fraunhofer ISE 2021)	1	1.73*	NA	–	–

Source: Authors' compilation

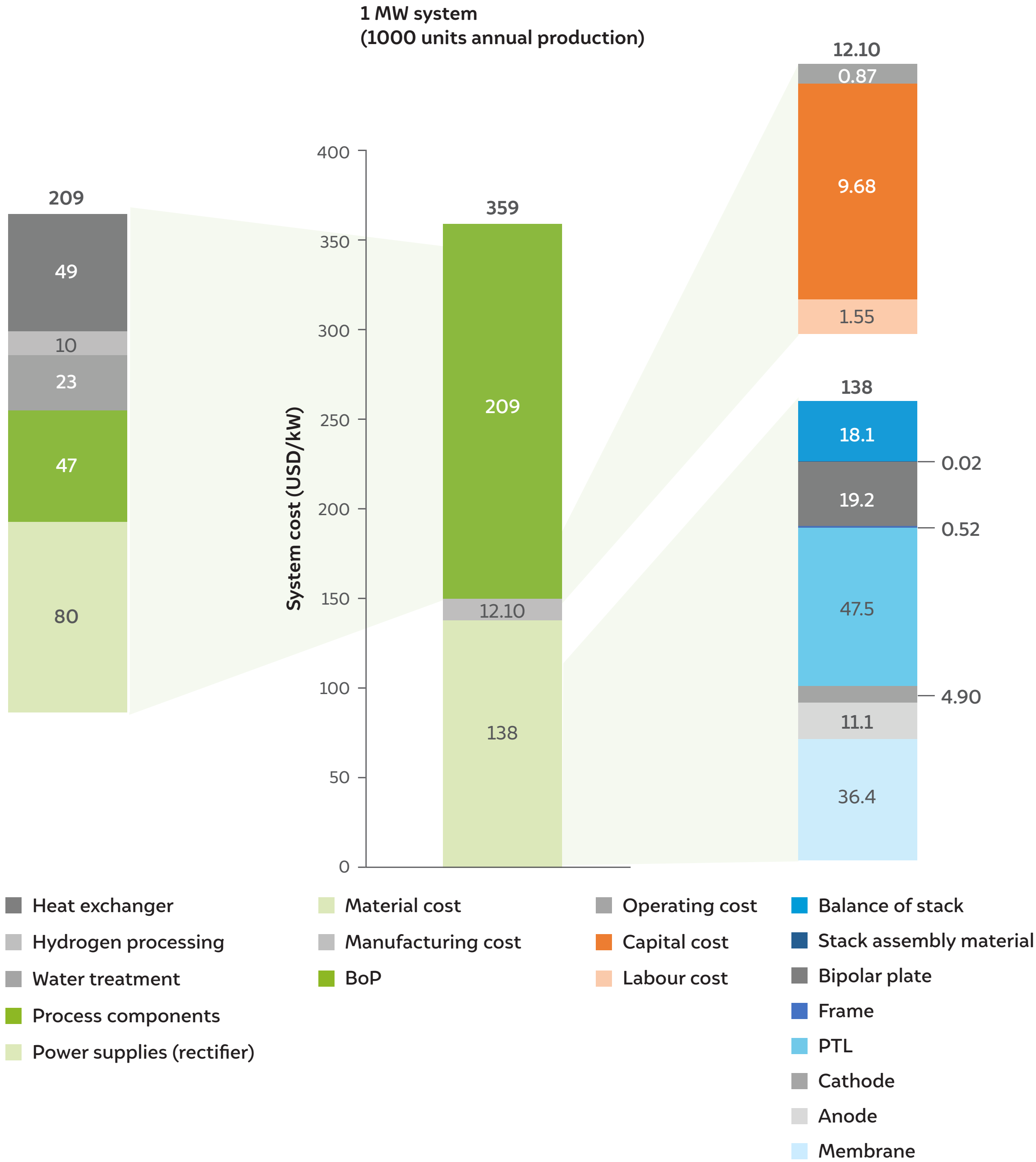
* Note: Estimate from IrO_2 loading of 2 mg/cm^2

Cost break-up of a PEM electrolyser system

In this subsection, we discuss the key findings from a bottom-up cost assessment of the manufacturing of PEM electrolysers. Our findings are based on assumptions around stack size, cell power, cell length, and material loading, as discussed in Table A1 and A2 in the Annexure. Figure 18 shows the bottom-up cost assessment for manufacturing 1,000 electrolyser units of 1 MW capacity each.

A bottom-up cost analysis shows that the cost of a PEM electrolyser system would be around USD 359/kW, of which the stack represents 40 per cent and the BoP represents 60 per cent of the overall cost. The literature indicates that the CAPEX of electrolyser manufacturing plant has a minor share – approximately USD 12.1/kW – in the overall system cost. The Nafion membrane and carbon cloth used for manufacturing the PTL constitute about 60 per cent of the total stack cost. Other components, such as cathodes, anodes, and BPPs, do not significantly impact the stack cost. Within the BoP, the power converter and the process components, such as heat exchangers, dominate the overall cost. As discussed in section 5.1.3, there is a significant uncertainty in the iridium loading for PEM electrolysers. If we were to consider an iridium loading of 2 mg/cm² (from 0.2 mg/ cm² in the base case), the cost of PEM electrolysers would increase by 6–7 per cent, i.e., from the current level of USD 359/kW for an iridium price of USD 31 per gram (USD 970/troy oz) to USD 383/kW (Metalary 2018).

Figure 18 **Material requirement for a PEM electrolyser**

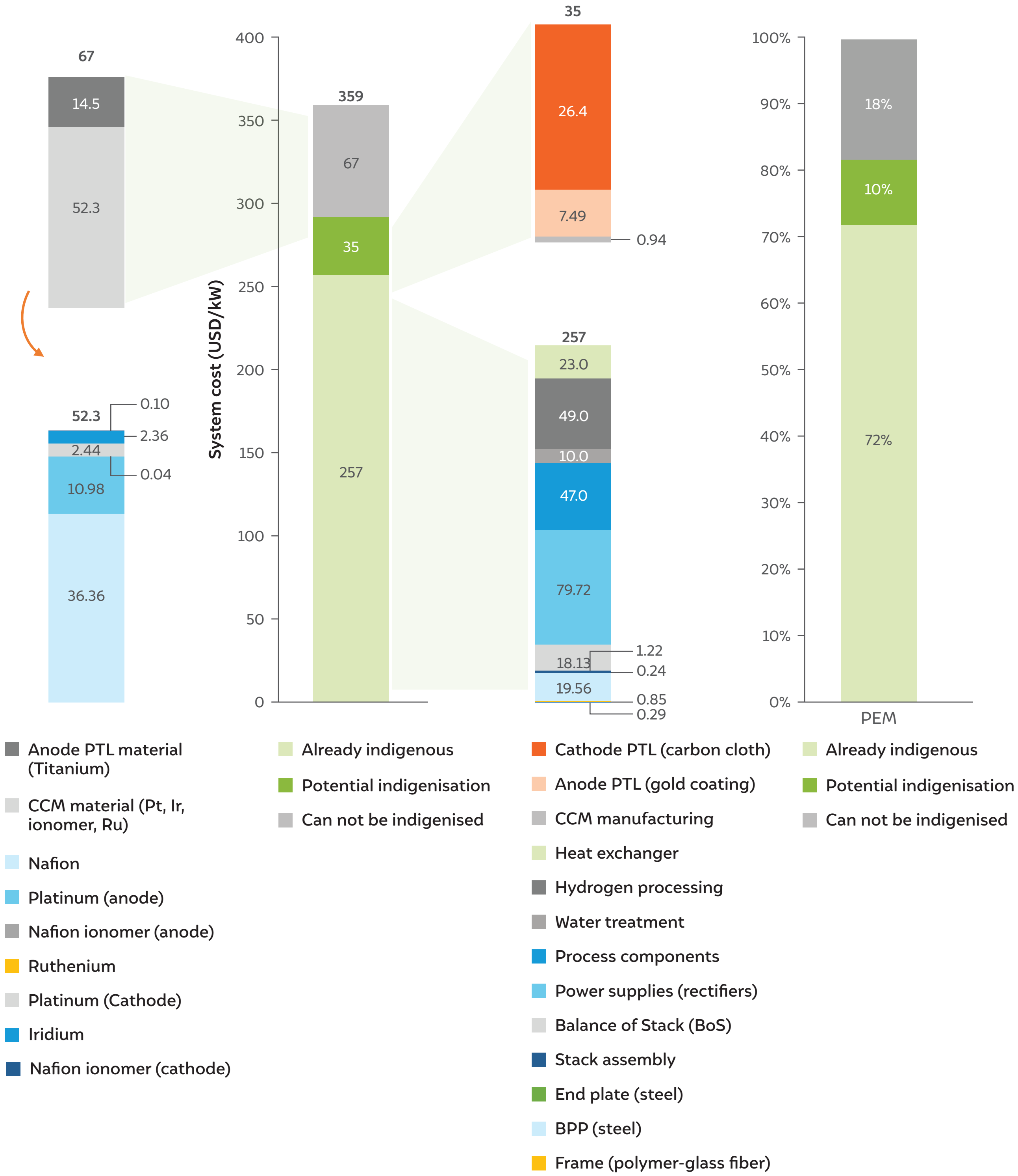


Source: Authors' analysis

Indigenisation of PEM electrolyser manufacturing

We further extended the bottom-up cost assessment study to evaluate India's potential for indigenising PEM electrolyser manufacturing costs. As Figure 19 indicates, the manufacturing costs can be divided into three categories: components that are already indigenous, components that can be indigenised with some effort, and components that cannot be indigenised due to technology and material constraints.

Figure 19 Indigenisation potential in PEM electrolyser manufacturing



Source: Authors' analysis

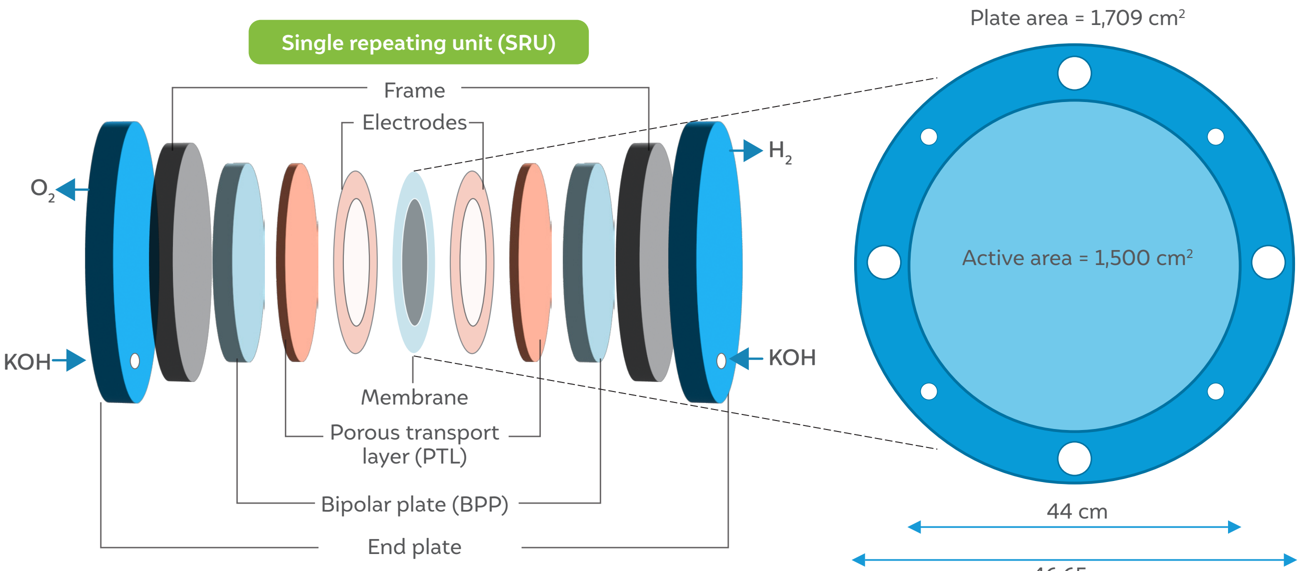
Our research indicates that about 72 per cent of the electrolyser manufacturing cost can be indigenised. All BoP components, such as power converters and heat exchangers, are already manufactured in India for various applications and can be readily used for electrolyser manufacturing. However, components such as the Nafion membrane have not yet been developed in India. Therefore, these components will have to be imported in the initial years. Further, key minerals such as platinum and iridium are not available in India. Thus, India will be import-dependent for these minerals unless alternatives are developed. Nonetheless, our study finds that these components contribute only 19 per cent of the total manufacturing cost.

Further, the indigenisation of a few components can be increased if only the raw materials are imported and the actual manufacturing takes place in India. For example, while titanium powder might have to be imported especially for meeting India's future electrolyser demand, its compacting, sintering, and gold coating can be conducted in India. Similarly, key minerals and Nafion membranes have to be imported, but CCM and carbon cloth can be produced in India. With such incremental efforts towards indigenisation, we expect an additional 10 per cent indigenisation of electrolyser manufacturing in India.

5.2 Alkaline electrolyser manufacturing

Alkaline electrolysers, when powered by renewable electricity, split water molecules such that anions (i.e., OH^- ions) from the KOH solution are transferred across the membrane, producing hydrogen at the cathode and oxygen at the anode. Figure 20 shows the construction of a typical alkaline electrolyser. Typically, an alkaline electrolyser uses an OH^- conducting membrane, such as Zirfon (a proprietary material by Agfa). The Zirfon membrane comprises 85 per cent zirconium dioxide (ZrO_2) and 15 per cent PPS polymer. Alternatives to Zirfon – such as Fumasep (Fumatech n.d.), Sustainion (Dioxide material n.d.), Tokuyama (Tokuyama n.d.), Aemion (Ionomr 2018), and Orion (Orion n.d.) – are available in the market. These membranes have also demonstrated promising long-term stability and performance (Fernández, et al. 2021). Further, a few companies plan to focus on fluorine chemistry, specifically in developing products like PVDF and Teflon-based membranes. However, our bottom-up cost assessment study is based on using a Zirfon membrane in an alkaline electrolyser, as this is the most favourable product per industry standards.

Figure 20 Alkaline electrolyser cell design



Source: Authors' analysis

The electrodes used in alkaline electrolysers are made of a 50 per cent porous nickel sheet coated with a Nickel-Aluminium (Ni-Al) alloy known as raney nickel. The anode side is coated with raney nickel, while the cathode side is coated with molybdenum-doped raney nickel. The electrolyte with 20–30 per cent KOH provides the necessary alkaline medium, circulated via a pump across the stack. The PTL adjoining the electrodes is made of 80–90 per cent porous nickel foam, which provides a microscopic passage to draw out the generated hydrogen and oxygen. This arrangement is supported by 40 per cent fibreglass-reinforced PPS-40GF thermoplastic frames that give the stack the required rigidity. Finally, the stack is enclosed within end plates, with provisions for inlet and outlet manifolds.

Due to its simple construction, an alkaline electrolyser has multiple advantages. However, it also has some challenges due to its use of an electrolyte. Table 6 lists the advantages and challenges of using an alkaline electrolyser.

Table 6 Advantages and disadvantages of alkaline electrolyser

Advantages	Challenges
• Widely available and lower cost • Nickel catalyst is a low-cost, non-precious metal component • Stable operation suitable for large-scale production	• Use of liquid electrolyte requires maintenance to avoid corrosion • Medium-purity hydrogen (needs an additional purification step for some end uses) • Low operating pressure (requires additional compression) • Requires high-purity feed water

Source: Authors' compilation from Scottish Government. 2022. Assessment of Electrolysers: Final Report. September 23, 2022. Edinburgh: Arup.

Alkaline electrolyser cell specifications assumed for this study

Similar to the case of the PEM electrolyser discussed in Section 5.1, our techno-economic analysis for the alkaline electrolyser is based on an assumption of 1 GW of the electrolyser manufacturing facility. We assume a minimum stack size of 1 MW, which is consistent with industry data for an electrolyser gigafactory (Air Liquide 2024). Consequently, 1,000 stacks of 1 MW power each will be produced annually in the electrolyser manufacturing facility. To be consistent with the literature, we assume that a stack constitutes 198 cells (NREL 2019). This assumption differs slightly from the discussion of the PEM electrolyser in Section 5.1, primarily due to the differences in cell designs and current densities. As Table 7 shows, the modelled alkaline electrolyser operates at a current density of 0.2 A/cm^2, whereas the PEM electrolyser modelled in Section 5.1 operates at a current density of 1.8 A/cm^2.

Based on the assumptions listed in Table 7, each electrolyser cell has an active area of 1,500 cm^2. Assuming the clearance margin for the end plate, the total plate area is around 1,700 cm^2. A detailed description of the alkaline electrolyser considered for this modelling can be found in the Annexure, in Table A3 and A4.

Table 7 Alkaline electrolyser cell parameters assumed for the bottom-up cost analysis

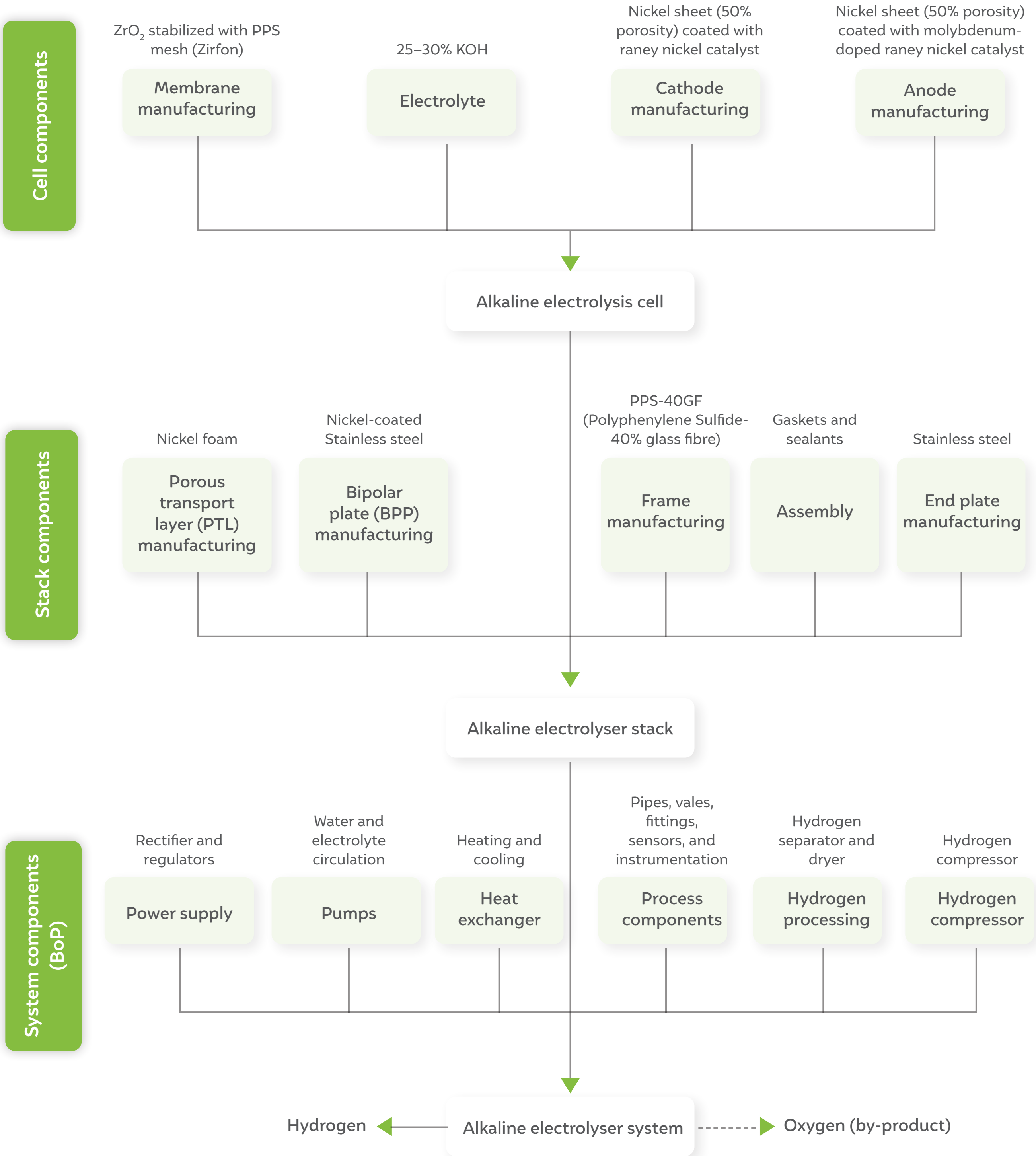
S. No.	Parameter	Value	Units	Formula
1.	System rated power	1,000	kW	a
2.	Single-cell amps	300	A	b
3.	Current density	0.2	A/cm^2	c
4.	Reference voltage	1.68	V	d = b × c
5.	Power density	0.336	W/cm^2	e = c × d
6.	Single-cell power	504	W	f = e × k
7.	Cells per system	1,983	cells	g = (a/f) × 1000
8.	Stacks per system	10	stacks	h
9.	Cells per stack	198	cells	i = g/h
10.	Diameter of an active electrode	44	cm	j
11.	Active electrode area	1,501	cm^2	k = ϖ × j × j/4
12.	Margin for plate on each side	1.47	cm^2	l
13.	Plate diameter	46.65	cm	m = j+2 × l
14.	Total plate area	1,709	cm^2	n

Source: Authors' analysis

Manufacturing levels of alkaline electrolyser

Similar to the detailed bottom-up manufacturing study of PEM electrolysers, we have split the bottom-up analysis of alkaline electrolysers into three levels – the cell, stack, and system – as shown in Figure 21. The cell-level detailing consists of the MEA and electrolyte. The stack-level analysis consists of the PTL, BPP, frame, and end-plate manufacturing and stack assembly. The system's BoP consists of miscellaneous equipment such as rectifiers, pumps, and heat exchangers, which are discussed in Section 4.3. In addition to these components, since alkaline electrolysers operate at low pressure, we also include the cost of a hydrogen compressor in this bottom-up analysis.

Figure 21 Levels of alkaline electrolyser manufacturing



Source: Authors' analysis

It is important to note that the cell and the stack need dedicated manufacturing facilities, whereas the BoP manufacturing is already commercialised and can be bought out. As with the PEM electrolysers, in this section, the detailed manufacturing process is provided only for the electrolyser stack.

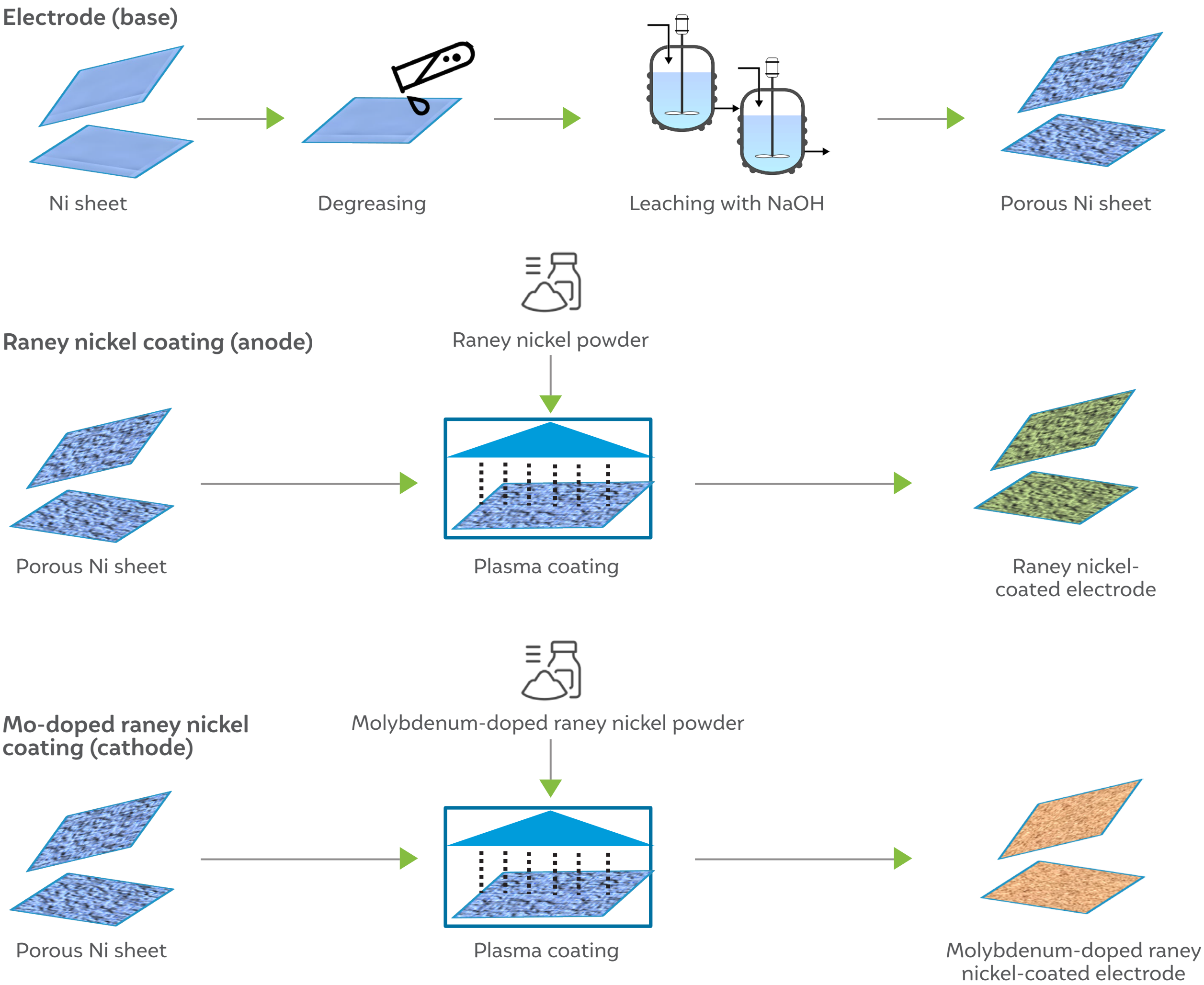
a. **Cell components**: As discussed, the electrolyser cell consists of a membrane and electrodes together called the membrane electrode assembly (MEA):

   i. **Membrane electrode assembly (MEA):** As we have discussed in Section 5.2, the Zirfon membrane is made of 85 per cent zirconium and 15 per cent polymer. We have considered it a bought-out item for this bottom-up cost analysis.

   Figure 22 shows that the membrane is enclosed within thin, nickel-coated electrodes. The anode is a raney nickel–coated porous sheet made by first degreasing the nickel sheets and then leaching them with sodium hydroxide (NaOH) solution. Subsequently, the porous nickel sheet is coated with raney nickel powder through a plasma coating process to produce a raney nickel–coated electrode, which is used as the anode in the electrolyser.

   The manufacturing process for the cathode is similar, except that during the plasma-coating process, the raney nickel powder is doped with molybdenum.

Figure 22 **The MEA manufacturing process**

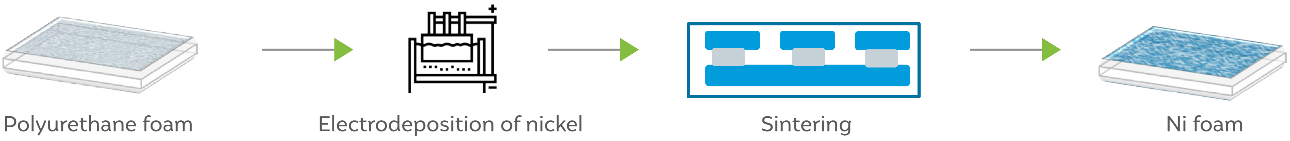


Source: Authors' analysis

b. **Stack components:** An alkaline electrolyser has the following stack components:

   i. **Porous transport layer (PTL):** Polyurethane foam is the base material for the PTL. For this study, we have assumed that polyurethane foam is a bought-out item for electrolyser manufacturing. Nickel is electrodeposited on the polyurethane foam and sintered to fabricate the nickel foam sheet as depicted in Figure 23.

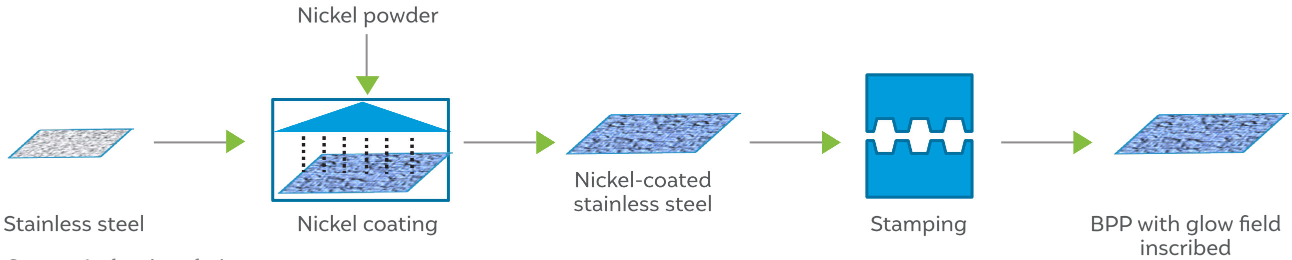
Figure 23 **Anode and cathode porous transport layer manufacturing process**



Source: Authors' analysis

   ii. **Bipolar plate (BPP):** Figure 24 shows the schematic of the BPP manufacturing process. Stainless steel is the base material for the BPP. It is spray-coated with nickel to provide the necessary conductivity for the electrolyser. The nickel-coated BPP is then stamped to inscribe the flow fields to transport water to the electrodes.

Figure 24 **The bipolar plate manufacturing process**



Source: Authors' analysis

   iii. **Frame, end plates and stack assembly**: Frames provide structural support to the electrolyser stack and are made by injection moulding, as discussed in Section 5.2.1 and show in Figure 17. The end plates and stack assembly have been discussed in section 5.2.1 and not repeated here for brevity.

c. **Balance of plant (BoP)**

   Please see Section 3.3 for a detailed discussion on BoP components.

Materials required in alkaline electrolyser manufacturing

We can classify the raw materials required for alkaline electrolyser manufacturing as non-critical and critical. Non-critical materials include stainless steel and polymers, whereas critical minerals include nickel, zirconium, and molybdenum. Table 8 tabulates the specific mineral requirement in terms of kg/MW. Alkaline electrolysers use the least number of critical elements. They would therefore be the preferred choice for technology development in the Indian context.

There is, however, significant uncertainty about nickel consumption in electrolyser manufacturing. While new studies indicate a nickel consumption of 800 kg/MW (IEA 2021), a few studies have indicated a requirement of 3,167 kg/MW (Koj, et al. 2017). Our bottom-up assessment based on NREL (NREL 2019) estimates a nickel requirement of 1,600 kg/MW. Further, we estimate a zirconium requirement of 94 kg/MW, which broadly agrees with the literature (IEA 2021). The molybdenum requirement is minimal, given that it is only used with raney nickel for cathode manufacturing.

Table 8 Material consumption for manufacturing alkaline electrolysers

S. No.	Material	Type	Quantity (kg/MW)	References
1.	Nickel	Critical mineral	800–3167	(Koj, et al. 2017)
2.	Zirconium		94–100	(IEA 2021)
3.	Molybdenum		0.15	This study based on (NREL 2019)
4.	Stainless steel	Non-critical mineral	8,546–10,000	(IEA 2021)
5.	Polymer		56	This study based on (NREL 2019)

Source: Authors' compilation

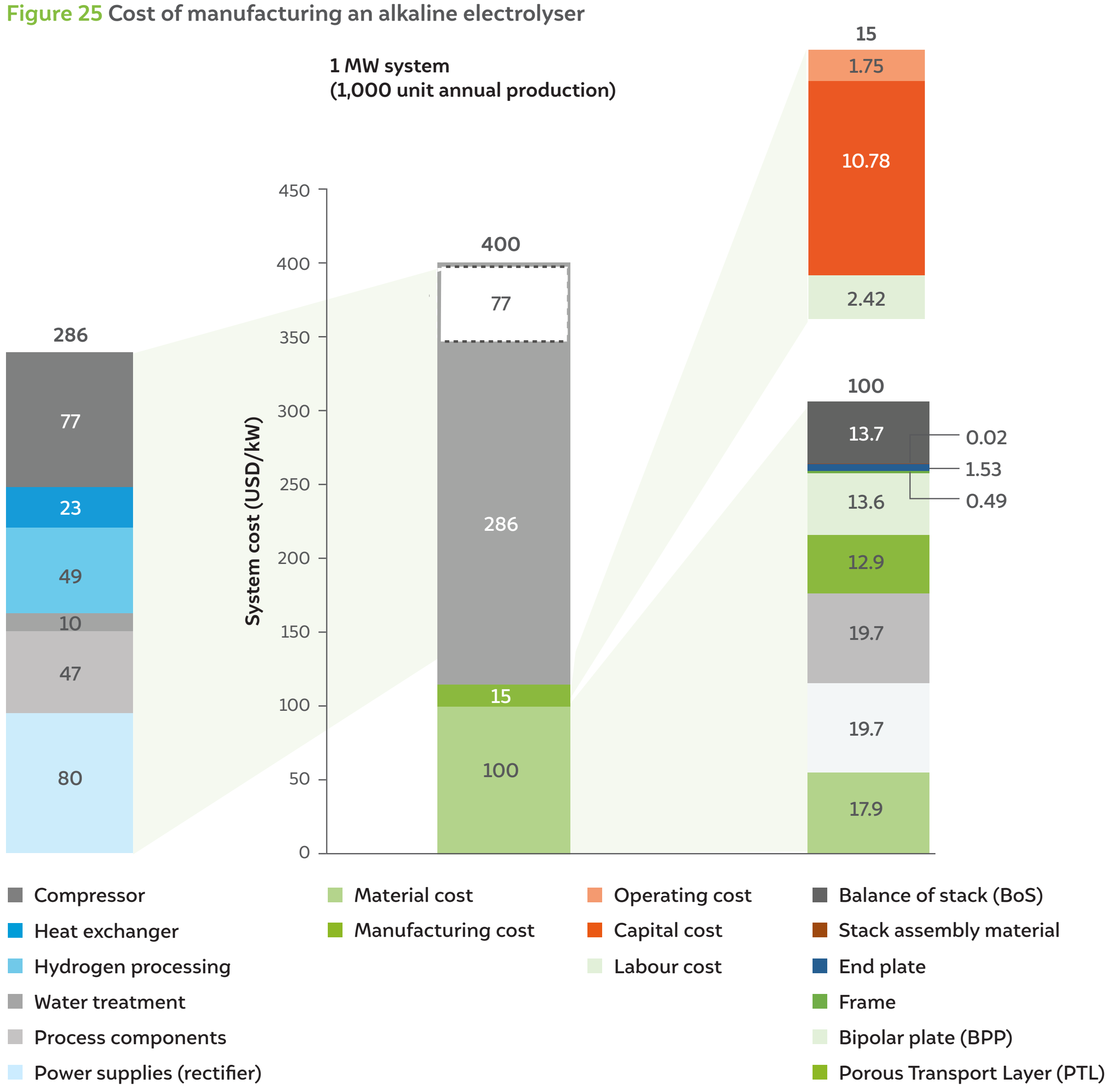
Cost break-up of an alkaline electrolyser system

Figure 25 shows a detailed breakdown of alkaline electrolyser manufacturing costs in India. The cost is split into three components: material, manufacturing, and BoP costs. The materials cost covers all components used in electrolyser stack manufacturing. The electrodes, the PTL, and the BoS components contribute almost equally to the stack cost.

While the Zirfon membrane is the only directly bought-out commodity considered in our analysis, its cost is uncertain and can range from USD 60/m^2 to USD 250/m^2. Based on conversations with industry experts, we assumed a membrane cost of USD 60/m^2. The cost of other materials consumed in electrolyser manufacturing also depends on the prevalent market prices, which keep fluctuating. The material costs we have assumed for alkaline electrolysers are indicated in Annexure 2.

Manufacturing cost is a small fraction of the overall electrolyser cost, consistent with the previous observation that the capital required for setting up an electrolyser gigafactory is trivial compared to the materials cost. We have assumed the cost of BoP components to be similar in alkaline and PEM electrolysers, except that the cost of a hydrogen compressor of USD 77/kW has been added, thus putting the cost of an alkaline electrolyser in the range of USD 323/kW to USD 400/kW.

Figure 25 Cost of manufacturing an alkaline electrolyser



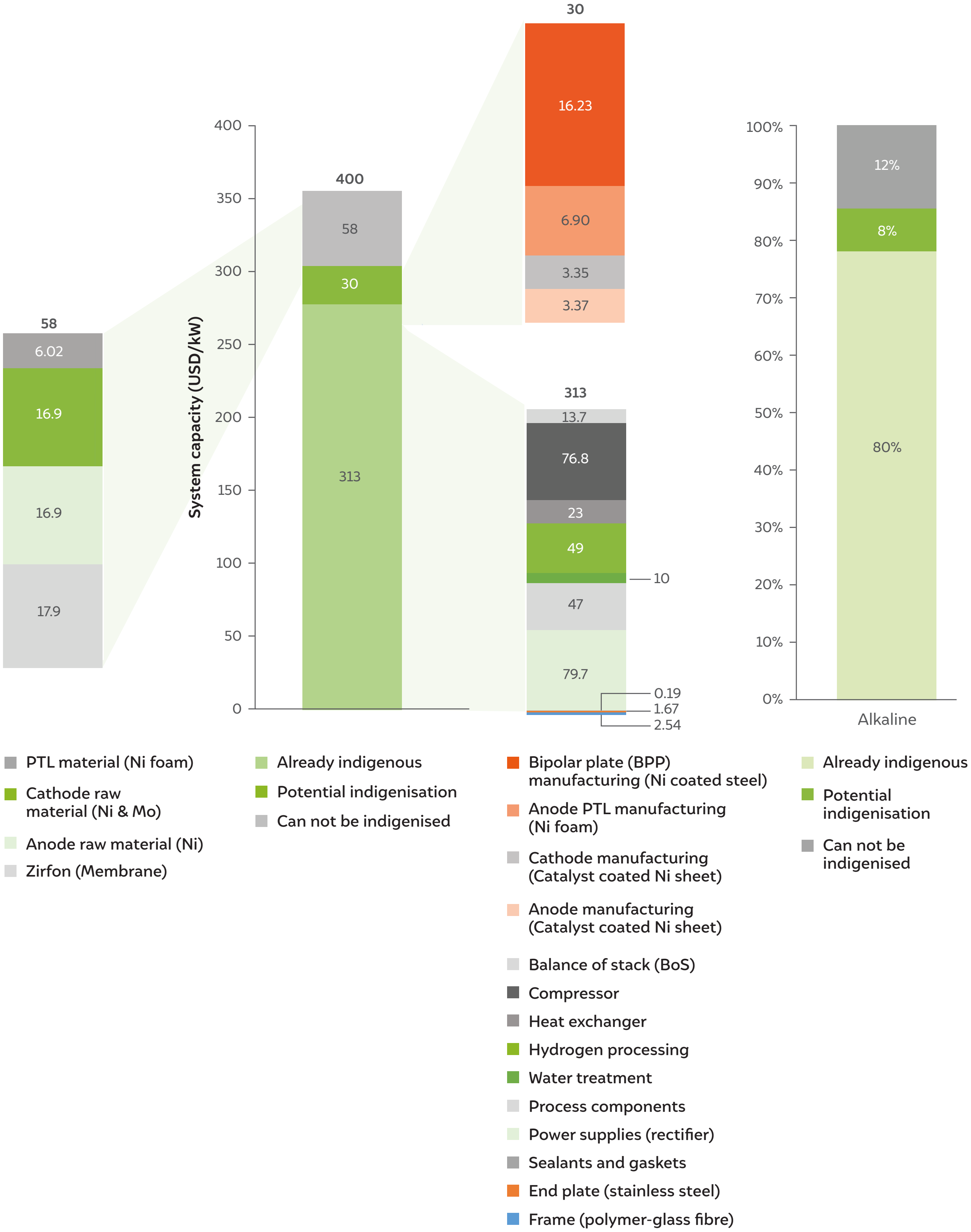
Source: Authors' analysis

Indigenisation of alkaline electrolyser manufacturing

Similar to the methodology for the PEM electrolyser, we split the potential for indigenisation into three parts: already indigenous, possible to indigenise, and costs that cannot be indigenised (Figure 26). All BoP components, including the hydrogen compressor, are expected to be manufactured within India and indigenised. While India does not have nickel resources, nickel coating on BPPs and electrodes can potentially be done in India, further bolstering domestic electrolyser manufacturing.

Based on contemporary technology, it is assumed that Zirfon membranes, nickel, and molybdenum are the raw materials required for the electrodes and coating. We consider that nickel foam manufacturing is not indigenised at present. The raw materials and imported commodities are placed in the 'cannot be indigenised' category. While the Zirfon membrane can be manufactured in India, zirconia (ZrO_2) accounts for around USD 10/kW in electrolyser manufacturing and needs to be imported, since there are limited reserves within India. Therefore, while India should focus on developing the domestic manufacturing capacity of these membranes, we must also develop alternatives to zirconia for higher indigenisation.

Figure 26 Indigenisation potential of alkaline electrolysers



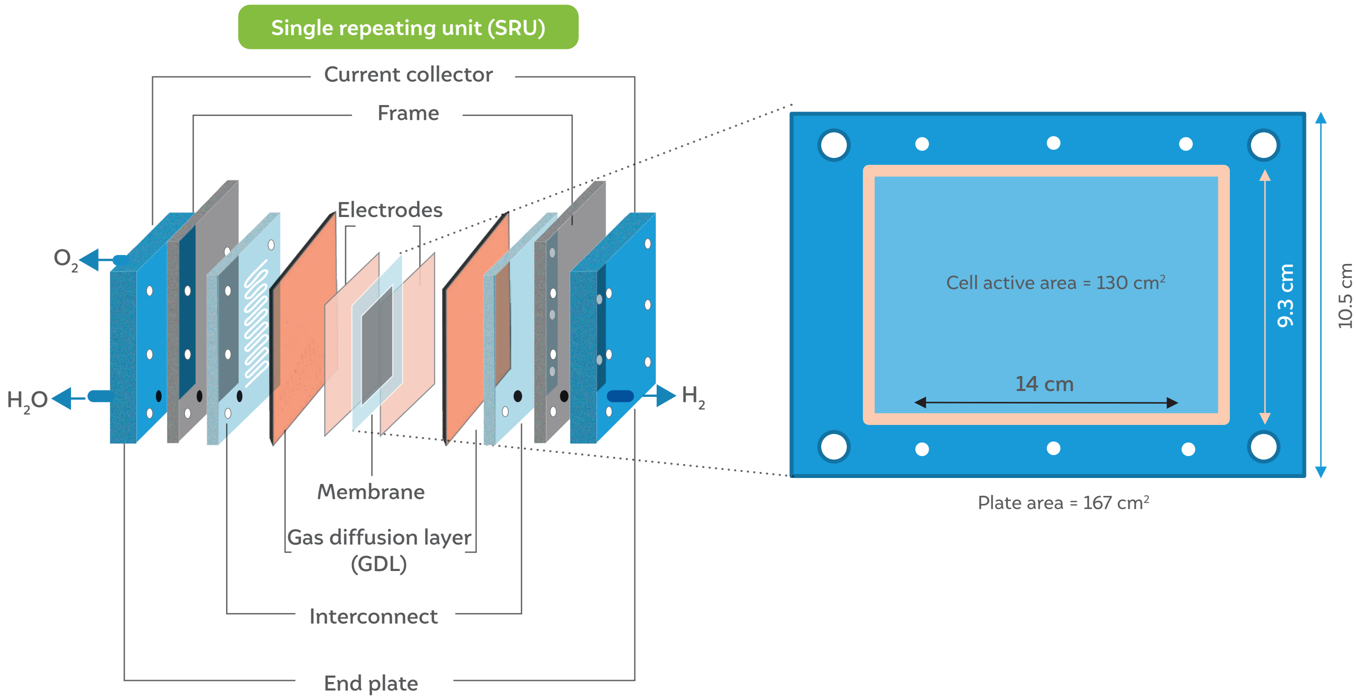
Source: Authors' analysis

Broadly, we believe that 80 per cent of the cost of alkaline electrolyser manufacturing can be readily indigenised. In comparison, 8 per cent can be potentially indigenised if only raw materials are sourced and their manufacturing occurs in India. The remaining 12 per cent is difficult to indigenise given that India does not have certain raw materials, such as the nickel and molybdenum required for electrolyser manufacturing, and critical components, such as the membranes.

5.3 Solid oxide electrolysers (SOEs)

The generic design of SOEs is similar to those of PEM and alkaline electrolysers. However, unlike alkaline and PEM electrolysers, the membrane used in SOEs conducts O^{2-} ions inherently. There are a variety of materials favourable for conducting O^{2-} ions. However, owing to lower TRL, the R&D is still in its early/nascent stages. Currently, electrolytes such as yttria-stabilised zirconia (YSZ), scandia-stabilised zirconia (SSZ), and barium zirconia ceria yttrium (BZCY) are the materials of choice across most SOEs. We have featured SSZ in our bottom-up cost analysis as the preferred electrolyte for SOEs due to ample research and information on it being available in the public domain (Anghilante, et al. 2018). Similarly, while there is ongoing development and evolution of electrode materials, we assess lanthanum strontium cobalt ferrite (LSCF) as anode and nickel oxide and gadolinium-doped ceria (NiO/GDC) as cathode materials.

Figure 27 SOE cell design



Source: Authors' analysis

Unlike the alkaline and PEM electrolysers which use a PTL, SOEs use a gas diffusion layer (GDL) (Figure 27). This is because the PTL used in alkaline and PEM electrolysers selectively conducts liquid electrolytes, whereas the GDL transports oxygen and hydrogen gases. The GDL is comprised of a thin GDC coating on both electrodes.

Another essential component of SOEC is interconnect, which connects neighbouring cells and provides flow fields for the input steam and the hydrogen product. The base material for interconnect layers is ferritic steel (Crofer 22 APU), which is coated with a protective coating to prevent oxidisation. Based on the literature, we selected a manganese cobalt oxide (MCO) coating on the interconnect (Anghilante, et al. 2018) in our model. While a few US companies are pioneers in SOEC, especially for interconnects, Indian research institutes like the International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) are also developing materials similar to ferritic steel that can be used as interconnect. The interconnect layers are responsible for connecting many cells in a series. Multiple cells together constitute an electrolyser stack. The stack is enclosed within the current collector, which ensures equipotential at each electrode and efficient gas transport from the electrode to the flow channels. Finally, the end plates pack the whole assembly into a single unit. Table A3 in the Annexure details the materials considered for the bottom-up assessment and their costs. Table 9 lists the advantages and challenges of using an SOE.

Table 9 Advantages and disadvantages of SOEs

Advantages	Challenges
• High efficiency, as they can withstand high-temperature operation • Solid electrolyte, which reduces corrosion and gas leakage • Do not require precious metals • Less sensitive to impurities; therefore, low-purity water can be used • Suitable for steady operations with a nearby (waste) heat source (e.g., nuclear) • Waste heat can be utilised elsewhere (e.g., in gas turbines) to improve efficiencies	• Long start-up time (≥ 12 hours) • Unsuitable for flexible operations • Currently at a lower stage of development and only used at a small scale due to cost • Need to be coupled with a high-waste heating process to achieve efficiencies

Source: Authors' adaptation from Scottish Government. 2022. Assessment of Electrolysers: Final Report. September 23, 2022. Edinburgh: Arup.

Solid oxide electrolysing cell (SOEC) specifications assumed for this study

SOEs are still at a lower TRL than alkaline and PEM electrolysers. Therefore, based on the literature, we assumed a 75 MW/year electrolyser manufacturing facility with five stacks producing 15 MW of power annually (Anghilante, et al. 2018). We assume the electrolyser stack consists of 160 cells worth 0.15 kW each. Table 10 shows the SOEC's dimensions and the details of its mass and volume requirements. Table A3 (Annexure) lists the materials consumption data.

Table 10 Assumptions for bottom-up cost analysis of SOE manufacturing

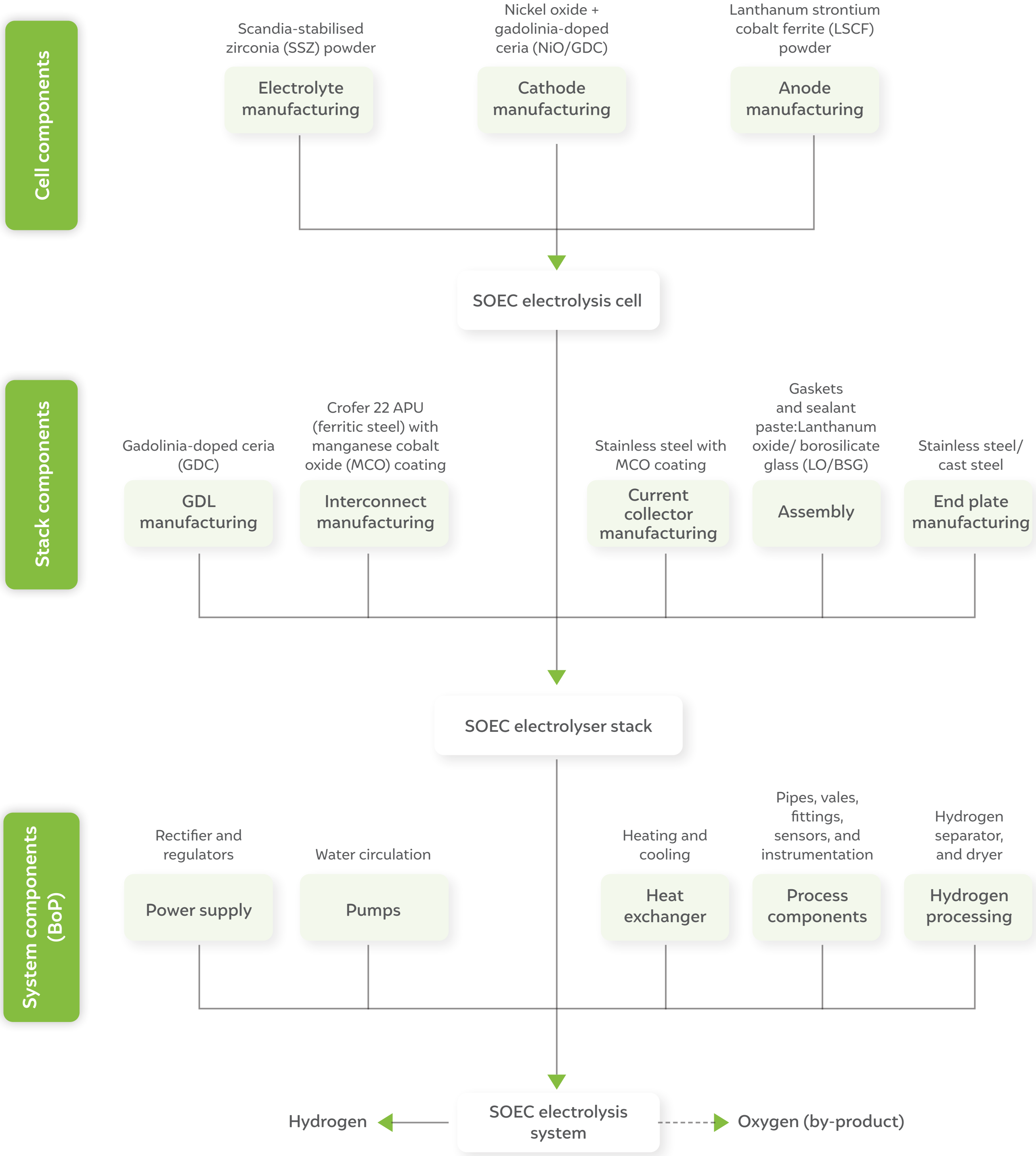
S. No.	Parameter	Value	Units	Formula
1.	SOEC unit electrical power	15	MW	a
2.	Capacity of the SOEC production line	75	MW/year	b
3.	Electrical power of an SOEC	0.15	kW	c = j × l × m/1000
4.	No. of cells required for annual production	4,93,097		d = b/c × 1000
5.	No. of stacks	3,082		e = d/h
6.	No. of modules	20		f = e/h
7.	Electrical power of an SOEC stack	24.3	kW	g = c × h/1000
8.	1 stack	160	cells	h
9.	Steam conversion rate	80	%	i
10.	Cell active area	130	cm^2	j
11.	Total cell area	167 (15.8 x 10.5)	cm^2	k
12.	Operation voltage	1.3	V	l
13.	Current density	0.9	A/cm^2	m
14.	Cell architecture	-	Electrolyte-supported cell	
15.	Cell geometry	-	Flat square cell	
16.	Electrolyte (6/1 mol% scandia/ceria-doped zirconia (6Sc1CeSZ or SSZ)	130	microns	
17.	Ion diffusion layer or adhesion layer (two layers in total) (GDC)	10	microns	
18.	Oxygen electrode (anode) (LSCF)	25	microns	
19.	Hydrogen electrode (cathode) (NiO/GDC)	25	microns	

Source: Authors' adaptation from Anghilante, Régis, David Colomar, Annabelle Brisse, and Mathieu Marrony. 2018. "Bottom-up Cost Evaluation of SOEC Systems in the Range of 10–100 MW." International Journal of Hydrogen Energy, 43 (45): 20309–22.

Manufacturing levels of solid oxide electrolyser

Similar to the alkaline and PEM electrolysers, the bottom-up cost for manufacturing SOEs is split across three levels: cell, stack, and system components. Figure 28 shows the various sub-components across these layers. Similar to alkaline and PEM electrolysers, cell and stack manufacturing for SOEs requires a dedicated manufacturing facility, whereas the BoP components are already commercialised and can be directly bought out by the electrolyser manufacturer.

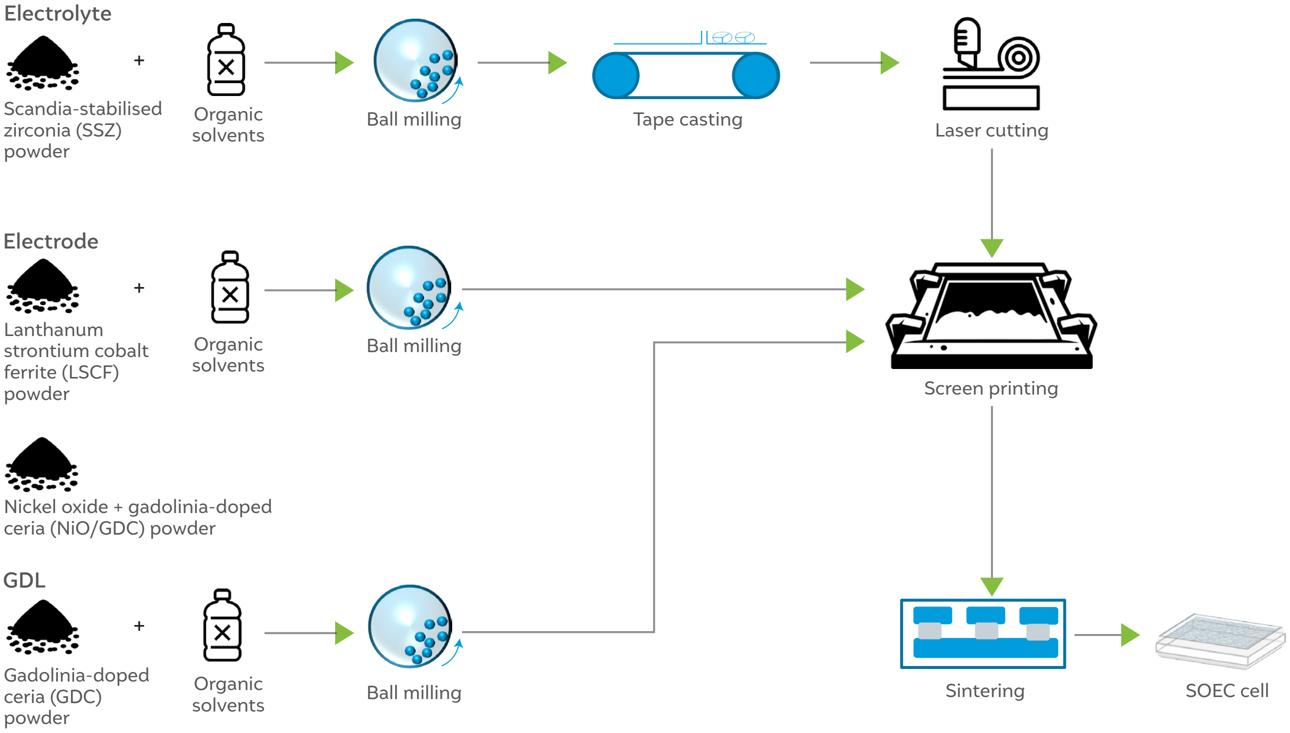
Figure 28 Manufacturing levels of SOECs



Source: Authors' analysis

As shown in Figure 28, we have assumed that the raw materials for electrolytes, electrodes, and GDL are procured in powder form. These powders are mixed with organic solvents to create a slurry. The electrolyser slurry first undergoes a tape-casting process, during which a thin electrolyte film is obtained. Laser cutting ensures proper dimensions are carved out and the obtained tape-casted electrolyte is screen printed, upon which the anode and cathode slurry are further screen printed. The GDL powder also goes through the same process, followed by screen printing and sintering (Anghilante, et al. 2018). The final assembly results in an SOEC (Figure 29).

Figure 29 Manufacturing processes of SOEC components



Source: Authors' analysis

Materials required in SOE manufacturing

SOEC manufacturing involves diverse critical and rare minerals such as lanthanum, cerium, gadolinium, scandium, and strontium. Additionally, manufacturing SOEs requires zirconium and nickel, which, although less critical, are also needed in considerable amounts. Table 11 indicates the specific mineral requirements for manufacturing SOEs.

Table 11 Material consumption for manufacturing SOEs

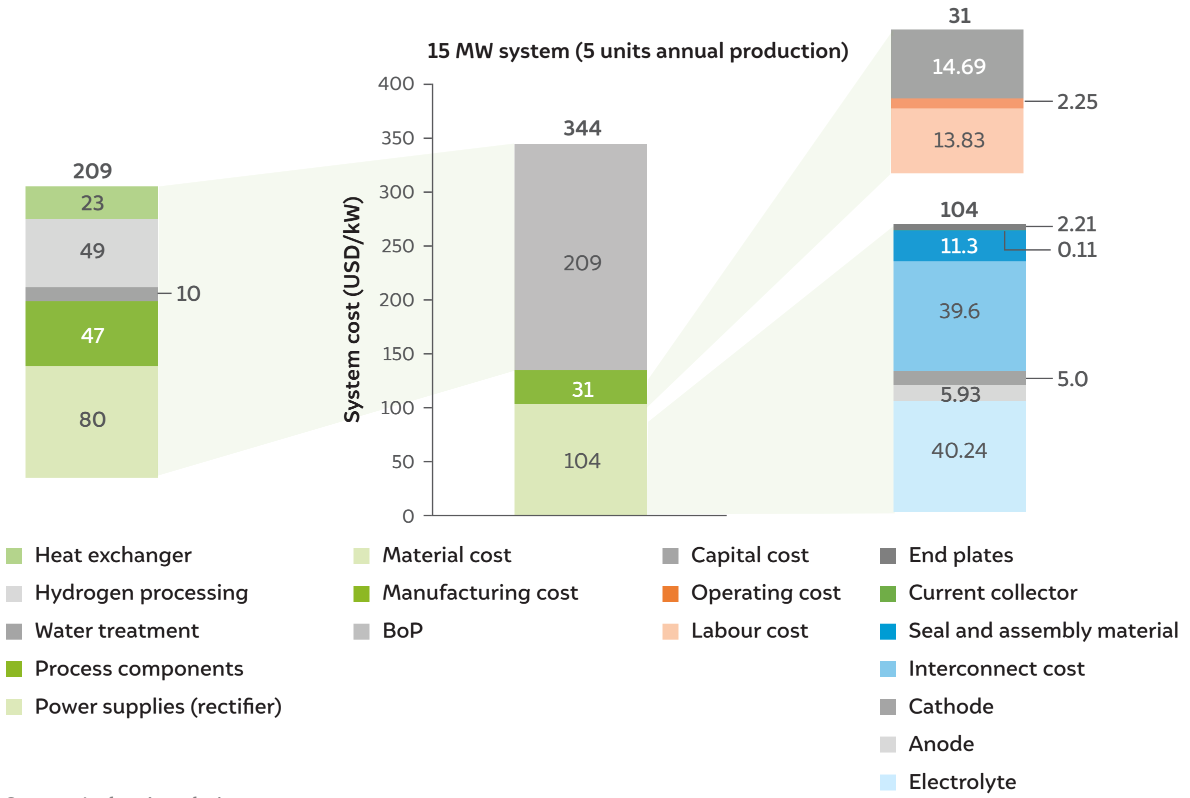
S. No.	Material	Type	Quantity (kg/MW)	References
1.	Lanthanum	Critical mineral	7.3–20	(IEA 2021)
2.	Cerium		30	This study based on (NREL 2019)
3.	Gadolinium		6.6	
4.	Scandium		1.7	
5.	Strontium		2.1	
6.	Zirconium		54	
7.	Nickel		9.1	
8.	Steel	Non-critical mineral	22,193	This study based on (NREL 2019)

Source: Authors' analysis

Cost break-up of an SOE system

Table A3 in the Annexure details the assumptions of stack size, cell power, cell length, and material loading for our bottom-up cost assessment. Figure 30 shows that the bottom-up cost assessment of an SOE system would come to around 344 USD/kW, out of which the stack costs approximately 30 per cent. The electrolyte and interconnect (Crofer 22 APU) account for 60 per cent of the stack cost. Compared to alkaline and PEM electrolysers, the manufacturing cost corresponding to the CAPEX of the electrolyser factory is significantly higher due to the complex processes of powder metallurgy, coating, spray paint, tape casting, assembly, etc., and a lower-capacity manufacturing plant. Similar to alkaline and PEM electrolysers, the rectifiers and heat exchangers dominate the BoP cost.

Figure 30 SOEC components manufacturing is higher than for PEM and alkaline electrolysers

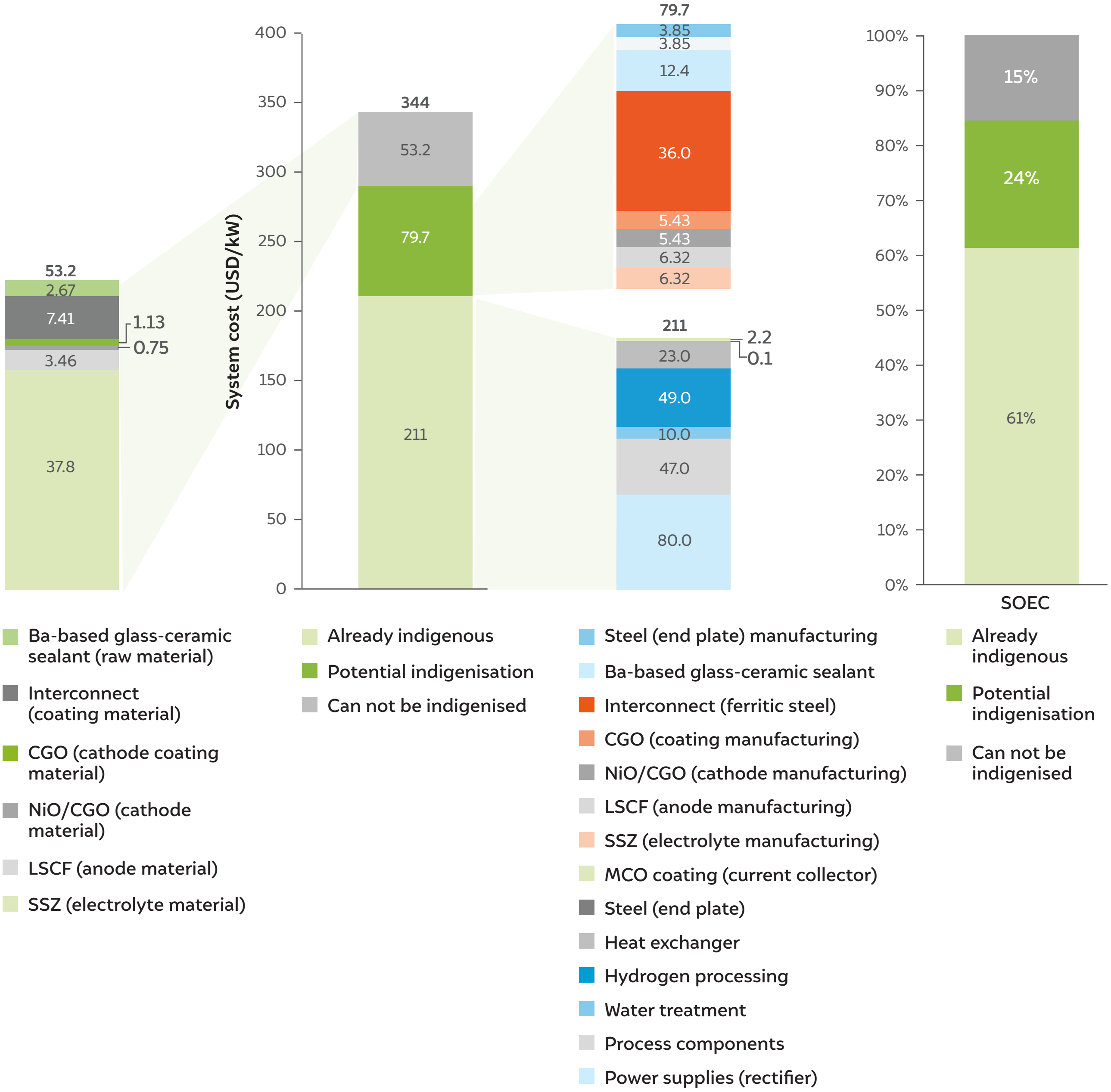


Source: Authors' analysis

Indigenisation of SOE manufacturing

Similar to PEM and alkaline electrolysers, we categorise indigenisation potential across the three options – already indigenised, components that can be potentially indigenised, and components that cannot be indigenised. The broad-level assumption still holds that BoP components are already indigenised, manufacturing finished components can be potentially indigenised, and critical raw materials for which reserves are not available within India cannot be indigenised. As shown in Figure 31, we expect that up to 61 per cent of the total manufacturing cost of SOEs is already indigenous. A further 24 per cent can be indigenised if components such as interconnects, electrolytes, and electrodes are manufactured in India although the raw materials might have to be imported. However, 15 per cent of the manufacturing cost cannot be indigenised, primarily because the reserves for crucial minerals such as nickel, molybdenum, and zirconium are unavailable in India. Full indigenisation is possible only if alternatives are developed for these minerals.

Figure 31 Indigenisation potential of SOECs



Source: Authors' analysis

High-purity nickel ore is a key raw material used in the production of alkaline electrolyser.

Image: iStock

6. Mineral requirement for electrolyser manufacturing vs global supply chains

This section covers requirement in India, imports in India and global production of various minerals for the mineral strategic planning to mitigate risks associated with global supply chains.

6.1 Mineral requirements for electrolyser manufacturing

The availability of minerals is critical for the success of domestic electrolyser manufacturing. Table 10 shows India's mineral requirements for manufacturing PEM, alkaline, and solid oxide electrolysers. The electrolyser capacity requirement for the future is obtained from the NITI Aayog report (NITI Aayog 2022). As in Section 5, there are significant uncertainties in mineral requirements across various electrolyser types. Therefore, we are indicating a range of mineral requirements in Table 12. The mineral requirement for each electrolyser type corresponds to 100 per cent penetration of that type in the long term. The corresponding global production and imports of the mineral are also indicated in the table.

Table 12 Mineral requirements for electrolyser manufacturing

S. No.	Critical mineral	Quantity per MW	Target			Global production (2022–23)	India's imports (2022–23)
			20 GW by 2030	112 GW by 2040	226 GW by 2050		
		(kg/MW)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
PEM electrolysers							
1.	Platinum	0.075–0.5	1.5–10	8.4–56	16.9–113	180	1.89
2.	Iridium	0.076–0.7	1.52–14	8.51–78.4	17.2–158	7	0.35***
3.	Titanium	414–528	8,280–10,560	46,368–59,136	93,564–1,19,328	92,00,000	612
4.	Gold	0.17	3	18	37	3,000	5.89
Alkaline electrolysers							
1.	Nickel	800–3,167	16,000–63,340	89,600–3,54,704	1,80,800–7,15,742	36,00,000	806
2.	Zirconium	94–100	1,880–2,000	10,528–11,200	2,12,44–22,600	16,00,000*	82,832*
3.	Molybdenum	0.15	3	17	34	2,60,000	109

S. No.	Critical mineral	Quantity per MW	Target			Global production (2022–23)	India's imports (2022–23)
			20 GW by 2030	112 GW by 2040	226 GW by 2050		
		(kg/MW)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
			SOEs				
1.	Nickel	9.1	181	1,015	2,049	36,00,000	806
2.	Zirconium	54	1,071	5,998	12,104	16,00,000*	82,832*
3.	Lanthanum	7.3–20	146–400	817–2,240	1,649–4,520	3,50,000**	7906.2****
4.	Cerium	30.3	607	3,397	6,856		
5.	Gadolinium	6.62	132	741	1,495		
6.	Scandium	1.70	34	191	385		
7.	Strontium	2.06	41	231	467		

Source: Authors' analysis

Note:

* Zirconium ore and not zirconium metal.

** REE = rare earth elements, a group of 17 minerals that includes scandium, yttrium, and lanthanides.

*** Imports includes iridium, osmium, and ruthenium.

**** *Imports includes REE oxides.*

We can see that in order to manufacture 20 GW of PEM electrolysers by 2030, the requirement for platinum, iridium, and titanium will exceed imports. India alone needs up to 5 per cent of the global platinum and at least 21 per cent of the worldwide iridium production to manufacture 20 GW of PEM electrolysers by 2030. India has a titanium production capacity of 2.2 million tonnes (MT), exports 1.2 tonnes, and imports 612 tonnes (Ministry of Commerce n.d.). Comparatively, the titanium requirement for PEM manufacturing in India will be 8–10 MT. While gold availability is not a challenge, India will need 3 tonnes of gold to manufacture PEM electrolysers.

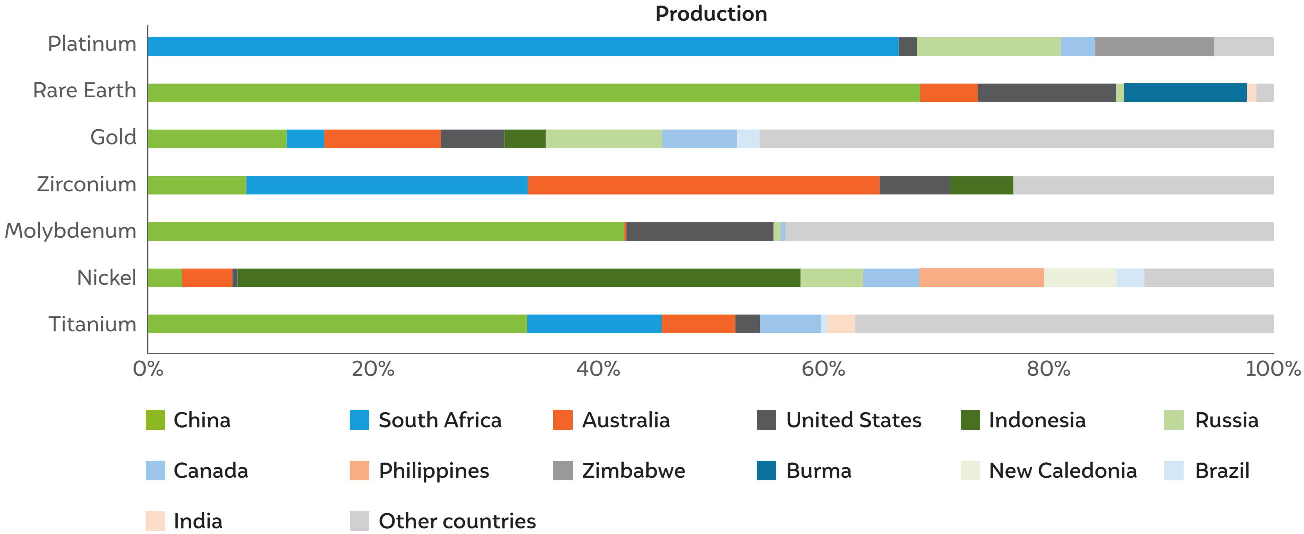
India does not have any nickel production capacity and imports around 800 tonnes. As per Indian Bureau of Mines, India has 189 MT of resource and no reserves at present. A few private players are planning to produce Nickel to meet domestic consumption (IBM, 2022). However, the nickel required for producing 20 GW alkaline electrolysers is 20 times India's imports – a significant increase. Zirconium and molybdenum requirements are a fraction of the total imports and constitute a negligible proportion of global production. Therefore, the availability of these minerals should not be a challenge for manufacturing alkaline electrolysers in India.

The availability of nickel for manufacturing SOEs might be challenging if the technology scales up. However, the availability of rare earth elements (REEs) such as lanthanum, cerium, gadolinium, scandium, and strontium is expected to pose a bigger challenge given the lower global availability. Although India does produce a few high-purity rare earths (HPRE) like lanthanum, its actual production is not known, given that its production is reported together with lanthanum carbonate, cerous carbonate, neodymium praseodymium oxalate, and samarium oxalate (Indian Bureau of Mines 2022). The supply chain of these critical minerals is also challenging, as we shall explain in Section 6.2.

6.2 Supply chain of critical minerals

Figure 32 shows the production of minerals used in electrolyser manufacturing. As indicated in Table 10, titanium is the most abundant mineral in terms of production volumes, while platinum is the rarest among the minerals listed in Figure 32. Minerals such as iridium, lanthanum, cerium, gadolinium, scandium, and strontium are considered a single REE category since the specific production data for these minerals is not available in the literature. We can see that there is a significant concentration of minerals in a few geographies. The production of more than 60 per cent of REEs is concentrated within one country. Similarly, more than 60 per cent of platinum production is only from one country.

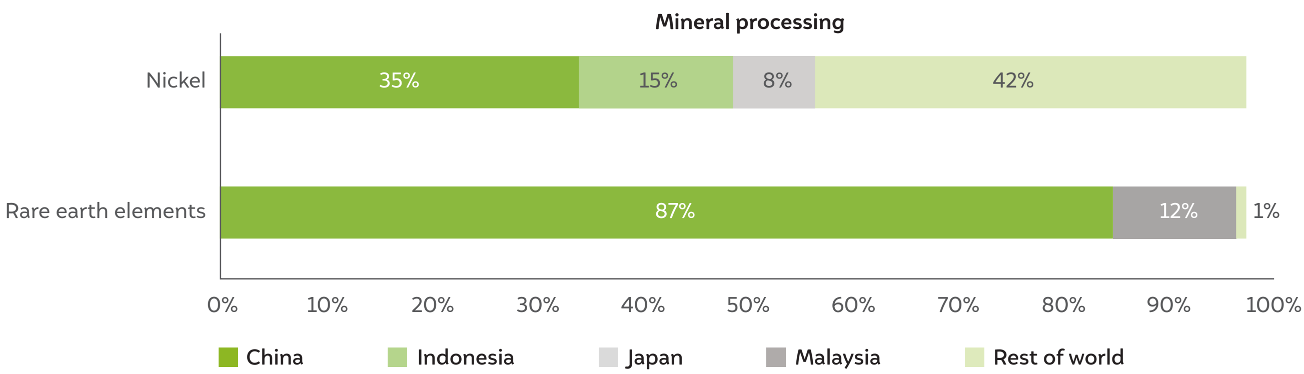
Figure 32 Mineral production globally



Source: Authors' analysis

While the production of critical minerals is relatively diverse, processing is strongly limited to only a few geographies. Figure 33 shows the country-wise processing capacity for select minerals used in the manufacturing of electrolysers. We can see that the actual processing is limited, especially for REEs, where more than 80 per cent of total processing is concentrated in one country. Further, only two countries together constitute about 50 per cent of the total nickel processing capacity. Therefore, scaling up electrolyser manufacturing capabilities in India requires us to develop resilient supply chains for these critical minerals.

Figure 33 Global mineral processing is dominated by China



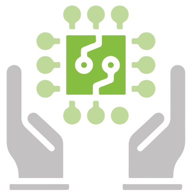
Source: Authors' analysis

Anion exchange membrane (AEM) electrolysers, capillary-fed, and electrochemical–thermally activated chemical (E-TAC) design are the key upcoming electrolyser technologies.

Image: iStock

7. The future of electrolyser technology and design

The previous sections discussed the bottom-up cost analysis of PEM, alkaline, and solid oxide electrolysers. Globally, OEMs and research institutes are developing new types of electrolysers, such as the AEM and E-TAC electrolysers. At the same time, there are also newer technologies such as zero-gap design for alkaline electrolysis and capillary-fed design. Developing bottom-up cost estimates for these newer electrolysers is difficult since they are at a lower TRL. However, in this section, we briefly discuss these new types and designs of electrolysers that have the potential to disrupt the green hydrogen market in the future.



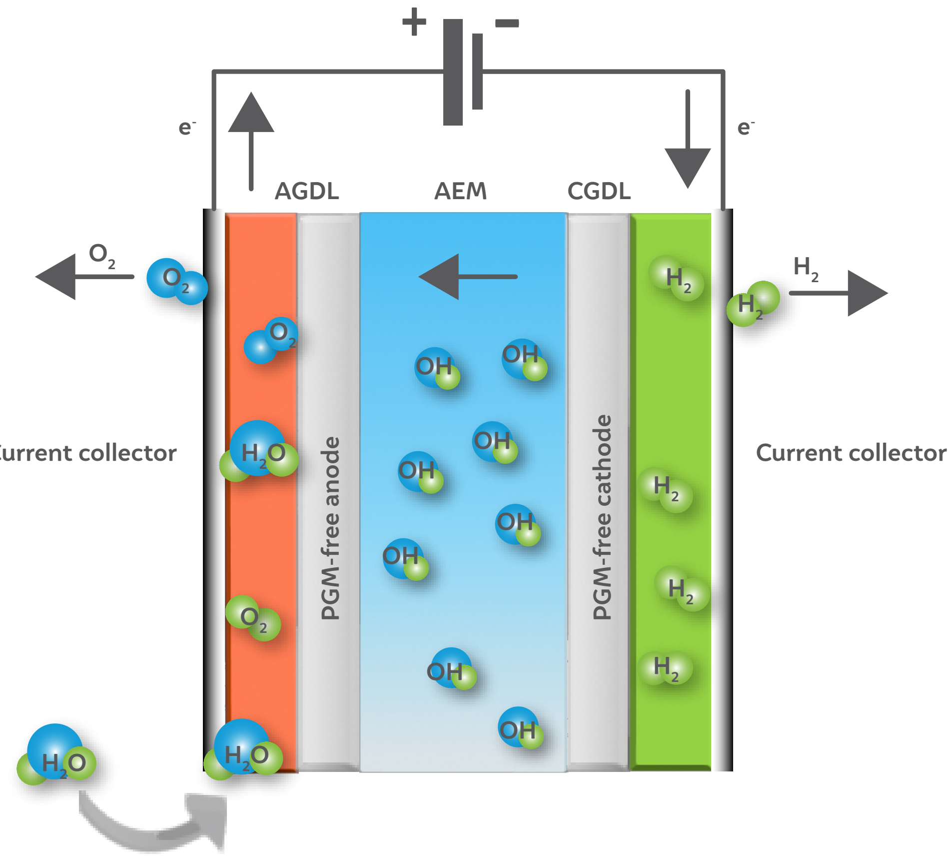
Anion exchange membrane, zero-gap, capillary-fed, and E-TAC are the future electrolyser technologies

7.1 Anion exchange membrane (AEM)

AEMs are polymeric materials that have gained significant attention in the past few years. The history of AEMs can be traced back to the early 1960s when scientists were developing ion exchange membranes for electrodialysis (Mardle, Chen and Holdcroft 2021). However, these early membranes faced challenges due to low selectivity, limited chemical stability, and high electrical resistance (Liu, et al. 2024). It was not until the late 1990s that high-performance AEMs were discovered by accident: in 1997, a new type of membrane composed of quaternary ammonium groups was discovered to conduct anions efficiently (Sata, Yamane and Matsusaki 2000). This discovery paved the way for the development of novel AEMs with improved selectivity, stability, and conductivity. Today, AEMs have various applications in electrochemical technologies, including fuel cells and electrolysers (Hagesteijn, Jiang and Ladewig 2018).

Figure 34 shows a schematic of an AEM electrolyser. Its construction is similar to that of the alkaline and PEM electrolysers discussed earlier; the difference is in the membrane used to separate the anode and cathode electrodes. AEMs use a polymer membrane that selectively allows the passage of anions (OH^- ions) – hence the name 'anion exchange membrane' – while preventing the transport of cations. The mechanism behind the selective transport of anions is the presence of positive charges on the polymer backbone or pendant groups (Lin, et al. 2013). The most commonly used functional group in AEMs is the quaternary ammonium group ($-N^+(CH_3)_3$). When a solution containing anions is placed on one side of the membrane, the positively charged quaternary ammonium groups attract anions from the solution and exchange them with the anions on the opposite side of the membrane. The exchange process is facilitated by ion diffusion through the membrane's pores. The size and shape of the pores also play important roles in determining the membrane's selectivity.

Figure 34 The AEM electrolyser derives its name from the anion (OH^-) exchange membrane



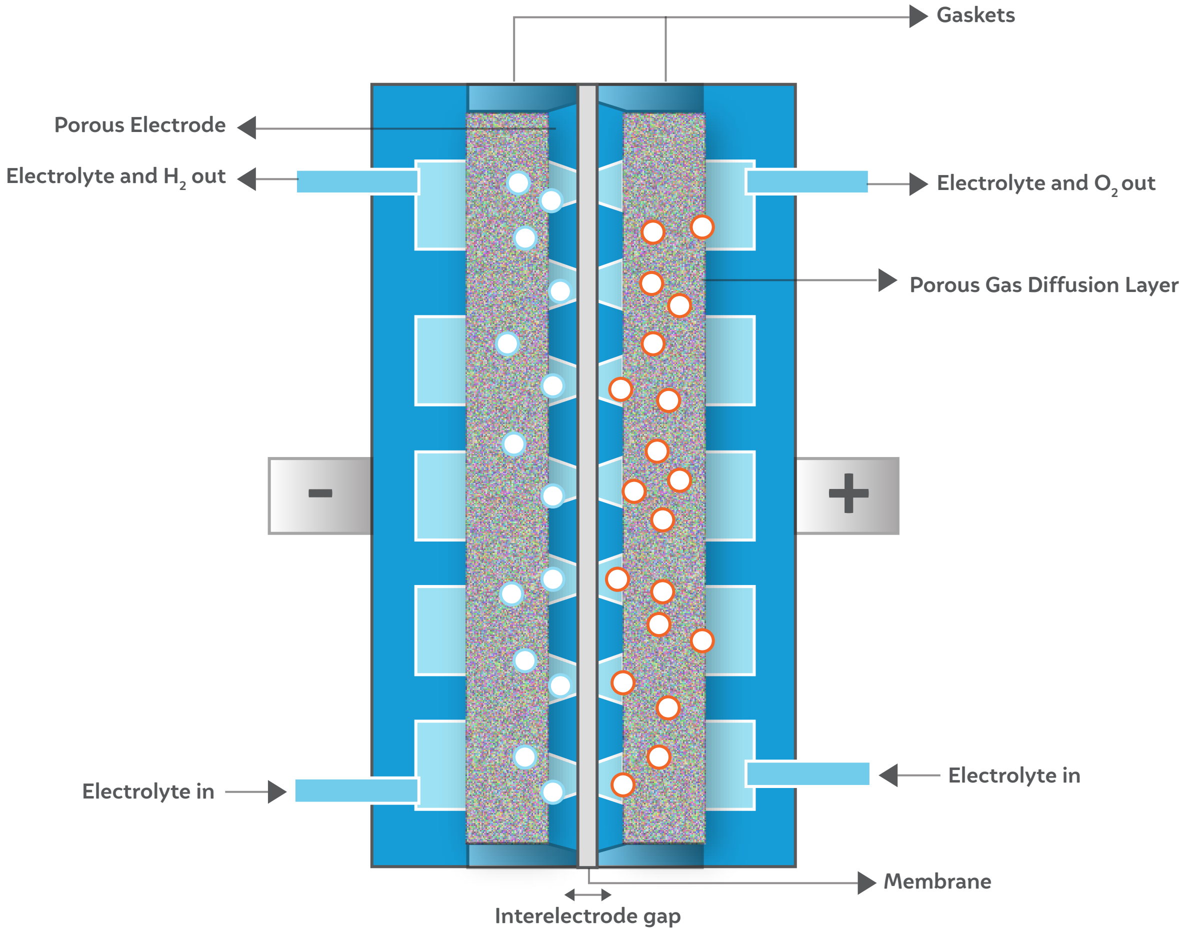
Source: Authors' adaptation from Hua, Daxing, Jinzhen Huang, Emiliana Fabbri, Moniba Rafique, and Bo Song. 2022. "Development of Anion Exchange Membrane Water Electrolysis and the Associated Challenges: A Review." ChemElectroChem, 10 (1). https://doi.org/10.1002/celc.202200999.

AEM electrolysers combine the advantages of both alkaline and PEM electrolysers (Enapter n.d.). Similar to alkaline electrolysers, AEM electrolysers do not require expensive critical minerals, the availability of which is a challenge for domestic manufacturing. Further, similar to PEM electrolysers, AEM electrolysers are compact, modular, and have good flexibility when coupled with variable renewable energy (VRE) sources to supply electricity. The specific power consumption of AEM electrolysers is approximately 50–55 kWh/kg of hydrogen (Enapter n.d.). AEM electrolysers have already been installed globally at an MW scale.

7.2 Zero-gap design for alkaline electrolysis

Zero-gap alkaline electrolysers essentially work on the same principle as other alkaline electrolysers, except that they use a zero-gap technology wherein the electrodes are positioned very close to each other, reducing the distance over which the electrolysis reaction occurs. The distance between the electrodes equals the membrane thickness (< 0.5 mm) as shown in Figure 35. As a result, the system can operate on a lower voltage and has a higher hydrogen production rate with minimum stack power (Amores, et al. 2021). Another significant difference between zero-gap alkaline electrolysers and conventional alkaline electrolysers is how the same materials are used in their construction. In zero-gap design, the catalyst is deposited directly onto the porous electrode or the membrane. In contrast, the traditional design of alkaline electrolysers has the catalyst deposited directly onto a flat electrode plate (Phillips 2019).

Figure 35 Zero-gap design minimises the distance between anode and cathode in alkaline electrolysers

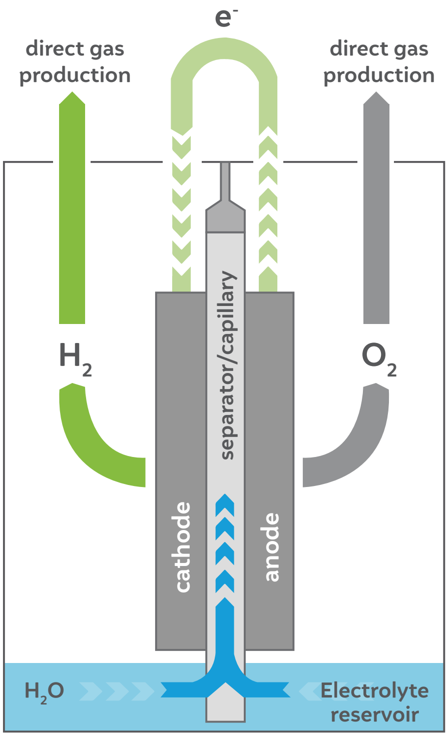


Source: Authors' adaptation from Phillips, Robert. 2019. "Zero Gap Cell Design for Alkaline Electrolysis." PhD thesis. Energy Safety Research Institute, Swansea University

7.3 Capillary-fed design

Capillary-fed electrolysers feature a unique design of porous electrodes separated by a membrane allowing fluid flow from the anode to the cathode by capillary action. An Australian start-up Hysata, which is partially supported by the Australian Renewable Energy Agency (ARENA) (Hysata n.d.)., Hysata, is commercialising capillary-fed electrolysis technology developed at the University of Wollongong in 2022 (Hodges, et al. 2022). The difference with the conventional electrolyser design can be attributed to the pumping requirement. A conventional electrolyser has two electrodes submerged in liquids and requires a pump to move the fluid between them. This increases the operational cost of the electrolysis due to significant energy loss. In contrast, as shown in Figure 36, capillary-fed electrolysers rely on capillary action to cause the liquid to flow, reducing energy requirements and pumping costs. This design is, therefore, more efficient, with an electricity consumption of 40.4 kWh per kg of hydrogen (98 per cent efficiency), vis-à-vis conventional alkaline and PEM electrolysers, which a power consumption of 47.5 kWh/kg (Hodges, et al. 2022). Further, capillary-fed design is reported to be more reliable and has reduced maintenance costs compared to conventional electrolysers (Hodges, et al. 2022). This technology is being developed further by Hysata; ARENA has provided AUD 2.97 million of the total project cost of AUD 5.94 million (Hysata n.d.).

Figure 36 Capillary-fed design uses capillary action to reduce the operational power requirements



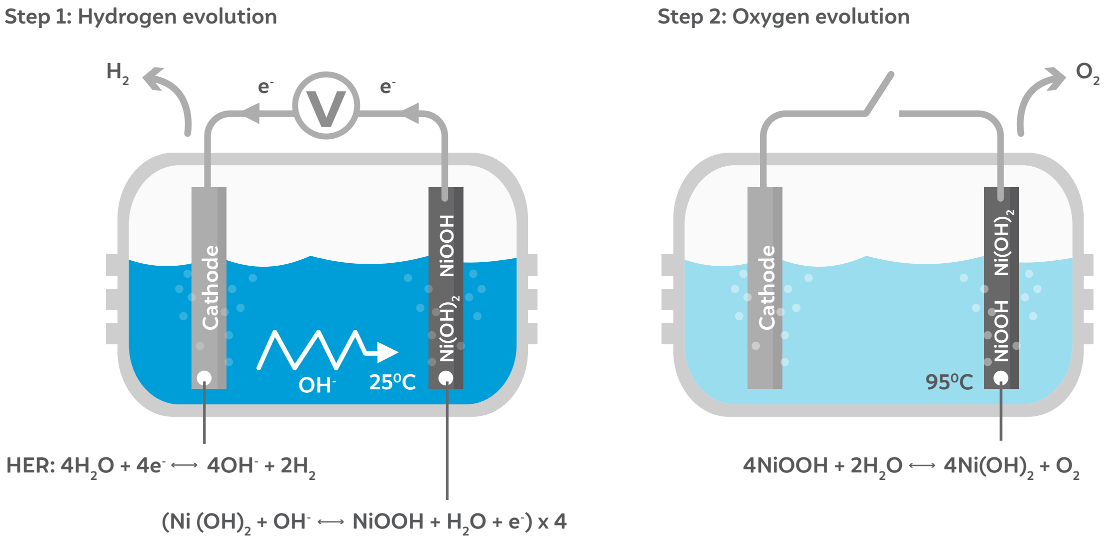
Source: Authors' adaptation from Hodges, Aaron, Anh Linh Hoang, George Tsekouras, Klaudia Wagner, Chong Yong Lee, Gerhard F. Swiegers, and Gordon G. Wallace. 2022. "A High-Performance Capillary-Fed Electrolysis Cell Promises More Cost-Competitive Renewable Hydrogen." Nature Communications, 13. https://doi.org/10.1038/s41467-022-28953-x.

7.4 Electrochemical–thermally activated chemical (E-TAC)

A major limitation of the conventional electrolysis route is that the hydrogen evolution reaction (HER) is spatially and temporally coupled to the oxygen evolution reaction (OER). This introduces operational challenges, especially for integrating electrolysers with VRE, where H_2/O_2 crossover is possible at a lower current density, as the electrolyser can operate in part-load conditions as well. In conventional electrolysers, this cross-over is prevented by using expensive and proprietary membrane technologies that require critical minerals. However, this challenge can also be overcome by decoupling the HER and OER.

New pathways of decoupled water splitting are being explored by researchers, of which E-TAC is one technology that seems amenable to commercialisation. The coupling challenge is addressed here in two phases. As shown in Figure 37, in the first phase, electricity is consumed and hydrogen is generated at room temperature at the cathode (by an electrochemical process) by producing OH- ions. There is no oxygen production at this stage. Subsequently, the OH- ions oxidise the nickel hydroxide ($Ni(OH)_2$) in the anode into nickel oxyhydroxide (NiO(OH)). In the second phase of the process, no electricity is consumed, but the electrolyte is thermally activated to 120°C to generate oxygen. This spontaneous chemical reaction reduces the anode (NiO(OH)) to its initial state ($Ni(OH)_2$) by oxidising water. Since the HER is endothermic and the OER is exothermic, the two processes balance out. This design was introduced in 2019 in a research paper (Dotan, et al. 2019) and is now being commercialised by H_2Pro (H_2Pro n.d.), a company based out of Israel. Since the process design does not require a membrane or specific critical metals, the materials cost of the system is lower compared with alkaline and PEM electrolysers.

Figure 37 E-TAC design



Source: Authors' analysis

The E-TAC process has achieved a low electricity consumption of only 39.9 kWh/kg of hydrogen, which is at par with the capillary-fed design and significantly lower than alkaline and PEM electrolysers. The electrolyser has an energy efficiency of 98.7 per cent (on the basis of higher heating value or HHV) and an overall system efficiency of 95 per cent (H2Pro n.d.). The E-TAC process further supports hydrogen production at 45+ bar, reducing the compression cost for high-pressure applications.

Other decoupled water-splitting designs at lower TRL levels include the solid-state redox mediator , soluble electron-coupled proton buffer, and electrodeposition and dissolution (Mathur and Diesendruck 2024, Ifkovits, et al. 2021).

Some innovative electrolyser design include membrane less electrolyser technology (Hadikhani, et al. 2021) on which some companies such as Newtrace, H2REMA, sHYp, etc are actively working on.

The cost of electrolyser can be reduced by using levers like increasing current density, reducing catalyst loading, reducing coating thickness, and using alternative materials.

Image: Alamy

8. Technology improvements and cost reduction strategy for electrolysers

The characteristics and performance metrics of PEM and alkaline electrolysers, considering current density, voltage, temperature, pressure, efficiency, lifetime, and cold start time are shown in Table 13. These parameters take into consideration the current technological readiness as well as future targets. Compared to alkaline electrolysers, PEM electrolysers have a higher current density, implying a compact size. However, the current density of both types of electrolysers should at least double without a significant increase in voltage levels to ensure an overall decrease in cost and specific power consumption. Increased operating pressure is desirable, as it reduces the compression energy requirement for high-pressure applications such as mobility. Further, the electrolysers' flexibility and start-up time should improve for better integration with VRE resources.

Table 13 Improvements needed in PEM and alkaline electrolysers

		PEM electrolysers		Alkaline electrolysers	
S. No.	Parameters	2020	Target 2050	2020	Target 2050
1.	Nominal current density	1–2 A/cm^2	4–6 A/cm^2	0.2–0.8 A/cm^2	> 2 A/cm^2
2.	Voltage range (limits)	1.4–2.5 V	< 1.7 V	1.4–3 V	< 1.7 V
3.	Operating temperature	50–80°C	80°C	70–90°C	> 90°C
4.	Cell pressure	< 30 bar	> 70 bar	< 30 bar	> 70 bar
5.	Load range	5%–120%	5%–300%	15%–100%	5%–300%
6.	Lifetime (stack)	50,000–80,000 hours	1,00,000–1,20,000 hours	60,000 hours	1,00,000 hours
7.	Stack unit size	1 MW	10 MW	1 MW	10 MW
8.	Cold start (to nominal load)	< 20 minutes	< 5 minutes	< 50 minutes	< 30 minutes
9.	Capital costs (stack) minimum 1 MW	–	< USD 100/kW	Unknown	< USD 100/kW
10.	Capital costs (system) minimum 10 MW	–	< 200 USD/kW	Unknown	< USD 200/kW

Source: Authors' compilation from IRENA. 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal. Abu Dhabi: International Renewable Energy Agency.

Table 13 indicates the technology development targets for solid oxide and AEM electrolysers. While the operating temperatures of PEM and alkaline electrolysers are the same, SOEs operate at significantly higher temperatures. A lower operating temperature would be desirable to reduce the thermal energy requirement of the unit. An increase in current density without a significant increase in voltage would enable a compact size and lower costs as well. Similar to alkaline and PEM electrolysers, higher flexibility and lower start-up time would promote integration with VRE sources.

Table 14 Improvements desired in SOEs and AEM electrolysers

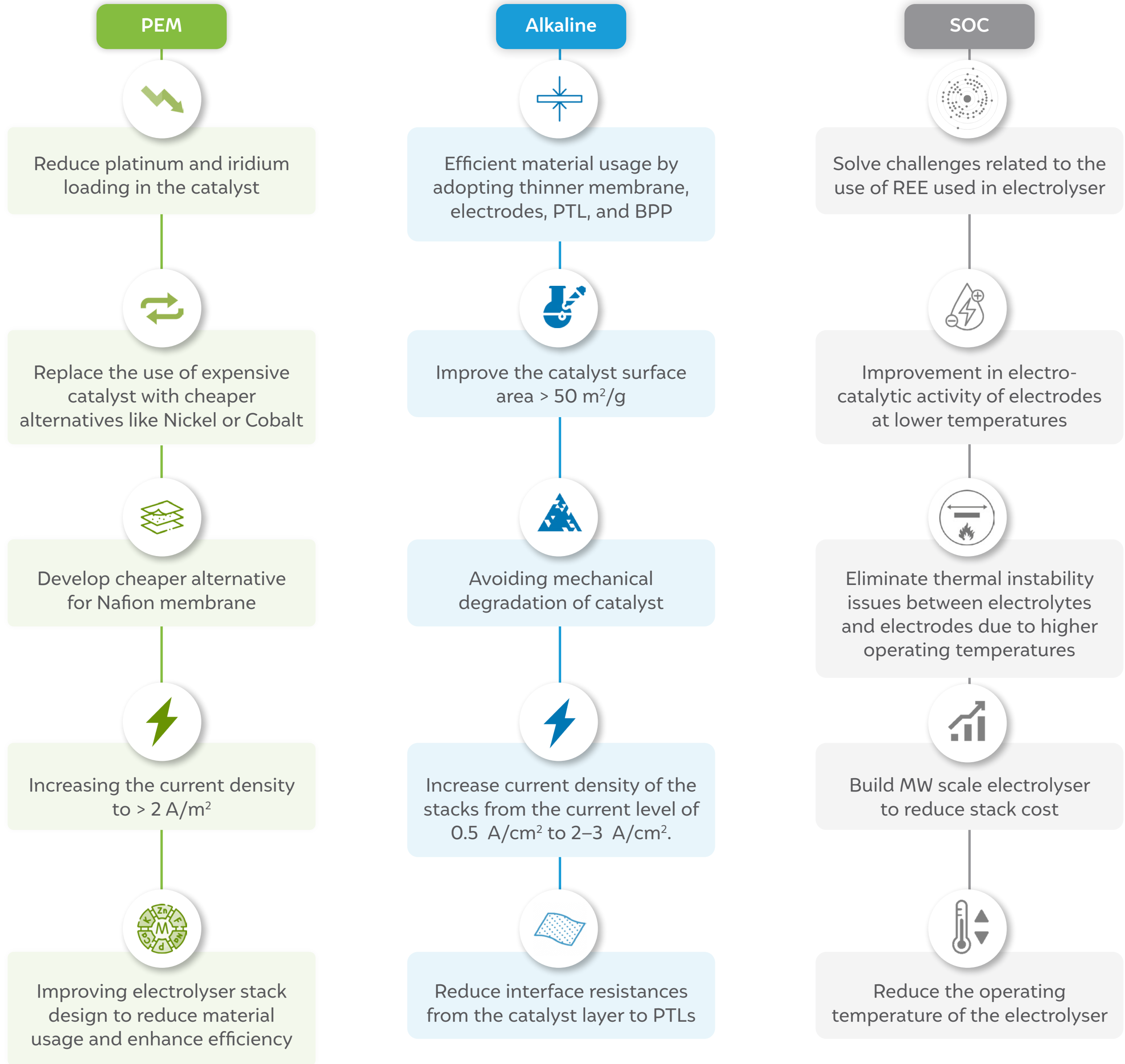
		SOE electrolysers		AEM electrolysers	
S. No.	Parameters	2020	Target 2050	2020	Target 2050
1.	Nominal current density	0.3–1 A/cm²	> 2 A/cm²	0.2–2 A/cm²	> 2 A/cm²
2.	Voltage range (limits)	1.0–1.5 V	< 1.48 V	1.4–2.0 V	< 2 V
3.	Operating temperature	700–850°C	< 600°C	40–60°C	80°C
4.	Cell pressure	Up to 20 bar	> 20 bar	< 35 bar	> 70 bar
5.	Load range	30%–125%	0%–200%	5%–100%	5%–200%
6.	Lifetime (stack)	< 20,000 hours	80,000 h	> 5,000 hours	1,00,000 hours
7.	Stack unit size	5 kW	200 kW	2.5 kW	2 MW
8.	Cold start (to nominal load)	> 600 minutes	< 300 minutes	< 20 minutes	< 5 minutes
9.	Capital costs (stack) minimum 1 MW	–	< USD 200/kW	Unknown	< USD 100/kW
10.	Capital costs (system) minimum 10 MW	–	< USD 300/kW	Unknown	< USD 200/kW

Source: Authors' compilation from IRENA.2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal. Abu Dhabi: International Renewable Energy Agency.

Cost-reduction strategies

In this section, we elaborate on the technology development goals to evaluate the potential for cost reduction in PEM and alkaline electrolysers. Figure 38 shows qualitatively the parameters for cost reduction in PEM, alkaline, and solid oxide electrolysers. The major strategies for reducing electrolyser cost focus on lowering the mineral loading, decreasing the membrane thickness, finding alternatives to critical minerals, and increasing the operating current density without any significant increase in voltage. While there are no quantitative targets yet for SOEs, there are technology development goals for PEM and alkaline electrolysers.

Figure 38 Cost reduction strategies for PEM, alkaline, and SOEs



Source: Authors' analysis

Table 14 lists the technology development goals for PEM and alkaline electrolysers. A major technology development goal is the improvement of electrolyser performance such that the current density can be increased significantly (up to 10 10 A/cm^2) without any increase in operating voltage. An increase in operating voltage would result in higher specific energy consumption and consequently lower efficiency. An increase in current density implies that the electrolyser size (in kW or MW) increases without any increase in material consumption.

Further, material consumption can also be reduced through technological improvements. For example, the consumption of platinum and iridium can potentially be reduced in PEM electrolysers while the thickness of the membrane in PEM and alkaline electrolysers can be decreased substantially. Alternative materials may also play a crucial role in reducing electrolyser costs. For example, the titanium used as the PTL in PEM electrolysers could be replaced with stainless steel, reducing the manufacturing cost of PEM electrolysers.

Table 15 Technology development targets for reducing the manufacturing cost of PEM and alkaline electrolysers

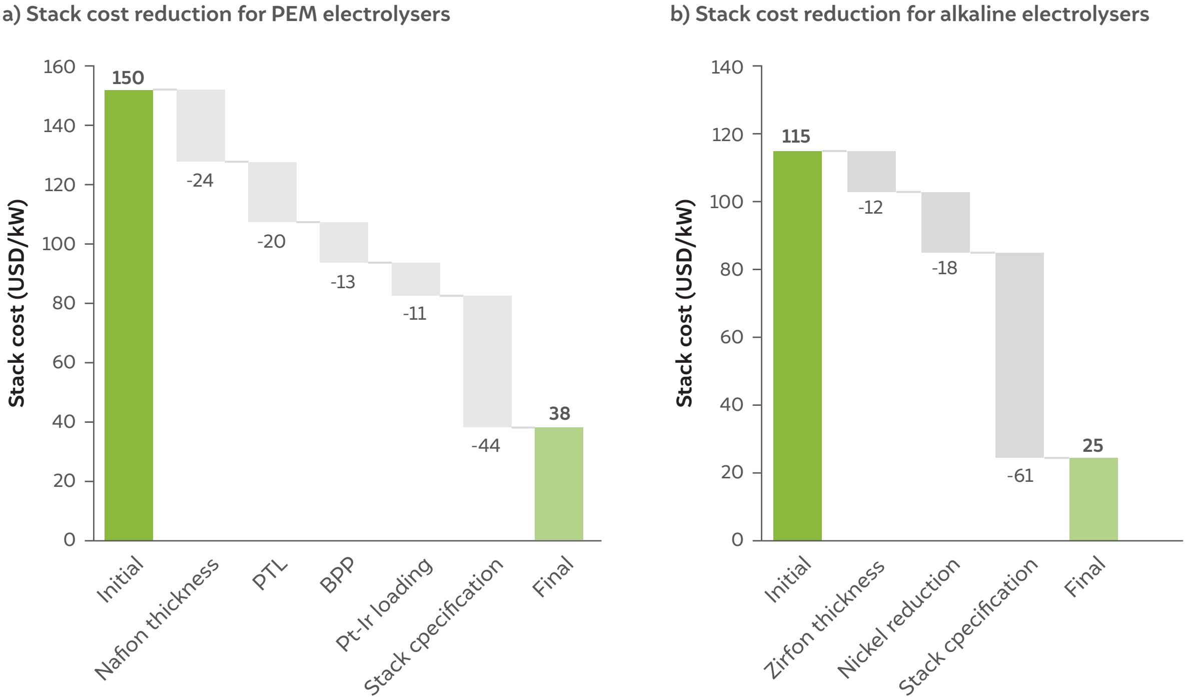
S. No.	Area	Parameter	Current status	Technology development goals	Reference
		PEM electrolyser			
1.	Stack specification improvement	Current density	1.8 A/cm^2	3.5A/cm^2	(Krishnan, et al. 2023)
2.		Voltage	1.6 V	1.8 V	(Krishnan, et al. 2023)
3.		Stack size	0.2 MW	0.44 MW	This study based on (NREL 2019)
4.	CCM	Nafion membrane thickness	183 microns	80 microns	(Krishnan, et al. 2023)
5.		Pt-Ir loading	Pt: 0.9 mg/cm^2 Ir: 0.2 mg/cm^2	Pt: 0.05 mg/cm^2 Ir: 0.1 mg/cm^2	(Krishnan, et al. 2023)
6.	PTL (anode)	Material	Titanium	Stainless steel	(Daudt, Hackemüller and Bram 2020)
		Coating and thickness	Gold: 100 nm	Niobium: 20 nm	(Kim, et al. 2021)
7.	BPP	Coating and thickness	Gold: 100 nm	Niobium: 20 nm	(Kim, et al. 2021)
		Alkaline electrolyser			
1.	Stack specification improvement	Current density	0.2 A/cm^2	1.3 A/cm^2	(Krishnan, et al. 2023)
2.		Voltage	1.68 V	1.79 V	(Krishnan, et al. 2023)
3.		Stack size	0.2 MW	0.69 MW	This study based on (NREL 2019)
4.	CCM	Zirfon membrane thickness	500 microns	220 microns	(Phillips 2019)
5.		Nickel reduction	1,602 kg/kW	800 kg/kW	(IEA 2021)

Source: Authors' compilation

Figures 39 (a) and (b) illustrate the potential cost reductions owing to various parameters listed in Table 13. The most significant reduction in electrolyser cost arises due to the higher current density, which increases the stack size by 2.2 times for PEM and 3.5 times for alkaline electrolysers, without increasing material costs. These are very ambitious technology development targets but, as indicated in Figure 39, they can reduce the electrolyser costs significantly.

Further cost reductions are possible through the reduction of mineral loading, alternative materials, and reduced membrane thickness. Our analysis indicates that the electrolyser stack cost can be potentially reduced from USD 150/kW to USD 38/kW for PEM and USD 115/kW to USD 25/kW for alkaline electrolysers. These findings are consistent with results obtained in the literature (Krishnan, et al. 2023). While these cost reductions are ambitious, they are essential to reduce the overall cost of the electrolyser, given that most BoP components are already at a commercial scale and future cost reductions are unlikely. Therefore, an overall electrolyser cost target of less than USD 200/kW (IEA 2019) can only be achieved if the cost of the stack reduces to less than USD 30/kW as indicated in Figure 39.

Figure 39 Electrolyser stack cost can be reduced to <USD 40/kW through technological improvements



Source: Authors' analysis

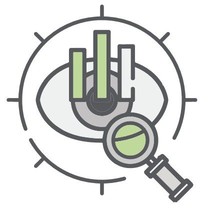
It is important to note that, as critical minerals have become crucial for energy security, trade agreements like the one between India and Australia can strengthen supply chains (ECTA 2022). This could potentially further lower the cost of critical minerals in India in the near term that can reduce the cost of electrolyser.

Transporting hydrogen via pipelines is a low-cost option for delivering large volumes of hydrogen.

Image: iStock

9. Policy recommendations and conclusion

Indigenising electrolyser manufacturing will need a strategic approach and support from the government, innovation from research laboratories and academic institutes and intent from the industry. The Government of India can support electrolyser manufacturing through the development of testing facility, resilient supply chain for key minerals and enhancing production capacity of components like power electronics. The research community can focus on reducing the cost of electrolyser by technology advancement, reducing the material consumption and developing alternatives to critical minerals. The electrolyser manufacturers can accelerate indigenisation by maximising domestic procurement especially for balance of plant components and developing manufacturing facilities (beyond assembly units) in India. The key policy recommendations for indigenising electrolyser manufacturing are discussed below:



India should follow a three-pronged strategic approach - import raw material wherever needed but finished products should be made in India, R&D for reducing loading of critical minerals and developing alternatives, development and manufacturing of membrane technologies

9.1 Develop a strategic approach towards maximising indigenisation

MNRE should strive to ensure maximum indigenisation of the electrolyser manufacturing in India. In this regard, MNRE should follow a three-pronged strategy. Firstly, while raw materials for electrolyser manufacturing that are not available in India will be imported, MNRE should try to ensure that finished products are made in India so that the 'can be indigenised' component of electrolyser manufacturing cost is indigenised. Secondly, research efforts should be focused on reducing loading of critical minerals and identifying alternatives to maximise indigenisation without compromising on electrolyser efficiency. Thirdly, development and manufacturing of advanced membrane technologies should be prioritised to reduce import dependency.

9.2 Develop a compendium for domestic suppliers of the components used for electrolyser manufacturing

The MNRE should develop a compendium of domestic suppliers for all components – especially those involving low-TRL components like PTL, BPP etc. used for electrolyser manufacturing – and place it in the public domain. This will ensure easy accessibility of domestic suppliers for electrolyser manufacturers in India.

9.3 Enhance local manufacturing of power electronics

Power electronics can significantly improve the efficiency and reliability of electrolyser systems. Power electronics, including rectifiers, choppers (or voltage regulators), and transformers, account for approximately 15–20 per cent of the total electrolyser cost in PEM and alkaline electrolysers and about 30 per cent in SOEs. Improved power electronics systems would not only support the scaling up of hydrogen production but also contribute to reducing the overall costs. The MNRE should provide the necessary support for the manufacture of power electronics for electrolysers through integration with existing Government of India schemes like Scheme for Promotion of Manufacturing of Electronic Components and Semiconductors (SPECS) and Modified Electronics Manufacturing Clusters Scheme (EMC 2.0) for domestic manufacture of electronics.

India should focus on developing resilient supply chains for sourcing minerals needed for electrolyser manufacturing

9.4 Establish electrolyser testing facility

A dedicated facility for electrolyser testing is crucial to foster innovation and efficiency improvement. The facility should enable rigorous performance and durability assessments of different electrolyser technologies under local conditions, provide a platform for the development and optimisation of indigenous electrolyser designs, and contribute to the broader goal of achieving cost-effective electrolyser manufacturing. The MNRE should strive to develop such a facility for electrolyser testing in India.

9.5 Focus on research and development for cost reduction and innovation

The MNRE should focus on advancing R&D capabilities to develop cost-effective alternatives to current electrolyser components that can enhance performance and achieve cost reductions. The R&D projects allocated under the NGHM should have clear and well-defined technology development targets that will enable a reduction in electrolyser manufacturing costs. Further, these R&D projects will support the indigenous development of new technologies such as AEM, E-TAC, and capillary-based electrolysers. The MNRE can also float an innovation challenge programme to reduce electrolyser costs and commercialise existing technologies.

9.6 Developing resilient supply chain of minerals used in electrolyser manufacturing

Under the aegis of the Ministry of Mines, Khanij Bidesh India Limited (KABIL) was established in 2019 as a joint venture by three public sector companies: National Aluminium Company (NALCO), Hindustan Copper (HCL), and Mineral Exploration Corporation Limited (MECL) (KABIL 2024). KABIL's role is to ensure a steady supply of 30 identified critical minerals, which include nickel and REEs used in electrolyser manufacturing (PIB 2019). The MNRE should coordinate with other ministries under the existing schemes to develop a resilient supply chain for the minerals used in electrolyser manufacturing to ensure the success of the *Make in India* scheme and support domestic electrolyser manufacturers.

9.7 Monitor imports of hydrogen-related components in India

In coordination with other ministries, the MNRE should work towards creating a new harmonised system (HS) code for monitoring imports of hydrogen-related components in India. This will enable the MNRE to monitor the import of hydrogen-related components and promote new domestic manufacturers to maximise the indigenisation potential of electrolysers.

Acronyms

AE	alkaline electrolyser
AEM	anion exchange membrane
ARENA	Australian Renewable Energy Agency
BoP	balance of plant
BoS	balance of stack
BPP	bipolar plate
BSG	borosilicate glass
BZCY	barium-zirconia-ceria-yttrium
CCM	catalyst-coated membrane
CCUS	carbon capture, usage, and storage
CGO	ceria gadolinium oxide
DMF	dimethylformamide
E-TAC	electrochemical-thermally activated chemical
EU	European Union
GDC	gadolinium-doped ceria
GDL	gas diffusion layer
HER	hydrogen evolution reaction
HHV	higher heating value
HPRE	high-purity rare earths
IPA	isopropyl alcohol
KABIL	Khanij Bidesh India Limited
KOH	potassium hydroxide
LO	lanthanum oxide
LSCF	lanthanum strontium cobalt ferrite
MCO	manganese cobalt oxide
MEA	membrane electrode assembly
MECL	Mineral Exploration Corporation Limited
MNRE	Ministry of New and Renewable Energy
MTPA	million tonnes per annum
MT	million tonnes
NALCO	National Aluminium Company
NGHM	*National Green Hydrogen Mission*
OEM	original equipment manufacturers
OER	oxygen evolution reaction
PEEK	polyether ether ketone
PEM	proton exchange membrane
PFSA	perfluorosulphonic acid
PLI	production-linked incentive
PPS-40GF	polysulphone-40 glass fibre
PTFE	polytetrafluoroethylene
PTL	porous transport layer
PVD	physical vapour deposition
R&D	research and development
REE	rare earth elements
SIGHT	*Strategic Interventions for Green Hydrogen Transition*
SOE	solid oxide electrolyser
SOEC	solid oxide electrolysing cell
SOFC	solid oxide fuel cell
SPEEK	sulfonated poly(ether ether ketone)
SRU	single repeating unit
SSZ	scandia-stabilised zirconia
TRL	technology readiness level
VRE	variable renewable energy
YSZ	yttria-stabilised zirconia

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