Prospects of floating photovoltaics in the green hydrogen production process

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***Abstract*—With the increasing energy demand and GHG emissions in urbanised areas, innovative solutions are necessary to facilitate a sustainable energy system. Given the spatial constraints of cities, floating photovoltaics (FPV) may provide a practical solution through increased efficiency, reduced evaporation and more effective area usage. However, renewables require stabilising measures to compensate for their intermittency. Consequently, green hydrogen is acknowledged as an essential component in achieving sustainable energy systems. Yet, several technical and financial challenges remain in the development and scale-up of green hydrogen production. Therefore, this review paper discusses the potential complementarity of FPV systems in the green hydrogen production process. Whereas the (F)PV technology is rather well-developed and affordable, more research is needed on ecological effects. Moreover, an efficient production method for green hydrogen is still lacking. Through technological advancements in electrolysers, large-scale FPV deployment and political support, the viability of such combined systems can be improved.**

***Index Terms*—Electrolysers, Floating Photovoltaics, Hydrogen, Renewable Energy, Solar energy**

I. Introduction

To mitigate the global temperature increase and inherent climate change that would induce disastrous effects on society and the environment, a significant reduction in the consumption of fossil fuels is necessary [1]. To achieve a reduction in greenhouse gas emissions, the scale-up of renewable energy sources is essential. Accordingly, the share of solar and wind energy has increased significantly over the previous decades [2]. As these renewable technologies mature and proceed further across the learning curve, production costs decrease and efficiencies increase [3]. More importantly, newer types of such technological applications have emerged which allows them to be integrated into the built environment more effectively. Since almost 80% of the total global energy consumption and roughly 60% of all GHG emissions originate from cities, it is important to localise renewables into urbanised areas [4]. Some examples of this are Building Integrated Photovoltaics (BIPV), Façade & roof integrated wind turbines, or floating photovoltaics (FPV) [5]–[10]. Despite the advantages of such renewable energy sources and the improved opportunities to integrate them within urbanised areas, broader challenges regarding renewables remain. The most prevailing is the emerging energy grid instability caused by the intermittency of renewable energy sources [11]. More often, the energy production of renewables exceeds the energy demand, hence PV modules and wind turbines are shut down and their full potential could not be exploited [12]. This conveys the idea that new innovative approaches are required to tackle these inherent challenges when integrating renewables into the energy grid.

Potential energy storage solutions are available such as mechanical (e.g. pumped hydro), thermal (e.g. heated water) or electrochemical (e.g. batteries and hydrogen) [13]. Nevertheless, pumped hydro is not always applicable and thermal storage faces significant energy losses [13]. Besides, the use of batteries also has some disadvantages such as relatively low shelf life, extensive material requirements and environmental pollution during its production [14]. Accordingly, a more promising and widely acknowledged solution is green hydrogen (i.e. hydrogen produced with renewable energy) [15], [16]. The advantage of hydrogen is that it is rather versatile in its use: it could be a direct source of energy replacing fossil fuels [17]; serve as a feedstock molecule for various industries [18]–[21]; and could be used in the production of alternative energy carriers or eFuels [21]–[23].

Despite the potential of green hydrogen, several challenges still have to be overcome. One of the primary challenges is solving electrolysis efficiency losses which reduce economic viability [21], [24]. Since higher energy yields are achievable with FPV than other PV systems [25], this could be a practical solution to improve the overall system efficiency when producing green hydrogen. Therefore, this paper examines the potential of a combined FPV and electrolyser system as this may result in a more viable green hydrogen production process.

In this review paper, a comprehensive overview of FPV and its challenges is described in Section II. Hereafter, a comparable discussion is given in Section III for the three main electrolysis technologies for producing green hydrogen (Alkaline-, Proton Exchange Membrane-, and Solid Oxide- Electrolysis Cells). Section IV illustrates the potential complementarity of a combined FPV and electrolyser system. Finally, Section V synthesises the main findings and discusses a probable outlook of such systems.

II. Floating Photovoltaics

A. Technical Overview of Floating Photovoltaics

Through technological advancements, PV systems have become one of the most developed and affordable solutions [3], [26]. Nevertheless, conflicts in the deployment of large-scale PV installations increasingly prevail due to the intense land use requirements of solar parks [27]. Accordingly, FPV systems have emerged as a technology to make effective use of fresh-, salt- and wastewater surfaces where available space is less constraining [8], [28]. Over the years, FPV systems have developed from smaller-scale projects to several MW-sized installations [29].

Besides solving land use issues, the use of FPV enables increased energy yields. As the temperature of PV modules rises, the efficiency of renewable energy production declines [30], [31]. Because of the positioning of PV modules on water surfaces, the lower water temperatures underneath induce a 'cooling effect' and could improve the efficiency by ~5-20% when compared to terrestrial PV systems, depending on seasons and local weather conditions [25], [32]–[35]. Due to the increased efficiency and reduced valuable land use, FPV is a financially attractive source of renewable energy [28].

Moreover, FPV systems could provide several ecological benefits as well. Because of the shading caused by the PV modules, water evaporation is reduced and excessive algae growth is prevented [8]. Additionally, previous pilot projects of FPV have indicated an increase in the nutrient levels in the water, thereby improving the overall quality of the water [36]. Based on the aforementioned characteristics, FPV systems can provide significant technical, financial, societal and environmental benefits.

B. Challenges of Floating Photovoltaics

Considering the advantages of FPV, the global installed capacity has doubled year after year [37]. Nevertheless, FPV also faces some unique challenges. Because of their positioning on wide-open surfaces, FPV systems are susceptible to heavy weather conditions such as extreme wind speeds with the potential of them to overturn or even sink [38]. Therefore, without proper anchoring and technical designs that consider potential forces on the system structure, this could lead to damage to the system [39]. Accordingly, this requires additional preliminary assessments in the form of water level fluctuations, bathymetry, project location and soil conditions for anchoring [40]. Consequently, the investment and maintenance costs of FPV systems are higher due to the need for floaters, anchoring, mooring, potential corrosion and the requirement for more complex technical designs [8], [34].

Additionally, unclarity remains about the specific effects of FPV systems on water bodies. As shading could prevent excessive algae growth, too much shading could cause detrimental effects on the aquatic food chains by depleting primary food sources [41]. Whereas the potential positive and negative impacts on water quality are known, empirical research is often not conducted [42], [43]. This lack of ecological research on FPV becomes particularly evident in two previous review studies which indicated that ecological aspects were often not considered enough as the main emphasis was on technological and financial aspects [8], [44]. Consequently, this conveys the idea that one of the main challenges relates to the assessment of the ecological side effects of FPV systems.

III. Hydrogen Production Through Electrolysis

A. Technical Overview of Electrolysers

Whereas hydrogen could be produced in multiple ways such as from fossil fuels (grey), fossil fuels with Carbon Capture & Storage (CCS) (blue) or with nuclear energy (purple), producing hydrogen with the use of renewable energy sources (green) is preferable as it is the least polluting [45]. For producing green hydrogen, renewable energy is used in an electrolyser to convert purified water into hydrogen and oxygen. Through the electrolysis process, a part of the (excessive) renewable energy could be stored in hydrogen to be retrieved when needed. Whereas there is a wide variety of electrolysers available, not all are suited for producing hydrogen. Therefore, the most common electrolysers for producing green hydrogen, including their (dis)advantages, are listed in [46-48, Tab. I].

Previously, the AEC was favoured due to the technological maturity and affordability of such systems [48]. However, complications regarding the dynamic operation, which is inherent to the intermittency of renewables, resulted in the favourability of the PEMEC systems for producing green hydrogen [46], [48]. Whereas PEMEC systems are more expensive than AEC because of scarce material use and increased complexity of the system, higher efficiencies could be achieved (AEC: 59-70%, PEMEC: 65-82%) [46]–[48]. Accordingly, PEMEC is estimated to become the dominant electrolysis technology towards 2030 [46]. However, SOEC shows significant potential in the long term. Even though SOECs are currently on a lab scale and not commercially available yet, these systems can achieve high efficiencies (up to 100%), have low material costs and facilitate bi-directionality to produce and use hydrogen [46], [47].

B. Challenges of Electrolysers

The main challenge for producing green hydrogen relates to economic viability. Some of these major factors that affect the cost-effectiveness of green hydrogen production entail 1) low conversion efficiencies, 2) expensive material use of some electrolysers and 3) the lifespan of electrolysers [46], [49]. For example, whereas the PEMEC is currently the most viable for green hydrogen production based on multiple dimensions [50], the efficiency of such electrolysers still varies between 65-82% [46], [47]. Considering all processes for producing green hydrogen through electrolysis, the overall efficiency is even lower and found to be only 52% [49]. This illustrates the significant energy losses that come along with the production of green hydrogen and would, therefore, require further development and research.

Moreover, material use can also form substantial challenges in the case of some electrolysers. For example, PEMEC requires expensive materials such as noble metals and SOEC endures high rates of component degradation due to high operating temperatures [46], [47]. When compared to AEC, the lifetime of PEMEC and SOEC systems are also significantly lower [46]. This suggests that further research should be focused on alternative electrolyser materials and reducing material deterioration to improve financial aspects.

Additionally, other complications emerge along the dynamic operation of electrolysers. Considering the intermittent nature of renewables, the continuous load hours of electrolysers are reduced. As a consequence, the dynamic operation of electrolysers emphasises the need for reduced capital investment costs and can also result in lower efficiencies in the case of AEC systems [46]. To mitigate these challenges, further electrolyser developments are required to facilitate improved compatibility with the irregularity of renewables.

Besides economic perspectives, safety aspects can also play an important role when integrating hydrogen production technologies [51]. With the higher operating temperatures of AEC, the immaturity of SOEC or the possibility of cross-permeation across membranes resulting in flammable hydrogen-oxygen mixtures in PEMEC amplifies the importance of continuous monitoring of the electrolysis process [51]. Nevertheless, some argue that the electrolysis processes are considered one of the safer options for producing green hydrogen and are potentially viable solutions for local production [52]. These electrolysis methods, however, have to meet additional safety requirements to take these local systems and environmental dimensions into account [52]. Arguably, more research needs to be conducted on the safety aspects on which clear regulations could be formed.

TABLE I. ELECTROLYSER OVERVIEW

Electrolyser type	Advantages	Disadvantages
Alkaline Electrolysis Cell (AEC)	Conventional large-scale electrolysis approach for over a century. Relative low investment costs.	Low current density and efficiency (59-70%). Not viable yet for solely renewables due to the negative impact of the dynamic operation on efficiency.
Proton Exchange Membrane Electrolysis Cell (PEMEC)	Relatively high power density & efficiency (65-82%). Suitable for renewables due to flexible operation.	Expensive materials. System complexity. Shorter lifetime than AEC.
Solid Oxide Electrolysis Cell (SOEC)	Not commercially available yet, primarily lab scale. High electrical efficiency (up to 100%). Low material cost. Option to function as a reversible fuel cell.	Higher operating temperatures cause wear and tear on used materials.

IV. COMBINED FPV AND ELECTROLYSER SYSTEMS

A. *Technical Overview of Combined Systems*

In the exploration of solving the complications of renewables and green hydrogen production, the complementarity of FPV and electrolysers might be a practical solution. Considering the aforementioned benefits of FPV, recent studies have assessed the potential of a combined FPV and electrolyser system for generating green hydrogen [53], [54]. With the increased energy yields of FPV and no valuable land use when compared with terrestrial PV systems, the cost-effectiveness of producing green hydrogen could be improved.

B. *Challenges of Combined FPV and Electrolyser Systems*

Considering the financial aspects as previously illustrated, large-scale renewable deployment is needed to facilitate a cost-effective way of producing green hydrogen. This means that FPV would require large water surfaces. This might spur societal conflicts in an urban environment once substantial amounts of sweet water surfaces are covered with FPV [55]. Through nature-inclusive architecture and design, the generation of renewable energy with minimised impact on the environment could be achieved [55]. Nevertheless, an abundance of renewable energy originating from FPV could more easily be accomplished when deployed on water surfaces where scalability is less of an issue such as large (dam) reservoirs, large natural lakes, or offshore [56].

In addition, the production of green hydrogen is primarily based on the available surpluses of renewable energy [47], [49]. Since the growing share of renewables causes an increasingly more volatile energy supply [11], it is debatable if a reliable energy supply for continuous electrolyser operation could be guaranteed. Therefore, a more stable renewable energy supply is required. This opens the avenue for hybrid solar-wind systems that make use of cable pooling as this could allow for a more continuous supply of renewable energy [57].

V. CONCLUSION & DISCUSSION

In this review paper, a combined FPV and electrolyser system is assessed. In line with the benefits of FPV when compared to terrestrial PV systems, they provide some unique advantages for producing green hydrogen. Whereas the production of green hydrogen is still expensive and inefficient, the increased efficiency and prevention of valuable land use improve the overall economic viability. However, the deployment of a combined FPV and electrolyser system in urban environments seems less suitable. Here, the main limitation is the scalability of the FPV systems which is essential for cost-effective green hydrogen production. Therefore, the deployment of such combined systems is deemed more feasible on large (dam) reservoirs, large natural lakes or offshore environments. Yet, offshore systems would require additional measures to withstand the more prevailing harsh weather conditions in such environments.

In addition to large-scale FPV deployment, a reliable renewable energy supply is needed to improve economic viability. Given the production patterns of solar and wind energy, hybrid systems of solar-wind could facilitate a more stable energy supply to mitigate the negative effects of the dynamic operation on electrolysers.

Moreover, there are some challenges among the FPV and electrolyser technologies themselves. For example, assessments of the ecological side effects of FPV systems are undervalued since technological and economic aspects are often prioritised. As a result, the positive and negative consequences on the surrounding environment are still uncertain. Hence, further research should emphasise the ecological aspects of FPV.

Regarding electrolysers, significant barriers persist before large-scale green hydrogen could be achieved. Economic viability is one of the main challenges and could be improved by 1) increasing electrolyser efficiencies, 2) reducing scarce & expensive material use, 3) increasing the lifespan, and 4) improving compatibility with the intermittency of renewables. Moreover, some ambiguity remains on the safety of electrolysis processes and their applicability in urban environments. This spurs the need for further research in overcoming these challenges.

Overall, the combination of FPV and electrolysers seems a practical solution to stimulate the development of green hydrogen and mitigate the challenges when developing sustainable energy systems. Once this configuration becomes more mature and affordable, this might also prevail in more inland settings.

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