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Original Paper

From Renewable Energy to Renewable Fuel: A Sustainable Hydrogen Production

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Abstract

Hydrogen, a zero-emission fuel and the universal energy vector, can be easily produced from many different energy sources. It is a storable, transportable product that can be used on demand to overcome supply and demand imbalances. As of today, most of the hydrogen produced comes from natural gas; the production process itself is in fact not so pollution free. As the world is looking for a low carbon future, researchers have therefore been looking for more sustainable, environmentally friendly pathways of hydrogen production by using renewable energy sources such as solar and wind. Among the different methods, water electrolysis is a conventional and promising method of hydrogen production if renewable energy sources are to be employed in the process. Lots of progress has been made over the past few years in extending the use of hydrogen in different sectors. This perspective article briefly covers the recent developments in the hydrogen fuel-based projects and technologies and provides a description of the advantages of employing renewable energy sources for sustainable hydrogen production.

Keywords

Hydrogen, renewable energy, electrolysis, thermoelectric, zero emission, sustainable production

1. Introduction

Renewable energy sources (solar and wind etc.) will be the fastest-growing power sources for electricity generation in the near future. These intermittent sources, however, suffer from supply and demand imbalances (Jones, Al-Masry et al., 2018; Quarton, Tlili et al., 2020), as there is no correlation between say the strength of the wind or the position of the sun in the sky and the consumers desire for electricity. At low levels this is not too much of an issue, but as the percentage mix increases this will become an increasingly important topic. Balancing this supply and demand is developing into one of the biggest challenges facing energy scientists around the globe. Much work is currently underway, correlating the supply with demand producing "Smart systems" however there is an alternative which is to decouple supply from demand using a university energy vector. The storage of energy in the form of hydrogen is just such a possible energy vector. All forms of energy can easily and relatively efficiently be converted into hydrogen and all forms of power can be utilized from the hydrogen; electricity and heat via fuel cells or heat from combustion, either 100% pure or as a enrichment to natural gas (Jones, Al-Masry et al., 2018). Once produced, hydrogen can be stored for unimaginable lengths of time thus decoupling supply from demand. As long as there is storage capacity and the demand does not exceed the supply, the inherently "Smart" system will balance itself out, even with a 100% renewable intermittent input.

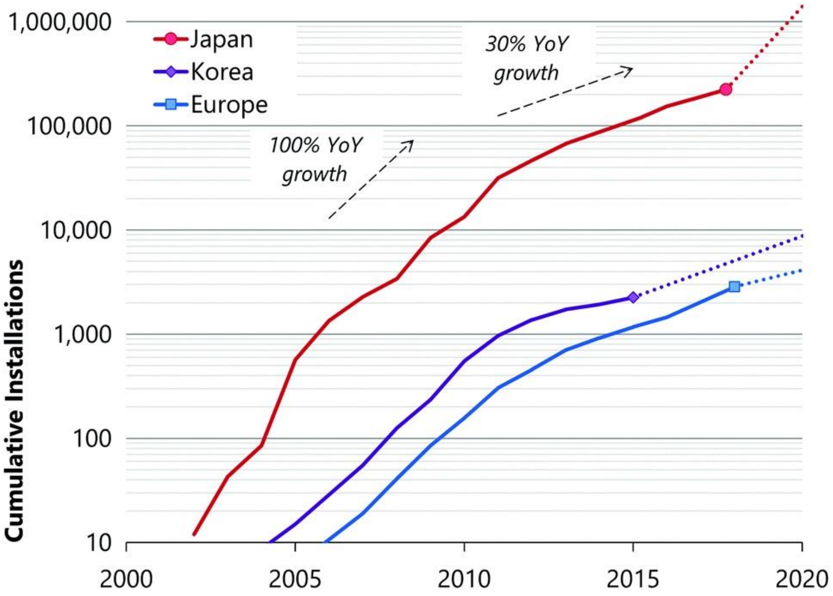

Figure 1. The Number of Micro-CHP Systems Installed to Date (Solid Lines) and Near-Term Projections (Dotted Lines) for Residential Use (YoY Stands for Year-Over-Year). Reproduced from (Staffell, Scamman et al., 2019) Published by the Royal Society of Chemistry

The implementation of hydrogen-fuel based technologies is growing rapidly all over the world to cut the burning of fossil fuels wherever possible. Japan has been working towards a hydrogen society to reduce environmental burdens and revitalize regional economies by extending its use by (i) promoting Fuel Cell Electric Vehicles (FCEVs), (ii) increasing hydrogen production, and (iii) introducing fuel cells for residential applications (Energy 2014; Staffell, Scamman et al., 2019). It is also envisioning to establish a carbon-free hydrogen supply by 2040 (METD 2017; Staffell, Scamman et al., 2019). Japan has deployed a large number of residential fuel cell systems (micro-CHP) and is one of the leading countries in the world in implementing hydrogen technologies for daily uses (micro-CHP technology: Micro combined heat and power, is a technology that generates heat and electricity from the same energy source, and the fuel cell is a device that converts the chemical energy of a fuel (hydrogen) into electricity). Recently, many European (EU) countries are beginning to promote hydrogen as a fuel in different fields; it is also being introduced for automobile industries as new techniques to store hydrogen in liquefied form have been developed and found to be successful on primary testing which is crucial to implement the technology for small vehicles such as scooters (FCW 2020). Figure 1 illustrates the contribution of major countries in implementing micro-CHP technology for residential use. The extension of hydrogen usage to automobile industry will improve air quality as vehicles' contribution to the CO_2 emission is very high and ever increasing. Similarly, France has launched a hydrogen project; hydrogen is produced from the renewable energy and will be stored and transported in the natural gas grid which flows in pipes under the streets of a village, aiming to energize hundreds of homes (ENGIE 2016). This year, Scotland is also planning for its first ever hydrogen-powered homes; as a part of a pilot scheme (Sampson, 2020), a few homes will be incorporated with micro-CHP fuel cell technology. Interestingly, hydrogen can also be burnt as a flame or catalytically (du Preez, Jones et al., 2019; du Preez, Jones et al., 2020).

When hydrogen burns, it produces no toxic/greenhouse gases but water (Figure 2), therefore, a 100% clean energy pathways can be created using production methods powered by renewable energy sources. At present most of the hydrogen is produced from steam reformation of fossil fuels, so called Brown Hydrogen and hence even hydrogen is also indirectly responsible for carbon emissions. This can be avoided or minimized by sequestering the carbon dioxide (Blue hydrogen, or by electrolyzing water using renewable energy such as excess wind; implementation of these clean methods is already under progress that releases virtually zero greenhouse gas to the environment.

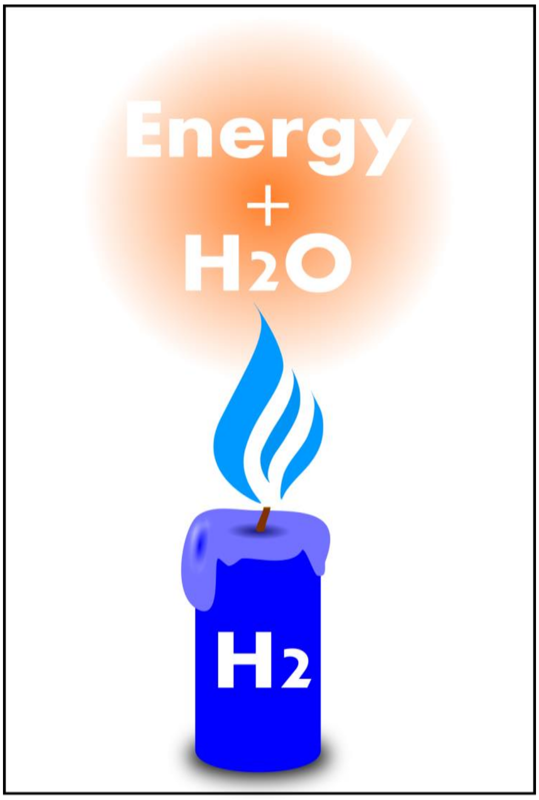

Figure 2. An Illustration Showing H_2 Burning Produces No Greenhouse Gases

2. Hydrogen Production from Renewable Sources

A direct and promising method to generate green hydrogen is found to be water electrolysis: a process of splitting water into hydrogen and oxygen using electricity (Gannon, Warwick et al., 2020). A simple two electrode (anode and cathode) unit called an electrolyzer (usually, it consists of three parts: electrodes, separators/membranes, and electrolyte) is used for the purpose (Mulla & Dunnill, 2019). There are three types of electrolyzer designs such as (i) Alkaline Electrolysis Cells (AEC), (ii) Proton Exchange Membrane Electrolysis Cells (PEMEC), and (iii) Solid Oxide Electrolysis Cells (SOEC) of which AECs have been in use in various industries as they have simple designs and can be built at a relatively low capital cost and are durable (Passas & Dunnill, 2015; Phillips & Dunnill, 2016; Phillips, Edwards et al., 2017; Mulla & Dunnill, 2019). To start electrolysis process, a DC electric supply is passed through an electrolytic solution, splitting water (H_2O) into its component parts (hydrogen (H_2) & oxygen (O_2)) where H_2 being generated on the cathode and O_2 on the anode (Figure 3). The decomposition of H_2O into H_2 and O_2 happens due to the application of electric voltage which forces ions to undergo either oxidation or reduction at the electrodes, the mechanism can be expressed as follows:

$$2H_2O_{(l)} + \ Energy = 2H_{2(g)} + O_{2(g)} \qquad \text{.................. (1)}$$

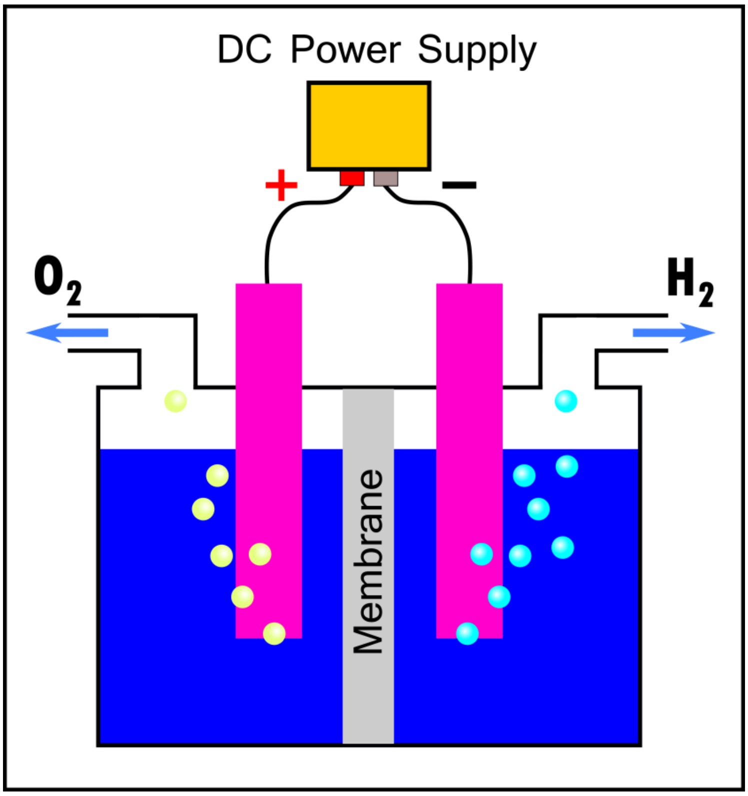

Figure 3. A Schematic of a Simple Electrolyzer for Hydrogen Production through Electrolysis

In general, the efficiency of water splitting is determined by the amount of electrical energy used to generate an amount of hydrogen, can be defined as follows (Phillips & Dunnill, 2016; Phillips, Edwards et al., 2017; Mulla & Dunnill, 2019):

$$Efficiency = \frac{Energy\ Output}{Total\ Energy\ Input} \qquad \text{......................} (2)$$

where the term "*Energy Output*" refers to the amount of hydrogen produced and "*Total Energy Input*" is in general refers to the total electrical energy consumed in the production.

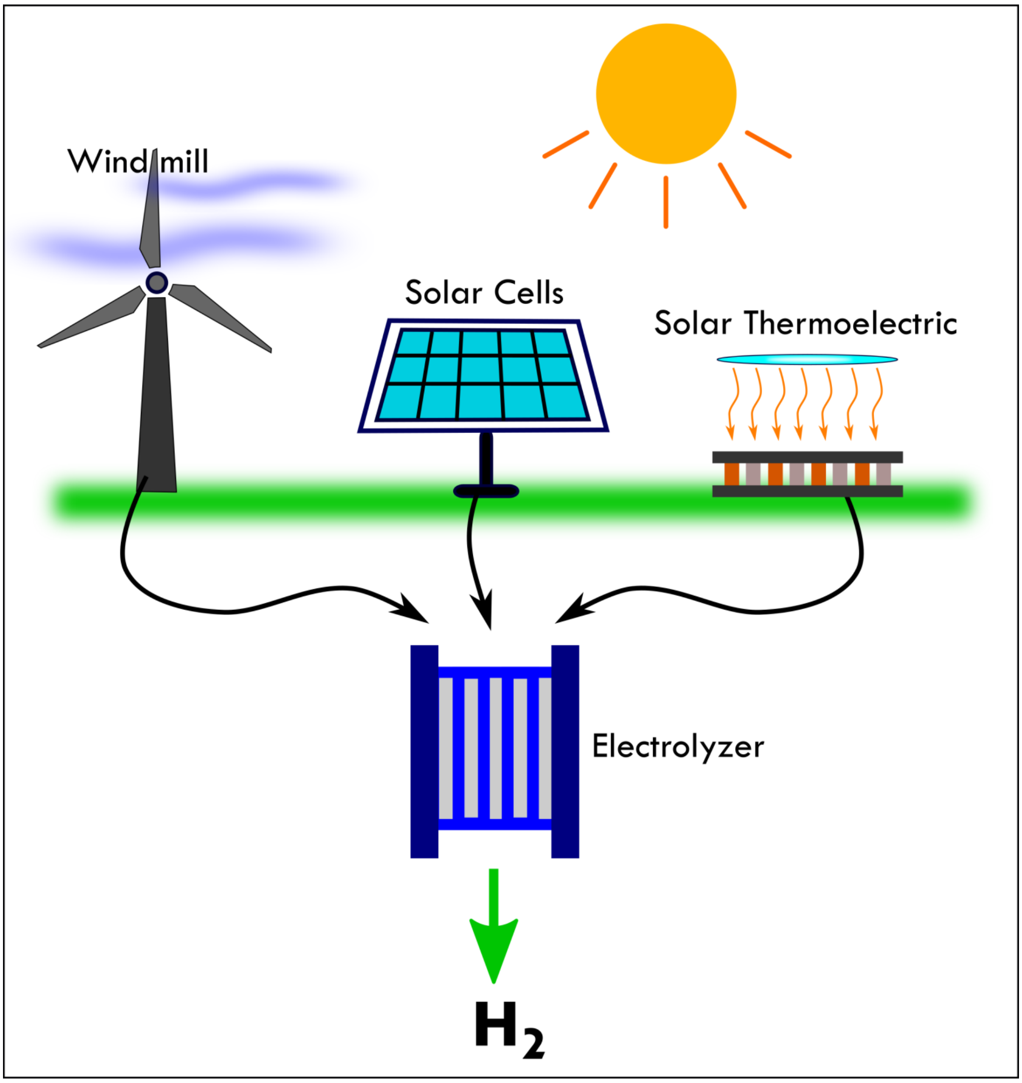

Figure 4. Water Electrolysis Powered by Renewable Energy for Hydrogen Production

As illustrated by Figure 4, the required electrical energy can be provided by different renewable energy sources such as wind turbine, photovoltaic (solar panels), and also from solar thermoelectric generators (STEG). Wind turbine and photovoltaic systems are already well-known, successfully working on a large scale in different sectors, and are also recently being linked to hydrogen production units. Both the energy sources appear to be promising for water splitting according to recent developments; alongside, research on coupling STEGs to the electrolysis is also under progress (Baranowski, Snyder et al., 2012). Industrial waste heat is a fantastic source of cheap energy that can be utilized for hydrogen production (Mulla & Dunnill, 2019). Thermoelectric generators work on the principle of Seebeck effect, in which a temperature gradient applied across the device produces useful electric potential. STEGs generate electricity from concentrated sunlight; solar radiation is used as a source of heat to develop temperature gradient across the device. Larger temperature gradients across the generators can be achieved by using solar concentrators/lenses which result in better output power density from the generator. The conversion efficiency (η) of the thermoelectric generators can be estimated using the following standard equation:

$$\eta = \frac{(T_h - T_c)}{T_h} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_c}{T_h}} \qquad \text{.....................} \ (3)$$

where ZT is the thermoelectric figure of merit of the materials used in the generator, T_c and T_h are the cold and hot side temperatures of the generators. Therefore, a large temperature difference across the generator designed with good thermoelectric materials (i.e., materials with high ZT value) is important to generate a decent electric power. Up to 15-30% efficiency is predicted from these STEGs when thermoelectric materials of $ZT > 2$ are used in the generators (Baranowski, Snyder et al., 2012).

3. Challenges and Opportunities

Currently, most of the hydrogen is generated from fossil fuels as they provide more economical methods over electrolytic water splitting. This production method, however, is unsuitable for a low carbon future. Presently, the largest consumers of hydrogen (produced by fossil fuels) are chemical industries where nearly half of hydrogen is used in ammonia production; it alone causes about 1% of total global greenhouse gases emission (Boerner, 2019). In the meantime, as the world is looking for a low carbon future, there is an increasing demand for renewable sources, shortly; they may become available at competitive prices. By utilizing clean nature of hydrogen, blending it with biogas (Mehr, Moharramian et al., 2020), implementing hydrogen injection in coal-dominated regions (Wang, Klemeš et al., 2020), etc can help reduction of CO_2 emission. Hydrogen can be safely mixed in small quantities with natural gas depending on the end-use appliances. Countries like Germany and the Netherlands have 10-12% (by volume) blending levels (Staffell, Scamman et al., 2019). The advantage of hydrogen blending can be seen from the data in Figure 5 that shows the relationship between energy content and carbon savings with respect to hydrogen injection mixtures (Staffell, Scamman et al., 2019). So, about 20% hydrogen (by volume) blend would give 13 gCO_2 per kWh carbon emissions savings. However, at present, higher blending is not possible due to technical and administrative constraints (Staffell, Scamman et al., 2019).

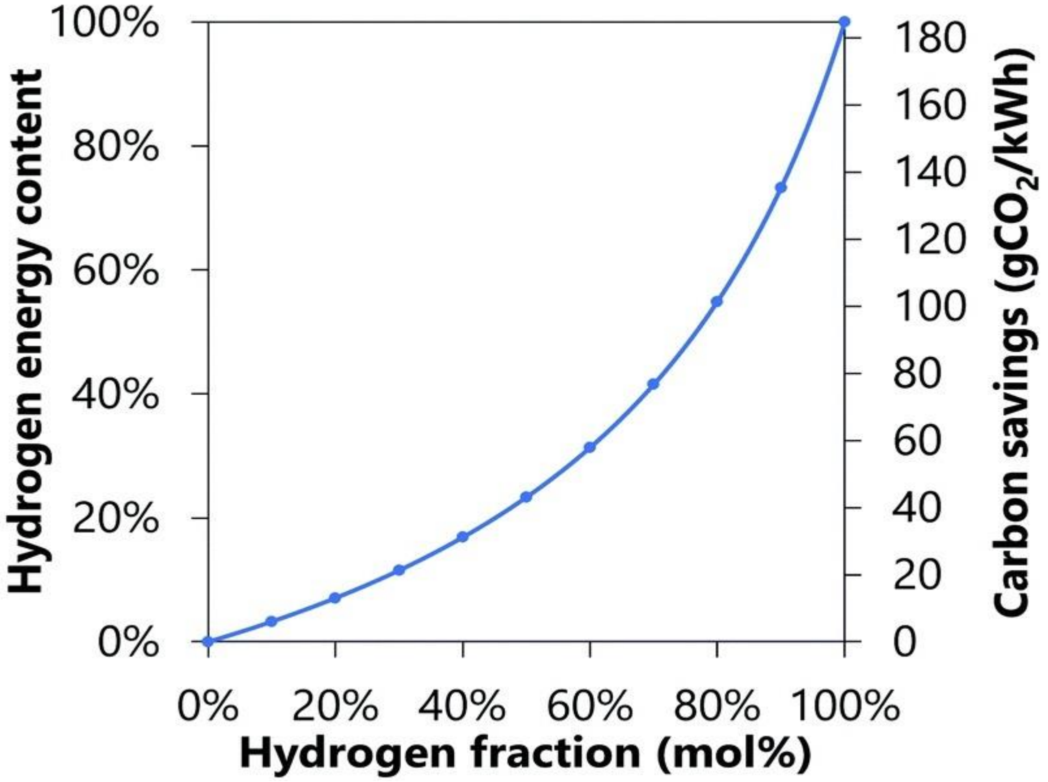

Figure 5. The Relationship between Energy Content and Carbon Savings with Respect Hydrogen Injection Mixtures. Reproduced from (Staffell, Scamman et al., 2019) Published by the Royal Society of Chemistry

The low efficiency of the thermoelectric generators is a major drawback to be used independently in the production of hydrogen, and therefore they can be used as a supplementary source by coupling with photovoltaic to improve overall efficiency or production rate (Mulla & Dunnill, 2019). At present, the commercial thermoelectric generators are mainly contained materials like Bi_2Te_3 and PbTe which makes them quite expensive, and also the elements like tellurium (Te) are highly toxic and scarce hence, a large-scale implementation facing difficulties (Mulla & Dunnill, 2019; Mulla & Rabinal, 2019). Nevertheless, rigorous scientific investigations are under progress which produced many new, low-cost and non-toxic materials and improvements can be realized in the near future (Mulla & Rabinal, 2018; Mulla & Dunnill, 2019). The efficiency argument however does need to be taken in context as the use of otherwise wasted heat yields green value from waste (Mulla & Dunnill, 2019) and is economically viable even with low efficiency, especially if the TEG can be produced cheaply (Mulla & Rabinal, 2018; Mulla & Dunnill, 2020; Mulla, Jones et al., 2020).

There are also other methods to generate hydrogen from solar energy such as photoelectrochemical (PEC) water splitting which also offers a promising approach for hydrogen production; however, requires scalable PEC cells in addition to the stable and efficient photoelectrodes (Landman, Halabi et al., 2020). Another drawback of this method is associated with the collection of hydrogen gas from millions of PEC cells (Landman, Halabi et al., 2020). Therefore, large-scale PEC water splitting under sunlight is yet to be demonstrated. Similarly, studies are under progress on improving photocatalytic hydrogen production using different and new photocatalyst materials and also on the use of photocathode materials (Warwick, Barreca et al., 2015; Crespo-Quesada, Pazos-Outón et al., 2016; Kuehnel & Reisner, 2018; Ghosh, Nakada et al., 2020).

Although producing hydrogen from electrolysis is currently dominated by the cost of electricity, the capital cost of electrolyzer will become important in the future when electricity generated from renewable energy becomes abundant and cheap (Esposito, 2017). The recent cost reductions of wind and solar power enable new opportunities for a competitive hydrogen production. In such scenario, the cost of electricity could be around $ 30/MWh (as estimated by wind farms in Morocco and solar plants in Chile and Dubai) and it is predicted that hydrogen production cost would not exceed $ 2/kg (Philibert, 2017). Research priorities with regard to electrolysers include reducing the capital cost of the electrolyzer units, operation life, improving their designs, and efficiency (Phillips & Dunnill, 2016). Typically, in basic design of an electrolyzer, the two electrodes are separated by a liquid electrolyte, which hinders the charge flow and results in low current densities. So, efforts on improving electrolyzer cell designs are going on and new design concepts like “zero gap cell” are under investigation where the charges can move much easier than in the basic cell design (Phillips & Dunnill, 2016). Similarly, research interest in membraneless electrolyzers is increasing to reduce the cost of the units (Esposito, 2017).

Further, when there is excess electricity available from windmills, instead of curtailing, it can be used to generate hydrogen which can be stored for the future and it could be integrated with electric power at a wind farm for better supply-demand flexibility (Perni, Liu et al., 2008; Cloete & Hirth, 2020). In addition, offshore renewable energy resources also have a great potential to contribute to the sustainable hydrogen production (Gondal, 2019). Overall, there are numerous opportunities to firmly establish a clean production technology for hydrogen production from renewable sources.

4. Conclusions

Hydrogen can be used in a wide range of applications and the hydrogen-powered fuel cells could power our vehicles, replacing the fossil fuels used in most vehicles today. In order to achieve a clean future, the use of hydrogen must be extended. Clean production of hydrogen, therefore, is essential to reduce greenhouse gas emissions. With the help of wind and solar powers, sustainable production of hydrogen can be achieved.

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Conflicts of interest

There are no conflicts of interest to declare.

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