Opportunities and challenges for wider deployment of directly coupled photovoltaic driven water electrolysis

Directly coupled photovoltaic driven water electrolysis is an attractive option for green hydrogen production because it can lead to inherently compact designs and thus modularity which allows flexibility in determining plant sizes. Moreover, appreciable solar to hydrogen efficiencies up to 31.5 % are achieved. However, the deployment of these technologies is still limited since their manufacture has not yet been commercialised to achieve scales of economy needed to reduce capital and operating costs.

In this contribution we describe the different configurations of directly coupled photovoltaic driven water electrolysis and discuss the opportunities and challenges for their deployment.
We then discuss the state of the art for the various technologies and identify the remaining challenges for their commercialisation from which we propose a roadmap towards higher technical and commercial maturity.
Next, we describe a selection of ongoing international and German national projects that are likely to contribute to the proposed roadmap.
Finally, we conclude by suggesting research, innovation and development priorities needed to enable the different technologies to significantly contribute to mitigation of adverse climate change.

1 Introduction and background

Adverse environmental impact as well as dwindling reserves of fossil fuels have spurred the search for alternative cleaner and more sustainable energy sources. The increased installation of wind and photovoltaics has led to a surge in demand for storage capacity for electricity to avoid wasteful curtailment when production exceeds demand. The two most promising storage options are batteries and electrochemical conversion of the electricity into an energy carrier such as hydrogen. Disadvantages of batteries are self-discharge with time and the need for continuous charge flow to maintain full charge state. The advantages of hydrogen are its high gravimetric energy density (33.6 kWh/kg) and the ability to store it over longer periods of time with minimal leakage. For this purpose, photovoltaic driven electrolysis and photoelectrochemical (PEC) generation could be attractive for widespread deployment of de-centralized hydrogen production because they are potentially a low-cost solution and minimally aesthetically intrusive.

▸ *Figure 1a* shows the direct electrical coupling of a photovoltaic module to an electrolysis cell or stack without the use of intervening power electronics. Photogenerated carriers produce electricity which is used to run an electrolysis cell or module and thus produce hydrogen. In this configuration, both components can be thermally integrated. The advantage of thermal integration is that the excess heat from the photovoltaic module is used to heat the electrolyser thus boosting the energy conversion efficiency of both components. Generally, the photovoltage of the PV module increases as the device is cooled, while the voltage demand by the electrolyser reduces as the operating temperature increases.

▸ *Figure 1b* shows the hybrid PV/photoelectrochemical (PEC) where the PV cell is used to generate and directly transfer the photogenerated carriers to one of the essential half reactions for water splitting at the interface with the electrolyte. On the other hand, the second half reaction occurs at a counter electrode that is similar to that used in electrolysers which receives photogenerated charge carriers via a wired connection.

▸ *Figure 1c* shows the third possible configuration: photocatalytic or pure PEC in which the photogenerated carriers are directly transferred to both half-chemical reactions for water splitting occurring at the interface of the electrolyte for this, no wires are needed for connection. The main challenge with this configuration is the limited device lifetime due to photo-corrosion since the photo-absorber is completely immersed in the electrolyte.

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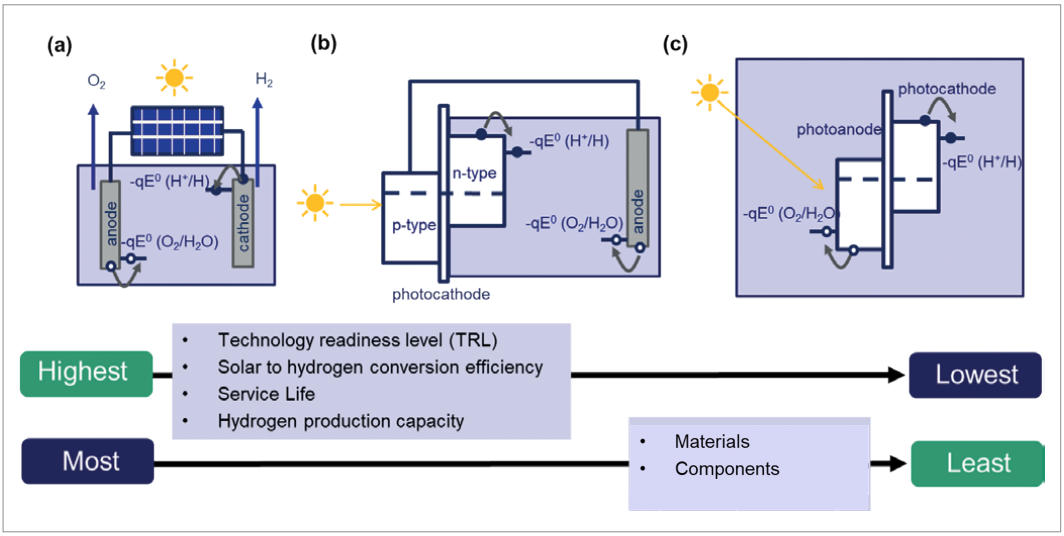


Figure 1

Simplified schematics of directly coupled photovoltaic driven water electrolysis technologies:

(a) directly coupled PV+EC

(b) monolithic PV-EC

(c) photocatalytic or Photoelectrochemical PEC

(source: HZB)

2 Opportunities and challenges

2.1 Opportunities

Firstly, it is expected that the implementation of favourable international and national policies, including the UN Sustainable Development Goals [1], the European Green Deal [2] and in Germany, the National Hydrogen Strategy [3], shall foster the development of green hydrogen technologies, and create a large market for them.

Secondly, from the technological perspective, the steep learning curve seen during scale up of photovoltaic production indicates what will be achievable in PV driven electrolysis. The current efforts in the scale up of electrolyser production would also provide synergetic benefits for the technological development of these approaches. Also, the inherent compact design of directly coupled photovoltaics and electrolysis, and thus modularity, allows flexibility in determining plant sizes ranging from kW to potentially GW size.

Thirdly, on the scientific side, the solar to hydrogen conversion efficiencies, achieved using naturally abundant materials e. g. silicon and non-platinum group catalysts, is steadily increasing. Together with the development of environmentally friendly materials and processes this will help to lower the costs of production of such technologies.

2.2 Challenges

There are several challenges that currently hinder the progress of directly coupled photovoltaics and electrolysis technologies towards wide spread deployment.

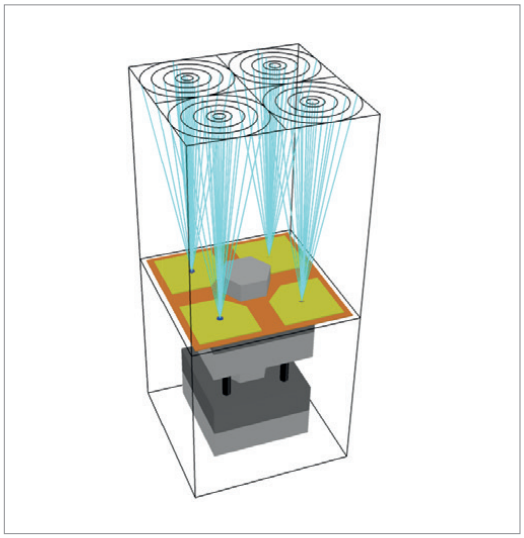
- The first one is to reach ***economies of scale in manufacturing***. This includes finding alternatives for scarce materials used in catalysts and in photovoltaic absorbers. In addition, there is currently virtually no suitable manufacturing supply chain for many essential components such as membranes, electrocatalysts, electrode materials as well as bipolar and end plates.
- Another challenge is increasing the (coupling and conversion) ***efficiency*** as well as closing the gap between theoretical and practical efficiency to increase output production and thus reduce the costs of hydrogen production.
- A third and important challenge is increasing the ***lifetime and reliability*** of the systems to reach 20 – 30 years which is typical for other energy conversion technologies. For the technologies shown in ▶ *Figure 1a* and *1c*, the challenge is to counteract the gradual irreversible degradation on the electrolyser and/or electrocatalysts caused by the day-to-day cyclic and diurnal dynamic nature of solar energy. Specifically, for the technologies in ▶ *Figure 1b* and *1c*, where the photo-absorber is immersed in the electrolyte, the challenge of limited lifetime is still serious with devices currently lasting a few days in operation at most.

3 State of the art

Since 2010, much progress has been made in increasing the solar to hydrogen efficiency and scale (hydrogen production capacity) of directly coupled photovoltaic electrolysers. In parallel, different device configurations have been developed with focus on benefitting from specific advantages e. g. concentrated photovoltaics, thermal management targeted at increasing the overall device efficiency, low cost materials, or extremely high efficiency to balance high cost of materials, reduction of device components, among others.

For purposes of illustration, the performance and technology readiness level (TRL) reached for selected devices representing the configurations shown in ▶ *Figure 1* are presented in ▶ *Table 1*. We limit the selection to either devices of reasonable scale that is, a solar collection area exceeding 50 cm² or if smaller, than that, with a solar to hydrogen efficiency greater than 15 %. Additionally, photographs of representative devices for each category of devices are shown in ▶ *Figure 2*.

Figure 2:
Examples of directly coupled photovoltaic electrolysis devices



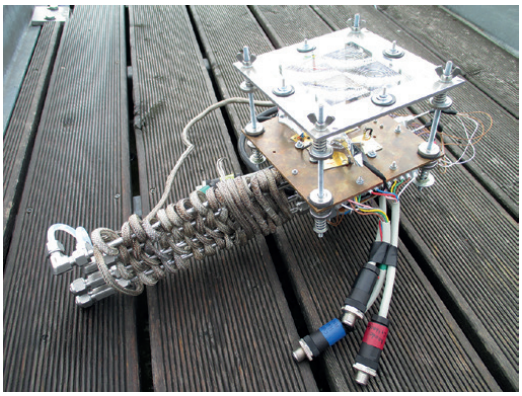


Figure 2 (a)
combination of concentrated photovoltaic receiver with PEM electrolysis cell coupled thermally to the solar cell

3.1 Concentrated photovoltaics directly coupled to electrolysers *(▶ Figure 2a)*

Concentrated sunlight may be used to drive a PV module that is directly coupled to an electrolysis unit. This allows the use of highest efficiency multi-junction solar cells made from typically more expensive III–V group semiconductors like GaInP or GaInAs. These solar cells reach conversion efficiencies up to 47 % under concentrated sunlight [4]. As a result, high solar to hydrogen efficiencies are also possible. This technology uses solar energy to provide both electricity and heat for the hydrogen generation using proton exchange membrane (PEM) electrolysers.

However, solar concentration is mostly feasible in regions with a higher proportion of direct solar irradiance. The performance and TRL reached for a selection of CPV driven electrolysis systems are presented in ▶ *Table 1*. It can be seen that in 2021, this technology has reached TRL 6 with the first demonstrators reported to have the capability to supply approximately 1 ton of hydrogen per year using a 100 m² solar collection area [5]. Barriers for deployment include de-risking of the technology and high capital costs as long as the technology is in an early stage of deployment. There is a need for research and development to improve system components from the solar cell to the electrolyser to increase conversion efficiency further, to ensure reliable operation and to reduce green hydrogen generation cost.

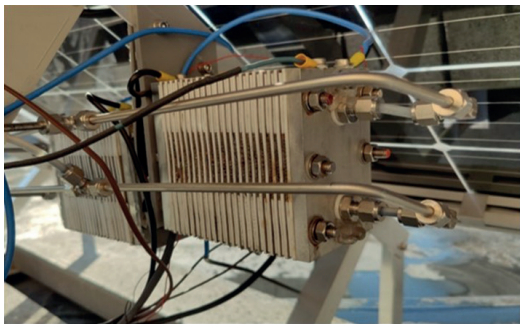


Figure 2 (b)
direct coupling of discrete photovoltaic modules with electrolysers where an electrolyser is directly fixed to the rear of the PV module

3.2 1-sun devices

The light intensity on a solar cell can be referred to in terms of the number of suns, where 1 sun corresponds to standard illumination at AM (air mass) 1.5, or 1 kW/m². 1-sun devices are designed to operate

under 1-sun conditions.
Different device configurations are possible as shall be discussed below.

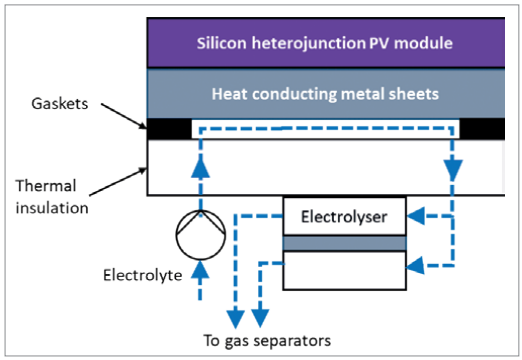


Figure 2 (c)
directly coupled and thermally integrated photovoltaic electrolyser using crystalline solar cells and transition metal catalysts for alkaline liquid electrolysis

3.2.1 Directly coupled photovoltaic electrolysers *(▶ Figure 2b and 2c)*

In this approach *(▶ Figure 2b)* commercial PV modules are directly coupled but with no thermal integration to advanced low temperature electrolysers without the use of power conditioning electronics. Since each sub-component can be separately optimised for high conversion efficiency, the only innovations required are for reducing coupling losses (ohmic and power mis-match) and for efficient operation using a minimal balance of plant.
▶ *Table 1* lists a selection of systems reported using this approach and it can be seen that production capacities of several hundreds of litres of hydrogen per hour have been demonstrated. This technology is considered to have reached TRL 6 (Technology Readiness Level) since the sizes demonstrated are comparable to that of the final product and all functions required of the operational system were tested.

In a related configuration *(▶ Figure 2c)*, the photovoltaic modules are directly integrated with the electrolyser such that in addition to direct electrical coupling, thermal coupling is achieved by circulating the electrolyte behind the PV module so that excess heat is used to warm up the electrolyser. This has the advantage of simultaneously increasing the photovoltage of the PV module while reducing the voltage bias needed to drive the electrolyser at a given electric current level. We note here that there are very few examples of this technology with prototypes larger than a few cm². This technology is considered to have reached TRL 5 since at least one of the prototypes has been tested under outdoor conditions and the behaviour in actual operating environment has been to the most part, validated.
Both directly coupled PV electrolyser technologies require reductions in the electrical coupling losses and enhanced efficiency of both the PV cells and electrolysers to achieve a higher power density. Also, to increase the reliability, the service life of the electrolysers must be increased to match that of the PV modules. Lastly, there is need to achieve a hydrogen output pressure comparable to that of steam methanol reforming (25 bar) to save energy costs for compression.

3.2.2 Monolithic photovoltaic electrolyser and PEC cells *(▶ Figure 2d)*

Monolithic photovoltaic electrolysers use semiconductor junctions to generate and separate charge carriers which are directly transported to an electrocatalyst at the interface between the photo-absorber and the electrolyte. In some cases, the counter reaction may take place on a counter electrode placed across the electrolyte. On the other hand, for photoelectrochemical (PEC) cells, the interface between the photo-absorber and the electrolyte forms the junction that is used to separate the photogenerated charge carriers and at which the water splitting reaction occurs, usually with the assistance of a co-catalyst. In both types of devices, at least one of the active photo-absorbers is in intimate contact with the electrolyte and the resulting corrosion leads to relatively short lifetimes. Since these two technologies are very closely related, numerous hybrid configurations using both exist. The selection presented in ▶ *Table 1* shows that generally these technologies have reached TRL 4 since the performance of the integrated systems was validated under laboratory conditions.
These technologies require more efficient protection of the photoelectrodes from chemical and photocorrosion to enhance device lifetime. Other challenges include increasing the energy conversion efficiency and reducing the cost of the absorber materials used. Furthermore, the scaling of modules to larger size presents many challenges which are currently addressed, for example, in the BMBF funded project H2Demo [6].

Ref, Year	TRL	Solar collection area	Test time (h)	Solar to H_2 eff. (% LHV unless otherwise noted)	H_2 production rate (l/hr)	Year
Directly coupled concentrated photovoltaics electrolysers						
InGaP/GaAs/ Ge + PEMEL	4	3 × 57 mm² lens; 3 × 2.5 mm² PV	-/-	24.4 (HHV, outdoors, concentration factor undisclo-	0.615	2015 [7]
InGaP/InGaAs/ GaInNAsSb + PEMEL	3	0.32 cm² PV	48	30 average (HHV) at 42 suns (indoors)	3.75×10^{-3}	2016 [8]
GaInP/GaInAs/PEMEL	4	2.8 cm² (PV) 72.56×10^{-3} m² (lenses)	1440	19.8 (HHV) at 500 suns	45×10^{-3}	2017# [9]
InGaP/InGaAs/ Ge + PEMEL	4	4 cm² PV	> 2	15 (HHV) at 474 suns (indoors)	12.0	2019# [10]
III-V/PEMEL	5	64 cm²	> 1	31.5 (HHV) at 500 suns	-/-	2021#, Figure 2(a) [11]
Undisclosed CPV & PEMEL	6	~1,500 m²	-/-	26.8 (HHV) at 1400 suns on 100 cm², Undisclosed for array	-/-	2021# [5]
Directly coupled discrete photovoltaic electrolysers						
C-Si & Cu(In,Ga)Se_2 & PEMEL	6	10.5 m²	>2680	~10	271	2020, Figure 2(b) [12, 13]
Poly c-Si & PEMEL	6	1.5 m²	~10	9.4	18.7	2020 [14]
Poly c-Si & PEMEL	6	21.5 m²	~20	~5	-/-	2013 [15]
Poly c-Si & AEL	6	47.2 m²	2616	8.2	753	2011 [16]
Directly coupled and thermally integrated photovoltaic electrolysers						
(Ag,Cu)(In,Ga)Se; Bifunctional NiFe	4	78 active of 100 (cm²)	~100	10	3.24×10^{-3}	2021 [17]
(Ag,Cu)(In,Ga)Se Bifunctional NiFe	4	82.32 active of 100 (cm²)	100+	13.4	3.44×10^{-3}	2021 [18]
C-Si; NiFe/NiMo	5	2480 active of 2600 (cm²)	500+	6.1	6.0	2021, Figure 2(c) [18]
Monolithic photovoltaic electrolysers and photoelectrochemical cells						
C-Si + $BiVO_4$	5	1.6 m²	-/-	3	33.6	2017 [19]
GaInP/GaInAs/GaAs; Rh & RuO_2	3	0.3 cm²	-/-	19.3	4.5×10^{-3}	2018 [20]
C-Si + $BiVO_4$; Pt & Co-Pi	3	50 cm²	-/-	2.1	-/-	2019 [21]
Thin film silicon; NiMoFe	4	64 cm²	< 10 h	4.5	~100 × 10^{-3}	2020, Figure 2(d) [22]

Table 1

Performance and technology readiness level (TRL) reached for a selection of CPV driven electrolysis systems for water splitting

- *HHV – higher heating value of hydrogen*
- *LHV – lower heating value of hydrogen*
- *c-Si – crystalline silicon*
- *PEMEL – proton exchange membrane electrolyser*
- *AEL – liquid alkaline electrolyser*

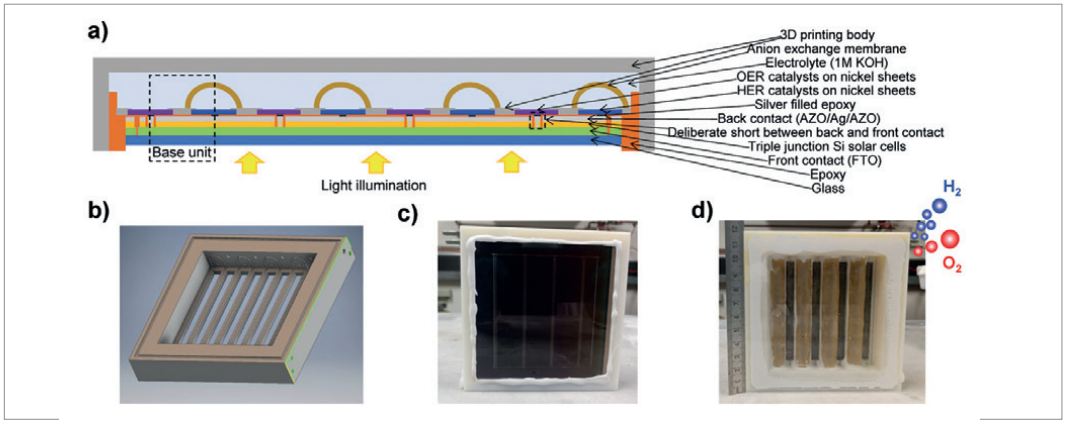


Figure 2 (d)

monolithically integrated photovoltaic electrolyser, the rear side of the thin film silicon PV modules is in direct contact with the alkaline liquid electrolyte via transition metal catalyst coated foil

4 Remaining challenges and proposed roadmap to higher TRL

Despite the advances reflected in ▶ *Table 1*, several challenges still remain to be solved to support deployment of directly coupled photovoltaic driven electrolysis in the existing energy network. The remaining challenges provide a framework for a roadmap that can be used to guide the research, innovation and development priorities for these technologies in the next years.

4.1 Remaining challenges that define future research and development priorities

Several challenges remain to make green hydrogen production from directly coupled photovoltaic electrolysis commercially feasible. These require prioritizing supportive developments in science, technology, material development and industry, in issues related to economic, social and environmental aspects as well as in policy making.

The biggest scientific challenge for all technologies is to reduce the gap between theoretical and practical solar to hydrogen conversion efficiency. There is also need to improve the durability of the materials used and thus the system reliability to reach service lifetimes of 20+ years typical of contemporary energy systems. In addition, alternatives to the critical and scarce materials used for the photo-absorbers (silver, indium, gallium) and the electrocatalysts (cobalt, platinum, iridium, ruthenium) in high efficiency systems are urgently needed.

Especially for the lower TRL technologies, there is a need to standardise the performance benchmarking for fairer comparison of feasibility and more accurate analysis of environmental impact and economic feasibility. Currently, even for the more promising directly coupled photovoltaic electrolysers technologies that have been scaled to achieve a daily hydrogen production approaching 1 m³, the cumulative installed capacity remains limited because of the low TRL compared to grid connected electrolysers. This is partly because there is a lack of commercially relevant manufacturing steps for most components of these devices as most steps are not yet automated. This culminates in delays in achieving cumulated production capacity and instalment in the MW-GW range needed for the widespread deployment of these green hydrogen technologies. The scientific, technological and industrial challenges mentioned above, especially relatively low efficiency, limited lifetime and lack of automated manufacturing, raise the levelised costs of hydrogen unfavourably compared to steam methanol reforming. Also, the low TRL constitutes a high commercial risk leading to a lack of investment for scale-up and commercialization which is necessary to overcome the „valley of death".

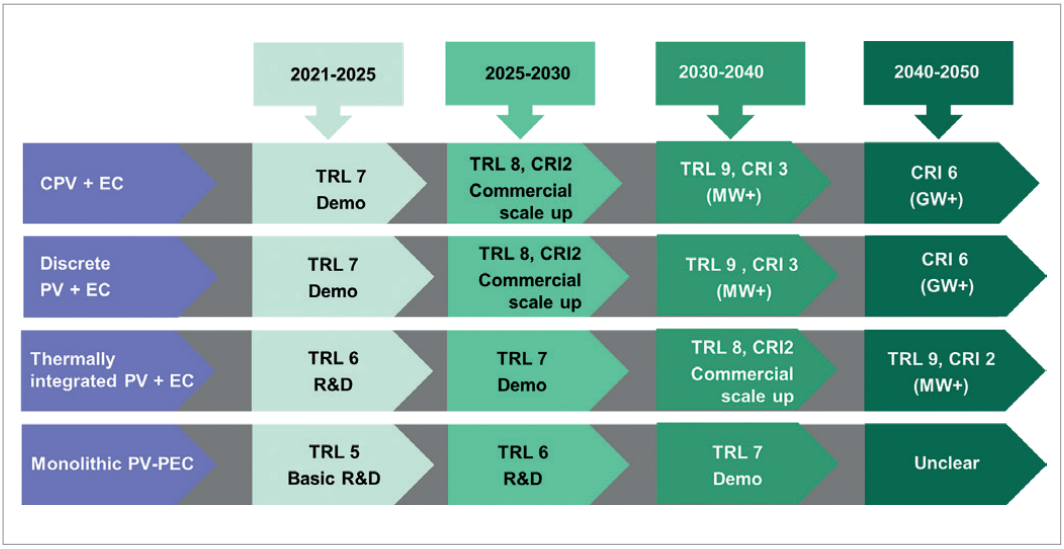
Guidelines for the safe operation of such technologies have not yet been established by the authorities thus making application for permits for larger scale systems in high visibility areas complicated. Moreover, the low environmental impact of these directly coupled photovoltaic electrolyser technologies has not yet been accurately quantified to support their green credentials. Additionally, these technologies, being of low technological maturity, suffer from low public visibility and thus a lower awareness of their potential contribution towards green hydrogen compared to MW-GW sized conventional PV or wind driven electrolysis systems.

Figure 3

Possible roadmap for wider deployment of various directly coupled photovoltaic driven water electrolysis technologies

- *TRL: Technology Readiness Level*
- *CRI: Commercial Readiness Index*

(source: HZB)



4.2 Proposed roadmap for development until 2050

To create a roadmap for deployment, the true measure of the maturity of a technology should consider not only the technological but also the commercial readiness. For the latter, a commercial readiness index (CRI) was developed by the Australian Renewable Energy Agency to assess the maturity of renewable energy technologies and is thus closely adaptable to directly coupled photovoltaic electrolyser systems [23]. Using these metrics, we propose a road map for the different technologies discussed in this article as shown in ▶ *Figure 3*.

It can be seen that the commercial scale up needed to achieve cumulative deployment of GW+ capacity by 2050 will only be reached by the discrete PV+EC and possibly CPV+EC. Thermally integrated PV+EC using 1-sun irradiance would likely only reach TRL 9 and CRI 2 because of the need to achieve the required technical performance that would support confidence in investment in large scale production as well as the need for technical skills and know-how to perfect the coupling of the devices in a reproducible way with high reliability. Monolithic PV-PEC would probably lag behind because of the need to achieve a long service life which is currently severely restricted by photochemical corrosion of the photo-absorber material. But such predictions have a high uncertainty as the technology is quickly evolving and solutions to such challenges may be found.

5 Conclusion

Since 2010, green hydrogen production using directly coupled photovoltaic electrolysis has undergone rapid advances in terms of both the solar to hydrogen conversion efficiency achieved as well as the scale in terms of hydrogen production capacity.
In particular technologies using discrete photovoltaic modules and electrolysers as well as thermally integrated concentrated photovoltaics with electrolysis with low temperature electrolysers have a real chance to reach the maximum TRL 9 and CRI 3 by 2050 and thus cumulative deployment in the GW range. To achieve this supportive policies, standards and regulations that reduce commercial risk for large scale manufacturing are urgently required.
Thermally integrated photovoltaics with electrolysis would likely reach TRL 9 and CRI 2 thus realistically a cumulative deployment in the MW range. This is largely dependent on the ability to increase the energy conversion efficiency and to reduce the capital costs.
For monolithic photovoltaic electrolysis or photoelectrochemical devices, it is unclear what level of deployment shall be reached because of the fundamental problem of photo-corrosion, which currently restricts the service lifetime. Generally, directly coupled photovoltaic electrolysers allow flexibility in plant size because of their modular nature, ease the restrictions caused by the still missing infrastructure for the transportation over long distances and final distribution of hydrogen to end users. Thus, envisaged applications are for de-centralised green hydrogen production across a broad range of users from residential, through to commercial to industrial, depending on the scale that can be achieved at a reasonable cost.

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References

1. United Nations, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. New York: UN Publishing. A/RES/70/1 available at: https://sdgs.un.org/2030agenda (Accessed 28 October, 2021).
2. European Green Deal. Available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (Accessed 28 October, 2021).
3. The National Hydrogen Strategy, 2020. https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html; https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=20. (Accessed 28 October, 2021).
4. M.A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, X. Hao, Progress in Photovoltaics: Research and Applications, 2021, 29(7) 657.
5. https://h2demo.de. (Accessed 03 November, 2021).
6. A. Nakamura, Y. Ota, K. Koike, Y. Hidaka, K. Nishioka, M. Sugiyama, K. Fujii, Appl. Phys. Express 2015, 8, 107101.
7. J. Jia, L. C. Seitz, J. D. Benck, Y. Huo, Y. Chen, J. W. D. Ng, T. Bilir, J. S. Harris, T. F. Jaramillo, Nat. Commun. 2016, 7, 13237.
8. A. Fallisch, L. Schellhase, J. Fresko, M. Zedda, J. Ohlmann, M. Steiner, A. Bosch, L. Zielke, S. Thiele, F. Dimroth, T. Smolinka, Int. J. Hydrogen Energy 2017, 42, 26804.
9. S. Tembhurne, F. Nandjou, S. Haussener, Nat. Energy 2019, 4, 399.
10. F. Dimroth, to be published, 2021.
11. https://www.fusion-fuel.eu/tech/. (Accessed 28 October, 2021).
12. M. Müller, W. Zwaygardt, E. Rauls, M. Hehemann, S. Haas, L. Stolt, H. Janssen, M. Carmo, Energies 2019, 12, 4150.
13. PECSYS Project (2020). Available at: https://www.helmholtz-berlin.de/media/media/projekte/pecsys/pdf-dateien/d7.6-deliverable-report.pdf. (Accessed 28 October, 2021).
14. S. Muhammad-Bashir, M. Al-Oufi, M. Al-Hakami, M. A. Nadeem, K. Mudiyanselage, H. Idriss, Sol. Energy 2020, 205, 461.
15. T. Maeda, Y. Nagata, N. Endo, M. Ishida. J. Int. Council Electr. Eng. 2016, 6, 78.
16. N. A. Kelly, T. L. Gibson, D. B. Ouwerkerk, Int. J. Hydrogen Energy 2011, 36, 15803.
17. I. B. Pehlivan, J. Oscarsson, Z. Qiu, L. Stolt, M. Edoff, T. Edvinsson. iScience 2021, 24, 101910.
18. S. Calnan, R. Bagacki, F. Bao, et al., Solar Rapid Research Letters, 2021, 2100479.
19. K.R. Tolod, S. Hernández, N. Russo, Catalysts 2017, 7, 13.
20. W.-H. Cheng, M. H. Richter, M. M. May, J. Ohlmann, D. Lackner, F. Dimroth, T. Hannappel, H. A. Atwater, H.-J. Lewerenz, ACS Energy Lett. 2018, 3, 1795.
21. I. Y. Ahmet, Y. Ma, J.-W. Jang, T. Henschel, B. Stannowski, T. Lopes, A. Vilanova, A. Mendes, F. F. Abdi, R. van de Krol, Sustainable Energy Fuels 2019, 3, 2366.
22. M. Lee, B. Turan, J. P. Becker, K. Welter, B. Klingebiel, E. Neumann,Y. J. Sohn, T. Merdzhanova, T. Kirchartz, F. Finger, U. Rau, S. Haas, Adv. Sustainable Syst. 2020, 4, 202000070.
23. ARENA (Australian Renewable Energy Agency). 2014, „Commercial Readiness Index for Renewable Energy Sectors“. Accessed 28 October, 2021 at https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf .