Cost-competitive green hydrogen: how to lower the cost of electrolysers?

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Abstract

The higher cost of green hydrogen in comparison to its competitors is the most important barrier to its increased use. Although the cost of renewable electricity is considered to be the key obstacle, challenges associated with electrolysers are another major issue that have important implications for the cost reduction of green hydrogen. This paper analyses the electrolysis process from technological, economic, and policy perspectives. It first provides a comparative analysis of the main existing electrolyser technologies and identifies key trade-offs in terms of cost, scarcity of materials used, technology readiness, and the ability to operate in a flexible mode (which enables them to be coupled with variable renewables generation). The paper then identifies the main cost drivers for each of the most promising technologies and analyses the opportunities for cost reduction. It also draws upon the experience of solar and wind power generation technologies with respect to gradual cost reduction and evaluates development paths that each of the main electrolyser technology types could take in the future. Finally, the paper elaborates on the policy mechanisms that could additionally foster cost reduction and the overall business development of electrolyser technologies.

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1. Introduction

Hydrogen has a critical role in enabling countries to achieve net zero carbon targets. Apart from being a fuel source and an energy storage solution, hydrogen is one of the serious long-term, scalable, and cost-effective options for the deep decarbonization of hard-to-abate sectors such as steel, maritime, aviation, and ammonia. Indeed, in its 2020 Hydrogen Strategy, the EU mentions hydrogen as 'essential to support the EU's commitment to reach carbon neutrality by 2050 and for the global effort to implement the Paris Agreement while working towards zero pollution' (European Commission, 2020). This is so because of the vast array of opportunities that hydrogen offers.

Hydrogen (H_2) is particularly valued for its versatility, as it is able to store large volumes of energy for a long time in a transportable form while producing zero CO_2 emissions when incinerated[1] (Hydrogen Council, 2019). As a result, it can be used as a feedstock, a fuel, or an energy carrier and energy storage, and thus has many possible applications in various fields, such as the transport, industry, power, and building sectors. In addition, alongside powering sectors not suitable for electrification, H_2 can provide flexibility to the electricity grid to address intermittency of renewable energy sources such as wind and solar. In this connection, hydrogen is often viewed as the missing link in the transition to a net zero world.

Figure 1: Global demand for pure hydrogen in Mt, 1975–2018
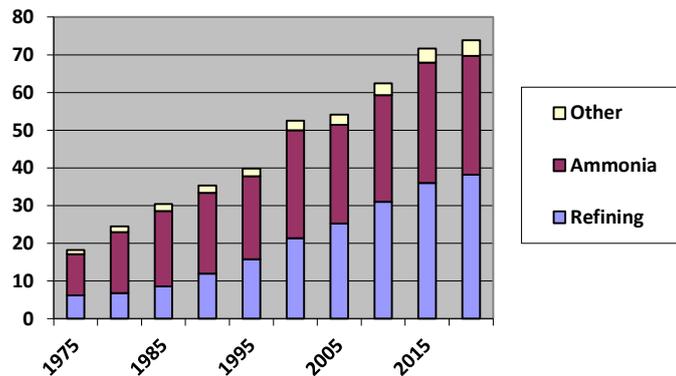
Source: IEA (2021)

While in recent years hydrogen has been considered essential for the decarbonization of economic sectors and industrial processes where reducing carbon emissions is both urgent and hard to achieve (European Commission, 2020), the industrial production of H_2 is not new but has long been a major business around the world. Since 1975, the demand for hydrogen has risen almost threefold and it is expected that it will continue to grow further in the future (see *Figure 1*). Hydrogen growth to date, however, has not been driven by net zero targets but rather the opposite – the build-up of some of the most polluting sectors such as hydrocarbon refining and fertilizer production (IEA, 2021). In addition, most of the world's hydrogen is currently being supplied from fossil fuels, such that around 6 per cent of global natural gas supply and 2 per cent of global coal are being used for H_2 generation (ibid.) (see *Figure 2*). As a result, the conventional production of hydrogen from fossil fuels through steam methane reforming or coal gasification is currently responsible for about 830 million tonnes of carbon dioxide

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[1] $2H_2 + O_2 \rightarrow 2H_2O$

released each year, which is the equivalent to the annual CO_2 emissions of the UK and Indonesia combined (ibid.).

In this sense, while H_2 per se can address a number of decarbonization challenges, hydrogen produced from fossil fuels without CO_2 capture cannot form the basis of the future decarbonized economy. Instead, 'green' hydrogen – H_2 generated with renewable electricity through electrolysis that splits water molecules into hydrogen and oxygen[2] – is well in line with net zero objectives. Given this, and in order to spur the development of 'green' H_2, some of the nations that had previously pledged to become carbon neutral in the next couple of decades have introduced specific targets on 'green' hydrogen production capacity; these targets are intended to promote the development of electrolyser technologies.[3] As a result, electrolysers – the technological devices generating H_2 via electrolysis – are currently gaining significant attention in Europe and other parts of the world.

Figure 2: Global hydrogen production by main source (%) in 2018[4]
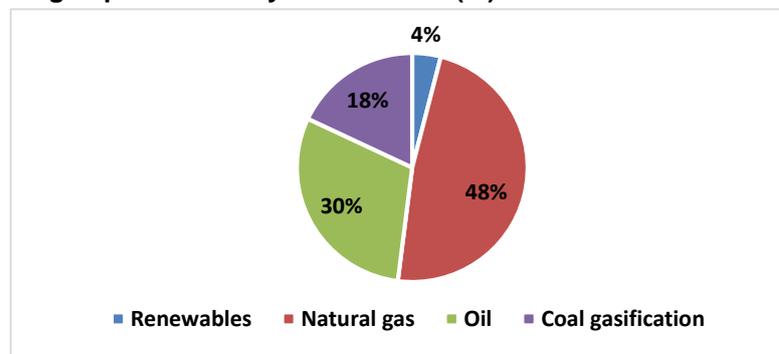
*S*ource: Adapted from IRENA (2018) and RMI (2019)

However, despite the active support of research and development into electrolysers, 'green' hydrogen is currently less competitive compared with other 'colours' of H_2 which have higher carbon footprints. For instance, in IRENA's December 2020 report, 'green' hydrogen was assessed as being 2–3 times more expensive than 'blue' hydrogen, produced from fossil fuels in combination with carbon capture and storage (IRENA, 2020b). Although Europe's current natural gas (the most common feedstock for conventionally-produced hydrogen) crisis is likely to make this price gap narrower for some time (Recharge News, 2021), a more fundamental cost decline is needed to make a real impact on the growth of green hydrogen. Therefore, the question of how cost decline in 'green' hydrogen production can be achieved, so that it becomes a real competitor to hydrogen with a higher carbon footprint within a shorter period of time, is of interest to policy makers, industry, and end users. To answer this question, this paper explores the process of electrolysis from technological, economic, and policy perspectives with a focus on the issues relating to technology maturity, cost, possibility of scaling up and the ability to operate in a flexible mode.

The outline of this paper is as follows: Section 2 provides a comparative analysis of the main existing electrolyser technologies. Through juxtaposing their key advantages and disadvantages, as well as describing their technological maturity, it identifies those types of electrolysers that have the greatest potential for being coupled with renewables and thus used for the production of 'green' hydrogen.

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[2] Cathode: $4H_2O\ (l) + 4e^- \rightarrow 2H_2(g) + 4OH^-\ (aq)$
Anode: $2H_2O\ (l) \rightarrow O_2(g) + 4H^+\ (aq) + 4e^-$
[3] For example, the EU and UK set targets of 40 GW and 5 GW electrolyser capacity by 2030, respectively (European Commission, 2020 and HM Government, 2021).
[4] Hydrogen is obtained as a by-product at chemical plants and refineries. For example, refineries produce by-product hydrogen from the catalytic reforming of naphtha into higher value high-octane products (EIA, 2016). H_2 is also produced from heavy hydrocarbons unsuitable for catalytic steam reforming via partial oxidation (ibid.).

Section 3 identifies the main cost drivers for each of the most promising technologies, before describing the opportunities for cost reduction in Section 4. In Section 5, the paper draws upon the experience of renewables with respect to gradual cost reduction, and evaluates what development paths each of the main technology types could take in the future. The paper elaborates on the policy mechanisms that could additionally foster business development and overall progress of 'green' hydrogen in Section 6. Finally, Section 7 provides concluding remarks.

2.   Review of existing electrolyser technologies

At the moment, the most promising electrolyser technologies that attract the greatest attention can be generally divided into six major groups: alkaline, acidic, acidic/alkaline amphoteric, solid oxide, microbial, and photo-electrochemical (see *Table 1* [5]). Although each of these broad categories possesses its advantages and drawbacks, not all of them are currently available for industrial use. Although the academic literature has extensively covered alkali (alkaline) and PEM (acidic) systems that have already been commercialized, its current growing interest is captivated by solid oxide and AEM (alkaline) solutions that are reported to be closer to commercialization than the rest of the electrolyser technologies. In addition, not all of these technologies are particularly suitable for coupling with intermittent renewable energy sources in order to form a power–hydrogen nexus. Indeed, electrolysers' performance features represent a set of trade offs among multiple factors such as cost, quantity of noble metals used, technology readiness, and the ability to operate in a flexible mode. This section will thus provide a detailed overview of all types of electrolysers that are currently available – at least at the research and development stage – and will represent their advantages and shortcomings.

2.1 Alkaline

Out of all the technologies mentioned, *alkaline water electrolysis* is the most technologically mature and thus is often viewed as a 'standard' for large-scale industrial H_2 production (Mittelsteadt et al., 2015). In fact, alkaline power-to-hydrogen solutions have been in use for more than a century, with the first large water electrolysis plant – with a capacity of 10,000 normal cubic metres per hour (Nm^3/h) – being launched in 1939 (Santos, Sequeira, and Figueiredo, 2013). This technology's popularity is primarily due to the number of important *advantages* that it offers.

First, alkaline electrolysers have the distinct benefit of employing primarily low-cost components for both electrodes and porous transport layer materials (normally, nickel (Ni)) (Saba et al., 2018). In addition, while using platinum (Pt) and ruthenium (Ru) as catalysts, such electrolysers are equally able to use non-noble and thus cheaper metals such as manganese (Mn) (Mittelsteadt et al., 2015). This further contributes to the overall cost reduction.

Second, while using robust cell separators, alkaline electrolysers possess high durability and tolerance to impurities. This results in the longest estimated lifetime of such systems among all the currently available electrolyser technologies (Koponen, 2015). As a result, their maintenance costs could be significantly reduced.

Finally, at the moment, alkaline electrolysers allow for the highest scale of 'green' hydrogen production at the lowest investment costs. Indeed, with the system size ranging between 1.8 and 5,300 kilowatts (kW), the investment costs vary between 800 and 1,500 USD/kW, which is around 2–2.5 times lower than the typical investment costs of the next commercially available H_2 generation technology – proton exchange membrane (PEM) electrolysers (ibid.).

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[5] Although low-carbon hydrogen production is also possible through the use of such technologies as thermochemical water splitting, this paper focuses primarily on the electrolysis of water that could be powered by renewable energy sources.

At the same time, while still appearing to be undisputable leaders in terms of popularity and scale, alkaline electrolysers have a number of disadvantages, which could significantly limit their use for power-to-hydrogen applications. The most important drawback is their high lower limit of minimum load, which prevents their coupling with some types of renewables (Ionomr Innovations, 2020). Additionally, their current density must be altered slowly (ibid.), as they are designed for operation at fixed process conditions. Therefore, although this drawback can be partially mitigated through the use of batteries and control systems (Becker, Brauns, and Turek, 2021), alkaline electrolysers do not seem to be the best option for balancing variable renewable energy sources such as wind and solar PV (Mittelsteadt et al., 2015).

Apart from that, due to the substantial internal resistance incurred across the thick porous diaphragm and electrolyte, alkaline electrolysers operate at low current density and efficiency (Ursúa, Gandía, and Sanchis, 2012). Such systems thus normally require a bulky stack design at large scales (Ionomr Innovations, 2020). As a result, stack costs appear to be major contributors to system capital costs, greatly increasing them.

Finally, most of the conventional alkaline electrolysers available on the market generally produce hydrogen of lower purity than other power-to-hydrogen options (such as PEM electrolysers) while consuming more energy (Sheffield, Martin, and Folkson, 2014). Furthermore, due to the corrosive nature of alkaline electrolytes and the resulting threat of their leakage, the entire alkaline electrolyser system should be carefully designed and maintained so that the produced gases (hydrogen and oxygen) do not mix, since their mixtures have high flammability (Santos, Sequeira, and Figueiredo, 2013).

2.1.1 Alkaline polymer

To overcome some of these challenges in the same alkaline electrolytic environment, such polymer technologies as anion exchange membrane (AEM) and molten carbonate electrolysis cell (MCEC) are currently being developed. Though they still appear to be *at relatively early development stages (R&D)*, they can potentially become a more successful step in the coupling of 'green' hydrogen production and variable renewable energy sources.

AEM electrolysers

Since, instead of applying concentrated potassium hydroxide (KOH) (as in the case of conventional alkaline electrolysers), AEM installations use an alkaline solution of lower concentration, they are less prone to corrosion (Vincent and Bessarabov, 2018). In addition, AEM facilities prevent any potential electrolyte and gas leakages through replacing the diaphragms separating the hydrogen and oxygen compartments with anion exchange membranes (ibid.). Furthermore, apart from reduced energy consumption and increased efficiency, the use of AEM technology also contributes to the higher purity of generated H_2 (Mandal, 2021). Finally, as with other alkaline and alkaline polymer electrolysers, AEM systems can use inexpensive catalysts and core materials for electrodes, which will significantly reduce the investment costs.

On the other hand, whilst representing a step forward from conventional alkaline electrolytic systems, AEM electrolysers have a number of significant drawbacks. Most importantly, just like their alkaline predecessors, their currently available minimum load still appears to be pretty high (around 10–20 per cent of design capacity) (Stanislaw, Gerhardt, and Weber, 2019). This makes them not very suitable to be powered by variable renewable generation. In addition, whilst designed to be more efficient than alkaline electrolysers, AEM systems still have significantly lower water splitting performance than PEM facilities (Faid et al., 2018). Moreover, the hydrogen production scale of the available AEM electrolysers is currently substantially limited (ibid.). Finally, due to the decreasing ion conductivity of the membrane and its extreme sensitivity to carbon dioxide (CO_2) intrusion, the overall performance of the system declines with time, which is generally reflected by the limited lifetime of AEMs (around 30,000 hours) (Vega, Chartier, and Mustain, 2010).

MCECs

Molten carbonate electrolysis cell (MCEC) technology is currently being developed to overcome some of the key challenges of AEM electrolysers, while further promoting the advantages of alkaline electrolysis in general. While similar to AEM electrolysers – in terms of high purity of the generated gas (H_2) and absence of the necessity to use expensive catalysts – MCECs have some advantages over AEMs. For instance, operating at significantly higher temperatures (600–700 $^\circ$C instead of 50–80 $^\circ$C), they are not prone to carbon monoxide (CO) poisoning and CO_2 intrusion (Hu, 2016). As a result, their lifetime is generally higher. In addition, MCECs can be significantly bigger in size and thus can produce more hydrogen per stack (up to 1,400 Nm^3/h) (ibid.). That is why, when this technology becomes mature, it might potentially be regarded as superior to AEM, performance wise.

Nonetheless, just like AEM, MCEC is still at the early development stage. At the same time, the currently estimated investment per stack (of around USD1,400) is already comparable to that of PEM, as well as to the most advanced conventional alkaline electrolysers, which can be of even greater capacity (ibid.). That is why, with a similarly high minimum load level (10–20 per cent of the design capacity), MCECs do not seem to represent an option that is particularly suitable for the production of 'green' hydrogen using intermittent renewable energy sources, if no additional technological improvements are achieved.

2.2 Acidic

Electrolyser technologies operating in an acidic environment could generally be divided into *acid electrolysers* and *acid polymer electrolysers* (Mittelsteadt et al., 2015). Although both technologies have already been commercialized, acid polymer facilities represented by electrolysers utilizing proton exchange membrane (PEM) technology have generally been considered significantly more advanced and more suitable for coupling with variable renewable energy sources.

2.2.1 Acid electrolysers

Normally utilizing lithium-ion membranes and sulphuric acid (H_2SO_4) as electrolyte, acid electrolysers possess a number of benefits as well as drawbacks. With the minimum load of 5–10 per cent of the design capacity, acid electrolysers generally outperform all types of alkaline electrolysis facilities and thus are generally viewed to be more suitable for being powered by intermittent energy sources (ibid.). In addition to producing high-purity H_2, they have a relatively broad system size range, reaching 1,500 kW, which is similar to that of PEM and more impressive than AEM analogues (ibid.).

On the other hand, using iridium (Ir) and platinum (Pt) – expensive noble metals – for electrodes and catalysts, acid electrolysers may not necessarily justify the investment, as their efficiency is relatively low (ibid.). In addition, currently available acid electrolysers appear to have a lower estimated lifetime than most other electrolysis options (see *Table 1*).

2.2.2 Acid polymer electrolysers

In the 1960s, the desire to overcome the major drawbacks of alkaline electrolysers finally led to the development of the first systems based on a solid polymer electrolyte concept (Russell, Nuttall, and Fickett, 1974). Having been improved over subsequent decades, this concept is currently associated with proton exchange membrane (PEM) facilities, which appear to be the most promising option for pairing hydrogen production with solar and wind power sources at the moment (Carmo et al., 2013). Nevertheless, despite the significant advantages of PEM technology in comparison to the alkaline alternatives, such electrolysers have a number of deficiencies impeding their broader industrial use.

One of the key advantages of PEM electrolysers is their low level of partial load (0–10 per cent of the design capacity), which significantly distinguishes this technology from the rest of the currently available alternatives (Mittelsteadt et al., 2015). Apart from that, the non-porous nature of the PEM separator allows for rapid cycling in flexible operational conditions and provides a speed of response suitable for electricity grid-balancing services (Ionomr Innovations, 2020). As a result, due to these remarkable

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features, PEM systems are more suitable for running on intermittent renewables. Thus, they are among the most attractive technological options for the energy transition to 'green' hydrogen.

Furthermore, PEM electrolysers demonstrate higher efficiency than alkaline electrolysers, with generally better hydrogen purity and comparable stack and system lifetime (Carmo et al., 2013). In addition, typically operating at higher temperature and current densities, in contrast to the alkaline analogues, they have compact design and can be containerized even at larger scales (ibid.). This provides significant advantages to both manufacturing and on-site development, and can also reduce transportation and maintenance expenditures.

However, despite possessing unique features that could turn PEM electrolysers into the key driver of power-to-hydrogen industrial growth, this technology is yet to successfully address some of the key impediments to its promotion. One of the major barriers impeding the use of PEM systems on a broader basis is the high cost of catalysts and electrodes, due primarily to the expense associated with noble metals (mainly Pt) (Ionomr Innovations, 2020). In addition, the perfluorinated membranes and titanium current collectors used are relatively complex in production and appear to be expensive (Arico et al., 2013).

The other issue is that in the acidic environment, most of the non-noble metal oxides are subject to corrosion and are thus not particularly suitable as catalysts for PEM electrolysis (ibid.). Furthermore, without the use of platinum alloy catalysts, the anode reaction of PEM electrolysers could be subject to CO poisoning, which will lead to a gradual decrease in membrane performance (Baschuk and Li, 2001). In this connection, such systems are challenged by the lack of options for additional substantial cost minimization.

2.3 Acidic/alkaline amphoteric

Since all of the already available technological solutions for electrolysis require high energy consumption, the development of acidic/alkaline amphoteric electrolysers, which might significantly reduce power use, has recently been proposed (Lei et al., 2019). Though this technology is still at the very early development stage, it can potentially offer some advantages over the existing (especially alkaline) electrolysis systems.

According to Lei et al. (2019), acidic/alkaline amphoteric electrolysers combine both alkaline and acidic environments, each of which is dedicated to production of the different gases resulting from water splitting. Specifically, being divided by a membrane that is employed centrally to restrain neutralization, the electrolyser generates hydrogen inside a chamber containing an acidic solution, whereas oxygen evolves in the other chamber under alkaline conditions (ibid.). During pilot tests, this design led to a significant decrease in energy consumption (by around 30 per cent) and a higher rate of H_2 generation, when compared to conventional alkaline and AEM facilities of similar size and design capacity (ibid.). In addition, while not using Pt-group catalysts and thus being potentially less expensive than acidic electrolysis options, acidic/alkaline amphoteric installations also have greater efficiency than MCEC solutions (ibid.).

Nonetheless, in spite of the promising advantages that this technology could offer, it still needs further development to comprehensively address the limitations that it has. For example, increasing the purity of the produced hydrogen, the size, and the overall lifetime of the system appear to be the most important next steps in the process of improving acidic/alkaline amphoteric electrolysers (ibid.). Finally, the overall system cost could be further reduced through substituting the Pt-based costly electrode coating with some less expensive alternatives (ibid.).

2.4 Solid oxide[6]

Apart from alkaline and acid polymer (PEM) hydrogen production technologies, solid oxide electrolysers are widely expected to become the third main water electrolysis technology in the foreseeable future. Although it is currently at the R&D stage and thus is still far from being mature, the technology itself is not new. In fact, since the very first pioneering steps in its development in the late 1960s, this technology has been gaining growing interest due to its potential to significantly increase the efficiency of water electrolysis through using high operating temperatures of up to 800–1000 $^{\circ}$C (Ursúa, Gandía, and Sanchis, 2012). As a result, through taking advantage of high temperatures for splitting water into hydrogen and oxygen, solid oxide installations appear to be steam electrolysers (ibid.).

One of the most remarkable advantages of solid oxide electrolysers relates to their extremely high efficiency. Estimated around 80–90.8 per cent, this potentially surpasses the efficiency of all the currently existing alternative electrolysis options (Andersson and Sunden, 2017). Such a high level of efficiency is generally due to the fact that solid oxide-based electrolysis cells are not limited by Carnot efficiency (Ishihara, Jirathiwathanakul, and Zhong, 2010).

With the lowest level of minimum load being expected to be around 3 per cent, solid oxide electrolysers may potentially rival PEM systems in the future, in terms of operating with variable generation (Mittelsteadt et al., 2015). In addition, they also demonstrate long-term stability and can be run at low operating costs with inexpensive catalysts (Moseley and Garche, 2015). In order for this technology to enter the market, these advantages should be sufficiently significant to outweigh the shortcomings.

Despite the impressive advantages that solid oxide technology could bring to the industrial production of hydrogen, some of its drawbacks limit its commercialization and broader use. Here, its most remarkable feature – high operating temperature – appears to be one of its key challenges too, as it makes its start-up and break-in times longer (Ishihara, Jirathiwathanakul, and Zhong, 2010). This may potentially hamper the system's coupling with intermittent renewables, despite the relatively low minimum load.

High temperatures also lead to such mechanical compatibility challenges as thermal expansion mismatch, and diffusion between layers of material in the cell (Andersson and Sunden, 2017). This causes rapid degradation of cell components, some of which are represented by brittle ceramics (ibid.). As a result, solid oxide electrolysers currently have relatively low durability and thus a low overall lifetime (Koponen, 2015). Hence, if combined with high investment costs, bulky system design, low production capacity, and small available scale of production, these features of solid oxide electrolysers leave some space for improvement before they can become feasible rivals for alkaline and PEM facilities (Moseley and Garche, 2015).

2.5 Microbial

Being capable of producing not only hydrogen but also various organic chemicals, microbial electrolysis cells (MECs) can utilize the chemical energy of biomass to support electrical energy (Ogawa, Tekauchi, and Kajikawa, 2018). As a result, water splitting can occur at relatively low temperatures of up to 30 $^{\circ}$C (ibid.). Though this option looks promising for hydrogen generation, this technology is still at a relatively early development stage and needs further improvement.

Since the chemical energy of the biomass used in MECs can augment the electric power, microbial electrolysis can theoretically produce hydrogen from a low energy input of 0.6–1 kilowatt hours per cubic metre of hydrogen (kWh/m^3 H$_2$) (compared to 4.5–50.6 kWh/m^3 H$_2$ for other systems) (ibid.). As a result, the operating costs of such facilities could be significantly reduced. In addition, with improved

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[6] Just like other technologies (such as PEM systems capable of operating both as a fuel cell and an electrolyser), solid oxide cells are attractive for the storage and regeneration of renewable energy by operating reversibly for solid oxide electrolysis, and in solid oxide fuel cells (Chen et al., 2015b).

design, operation, and electrochemical characterization, MEC pilots have been able to significantly reduce overpotentials and improve overall efficiency (Badwal et al., 2014). Furthermore, microbial electrolysis technologies have the potential for waste water treatment (ibid.).

On the other hand, as MECs normally use precious metal catalysts and electrodes and other associated materials, this technology is prevented from commercialization in the same way as the popularity of PEM electrolysers is limited (ibid.). Furthermore, since currently available MECs have extremely low production capacity and potentially lower H_2 purity than other alternative technologies, they need to undergo substantial technological improvement to be able to commercially compete with, or supplement, the alternatives.

2.6 Photoelectrochemical (PEC)

In photoelectrochemical water splitting, semiconductor materials are used to convert solar energy directly into hydrogen. These semiconductors are immersed in a water-based electrolyte, where sunlight drives the process of splitting H_2O into H_2 and O_2 (US Department of Energy, 2020a). Since this technology of hydrogen production requires sunlight, its use in conjuncture with other types of renewables is limited.

Combining a photovoltaic system and an electrolyser into a single monolithic device, PECs push down the size and capital costs (MacQueen, 2018). In addition, such a combination potentially reduces energy use, due to the direct photon-to-chemical energy conversion, and increases the overall efficiency of the system (reportedly by around 30 per cent) (Ma and Wang, 2017 and MacQueen, 2018). Finally, as there is no need for Pt-group catalysts, PECs become even more attractive cost wise (ibid.)

At the moment, further improvements in efficiency, durability, and cost are considered to be necessary for the market viability of PEC (US Department of Energy, 2020a). Here, though efficiencies have already been significantly improved through enhanced sunlight absorption and better surface catalysis, the pilot models have demonstrated their upper limit, to reach around 40 per cent (Fountaine, Lewerenz, and Atwater, 2016). Furthermore, in order for PECs to become competitive with other hydrogen-producing technologies, the lifetime of this system should be significantly increased, which could potentially be achieved through employing more rugged materials and protective surface coatings (US Department of Energy, 2020a). Finally, the overall costs of hydrogen production through PECs could be lowered via reduced materials and materials processing costs (ibid.).

2.7 Overall evaluation

From a technological standpoint, electrolysers are on a spectrum ranging from mature to very nascent. Of the existing technology types, only alkaline and acidic electrolysers appear to have already been commercialized. While the former has been in use for over a century,[7] the latter has been gaining popularity since the second half of the twentieth century. PEM (acidic) electrolysers currently represent the most suitable already available option for the integration of intermittent renewable energy sources into the power-to-hydrogen process. Nonetheless, their high cost – due to the use of platinum group catalysts as well as to the expense of membrane production – is still the issue that is likely to challenge electrolyser producers in the upcoming years. On the other hand, with their generally larger system size (although they benefit from the low-cost catalysts needed), alkaline electrolysers have a relatively high minimum load, which makes them less suitable for the use of electricity generated by variable renewables, as they favour stable operating conditions.

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[7] For example, alkaline electrolysers have long been used in the chemical and metallurgic industries for the production of fertilizers (Kreuter and Hofmann, 1998). More recently, large-scale PEM electrolyser systems have been applied to hydrogen production for the purposes of oil refining (Shell, 2021).

The solid oxide and anion exchange membrane (alkaline polymer) technologies have been trying to bridge the capacity gap, so the advantages of both alkaline and PEM systems are currently being exploited without any major challenge. This, however, requires further research and development as neither system (solid oxide or AEM) has yet been made widely available. In particular, apart from possessing relatively high minimum load, which ultimately does not make them the best option for 'green' hydrogen production, AEM installations have not been successfully scaled up and thus remain primarily low-capacity systems. Solid oxide electrolysers are closer to commercialization, and are simultaneously more suitable for coupling with intermittent renewables, but they have quite low production capacity available. Also, in addition to being expensive to produce, their durability is yet to be improved due to the issue of brittle ceramics.

Therefore, it is clear that none of the currently available electrolyser technologies outperforms the rest across all the features essential for efficient 'green' hydrogen production. Having said that, alkaline, PEM, solid oxide, and AEM electrolysers are likely to be the systems that would draw the greatest attention of both researchers and industries in the foreseeable future with respect to the global energy transition. Therefore, evaluating the costs associated with each of these technologies and comparing them with each other could be useful for identifying the opportunities for further cost reduction, as well as for mapping their future business development scenarios.

Table 1: Key existing electrolyser technologies: General overview

	Types of electrolysers								
	Alkaline			*Acidic/ alkaline amphoteric*	*Acidic*		*Solid oxide*	*Microbial*	*Photo-electro-chemical*
Type of electrolyte	Alkali	Alkaline polymer		Acidic & alkaline	Acid	Acid polymer	Solid oxide	Microbial	Acidic & alkaline
Key technology/ matrix	Microporous separator	Anion exchange membrane (AEM)	Molten carbonate electrolysis cell (MCEC)	Cation exchange membrane (CEM)	Li-ion exchange membrane	Proton exchange membrane (PEM)	Protonic ceramic electrochemical cell	Microbial electrolysis cell (MEC)	Photo-electro-chemical cell (PEC)
Most common electrolyte/ membrane	Na^- or KOH (usually aqueous KOH of 20–40 wt%)	Anion exchange ionomer (e.g. AS-4) + optional dilute caustic solution	Ceramic matrix (combination of alkali carbonates (Li, Na, K) retained in a matrix of $LiAlO_2$)	H_2SO_4 (cathode) & KOH	H_2SO_4 or H_2PO_4	Proton conductive polymer (e.g. Nafion®) membrane	Ceramic: Solid, nonporous metal oxide (usually Y_2O_3-stabilized ZrO_2)	Phosphate species; PEM: CEM & AEM	Anion/ proton exchange polymer electrolyte membrane
Reactant*	Water (liquid)						Water (gas)	Water (liquid)	
Most common electrodes (cathode)	Ni & Ni-Mo alloys	Ni & Ni alloys	Porous Ni electrode	Ni & Pt (coating)	Ir & Pt	Pt & Pt-Pd	Perovskite electrodes (e.g. $PrNi_{0.5}Co_{0.5}O_{3-\delta}$)	Stainless steel & Ni	Photo-electrodes (e.g. TiO_2/ CdS/ CdSe)
Most common catalyst	Pt and Ru, but *also Mn and W*		Non-precious metals	OH^-	Pt	Pt black, Ir, Ru, Rh	ZrO_2	Pt	Photo-catalyst (usually TiO_2)
Minimum load (% of design capacity)	15–40, 5 (state of the art)			10–20	5–10	0–10 ~5 (typical)	>3		n/a
Operating temperature (°C)	50–80	50–60	600–700	30–50	50–120	60–200	800–1000	4–30	25–65
Average system efficiency (HHV) (%)**	68–77	<=74	~60	>70	>40	70–80	80–90.8	67–90	~14–40 (currently achievable)
H_2 purity (%)	99.5–99.99998	99.99	~99.9	99.5–99.99998		99.9–99.9999	~99.99	~98	~99.99
Estimated stack lifetime (h)	~60,000–100,000	~30,000	~40,000	~60,000	>20,000	~50,000–90,000	~20,000–90,000	n/a	n/a
Estimated system lifetime (years)	20–30	<20	~20	>20	>10	20–30	10–20		<10

Approximate investment cost (USD/kW	800–1,500	n/a	~1,500	n/a		1,400–2,100	>2,000		n/a
System size range (kW)	1.8–5,300	>100	300–2,800	>100	0.2–1,150	100–1,300	1.5–200		
H$_2$ production per stack (Nm³/h	<760	n/a	<1,400	n/a		<400	<10	<2	
Technological maturity	Mature	R&D				Commercial	R&D		
	TRL9	TRL 2–5	TRL 1–4			TRL 7–8 (~9)	TRL 5–7	TRL <=5	TRL 1–3
Advantages	• Low-cost catalysts • Mature & developed technology • Low-cost production • High estimated lifetime • Large system size available • Tolerance to impurities	• Prevented electrolyte leakage • Increased efficiency • High H$_2$ purity • Reduced energy consumption • More compact • Low-cost catalysts	• Low-cost catalysts • Not prone to CO poisoning • Medium system size available • High H$_2$ production per stack • High H$_2$ purity	• Reduced energy use (compared to AEM) • Increased efficiency (compared to MCEC) • Cheap catalyst • Higher rate of H$_2$ production (compared to AEM)	• Medium system size available • Lower minimum load (compared to alkaline and alkaline polymer) • High H$_2$ purity	• Low minimal load • Low maintenance • High H$_2$ purity • High efficiency • High durability • Compact design	• Low minimal load • Inexpensive catalysts • High efficiency • Low operating costs	• Minimized over-potential • Low energy use • Potential for high efficiency • Potential for waste water treatment	• Potential for reduced energy use (due to direct photon-to-chemical energy conversion) • Potential for increased efficiency • No need for noble metals as catalysts
Drawbacks	• High minimal load • Designed for operation at fixed process conditions • Lower H$_2$ purity • Medium efficiency • Bulky stack design • Potential electrolyte leakage • Prone to corrosion	• Medium lifetime • Sophisticated AEM • Extreme sensitivity to CO$_2$ intrusion • Decreasing ionic conductivity of AEM • Low technological maturity • High minimal load • Small system size available	• Medium investment costs • Low technological maturity • High minimal load	• Costly electrode (coating) • Medium lifetime • Lower H$_2$ purity • Low system size • Low maturity of technology	• High cost of catalyst • Low system efficiency • Low estimated lifetime • Technology at R&D maturity level	• High cost of membrane • High-cost catalyst (Pt) • Hard to replace Pt-group catalysts • Medium system size • Prone to CO poisoning	• Immature technology • Low durability (brittle ceramics) • Bulky system design • Low production capacity available • High investment cost • Small system size available • High operating temperatures	• High cost of catalysts • Low production capacity currently available • Lower H$_2$ purity • Technology at R&D stage	• Low system efficiency currently achievable • Low system lifetime currently achievable • Technology at lab stage (R&D)

Source: Adapted from Tsoutsos (2010), Kulkarni and Giddey (2012), Aalborg University (2013), Hansen et al. (2012), Carmo et al. (2013), Bertuccioli et al. (2014), Decourt et al. (2014), Dias et al. (2014), Lehner et al. (2014), Moseley and Garche (2015), Parrondo et al. (2014), Argonne National Laboratory (2015), Chen et al. (2015a), Mittelsteadt et al. (2015), Hu (2016), Kadier et al. (2016), Andersson and Sunden (2017), Nandjou and Haussener (2017), Adnan et al. (2018), Das, Dutta, and Rana (2018), David, Ocampo-Martinez, and Sánchez-Peña (2019), Lei et al. (2019), Rivera, Schroeder, and Patil (2019), Zhao and Ci (2019), Ding et al. (2020), Lamb and Lien (2020), Miller et al. (2020), Breakthrough Energy (2021), FLEXCHX (2021), Fraunhofer IFAM (2021), Motealleh et al. (2021), Vincent, Lee, and Kim (2021). NOTE: * *water purity is crucial for the long-life performance of an electrolyser as impurities deposit on electrodes and membranes hamper the transfer of ions and electrochemical reactions (Zhang et al., 2020, p.* 59).***The calculation of HHV (high heating value) efficiency considers the water vapour produced during the combustion process (in contrast to the calculation of LHV (low heating value) efficiency) (Fulton, 2021).*

3.   Key cost drivers of electrolysers

Assessing the exact expenses associated with specific electrolyser technologies appears to be challenging. In fact, the precise estimation of the overall costs for electrolysers is impeded by two main factors. First, due to the relative novelty of some of these technologies, cost-related data are not always provided by companies that wish to gain or retain competitive advantage. Second, the boundaries for the estimation of costs are often either unspecified or inconsistent. This makes a comparison across all technologies less accurate.

It is, however, possible to compare the costs of the major currently available technologies: alkaline and PEM systems. Quite predictably, at the moment, the less mature but already commercialized PEM systems of water electrolysis are generally 50–60 per cent more expensive than the well-matured alkaline ones (IRENA, 2020a). While both technologies are broadly considered to have untapped potential for cost reduction with respect to such factors as economies of scale, automation, and availability of components, the process of decreasing their costs may potentially be paralleled with the commercialization of solid oxide and AEM alternatives that could enter the market with comparable offers.

At the same time, though the commercialization of AEM and solid oxide electrolysers has been launched by some business pioneers, many components of these systems are still laboratory-based, with no original equipment manufacturer being responsible for their production and scaling (ibid.). As a result, pilot AEM and solid oxide projects mostly represent small stacks with total system sizes of only up to a few kilowatts (ibid.). Hence, while still being potentially capable of contributing to low cost 'green' hydrogen generation, their large-scale presence on the market for electrolysers is yet to be fully established.

Nevertheless, out of all the technologies currently considered for the production of 'green' hydrogen, conventional alkaline, AEM, PEM, and solid oxide electrolysers are considered by manufacturers as the most promising options (ibid.). That is why reviewing and comparing their key cost drivers could be useful. In what follows, we compare the key cost drivers – stack, power electronics, gas conditioning, and balance of plant – across the aforementioned four types of electrolysers (see *Figure 3*).

3.1 Stack

Normally comprised of cell units, porous transport layers, bipolar plates, end plates, and various smaller parts (such as spacers, seals, frames, and bolts), *stacks* represent the main cost driver of the electrolyser technologies currently available on the market – alkaline and PEM systems (IRENA, 2020b). Here, the cell unit itself – namely the core technology enabling the main electrochemical process of water splitting – usually includes the membrane where the catalyst layers are coated as electrodes onto it (in PEM systems) and the electrodes and diaphragms (in alkaline systems) (ibid.). Constituting between 40 and 60 per cent of the total electrolyser expenses, stacks usually comprise around half of alkaline electrolyser cost and about 60 per cent of the costs of PEM systems (Böhm, Goers, and Zauner, 2019). This difference is attributed primarily to the use of precious platinum-group metals, which make PEM electrolysers more expensive, with implications for their commercial spread.
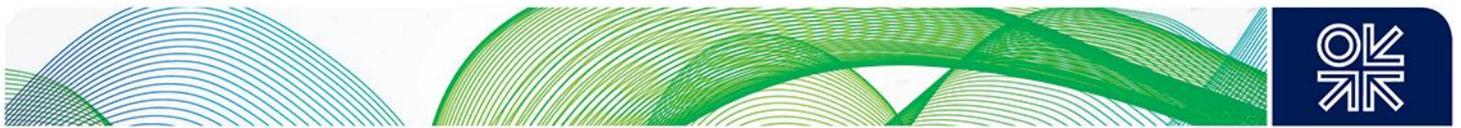
Figure 3: Approximate cost breakdown for 1 MW electrolysers
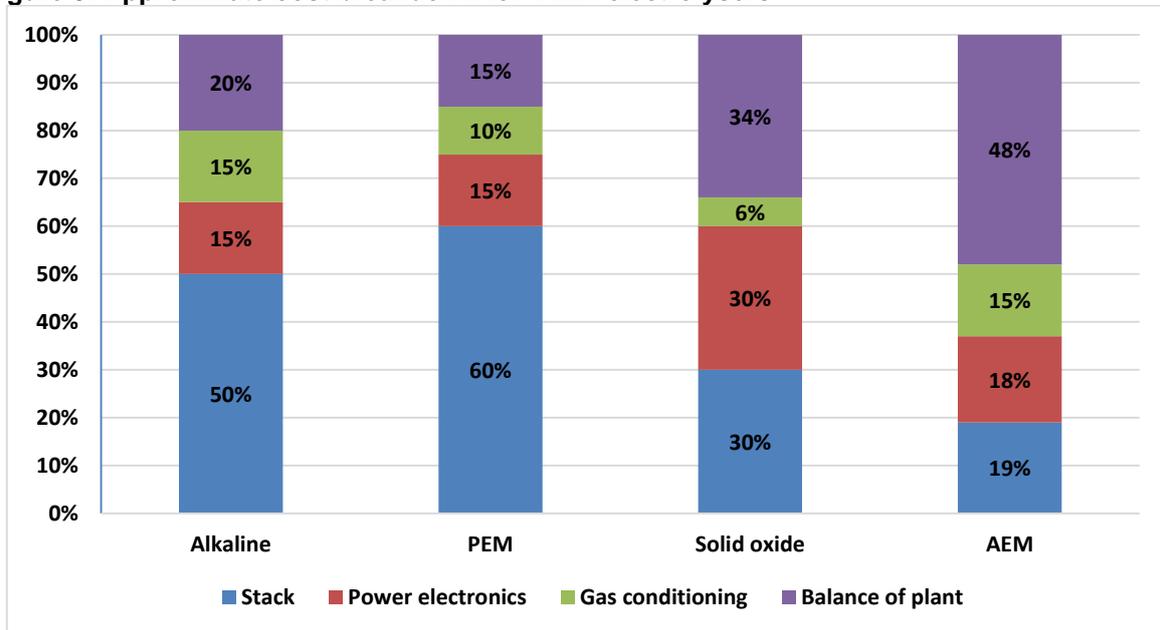
Source: Adapted from Smolinka, Günther, and Garche (2011), Bertuccioli et al (2014), Smolinka et al. (2018), Böhm, Goers, and Zauner (2019), Ionomr Innovations (2020).

To avoid these challenges, solid oxide and AEM electrolyser technologies are experimenting with cheaper catalysts and materials (Vincent and Bessarabov, 2018). In general, this allows a reduction in the share of stack costs to around 30 per cent for solid oxide and 19 per cent for AEM installations (ibid.). Though percentage-wise this might seem like a significant improvement, the low scalability of these systems, owing to their current low maturity, makes this component still relatively expensive in absolute terms, especially if more expensive solid oxide installations are compared to the alkaline and PEM ones (*Table 2*):

Table 2: Approximate component costs (USD/kW) for 1 MW electrolysers in 2019

Key components	Technologies			
	Alkaline	*PEM*	*Solid oxide*[8]	*AEM*[9]
Stack	270–450	400–870	690–2,000	>177
Power electronics	81–135	100–217.5	690–2,000	~167.5
Gas conditioning	81–135	67–145	140–400	~139.5
Balance of plant	108–180	100–217.5	780–2,267	~447
Total	**540–900**	**667–1,450**	**2,300–6,667**	**>931**

Source: Adapted from Böhm, Goers, and Zauner (2019), Ionomr Innovations (2020), and IRENA (2020b)

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[8] The estimations of the costs for solid oxide electrolysers are based on the research conducted by Böhm, Goers, and Zauner (2019) and thus are indicative, since this technology has not been fully commercialized.

[9] Since the cost estimations for AEM electrolysers are based on the estimations provided by Ionomr Innovations (2020), a Canadian pioneer in AEM technology commercialization, they should be perceived as approximate and desirable rather than actual, as the technology is still at the early pilot stage.

3.2 Power electronics

Power electronics could be generally described as the application of solid-state electronics to the control and conversion of electric power. Such a conversion could be used for the connection of renewable energy systems to the grid, since the direct current (DC) of the power source needs to be transformed into the alternating current (AC) of the grid (Fuel Cell Store, 2017). In electrolyser systems, however, the main purpose of power electronics is to convert alternating current from the network to the direct current that is required by the electrolysis cell stack (ibid.).

The AC/DC conversion is typically done by *rectifiers* – electrical devices that transform alternating current, which periodically reverses direction, to direct current, which flows in only one direction. Apart from that, the power electronics of most electrolysers also contains *choppers* – namely static power electronic devices that convert fixed DC voltage or power to variable DC voltage or power; this essentially represents a switch used to interrupt one signal under the control of another (Solanki et al., 2015). Finally, *transformers* are usually utilized as a passive component that manipulates the level of voltage flowing through any point in a power grid (ibid.).

Although the cost of power electronics in both alkaline and PEM systems constitutes only around 15 per cent (see *Figure 3*), its share for AEM installations is expected to be higher (about 18 per cent) (Ionomr Innovations, 2020). For the more expensive solid oxide electrolysers it appears to be even more significant, at 30 per cent, which is comparable to the cost of its stack and, in absolute terms, is 7–8 times higher than the cost of power electronics in alkaline and PEM systems (*Table 2*) (Böhm, Goers, and Zauner, 2019). At the moment, this is primarily due to the relative complexity of the hydrogen production process through these technologies owing, among other factors, to the extremely high operating temperature, mechanically unstable electrodes, brittle ceramics, and sealing issues (CSIRO, 2021). In these circumstances, power electronics and balance of plant play an extremely important role.

3.3 Gas conditioning

Gas conditioning in electrolysers generally includes the mechanical compression of gas to a defined storage pressure, and gas drying to purify the raw hydrogen (Tjarks et al., 2018). There, depending on the technological advancement, hydrogen is purified to 99.5–99.9999 per cent and compressed to more than 50 bar, so that its storage is facilitated (IAV, 2019). Though this stage is very important in the overall H_2 generation process, it appears to be the least expensive component out of the four main ones mentioned above for each of the reviewed electrolyser types (*Table 2*).

In particular, while constituting around 15 per cent of costs for alkaline and AEM systems, the share of gas conditioning falls to about 10 per cent in PEM installations and to only around 6 per cent in solid oxide ones, as non-alkaline systems are based on different technologies (*Figure 3*). At the same time, due to the dramatic cost difference in favour of the commercialized alkaline and PEM electrolysers, gas conditioning in solid oxide and AEM systems is generally of similar or higher expense, if expressed in absolute terms (Böhm, Goers, and Zauner, 2019 and Ionomr Innovations, 2020).

3.4 Balance of plant

Finally, the balance of plant system represents the remaining share of key electrolyser costs. Normally, it includes such components as heat recovery and heat rejection equipment, process material transport systems (such as pumps, valves, and piping), control systems, safety systems, waste collection and disposal systems, equipment for maintenance and repair, heating/ cooling/ ventilation/ air conditioning, power supply and distribution, and others (Ward, 2006). Although the share of this cost component in conventional alkaline and PEM electrolysers varies between 15 and 20 per cent (*Figure 3*), more advanced systems that are currently at their development and early commercialization stage associate with it a greater part of their expenses.
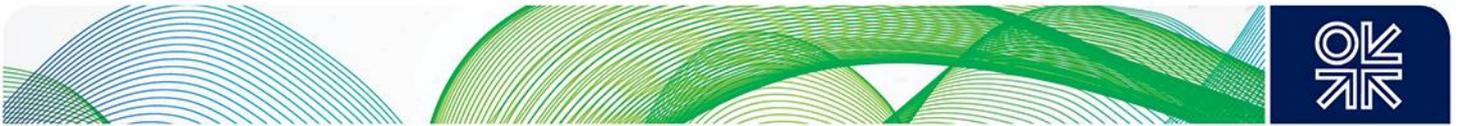
Specifically, the estimated share of the balance of plant for the cost of solid oxide electrolysers is over two times higher than that for PEM installations: 34 vs. 15 per cent (Böhm, Goers, and Zauner, 2019). In absolute terms, this difference is even more significant, as this cost component in solid oxide systems is at least eight times more expensive (*Table 2*). Similarly, for AEM electrolysers, the balance of plant is estimated to constitute almost half of the costs (48 per cent), which in pure terms is two to four times more expensive than in alkaline and PEM systems (*Figure 3*). Here, similarly to the case of power electronics, the balance of plant plays an extremely important role in contributing to the extension of the durability of membranes (AEM or solid oxide), which currently appears to be significantly limited due to the relative novelty of these technologies (CSIRO, 2021 and Li et al., 2021).

4. Opportunities for cost reduction

Although a dramatic reduction in the cost of electricity used for electrolysis is generally viewed as the first key prerequisite for the increased competitiveness of 'green' hydrogen, it cannot be viewed as the only element in the process of cost reduction necessary for the power-to-hydrogen technologies to successfully compete with hydrocarbons-based H_2 production (Wood Mackenzie, 2019). Indeed, according to IRENA (2020b) 'green' hydrogen costs are, at the moment, at least two or three times higher than those of blue hydrogen. Whilst gradually falling renewable power costs contribute to narrowing this gap, further reductions in the costs of electrolysers – the second greatest share of expenses associated with power-to-hydrogen – should be given close attention (*Figure 4*).

Figure 4: Main cost drivers (%) for 'green' hydrogen in 2019
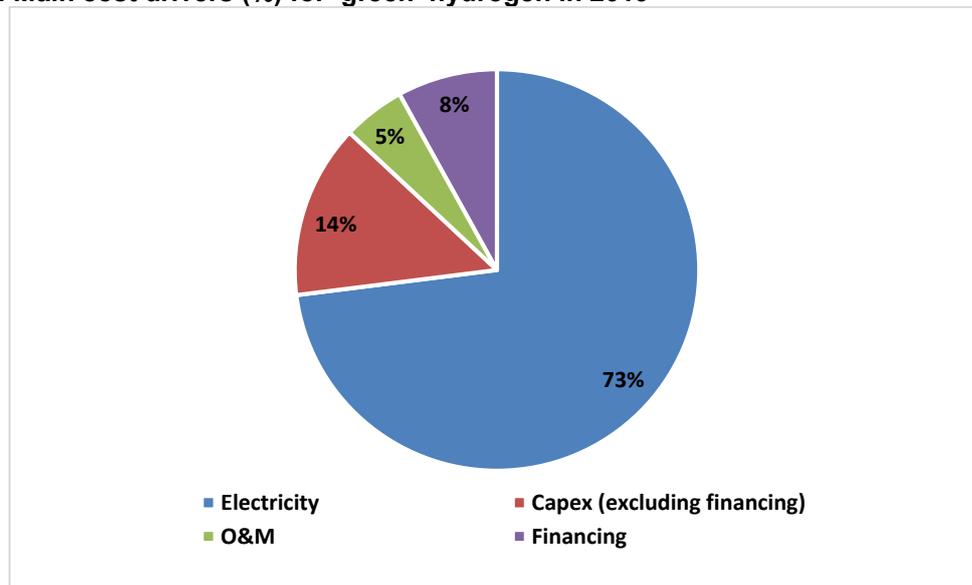
Source: Wood Mackenzie (2019)

Indeed, depending on the specific characteristics of each type of electrolyser technology, average costs for a 1 MW unit could vary significantly: from around 550 USD/kWh (for alkaline technologies) to more than 6,500 USD/kWh (for solid oxide ones) (*Table 2*). This, in turn, makes the ultimate cost range of 'green' hydrogen broad as well.

While technological progress has been actively pushing down the costs of renewable electricity for a number of decades, the full potential for reducing the costs of electrolysers in a similar way is yet to be properly estimated. There are several technical aspects, improving which could make electrolysers, and consequently green hydrogen, more competitive on a global market. These aspects generally include: energy consumption per unit of production, stack lifetime, stack size, load range, start-up time,

electrolyser's scale of industrial production, and use of scarce materials. Given that each electrolyser technology is currently at a different stage of improving these features, it is useful to compare their current characteristics with the ultimate targets. In Table 3, the most successful in this respect are highlighted in 'green', the least successful to date with 'red', and the ones in between with 'amber'.

Table 3: Potential improvement opportunities for key electrolyser technologies[10]

Goals			Alkaline	PEM	Solid oxide	AEM
Decreased energy consumption per unit	kWh/ kg of H_2	Current	50–78	50–83	45–55	57–69
		Aimed	<45		<40	<45
Increased stack lifetime	h	Current	60,000–100,000	50,000–90,000	20,000–90,000	~30,000
		Aimed	>100,000	>100,000–120,000	>90,000	>100,000
Increased module and stack size	MW/ unit	Current	1		0.005	0.0025
		Aimed	5–10		0.2	2
Broadened load range (lower minimum and higher maximum load)	%	Current	15–100	5–120	3–125	5–100
		Aimed	5–300	5–300	0–200	5–200
Minimization of the use of scarce materials	Rare earth &	Current	Pt, Ru, W	Ir & Pt	Zr, Sm, La	None
		Aimed	Elimination	Minimization	Minimization	N/a
Typical start-up time (cold)	min	Current	~30–60	15–28	>60	~30
		Aimed	<30	<15	<60	<30
Increased scale of production of electrolysers	GW/ year	Current	>0.04	0.01–0.04	<0.025	~0.01
		Aimed	>1		0.5–1	
Decreased average stack cost	USD/ kW	Current	270–450	400–870	690–2,000	>177[11]
		Aimed	<100		<200	<100

Source: Adapted from Sakai et al. (2005), Ursúa, Gandía, and Sanchis (2012), David, Ocampo-Martinez, and Sánchez-Peña (2019), Mayyas and Mann (2019), nel (2019), FCH JU (2020), IRENA (2020b), World Bank (2020), Enapter (2021), Greensight (2021), Haldor Topsoe (2021)

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[10] The specific targets for each category were roughly defined by industries following the evaluation of technological maturity and production capacity for each electrolyser technology. They should generally align with climate commitments of the key electrolyser producers (IRENA, 2020b).

[11] The average stack cost of AEM electrolysers is very approximate due to the lack of detailed information available and should thus be regarded as indicative.

4.1 Energy consumption per unit of production

With the share of electricity costs constituting up to 73 per cent of the total cost of 'green' hydrogen (*Figure 4*), increasing the electrical efficiency of electrolyser systems, and thus decreasing the amount of energy (kWh) consumed per unit of produced hydrogen (kg), will directly contribute to the ultimate cost reduction of the H_2. This, however, is not an easy task, as some technological processes involved are highly energy demanding. On the other hand, other characteristics normally attempt to compensate for high energy demand.

For instance, the high amounts of energy that are consumed to elevate the operating temperature of solid oxide electrolysers simultaneously create the environment for easier splitting of water with thermal energy (heat) and not just electricity (Holladay et al., 2009). As a result, higher temperatures minimize power loss during electrolysis, through decreasing the anode and cathode overpotentials and thus increasing the electrolyser efficiency (ibid.). Due to these reasons, and despite their low commercial readiness, solid oxide systems appear to be among the most advanced in terms of reducing electricity consumption (*Table 3*).

However, at the moment, the same characteristics do not relate to AEM electrolysers, whose commercial readiness is the lowest of the four electrolyser types described here. Specifically, with an estimated energy consumption of between 57 and 69 kWh per kg of H_2, they are generally expected to be less electrically efficient than solid oxide, alkaline, and PEM electrolysers (IRENA, 2020b). In this connection, to be able to successfully compete with other systems, apart from building up their overall technological maturity, they will need to reduce the energy consumption per unit of hydrogen they produce.

In contrast, alkaline electrolysers with energy consumption of between 50 and 78 kWh per kg of H_2, appear to generally have greater electrical efficiency than PEM and AEM systems. Though alkaline electrolysis can work either under atmospheric or pressurized conditions, the use of high pressure can help to save energy through producing hydrogen internally, as high-pressure alkaline electrolysis eliminates the need for an external H_2 compressor. At the same time, this may reduce the overall purity of the gas while simultaneously requiring greater amounts of energy to be consumed for the pressurization itself (Bhandari, Trudewind, and Zapp, 2014). That is why further cost-reduction opportunities for alkaline systems lie in the possibility of addressing this trade-off between maintaining the optimal pressure while reducing energy consumption.

Finally, PEM electrolysers generally consume more electricity per kg of hydrogen than alkaline and solid oxide systems (*Table 3*). This is partially because PEM systems usually operate at a higher pressure than alkaline ones, with some models reaching 80 bar or more (Carmo et al., 2013). Such higher-pressure configurations generally allow for the cathode (hydrogen) side to be under pressure without pressurizing the anode side (ibid.). As a result, the hazards of handling high-pressure oxygen are avoided (Brynolf et al., 2018). At the same time, despite the benefits that high-pressure operations bring, improving the electrical efficiency of PEM electrolysers could further reduce their costs.

4.2 Stack lifetime

Increasing the lifetime of electrolysers will spread the cost of the facility over a larger hydrogen production volume and thus reduce the expenses per unit of generated H_2. That is why improving the durability of power-to-hydrogen production systems is important for the overall cost reduction of their 'green' product. At the moment, as the most mature systems, alkaline electrolysers appear to have the longest lifetime.

Indeed, alkaline electrolysers are currently the most robust, with their stack lifetime varying between 60,000 and 100,000 hours and proven system durability being above 30 years (IRENA, 2020b). Although other types of electrolyser technologies are trying to rival the durability of the alkaline systems, they are yet to achieve it (*Table 3*). At the same time, their lifetime is affected by various factors,
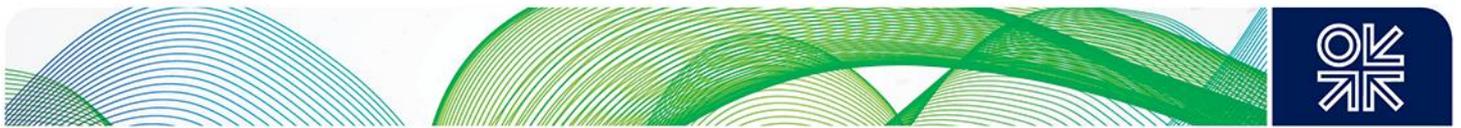
depending on which each particular system may ultimately happen to be more or less durable. For alkaline electrolysers, some of these factors relate to *gas permeation*, *electrodes*, *nickel alloys*, and *water purity/impurity*.

Specifically, being exposed to a continuous gas permeation, the diaphragm in alkaline electrolysers tends to suffer from increasing pin-hole failures leading to gas contamination, which ultimately reduces the overall lifetime of stack and system (ibid.). In addition, nickel alloys that are used to deal with highly caustic KOH at high concentrations need to be free from chromium and iron, as they could contaminate the electrodes while leaching, which will also significantly reduce the lifetime (Guandalini, Campanari, and Valenti, 2016). Finally, water impurities have a strong negative effect on some of the key components of alkaline electrolysers, such as the diaphragm and catalysts, among others (ibid.). That is why addressing these factors would significantly improve the durability of such systems which, in turn, will have a positive effect on the marginal cost of the 'green' H_2.

With a reported lifetime of between 50,000 and 90,000 hours, PEM electrolysers are currently still lagging behind the alkaline systems. Though this is partially due to their relative novelty, there are also a number of factors that have a strong impact on their lifetime. These factors usually include *operating conditions*, *variable load*, *anode dissolution*, *gas permeation*, and *water purity/impurity*.

While PEM systems, if compared to conventional alkaline ones, normally have higher operating pressure, temperature, and current density, these conditions are often detrimental for their durability. That is why newer generations of such systems normally address these challenges through overdesigning stacks with thick membranes, high catalyst loadings and protective coatings over porous transport layers, and bipolar plates (IRENA, 2020b). These measures, in turn, increase the overall cost of such PEM systems.

Another detrimental factor for the lifetime of PEM electrolysers is variable load. In fact, although PEM installations are currently best suited for operating with intermittent power supplies in comparison to other systems, voltage fluctuations are likely to cause additional corrosion of stack components, which will obviously reduce the overall durability and thus increase the cost (ibid.). Furthermore, depending on the temperature and voltage, the iridium oxide usually present on the anode is prone to dissolution (Siracusano et al., 2017). To address this challenge, a greater amount of catalyst, together with additional high loadings of precious metals in protective layers over the stack components, are added (ibid.). Both measures, however, further contribute to the cost increase.

Similar to the alkaline systems, PEM electrolysers are also prone to gas permeation and are vulnerable to water impurities. Specifically, if PEM membranes are subject to a large differential pressure, their mechanical stability is significantly affected, which leads to the permeation of H_2 and further degradation issues (IRENA, 2020b). Water impurities also appear to be a common cause of stack failure due to their adverse effect on membranes, porous transport layers, ionomers in the catalyst layers, and the catalysts themselves (ibid.). Here, the first challenge is normally addressed through the use of additional catalyst to reconvert the hydrogen that permeated to the oxygen side back to water, while the second one is dealt with through the use of water purifiers. Since both measures further increase marginal costs, the lifetime of PEM electrolysers needs to be improved in a cost-efficient way in order for PEM technology to spread further.

When it comes to solid oxide electrolysers, the estimated lifetime of such systems varies significantly, depending on the information source, since this piece of technology has not yet been fully commercialized. At the same time, while their stack lifetime has already been shown to steadily achieve 20,000 hours, the current experimental durability ceiling is expected to be around 90,000 hours (*Table 3*). Though these characteristics place them in second position behind alkaline electrolysers, it should be noted that most of the measurements have been conducted with solid oxide installations that were powered by constant energy sources with well-defined operating conditions (ibid.). It is expected, however, that coupling solid oxide electrolysers to variable renewable energy sources may result in faster degradation and shorter lifetime of such systems due to thermochemical cycling, especially under

shutdown/ramping periods (ibid.). Thus, apart from increasing the lifetime of such electrolysers, further improvement in their suitability for coupling with intermittent renewables should be achieved.

Finally, AEM electrolysers are currently demonstrating the least impressive lifetime, which is estimated to barely reach 30,000 hours (*Table 3*). Though specific information on all the key aspects related to this technology is scarce due to its low level of commercialization, AEM systems are generally recognized to have a number of challenges that limit their durability. Specifically, the stability of the AEM polymer that is utilized to fabricate membrane and catalyst layers is generally viewed as a major problem as, with hydroxide (OH^-) attack on the polymer backbone, the membrane tends to collapse and the catalyst layer tends to dissolve within a few days (ibid.). While engineers around the world are trying to address these chemical and mechanical stability problems, the solutions that have been offered so far generally lead to a decrease in the efficiency of AEM systems and further increase in their costs.

4.3 Stack size

According to the fundamental concept of economies of scale, the average cost per unit of production decreases with the increasing number of produced units. In this sense, for electrolysers, making the size of stack bigger or mass-producing standard-sized stacks (which can then be put together in a modular way) and thus increasing their H_2 production capacity, is expected to reduce the unit cost of hydrogen produced. Following this logic, IRENA (2020b) estimates that scaling up the plant from 1 MW to 20 MW would result in significant cost reductions equivalent to one third of the original expenses. At the moment, most alkaline and PEM electrolysers with an average size of 1 MW appear to be a lot more successful in reaching this goal than solid oxide and AEM systems which, at their sizes of 0.005 and 0.0025 MW, are still at the very early stage of being scaled up (*Table 3*).

At the same time, with the overall scale up of hydrogen plant, and not just the stack size, the greatest effect on cost reduction is expected to be achieved for the balance of plant, power electronics, and gas conditioning (ibid.). This is primarily due to the physical and technological limitations associated with increased stack size. For instance, larger stacks might face more frequent challenges of leakages and mechanical instability, while increasing the area of the cell might simply not be physically possible at the current stage of technological development. Therefore, the remaining cost components are likely to have stronger economy of scale effects due to their lower overall technological complexity. For example, a ten-times increase in the size of a compressor is normally associated with only a four-times increase in its price (ibid.). This would generally mean that, for the same capacity increase, the stack size increase would be associated with a greater share of the overall cost than the increase in the size of the compressor. Hence, with the scale-up of module size, the stack is likely to have a larger contribution to the total cost than the rest of the components (*Figure 5*).

On the other hand, the size of the facility is normally not defined solely by cost considerations. Instead, the application (for residential, industrial, transport, or other purposes) also plays an important role. Here, smaller scale and thus higher production costs could be justified by additional savings stemming from such aspects as delivery of hydrogen when it is produced on site. Hence, a proper cost management strategy of electrolyser facilities should consider both aspects.

Alternatively, instead of increasing the size of a hydrogen plant designed as a single train, a modular system design could be applied. In principle, this could mitigate some of the key technological challenges associated with the increase of stack size. As a result, further cost reduction could be achieved.
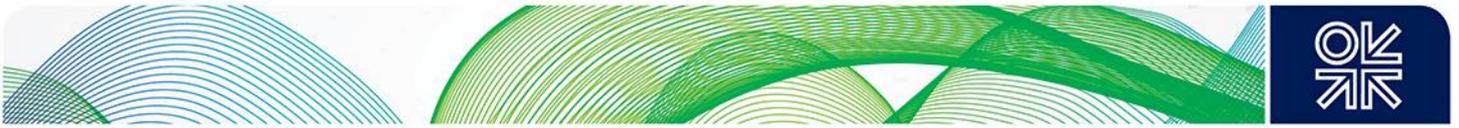
Figure 5: Estimated cost breakdown by major component for 1 MW, 10 MW, and 100 MW alkaline and PEM electrolysers based on current costs
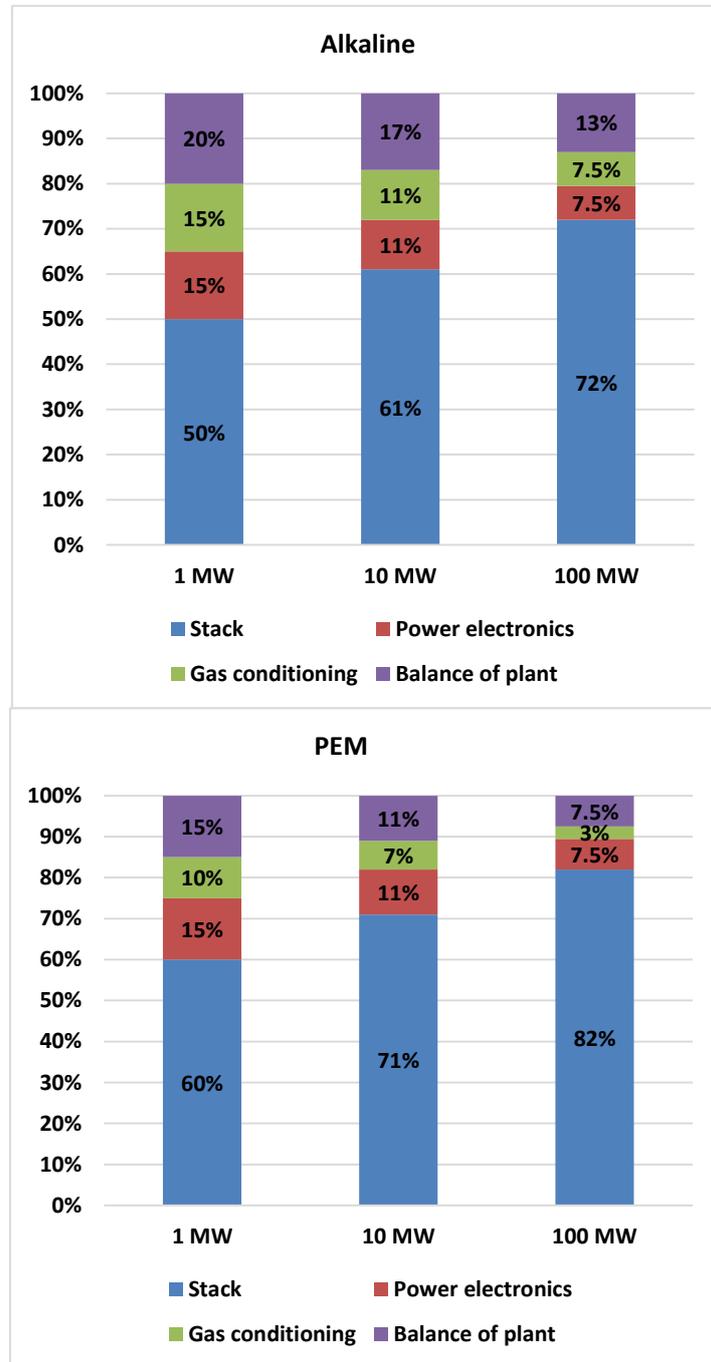
Source: Adaptation from IRENA (2020b) and Böhm et al. (2020).

4.4 Load range

Given that renewable energy sources such as wind and solar power are characterized by significant seasonal and daily variability, in order to successfully operate in the conditions of intermittent load, electrolysers need to have a broad load range. This is so because load changes affect their temperature
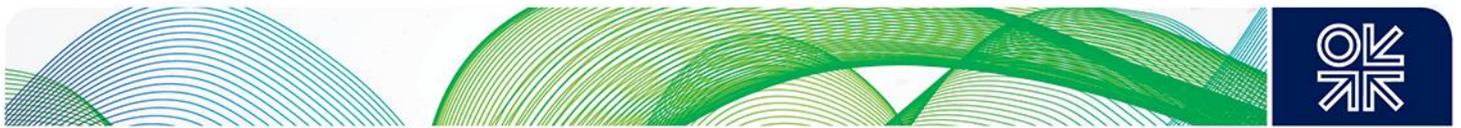
and pressure conditions (Wulf, Linssen, and Zapp, 2018). Here, since each type of electrolyser has its own optimal operating temperature and pressure characteristics, using variable power that may not allow these characteristics to be sustained will adversely influence the efficiency of the entire hydrogen production process (ibid.). As a result, it will be harder for such power-to-hydrogen systems to compete with H_2 production systems running on hydrocarbons, as the cost of 'green' hydrogen generation will grow.

For instance, operating on lower loads generally leads to the underproduction of heat which, in turn, makes it harder for the electrolyser to reach the optimal temperature. In addition, since the balance of plant (for example pumps and cooling) has a constant energy demand that does not depend on the generation of hydrogen, a load lower than 30 per cent of nominal power will eventually lead to a greater energy consumption per kg of H_2 (Bourasseau and Guinot, 2016). That is why electrolyser systems with greater tolerance to lower minimum load appear to be more suitable for power-to-hydrogen production, as their ultimate efficiency losses are less affected.

At the current stage of technological development, alkaline systems, with their minimum acceptable load of around 15 per cent, are the ones with the greatest need for further improvement in load range, when compared to the more advantageous PEM, solid oxide, and AEM systems that tolerate a minimum load of around 5 (PEM and AEM) and 3 (solid oxide) per cent (*Table 3*). In fact, due to their relatively high minimum load, most alkaline systems need to be completely shut down and depressurized when not enough electricity is provided (Wulf, Linssen, and Zapp, 2018). After this, the electrolyser also needs to be flushed so that no unwanted reactions of the remaining hydrogen take place (Tjarks, Mergel, and Stolten, 2016).

At the same time, intermittent renewables can also generate surplus power, which will also have to be dealt with. For electrolysers, operating in overloads usually means efficiency losses and additional stress for the materials, which may potentially result in a reduced lifetime for the system (Bourasseau and Guinot, 2016). Overheated systems operating in overloads will also need additional cooling which, in turn, will further raise the overall costs of operations (Wulf, Linssen, and Zapp, 2018). In general, fluctuations of electricity input cause degradation of materials in both the electrical and mechanical parts of electrolyser systems, when compared to constant load operation (ibid.). For instance, in solid oxide systems, temperature changes in the stacks caused by varying load create micro cracks in the ceramic, thus reducing the lifetime of the stacks (Smolinka, Günther, and Garche, 2011).

At the moment, however, only PEM and (theoretically) solid oxide electrolysers are able to conduct overload operations (*Table 3*). Indeed, with a load range of between 5 and 120 per cent and 3 and 125 per cent respectively, PEM and solid oxide systems have already made their first steps on the path towards achieving greater variability tolerance. In contrast, the nominal upper tolerance level of most alkaline and AEM electrolysers is still 100 per cent. Whilst indicating space for further improvement, this also suggests that PEM electrolysers are more suitable in terms of operating with intermittent power supplies than the rest of the systems (given that the solid oxide technology is currently insufficiently mature). Hence, as a result of their efficiency, PEM electrolysers may ultimately be cheaper to operate if coupled with solar and wind power. Also, if further technological improvement takes place, additional cost reductions could be achieved for this technology.

4.5 Start-up time

Alkaline electrolysers represent the most mature power-to-hydrogen technology among the reviewed types of water electrolysis systems; they have already been present for about a century and their design was tailored for the dominant form of power supply at the time of their initial development. Hence, they have been traditionally purposed for stationary application with grid connections, rather than intermittent power supplies from variable renewables that are not integrated into the grid. That is why, with the greater spread of renewable energy, alkaline electrolysers required further improvement, which was
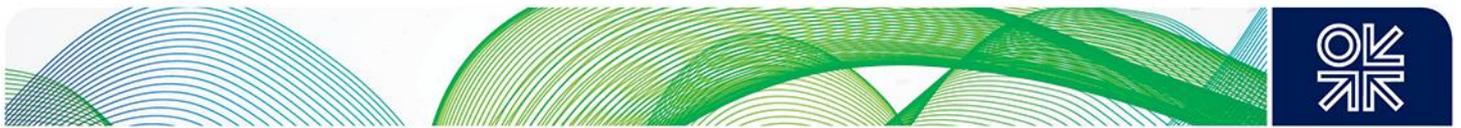
partially achieved with the introduction of pressurized alkaline electrolysers – the most efficient and least expensive alkaline systems for water electrolysis (Bowen et al., 2015).

At the same time, despite all the technological advancements and increased tolerance to variable power supplies, these pieces of technology are still less suitable for low load operation than PEM electrolysers (Greensight, 2021). In fact, when stopped and flushed due to insufficient power supplies, they will need at least half an hour, or even a full hour, for a cold start-up (ibid.). Similar cold start-up time is also expected from AEM electrolysers (ibid.). This, in general, means that more time, power, and expense, will be expended – not on the actual production of hydrogen, but on the system's warm-up.

On the other hand, although solid oxide electrolysers are potentially capable of very fast electric load changes due to their broad load range (*Table 3*), their start-ups and shut-downs need to be conducted slowly and the temperature should be kept above 600 °C (Smolinka et al., 2018). If these electrolysers need to be shut down, their cold start-up will normally take more than an hour (ibid.). All this makes PEM electrolysers that need only several minutes (up to half an hour) in order to gain their optimal operating temperature particularly remarkable (Eichman, Harrison, and Peters, 2014).

4.6 Use of scarce materials

As seen from Table 3, the use of scarce materials – notably, platinum (Pt) and iridium (Ir) – appears to be one of the most significant cost reduction challenges for PEM water electrolysis systems, preventing them from taking over from alkaline installations on the world's electrolyser markets. The situation is different for other types of electrolysers. For example, although solid oxide electrolysers are currently utilizing zirconium (Zr), samarium (Sm), and lanthanum (La) – primarily for their catalyst layers – their main production expenses are associated with sophisticated ceramics and not rare earth metals (IRENA, 2018). The remaining electrolyser systems, in turn, are either very close to eliminating the need for scarce materials (for example alkaline electrolysers) or have quite successfully tried to exclude them from the design altogether (for example AEM electrolysers) (IRENA, 2020b). Hence, at the moment, PEM electrolysers appear to be in the greatest need of reducing their dependence on these expensive critical materials (Kiemel et al., 2021).

In fact, in PEM electrolysis, challenges associated with the hydrogen evolution reaction (HER) are normally addressed through the use of platinum-type metals as catalysts, due to their excellent HER activity and remarkable stability in acidic environments (Siracusano et al., 2013). Though substantial efforts have been made to find a suitable replacement for such catalysts, most of the suggested alternatives have so far been proven to be a relatively poor substitute for platinum (Kumar and Himabindu, 2019). In addition to complicating any potential cost reduction in PEM electrolysers, this makes the deployment of PEM electrolysers dependent on the supplies of critical materials from a very limited number of countries (IRENA, 2020b). Here, for example, the spread of PEM systems is extremely likely to be subject to the fluctuations of platinum and iridium shipments from South Africa – the current provider of over 70 per cent of global platinum and over 85 per cent of global iridium (*Figure 6*).
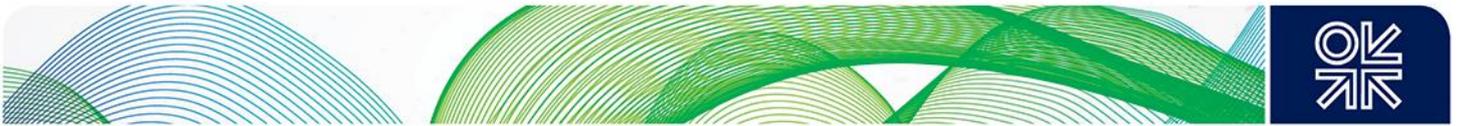
Figure 6: Average contribution of primary global suppliers of some critical raw materials (% of global supplies)[12]

Country	Material	%
Russia	Palladium	46 %
France	Hafnium	43 %
USA	Beryllium	90 %
	Helium	73 %
Turkey	Borate	38 %
DRC	Cobalt	64 %
Rwanda	Tantalum	31 %
Thailand	Natural rubber	32 %
Brazil	Niobium	90 %
South Africa	Iridium	85 %
	Platinum	70 %
	Rhodium	83 %
	Ruthenium	93 %
China	Antimony	87 %
	Baryte	44 %
	Bismuth	82 %
	Coking coal	54 %
	Fluorspar	64 %
	Gallium	73 %
	Germanium	67 %
	Indium	57 %
	Magnesium	87 %
	Natural graphite	69 %
	Phosphate rock	44 %
	Phosphorus	58 %
	Scandium	66 %
	Silicon metal	61 %
	Tungsten	84 %
	Vanadium	53 %
	LREEs	95 %
	HREEs	95 %

Source: European Environment Agency (2020)

4.7 Scale of industrial production

Economies of scale are also expected to play an extremely important role in the reduction of costs for electrolysers. According to IRENA (2020b), the relatively low manufacturing rates that are still dominant result in the cost of the stack contributing around 45 per cent of the total cost, while higher production intensity could potentially decrease it to around 30 per cent. That is why increasingly automated stack manufacturing at a GW-level could significantly reduce the cost of most electrolysers, while simultaneously making them more abundant in the global market.

Since alkaline electrolysers still represent the dominant type of water electrolysis technology currently in production, they are closest to achieving the 1 GW milestone (*Table 3*). AEM installations, in turn, being at the laboratory stage, are the farthest away from reaching this goal, as their production is estimated to be only around 0.01 GW per year. Also, with annual manufacturing scales of 0.01–0.04 GW and around 0.025 GW respectively, PEM and solid oxide systems appear to take a place right between the AEM and alkaline electrolysers, which means that the scale of their manufacturing should also be significantly improved.

This is particularly important for the already commercialized PEM electrolysers, as increasing their production to around 1,000 units (of 1 MW) per year (in other words, reaching the 1 GW/year point) would allow for an almost 50 per cent cost reduction in stack manufacturing (ibid.). A similar cost reduction effect is anticipated from the scale-up of solid oxide and AEM electrolyser production – although their early stage of development makes the exact estimations particularly challenging. Nevertheless, despite the theoretical possibilities of a gradual production increase of these key electrolyser technologies, several factors may put significant barriers in the way of these prospects.

For instance, further dependence on scarce materials (see the previous section) is extremely likely to represent an important barrier for the scale-up. In fact, platinum and iridium (widely used in PEM

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[12] Here, 'LREEs' stands for 'light rare-earth elements' and 'HREEs' stands for 'heavy rare-earth elements'
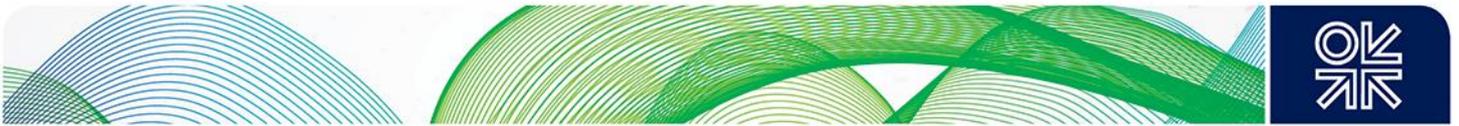
electrolysers) happen to be among the scarcest and most energy- and emission-intensive metals (Nuss and Eckelman, 2014). Indeed, at the current level of annual production of Ir and Pt, the manufacturing of PEM electrolysers will only be supported at an estimated level of 3–7.5 GW per year (compared to an estimated annual manufacturing requirement of around 100 GW by 2030) (IRENA, 2020b).

Additionally, as mentioned before, while dependence on Pt and Ir will almost automatically mean reliance on supplies of these metals from South Africa for the deployment of PEM electrolysers, a similar challenge is likely to be faced with respect to the scale-up of solid oxide technologies. This is because around 95 per cent of the supply of all the critical materials used in these electrolysers is currently provided almost solely by China (*Figure 6*) (SINTEF, 2012 and European Environment Agency, 2020). That is why, although such measures as increased efficiency of the equipment and less active use of critical materials (both due to technological advancements and recycling of old equipment parts) seem to represent sound policies for the minimization of any potential dependence on a monopolist supplier, they are unlikely to completely eradicate the problem.

5.   Cost reduction of technologies: Lessons from cost evolution of solar and wind power generation technologies

Renewable energy sources have experienced a significant cost decline since the beginning of the new century. Out of all renewables, solar PV and onshore wind power are technologies whose costs have fallen most substantially. This is particularly vivid if one compares their mean levelized costs of energy (LCOE) – the average costs of generation per unit of electricity – to those of other systems (*Figure 7*). This section investigates the insights which might be provided for the future of electrolyser technology by the cost evolution of solar and wind power technologies.

Figure 7: Changes in mean levelized costs of energy (2009–2018) and learning curves for selected renewables (2002–2018)
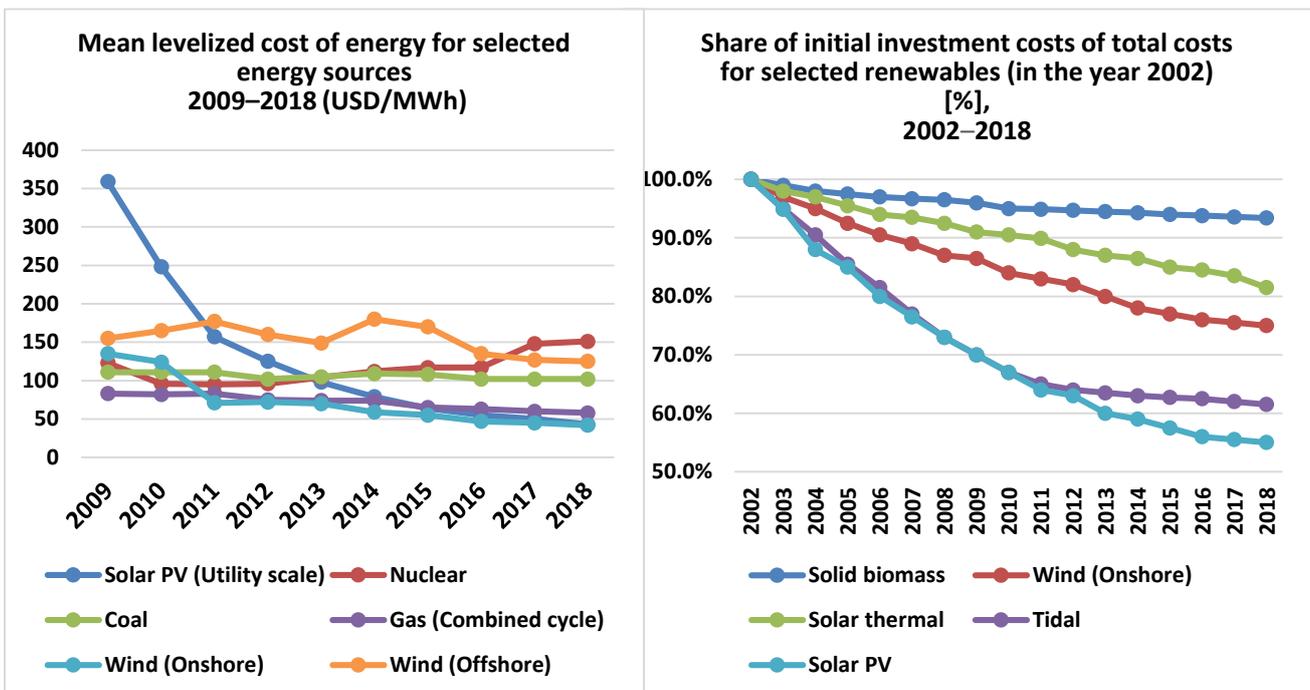
Source: Adapted from Walz (2006), Foster et al. (2011), IRENA (2019), Lazard (2018), and Lazard (2019)

5.1 Learning rate

While the idea of learning-by-doing is not new, it generally represents innovation by production, which is driven by competition between firms in the market that complements innovation spurred by research (IRENA, 2020b). Here, the concept of 'learning rate' generally refers to the percentage by which the cost decreases when the production is doubled (Grafström and Poudineh, 2021). Although, with respect to 'green' hydrogen, there are different ways to increase the learning rate and thus decrease the ultimate cost, some of the most obvious ways include: standardization within the main types of electrolyser technologies, specialization of certain companies on the production of specific parts of electrolysers, and simplification of the production processes. (Lee et al., 2019.) At the same time, since electrolysers generally represent complex systems with a large number of elements depending on a specific technology, each element or component tends to have its own learning rate (Böhm, Goers, and Zauner, 2019). This is one of the reasons why the estimated cumulative learning rates for specific types of power-to-hydrogen systems vary quite significantly (*Table 4*).

Table 4: cumulative learning rates for different types of electrolysers

Goals			Alkaline	PEM	Solid oxide	AEM
Learning rates	%	Current	16 ± 8	9 ± 2	12–28	–
		Aimed	9	13	27	–

In general, solid oxide and alkaline electrolysers appear to represent the leaders, with their learning rates ranging between 12 and 28 per cent and 16 ± 8 (in other words, 8–24) per cent, respectively, while PEM systems with a rate of around 9 ± 2 per cent are slightly lagging behind (IRENA, 2020b). With respect to AEM electrolysers, however, it is unclear how fast their cost will decrease, as their technological maturity is very low and most of the data are not publicly available. It should also be noted that, although a number of estimates have been conducted to predict how fast costs will decline, emerging technologies tend to develop in several stages and may also be stagnant for some periods (Grafström and Poudineh, 2021). Thus, all such predictions and estimates should be considered as rough and indicative, rather than precise and guiding.

As seen, none of the discussed electrolyser technologies appears to represent an absolute paragon of excellent performance across all the mentioned categories. At the same time, alkaline and PEM systems are currently outperforming solid oxide and AEM electrolysers in most of the aspects viewed (*Table 3*). As a result, alkaline and PEM electrolysers, with their average stack costs of 270–450 USD/kWh and 400–870 USD/kWh, respectively, are a lot closer to becoming competitive producers of 'green' hydrogen than the remaining types of electrolysis systems.

At the same time, due to their expected high efficiency and impressive estimated learning rate, solid oxide electrolysers are still considered to be a prospective piece of technology for power-to-hydrogen applications in many countries. That is why there is a decent number of ongoing pilot projects in Europe that aim to commercialize these systems while dramatically reducing their costs (*Figure 8*). Here, however, due to their better current suitability for coupling with intermittent renewables, PEM electrolysers are still the leader in terms of project number. AEM systems, on the other hand, are yet to be included in the race, which will happen when they become more technologically mature.
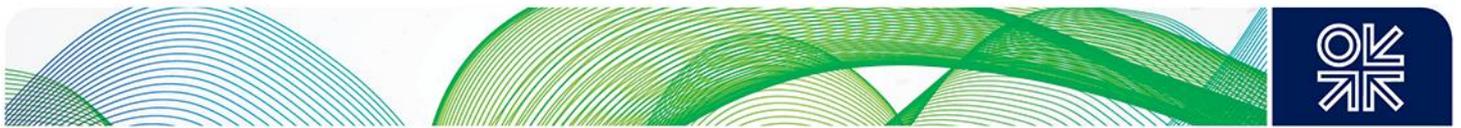
Figure 8: Distribution of water electrolysis technologies for announced green hydrogen projects in the EU and UK between 2020 and 2040 based on total capacity and number of projects
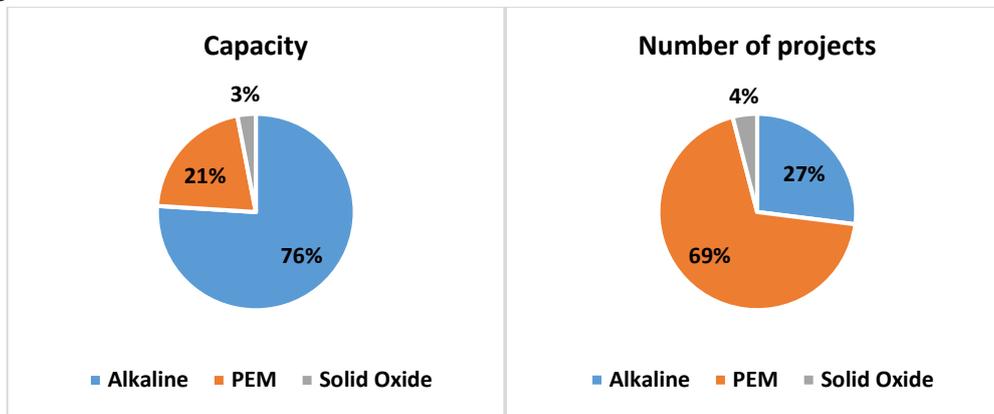

Source: Hydrogen Europe (2020)

5.2 Lessons from solar and wind power

The fact that renewable energy technologies follow learning curves – in other words, their historically observed cost reductions relate to the cumulative installed capacity – is often considered to be the most important and fundamental prerequisite for their significant decrease in costs (Grafström and Poudineh, 2021). Indeed, the price of solar and wind technologies substantially declined when more of such power installations were produced and, consequently, the manufacturers learned how to facilitate and optimize the production process. This appears to be a classic example of 'learning-by-doing', as a greater scale of production led to the improvement of the production process itself.

At the same time, just as in in many other cases, this mechanism of constant improvement of solar PV was launched by the initial demand in the high-tech sector (space industry), which had to cover the technology's original extreme costs due to the lack of any other cheaper alternatives capable of solving an urgent technical problem (delivering electricity to a satellite) (Roser, 2020). This initial production started a virtuous cycle of growing demand which, in turn, caused the prices to fall, as new solar models were deployed. Finally, the lower prices that caused the technology to become cost-effective in new applications stimulated the growth in demand further.

At the moment, the development of some electrolyser technologies appears to be similar to that of these variable renewables. For instance, starting with PEM fuel cells powering NASA's Gemini missions in the 1960s, General Electric later developed PEM water electrolysis technology for undersea life support in the US Navy (Warshay and Prokopius, 1989 and Dincer, 2018). Hence, just as in the case of solar PV, the high initial cost of PEM electrolysers was covered by the industries and sectors that could afford it and that had additional non-financial priorities in mind.

This starting-up of initial production seemed to have launched a virtuous circle similar to that of intermittent renewables. As a result, the cost of hydrogen generated by PEM electrolysers has been steadily pushed down. Experts attribute this to the high learning rate of PEM systems (see *Table 4*), which resulted in the overall investment costs for PEM electrolysers producing one standard cubic metre of H_2 per hour falling from USD7.600 to around USD4.900–6.000 just over the course of the last five years (Fraunhofer ISE, 2019 and PV Magazine, 2019). In fact, industry experts aim to increase the learning rate of PEM systems to 13 per cent (from the current 9±2 per cent) which, in general, strongly corresponds to the highest learning rate of solar PV (12 per cent) (IRENA, 2018). That is why it is sometimes argued that PEM systems might follow a path somewhat resembling that of intermittent renewables, in general, and solar photovoltaic technology, in particular (Möst et al., 2018 and Store&Go,
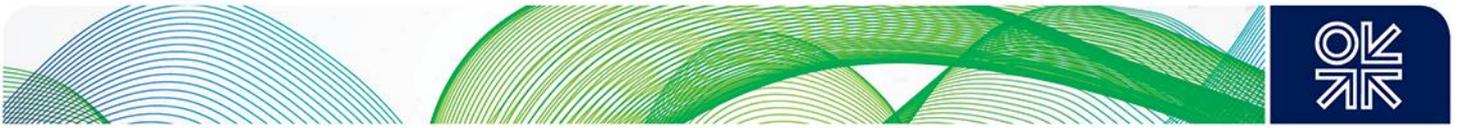
2018) (*Figure 9*). This is mainly because, similar to solar PV, electrolysers are expected to initially benefit from module efficiency driven by government-funded and private R&D, and at a later stage from scale economies and, to some extent, from learning-by-doing.

Figure 9: Resulting learning curves for alkaline, proton exchange membrane, and solid oxide electrolysis systems with an uncertainty of ±15% on initial CAPEX (light-coloured areas)
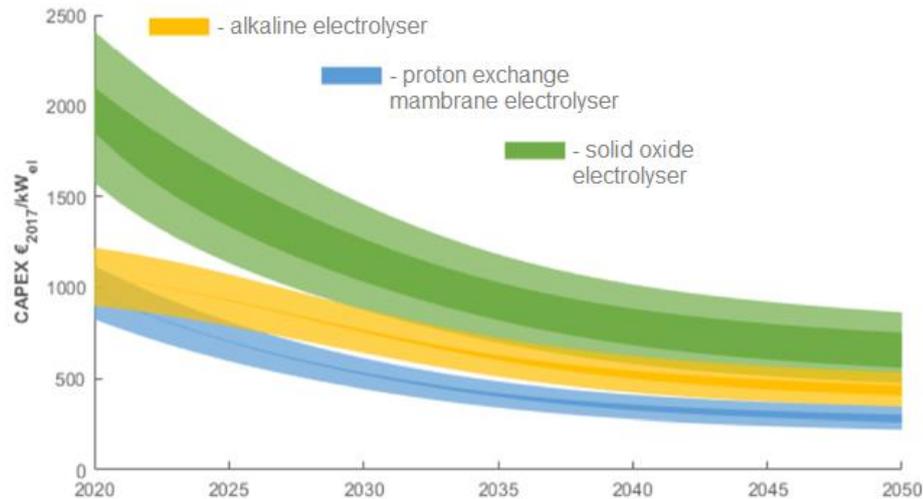
Source: Store&Go (2018)

An important caveat here is that although the learning rates of such intermittent renewables as onshore wind and solar PV appear to be within a range that is close to the estimated learning rates of the three currently most promising electrolyser technologies (alkaline, PEM, and solid oxide) (see part 4), it would be misleading to expect that the cost decrease of water electrolysis will exactly follow the cost reduction pattern of these renewables. In fact, even in the case of wind technology, the cost reduction of offshore wind technologies did not exactly mirror their onshore alternatives, as their costs experienced an unexpected rise in the mid-2000s due to such factors as lack of competition in component production, bottlenecks in the supply chain, and increases in commodity prices (Greenacre, Gross, and Heptonstall, 2010). As a result, up to the beginning of the new century, the learning rate for offshore wind generation technology was just around 3 per cent, not the 11 per cent typically calculated for onshore installations (Zvaan et al., 2012).

Similarly, the costs of electrolysers are likely to be subject to a number of factors. For instance, following the invention and industrial deployment of alkaline electrolysis technology at the end of the nineteenth century, the world could already count about 400 industrial-scale electrolysers by 1902 (Dincer, 2018). Nevertheless, just like the case of offshore wind, the cost reduction of alkaline electrolysers failed to maintain a steady pace. In fact, with the progress of steam methane reforming as an economically competitive hydrogen generation method, based on abundant energy sources (fossil fuels), interest in the development of large-scale electrolysers subsided, and this piece of technology was used primarily for limited hi-tech applications (such as in the pharmaceutical industry) (ibid.).

The 1970s oil crises, in turn, revived and further encouraged industry interest in the research on electrolyser technologies. As a result, alkaline electrolysis technology was further advanced and a new type of water electrolysis system – high temperature solid oxide water electrolyser – was developed by 1982 (ibid.). However, given that the solid oxide electrolysis technology still appears to be at the pre-commercialization stage, it becomes evident that the initial start of the production and the follow-up learning-by-doing process may not necessarily result in smooth cost decrease, since this process often
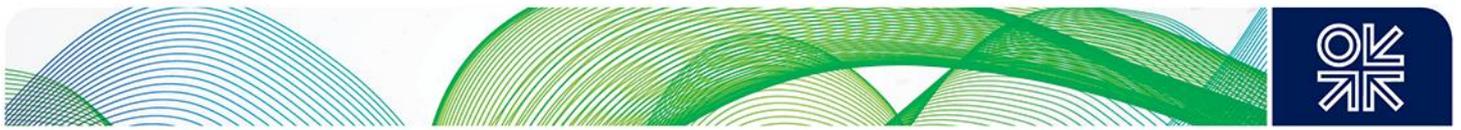
appears to be influenced by a wide range of external factors such as the emergence of rival technologies and economic crises.

The experience of renewable energy sources demonstrates that supportive policies may play a crucial role in smoothing the learning curves of advanced technologies and thus accelerating their cost reduction (Cleveland, 2004). In fact, the IEA claims that even with the costs of technology steadily going down, policy support is essential for ensuring bankability – in other words, the 'fuel' that drives investment in such projects (Jacobs et al., 2016). It is argued that without it, investors will be hesitant to put their money at risk (ibid.). In this respect, for a faster decrease in the cost of power-to-hydrogen as well as its long-term sustainability, relevant supportive policies need to be considered.

6. The role of policies in reducing the cost of electrolysers

Despite the general interest in development of power-to-hydrogen technologies expressed by the world's leading economies, as well as the more specific targets associated with installed electrolyser capacities set by the EU,[13] at the moment, there still appears to be a certain lack of clarity with respect to the future demand for 'green' hydrogen (IRENA, 2021). While most countries still do not have specific hydrogen strategies, many of those who do also consider 'blue' hydrogen (namely H_2 produced from fossil fuels with carbon capture and storage) to be among the possible alternative options generally suitable for future decarbonization (ibid.). More importantly, the current demand for hydrogen is mostly irrespective of its specific origin and thus very little value recognition exists for 'green' hydrogen (IRENA, 2020a). As a result, there is still no 'green' hydrogen market and no valuation of the lower CO_2 emissions that it could deliver (ibid.). This all substantially inhibits many of the possible downstream uses of this product and further limits its demand.

In these circumstances, taking into consideration the fact that green hydrogen production is a nascent industry, government support policies are needed to create a growing supply chain, mitigate investors' risks, facilitate innovation, and deploy necessary infrastructures. These policies, in turn, will have a positive impact on the key cost categories of green hydrogen production – such as electrolysers and decarbonized electricity (as the input). In fact, many researchers admit that adequate development of hydrogen infrastructure is crucial for the delivery of both 'blue and 'green' hydrogen at an industrial scale (Adam et al., 2020 and NS Energy, 2021). Apart from that, without stimulating industrial and sectoral demand for H_2 in general, and 'green' hydrogen in particular, power-to-hydrogen is likely to remain an 'expensive toy' rather than a useful tool in a set of energy transition mechanisms (Forbes, 2021).

That is why, for a comprehensive development of 'green' hydrogen, supportive policies should focus not only on the promotion of renewable energy and electrolysers, but also on the build-up of hydrogen infrastructure as well as demand among end users – industries and sectors.

Nonetheless, a review of support policies for the entire supply chain is beyond the scope of this paper, as these policies will only indirectly relate to the support of power-to-hydrogen technologies. Therefore, since electrolysers constitute the main focus of this paper, we only analyse the key measures that directly stimulate their development.

6.1 Electrolysers and their technology readiness levels and commercial readiness indices

The higher cost of 'green' H_2 in comparison to that of most of its competitors appears to be the key barrier to its spread (Renewable Energy Magazine, 2021). Although here the expenses associated with

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[13] The EU sets a target to install at least 6 GW of renewable hydrogen electrolysers by 2024 and 40 GW of renewable hydrogen electrolysers by 2030 (European Commission, 2020).

renewable power generation are considered to be the key obstacle, the excessive cost of electrolysers is the second most important factor contributing to the lower market attractiveness of 'green' hydrogen (see *Figure 4*). That is why, while technology progress is likely to naturally reduce their cost with time, policy support is necessary to facilitate this process. At the same time, due to the different maturity levels of the available electrolyser technologies, their progress towards becoming competitive energy solutions needs to be assisted in different ways (see *Table 5*).

Table 5: Technology readiness level (TRL), commercial readiness index (CRI) of key available electrolyser technologies and respective support policies

		Development stages												
		Technology readiness level (TRL)									Commercial scale-up	Multiple commercial applications	Market competition/ Driving widespread development	Bankable asset class
		1	2	3	4	5	6	7	8	9				
		Basic principles observed and reported	Technology concept (practices implications) formulated	Experimental proof of concept	Technology validated in a laboratory	Technology validated in relevant environment	Technology demonstrated in relevant	System prototype demonstration in operational environment	System complete and qualified/ certified	Actual system proven in operational environment				
		Research (Basic academic/ technology research)			Development (Technology development)			Deployment (System/subsystem development)						
		Idea	Hypothetical commercial proposition						Commercial trial (small-scale)					
			1						2		3	4	5	6
		Commercial readiness index (CRI)												
Support policies	**Fiscal incentives**	+	+	+	++	++	++	++	+++	+++	+++	++	++	+
	Direct financial — **R&D**	+++	+++	+++	++	++	++	++	+	+	+	+	+	+
	Direct financial — **Manufacturing**	–	–	–	–	–	–	–	+++	+++	+++	++	++	+
	Capacity targets	–	–	–	–	–	–	–	+++	+++	+++	++	++	+
	Electrolyser technologies and their current TRL/CRI	Photoelectrochemical; MCEC, CEM, Li-ion exchange membrane; Microbial; Anion exchange membrane; Solid oxide; PEM; Alkali alkaline												

Source: Authors' adaptation from ARENA (2014), Heder (2017), IRENA (2020b), FLEXCHX (2021), Fraunhofer IFAM (2021), IRENA (2021).

As seen from Table 5, out of all the currently available electrolyser technologies, only conventional alkaline (namely alkali alkaline) installations have progressed from the upper level of technology readiness (TRL 9) into the third and upper stages of commercial preparedness indicated with commercial readiness indices (CRI 3–6). As a runner-up, PEM systems are barely approaching TRL 9,

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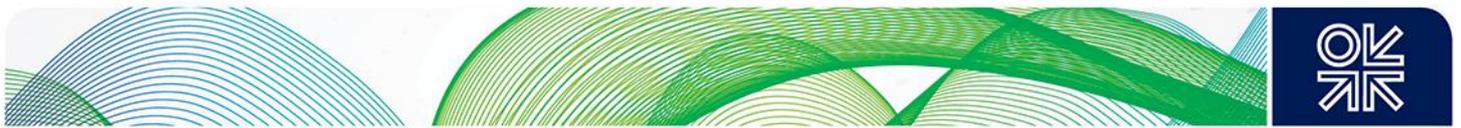
being most often associated with TRL 7 and 8 and CRI 1 and 2, respectively. Solid oxide electrolysers, in turn, are even less mature, as their TRL is between 5 and 7 – all within CRI 1. Finally, anion exchange membrane systems, representing the fourth most promising technology, are still somewhere between TRL 2 and 5 (all within CRI 1). Here, as seen from Table 5, the remaining technologies which are normally estimated to be less promising for large-scale hydrogen production (namely microbial, photoelectrochemical, MCEC, CEM, and Li-ion exchange membrane electrolysers) have either not reached, or are barely approaching, TRL 5.

Based on this variety in technological maturity levels, the policies that governments can apply to foster electrolyser research, manufacturing, and market performance would differ in their intensity. For instance, out of the three main types of support mechanisms (fiscal incentives, direct financial support, and capacity targets), only grants and loans for research and development (part of the direct financial support for R&D) are usually most active and abundant at the lowest technology readiness levels (see '+++' for TRL 1–3). As the technology gets more mature, at TRL 4–7, the magnitude of this support goes down to '++', while finally retaining the least impressive force of '+' from TRL 8 to CRI 6. This should be no surprise, as commercialized electrolyser producers are more likely to be able to substitute governmental financial support with investors' funds.

On the other hand, fiscal incentives to support electrolyser research and production build up momentum alongside the maturity of the actual product – namely electrolyser systems. In fact, being quite insignificant ('+') at TRL 1–3, they intensify ('++') at TRL 4–7 before reaching their maximum ('+++') approximately from TRL 8 to CRI 3 and subsiding again after that. This is because they are supposed to target primarily investors in electrolyser technologies. Just like any other new technology, investors are usually more active once an actual prototype is obtained and tested (TRL 6–7) – in other words, they are more likely to invest in further development of the project. In order to make such electrolyser initiatives more competitive on the market right after their entry (TRL 8–9 and CRI 3), however, some levels of fiscal incentives might be needed.

Finally, since setting capacity targets and exercising direct financial support for the production of electrolysers only makes sense once a viable product is achieved (CRL 8–9), these support policies should be of greatest magnitude ('+++') at the first stages of market entry and scale-up – in other words, until the economies of scale begin to work and the product becomes fully competitive with the rival ones. At the same time (just as in the case of other support policies) with greater product success, such support mechanisms should be applied with lesser intensity; specific market conditions are ultimately defining the exact set of policy tools in each case. Nevertheless, a brief overview of all the main policy tools would be useful.

6.2 Support policies

Fiscal incentives are actively being provided to electrolyser producers by countries and regions that have decided to stimulate 'green' hydrogen development. In California, for example, projects that merge solar PV with power-to-hydrogen are eligible for a 3.9 per cent tax exemption for manufacturing and research and development – the Sales and Use Tax Exclusion Program (up to USD20 million per project per calendar year), and the California Research Credit and the 'California Competes' Tax Credit (a minimum of USD20,000) (Eichman et al., 2020). Though, due to the relative novelty of the issue, these incentives appear to be quite unique, it is widely expected that a greater number of governments will soon understand the vital importance of such supportive fiscal policies for the success of 'green' hydrogen development.

Direct support policies in the form of grants and loans have already been used by some of the world's strongest economies. For instance, in its 2020 budget, Germany included EUR445 million dedicated specifically to support broader and greater industrial use of 'green' hydrogen, which is generally viewed as being essential for the decarbonization of the country's energy-intensive sectors such as the steel, cement, and chemical industries (Federal Ministry for the Environment, Nature Conservation, and
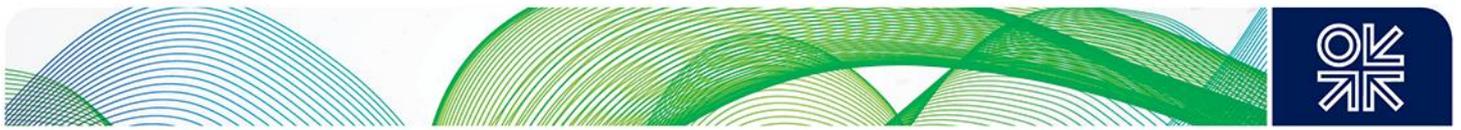
Nuclear Safety, 2019). In 2020, Australia, in turn, granted USD52 million to 'green' hydrogen development, targeting electrolysers with the capacity of 5 MW and above (ARENAWIRE, 2020). Finally, in their national COVID-19 recovery package, many countries decided to allocate separate funds for the development of 'green' H_2. France, for instance, granted USD2.4 billion for these purposes just for 2020–2022 (Renewables Now, 2020).

The other area in which policy can play a role is in manufacturing/production capacity support. The EU is planning to install 40 GW of renewable energy hydrogen electrolysers by 2030 to help 'green' hydrogen become one of the major fuels of energy transition by mid-century (European Commission, 2020). Such a capacity increase may not be possible without specific stimulating measures, even within the world's largest economy. In fact, in 2018, the total global electrolyser manufacturing capacity was only around 135 MW/year but by the end of 2021, it is expected to rise to about 3.1 GW/year (BloombergNEF, 2021). On a global scale, to meet the carbon neutrality target by 2050, the current annual manufacturing rate needs to be up to 50 times the manufacturing capacity of 2021 (IRENA, 2021). That is why, in order to meet the targets for installed capacity and the overall energy transition objectives, the EU's total electrolyser manufacturing capacity needs to expand exponentially, which is unlikely to be achieved without dedicated supportive policies.

At the moment, industrial policies supporting the scale-up and improved efficiency of electrolyser manufacturing are mostly related to defining long-term targets and establishing dedicated funds supporting the improvement of production processes and technological advancements (ibid.). For instance, in 2020, the US Department of Energy allocated around USD17 million to various electrolyser manufacturers so that they could scale up their output (US Department of Energy, 2020b). Germany, in turn, shared a EUR700 million fund from the country's research ministry among three projects aiming to develop the gigawatt-scale serial production of electrolysers that could later be exported (S&P Global, 2021). As seen, having realized the importance of increasing the scale of electrolyser manufacturing, some of the world's leading economies are currently allocating specific funds for this purpose.

Apart from supporting electrolyser manufacturing, direct financial support should be applied to projects at their early development stages to stimulate R&D activities. When applied to the currently most promising electrolyser technologies, the greatest attention should currently be paid to the improvement of PEM technology as the most suitable solution for coupling with intermittent renewables (Mayyas et al., 2019). While most of the crucial characteristics of PEM systems are either comparable to or exceed those of alkaline electrolysers, strong reliance on Pt-group materials appears to be the main challenge impeding their cost reduction (see *Figure 4*). Hence, reducing the use of scarce materials for the production of PEM electrolysers is generally viewed as the most important direction for further research and development (ibid.).

Similar to the already commercialized PEM systems, solid oxide electrolysers also use scarce materials. Though this obviously increases their cost significantly, reliance on expensive components is not the only challenge preventing this technology from commercialization. In fact, apart from reducing their dependence on scarce materials, research and development should also focus on increasing the stack size while reducing the cold start-up time (Wang et al., 2019). If this is achieved, fully commercialized solid oxide systems could significantly reduce the consumption of electricity for the hydrogen production process due to their greater efficiency (reportedly, around 90 per cent) (see *Table 1*). This, in turn, will ultimately lead to the cost reduction of 'green' hydrogen.

Finally, when applied to AEM electrolysis, tailored research and development policies should focus on increasing the stack size and lifetime as well as the overall production scale (see *Table 3*). Though, out of the mentioned four technologies, AEM systems appear to lie the farthest from commercial use, their introduction to the market is likely to reduce the overall cost of 'green' hydrogen (Recharge, 2021). This is so because of the relative inexpensiveness of their components, high expected energy efficiency, and low operating costs (see *Table 1*).

7. Conclusion

The development of the hydrogen economy is generally viewed as an important step on the road to full decarbonization in many countries around the world. While 'green' hydrogen is an important element in this process, it is currently significantly more expensive than other forms of H_2 with a higher carbon footprint. Thus, apart from reducing the cost of renewable electricity, which is the main price component for 'green' hydrogen, further reduction in the cost of electrolysers themselves – the second most important element – is needed. This is likely to be achieved through a combination of technological progress and policy support mechanism.

Although none of the main currently existing electrolyser technologies is perfectly suitable for the large-scale production of 'green' hydrogen at a price that would allow it to easily compete with hydrocarbons-based H_2, four types of electrolysers are currently considered to be the most suitable candidates for potentially playing this role in the future. Here, despite having high minimum load and thus not being particularly tolerant to power produced by variable renewables, alkaline systems offer the largest system size at the lowest cost. On the other hand, PEM electrolysers, in turn, being the most suitable for coupling with intermittent renewable energy sources, are significantly more expensive due to the use of hard-to-substitute platinum-group catalysts. While slightly cheaper, AEM systems, on the other hand, are not available at larger size and still need to be commercialized. Finally, although solid oxide electrolysers are similarly immature for a large-scale market entry, they are also currently extremely expensive.

While stack cost represents the lion's share in the cost of the two commercialized types of electrolysers (alkaline and PEM), its importance as a cost component of solid oxide and AEM systems is less significant (see *Figure 3*). There, power electronics, gas conditioning, and balance of plant are playing a more significant role. Nonetheless, a further increase in the size of the system can increase the share of the stack's cost. Therefore, further research and development are needed to minimize the cost of electrolysers, as it will ultimately make 'green' hydrogen produced by each of these types of electrolysers more competitive while contributing to the successful market entry of the yet-to-be-commercialized systems.

An important area for cost reduction is the minimization of use of scarce materials, which currently has an important impact on the expenses associated with PEM and solid oxide systems. In addition, stack lifetime in AEM installations should be further increased alongside the system size, so that large-scale hydrogen production could be initiated. Finally, while alkaline electrolysers would need to tolerate greater load range, solid oxide systems would need to reduce their cold start-up time. Though addressing all these issues will definitely take time, experience of the development of renewable energy sources demonstrates that intensified production of electrolysers is likely to help with their cost reduction, as they may generally follow similar learning curves to those of onshore wind and solar PV generation technologies.

At the same time, to ensure that cost reduction makes a meaningful contribution to decarbonization objectives, policy support needs to be aligned with research and development, as well as business initiatives. This requires stimulating not only the production of renewable power and electrolyser systems, but also 'green' hydrogen demand itself. This, among others, includes hydrogen infrastructure as well as all the stakeholders that would become part of the 'green' H_2 supply chain, such as industries and transport.

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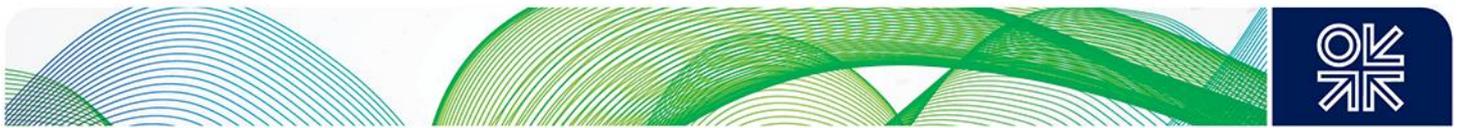
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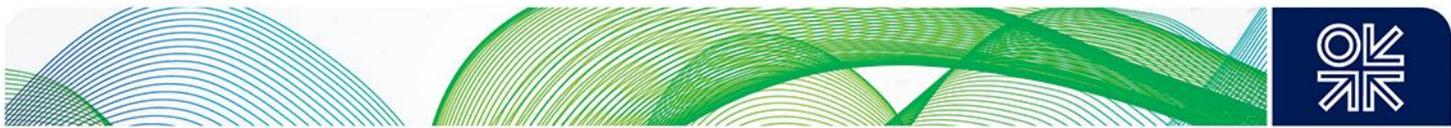
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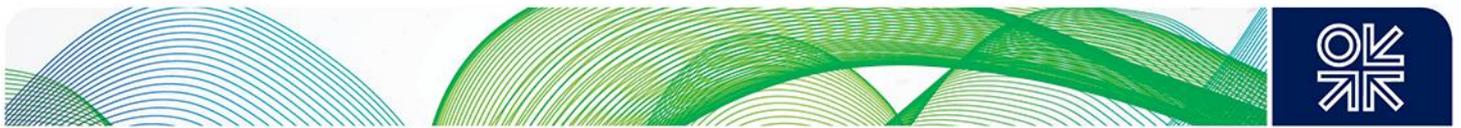
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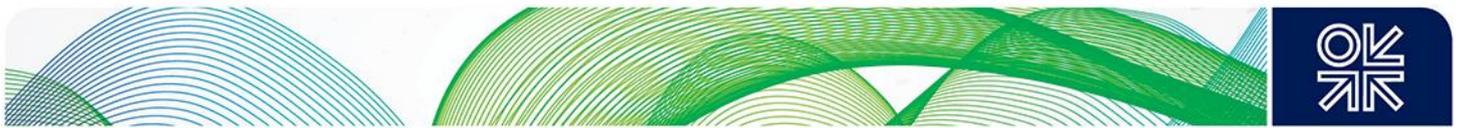
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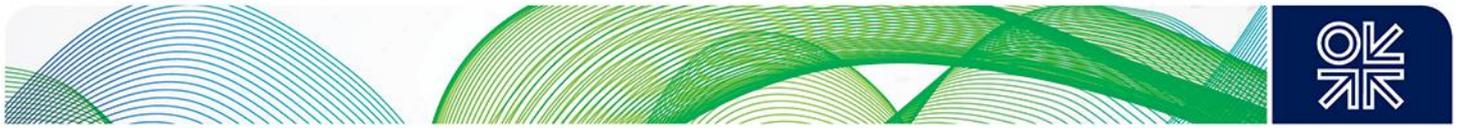
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