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The green hydrogen revolution

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ABSTRACT

Green hydrogen is considered the most suitable choice for the future energy market, both as energy storage media, energy vector and fuel for transportation, industry and other applications.

In the last twenty years, increasing efforts have been dedicated to green hydrogen technologies development, but still today a number of issues are claimed in justifying the delay in its large scale application and the starvation of its market. Moreover, some new questions seem ready to be put on the table for justifying the delay in green hydrogen technologies applications.

In this paper, a critical analysis of recent literature and institutional reports is carried out with the aim of understanding what is the real state of the play. In particular, peculiar advantages and shortcomings of different green hydrogen technologies (biomass pyrolysis and gasification, water electrolysis, etc.) have been analysed and compared, with a focus on the electrolysis process as the most promising method for large scale and distributed generation of hydrogen.

Some geopolitical and economic aspects associated with the transition to a green hydrogen economy - including the feared exacerbation of the water crisis - have been widely examined and discussed, with the purpose of identifying approaches and solutions to accelerate the mentioned transition.

1. Introduction

To reduce the greenhouse gases (GHGs) emissions and the dependence of the energy market on fossil fuels, most countries in the world are focusing on the development of renewable energy sources (RESs) to drive the energy transition and to reduce their dependence on external supplies [1–3]. These efforts will result in an increasing share of green electricity and gradual introduction of green hydrogen [2].

Although it is possible to produce biogas and hydrogen from residual biomasses [4,5], other forms of RES (like hydraulic, solar, wind, geothermal, sea waves and tidal streams) can be easily converted into electricity or heat.

In particular, photovoltaic (PV) and wind are considered as the most suitable and cost-effective technologies for large scale application and power generation potential, and this has led to their continuous and considerable growth within the energy mix [6–8].

Unfortunately, both photovoltaic and wind power generation are highly dependent on location and weather conditions. These constraints pose a problem since very often the timing of energy supply and demand do not coincide [9–11]. For this reason, storage technologies play a key role, so that the energy generated mainly from these renewable sources can be fully harnessed [12].

Among the most widespread and common storage systems, batteries are the most common storage facility, characterised by high round-trip electrical efficiency (>90%) [8]. In a battery, the electric energy is converted by an electrochemical reversible process into chemicals (charge phase), these last when necessary can be converted back to electric energy (discharge phase). Batteries are competitive with other energy storage systems also because they allow decentralised energy storage [13,14]. But even these devices currently have a number of technical shortcomings, such as: limited number of useful cycles (charge-discharge), use of critical raw materials and/or polluting compounds, difficulty of recycling (costly and/or lacking technologies) [15].

For this reason, interest in hydrogen as an environmentally friendly and economically competitive solution for energy storage has been growing dramatically [16–18]. Hydrogen can be produced by different paths, each having a different environmental impact, that is usually associated to a "colour" attribute. Today, a number of different colours are used to classify the hydrogen according to the CO_2 emissions related to the production path [19].

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Although hydrogen is defined green when there are no CO_2 emissions, the most suitable and well developed technology is based on electrochemical water splitting (electrolysis), then common meaning of "Green Hydrogen" is as "Hydrogen made via electrolysis using renewable electricity". This last definition of green hydrogen is present in documents and articles which consider electrolysis to be the preferred and main route for future hydrogen production.

As in batteries, in water electrolysis electricity is converted into chemicals (hydrogen and oxygen). Apart from the fact that electrolysis relies on a non-spontaneous reaction driven by an external power source, the main difference with batteries is that hydrogen has several possible applications [20–24]. In fact, hydrogen can be converted back to electric energy by electrochemical process in fuel cells; it can be used as a fuel in internal combustion engines and turbines for mechanical energy; it can be burned in ovens to generate heat; it can be used as a feedstock in many industrial applications that use hydrogen obtained by processing fossil fuels (e.g., methane, oil and its derivatives, carbon); and it could be applied in other industrial and civil applications to replace natural gas.

For these reasons, many countries look at hydrogen as the solution for the future energy management and are increasingly supporting the introduction of hydrogen technologies aimed at a "decarbonised" economy. For this purpose, several "plans and strategies for the development and deployment of hydrogen" have recently been drawn up [25]. To support these plans, governments are launching support policies through the provision of incentives for both the construction of new delivery infrastructures and the production of green hydrogen. The production costs of green hydrogen are considered the main hurdle to the introduction and large-scale application of green hydrogen. Furthermore, in recent years, there has been discussion of the implications of hydrogen production by water electrolysis in relation to water availability and reserves (see Section 4). This because, as a consequence of conceiving green hydrogen just as that produced by electrolysis powered by renewable sources, a large quantity of water is requested.

According to the authors of this article, the definition of green hydrogen in relation to electrolysis technology needs to be broadened to include the CO_2 cycle and therefore all technologies that are carbon neutral. For example, hydrogen from biomass is CO_2 neutral and can be called 'green', also without carbon capture, because the CO_2 output in the final hydrogen production step is coming from a previous capture operated by the plants.

From this perspective, the authors carried out an overview of the state of play of hydrogen production technologies, and explored some considerations related to major geopolitical and economic aspects and implications of the hydrogen economy development, including the water aspects. With this research, the authors like to contribute to the analysis of both technical and socio-economic factors that may hinder or instead favour the uptake and use of hydrogen. For this reason, we have adopted a holistic approach in which, in addition to the technical issues, a number of problems have been identified and studied, such as the issue of water, which could have an impact on national and local economies, especially in some countries of the Global South. We hope that this study will contribute to the development of future research in this area, while providing policy makers with a broad vision that includes the various socio-technical impacts associated with the deployment of hydrogen technologies.

The paper is organised as follows. After this introduction, Section 2 provides an overview of the green hydrogen production technologies. Section 3 highlights the close correlation between green hydrogen and RESs, with an emphasis on the electrolysis technology. Some geopolitical implications of large-scale adoption of green hydrogen are evidenced in Section 4, with discussions of possible impacts of hydrogen-based scenarios on global energy and fuel markets and on water resources. In Section 5, we focused our attention on the distributed hydrogen generation and the valorisation of electrolysis by-products (oxygen, heat, etc.). Finally, the main findings and conclusions of our analysis are summarised in Section 6.

2. Green hydrogen production technologies

Hydrogen can be produced with different methods and technologies using both fossil fuels and renewable sources. As already mentioned, "green hydrogen" is usually conceived as hydrogen produced by RES-based electrolysis. While the general definition of green hydrogen is to be related to the absence of CO_2 emissions, i.e. produced through technologies using renewable sources, or carbon neutral technologies [26–28]. Then, hydrogen made from biomass is CO_2 neutral and can be defined as "green".

Converting waste into something value makes a lot of sense and is part of the circular economy concept. However, the use of agricultural products that could be used for food production is not considered, because it is not logic and can generate social conflicts. But it has to be noticed that there are a number of wastes from food industries and transformation industries that today are not valorised. Expanding the green hydrogen concept also broadens the available hydrogen production technologies to be considered for large-scale hydrogen applications and industrial decarbonisation. Probably, it is possible to add two new colours, "dark green" hydrogen for the hydrogen produced by electrolysis, and "light green" hydrogen for the other approaches, but thereafter this is not considered and the terminology "green hydrogen" will be used for all cases.

The main environmental characteristics of the principal technologies that could be applied to yield green hydrogen are listed in Table 1. With the exception of electrolysis, which does not use biomass, several types of feedstock are valuable: waste biomass, e.g. waste from agricultural and food production, waste wood, residual agricultural products, sewage sludge, bio-methane and other bio-fuels.

2.1. Steam reforming of bio-feedstocks

Steam reforming is a well-known process that today supplies large parts of the hydrogen for industrial applications by using methane as a feedstock. It is a catalytic reaction of a hydrocarbon with water vapour. In the case of methane, the reaction allows the production of a gas mixture of carbon monoxide, hydrogen and carbon dioxide usually named reforming gas. Industrial systems are usually based on tubular reactors containing catalyst particles, like nickel particles supported on

Table 1
Green hydrogen technologies, main environmental characteristics.

Production technology	Advantages	Drawbacks
Steam Reforming of bio-feedstocks	No oxygen needed; high conversion efficiency; well known technology already used for natural gas.	Although carbon neutral, there are CO_2 and CO emissions.
Biomass Gasification	Residual and waste biomass as feedstock.	Although carbon neutral, there are CO_2 emissions; a post treatment of exit gases and residuals is requested.
Biomass Pyrolysis	Low water content residues and waste biomass as feedstock; no oxygen is needed.	Although carbon neutral, there are CO_2 and CO emissions; formation of TAR that must be treated and it is not easy to manage.
Water Electrolysis	No direct emissions; oxygen is a by-product.	Low cost green electricity is needed; low conversion efficiency (about 60%); pure water is requested.
Direct production by biological processes	Large variety of wastes could be used as a feedstock; possibility to use CO_2 as co-feedstock; possibility to produce useful by-products.	Technology at low level of development; low production density; pre-treatment of the feedstock required to fit the applied microorganisms necessities.

alumina silica, with K_2O as activator. The catalytic particles are lapped by the stream of reactants at an average temperature of around 850–870 °C. The process can be applied to a number of hydrocarbons like methane, methanol, ethanol, glycerol. Methane is the largest used feed and steam methane reforming (SMR) is today a cheap technology for large industrial applications. In many cases, steam reforming is coupled with the water gas shift reaction to increase the hydrogen yield according to the process to be fed. For example, reforming gas is largely used for methanol and synfuel production. But, using methane (natural gas) and other fossil fuels there is a net CO_2 emission and the produced hydrogen is called “grey hydrogen”. To produce pure hydrogen with this process a separation from the other components of reforming gas is necessary. By this separation process it is possible also to capture the produced CO_2 and to dispose it in some way (like in exhaust oil field), a process named CO_2 sequestration.

By CO_2 sequestration, it is possible to obtain a clean form of hydrogen named “blue hydrogen”, but this means anyway having CO_2 to manage and additional production costs related to this management. While using bio-gas, bio-alcohols or bio-oils it will be carbon neutral and the resulting hydrogen can be classified as “green hydrogen” [29–31].

The steam reforming technology is well assessed and largely used, although further advancements are possible. Nowadays, methane steam reforming is the cheapest approach for hydrogen production, but the result is grey hydrogen. By capturing CO_2 the emissions can be strongly reduced but not totally avoided. Moreover this kind of hydrogen is not suitable for application in fuel cell and in other applications that require very pure hydrogen, requiring further separation processes.

Using bio-hydrocarbons as feed, steam reforming can be considered green, but anyway a number of purification steps and separation of hydrogen will be requested to obtain pure hydrogen.

A solution to this aspect are the metal membrane reactors. When the process is conducted by metal membrane reactors the separation of hydrogen from other reforming gases is realised directly in the reactor [32].

2.2. *Biomass gasification*

Gasification is a chemical process that converts carbon-rich material (such as coal, oil or biomass) into a gas mixture usually called “syngas”, containing carbon monoxide, hydrogen, carbon dioxide and other gaseous substances. The process is known and applied since the XIX century, when it was largely used for supplying the city gas, a mixture of hydrogen (about 50%), 3-6% of carbon monoxide and the remaining part as methane and carbon dioxide. City gas was produced from coal in extreme conditions: 30 bar or more, and temperatures up to 1200 °C [33]. The process consists of the combustion of the feedstock in poor oxygen conditions (from this the name of “partial oxidation”) and in presence of steam; it is usually carried out at temperatures between 700 and 800 °C [33,34].

Also in this case, when fossil fuels are used by appropriate cleaning, blue hydrogen can be produced.

If biomass is used as feedstock, the process is carbon neutral and the hydrogen coming from effluent gases purification is green. Combustion is exothermic, so that a large amount of energy is released as heat, and this technology becomes really interesting in cogeneration processes [35,36]. As high temperature heat is released during the process, it is of great interest when cogeneration of heat and power is considered [37,38]. Moreover, as the presence of steam is needed, the biomass feedstock could be not dehydrated. A schematic and detailed analysis of the different gasification reactor technologies can be found in Ref. [39].

Within the issues that limit the diffusion of the technology for the hydrogen production by biomass gasification there are the control of the biomass quality and water content, the ash management, syngas quality control and syngas purification to hydrogen, hot gas management and reuse. Besides, reforming of liquid residual contains paraffins, iso-paraffins, olefins, aromatic hydrocarbons and a number of oxygenated, chlorinated and sulfurised compounds in relation to the starting material (usually known as TAR), and the management of this residuals originates socio-environmental issues [40,41].

2.3. *Biomass pyrolysis*

Pyrolysis is a heat treatment process consisting of non-oxidative thermal decomposition, i.e. without additional oxygen. It can be used for the energy conversion of various organic materials as long as they have a low water content (<15%). The pyrolysis reaction is characterised by very complex chemical reactions occurring in the temperature range of 400–800 °C. The products of the decomposition reaction consist in:

- solid fraction: 20–30% by weight of the initial material, carbonaceous based. It has a good calorific value (8000 kcal/kg) and, therefore, it can be used as a fuel;
- liquid fraction (TAR): 50–60% by weight. The energy content is about 22–23 MJ/kg on a dry basis and 16–18 MJ/kg with 20% water;
- gaseous fraction (pyrolysis gas): it constitutes 15–30% by weight, and is mainly composed of hydrogen, carbon monoxide, carbon dioxide, light hydrocarbons. It has a medium-high calorific value (15–22 MJ/kg) and can be used for various purposes.

The way of carrying out the pyrolytic process determines the balance in production of bio-oil, syngas and carbonaceous residue.

- Conventional pyrolysis takes place at moderate temperatures (around 500 °C), with long reaction times and it results in a balance of the three fractions;
- Carbonisation, the oldest and best known pyrolysis process, has been used for the production of vegetable charcoal since about 2500 years ago. It occurs at temperatures between 300 and 500 °C and only the solid fraction is recovered, the other fractions are minimised;
- Fast pyrolysis, at temperatures from 500 to 650 °C, is addressed to reduce the reforming of intermediate compounds, favouring the production of the liquid fraction up to 70–80% by weight of the incoming biomass;
- Flash pyrolysis is carried out at above 650 °C and with contact times of less than 1 s, in order to favour the production of the gaseous fraction.

Although this technology is well known and largely studied, a number of issues limit its diffusion and application. First of all, the necessity to have well characterised biomass feedstock to have a well controlled system and products quality. The system efficiency depends also on some feed characteristics like dimension of particles, density and humidity, just to mention the simplest ones. This introduces the need of appropriate physical, chemical or biologic pre-treatments that have to be tailored to the used biomass. Moreover, the products of pyrolysis are heat, bio-oil, bio-char and gases. To obtain hydrogen it is necessary a post-treatment of the products in gas and liquid phase by a reforming process. Not the least, for plants of significant size, biomass storing introduces significant fire issues and the biomass has to be collected over a large area. This last introduces additional costs and issues related to biomass transportation, storage and pre-treatment [42,43].

2.4. *Electrolysis*

Electrolysis is an electrochemical technology that uses direct electric current (DC) to drive a chemical reaction along a non-spontaneous reaction path. In particular, water electrolysis allows the split of water (H_2O) into hydrogen and oxygen. If the water electrolysis is done only by RES power, no CO_2 emission will be present. Also this technology has been known for a long time, and is applied on the industrial scale [44–46], usually for production processes requiring high purity hydrogen.

For every kg of hydrogen produced by electrolysis, approximately 8 kg of oxygen is produced using about 9 kg of pure water and consuming about 50–55 kWh of electricity (depending on the electrolysis technology). But, usually, only hydrogen is cost-assessed without considering oxygen; only in recent few years the valorisation of oxygen was considered [22,23,47,48].

Due to the increasing large diffusion of PV and wind technologies converting sun and wind power into electric power, and a vision for the transition to 100% electric energy from RES, the water electrolysis is considered the most suitable way for hydrogen production.

More details about water electrolysis will be discussed in the next sections.

2.5. Direct production by biological processes

Microorganisms were applied for biomass transformation and waste treatment at the dawn of time, but only in the last few centuries this practice evolved and was accurately studied. Nowadays, looking at energy and fuels, the most important products are biogas, alcohol and biofuels.

Green hydrogen can be obtained both by reforming these products, as reported before, and by direct production from organic feedstocks applying selected microorganisms [49–51]. Applicable technologies, according to the specific microorganism, are dark-fermentation, photo-fermentation, photolysis, CO_2 gas-fermentation. In fermentation, hydrogen evolution is the result of microorganism metabolism in anaerobic conditions. Moreover, in some cases CO_2 is a feed for the culture and this approach can be used for carbon dioxide capture and conversion. In photolysis, both bacteria and algae are applied, also in this case in anaerobic conditions, for a direct photolysis of water or for CO_2 fixation process with hydrogen release.

These technologies are very interesting because they offer the opportunity to produce hydrogen from wastewater and other wastes containing organic compounds like sugars, starches, cellulose, acetate, butyrate, lactase. But they suffer from some issues for large-scale application like large volumes of the bio-reactors, the rate of hydrogen production, the control of the microorganism population against mutation and competitor microorganism infection, the pre-treatment of the wastewater to be used [49–51].

In addition to the previous processes for green hydrogen production, other possibilities are under study, like direct solar water splitting [52, 53], and electrochemical reforming of bio-compounds [54,55]. These processes, although promising, are today at low development level and require more research to reach the readiness level for commercialisation; then they are not treated here.

What is interesting to note is that in talking about green hydrogen usually only water electrolysis is considered, this is due to the dependence of electrolysis by electric power availability, a condition that creates a strong link between RES and electrolytic hydrogen.

3. Green hydrogen and RES

To face the pollution and global warming issues a shift towards renewable energy technologies is currently running in the world energy mix. Renewable energy in 2016 accounted for less than 15% of electricity, nowadays it represents 28% of the world's electricity production [56] and 13.8% of the global energy consumption [57]. The progressive increase of the RES power share in the electric grid introduces issues related to the natural discontinuity and fluctuations of RES, that are the object of an increasing number of investigations, and require energy storage systems to mitigate them [9,11,58].

Although there are different possible technologies for energy storage, hydrogen is considered the most suitable choice for massive and long term storage of RES power. This is because hydrogen is an energy vector (fuel) and also a commodity gas and a feedstock for many industrial applications [22,58].

3.1. The current state of green hydrogen in the energy transition

Nowadays, almost all hydrogen is produced by Steam Methane Reforming (SMR). According to the IEA Global Hydrogen Review 2022 [59] about 82% of the hydrogen produced (94 Mt, in 2021) is directly derived from methane, oil and carbon. About 18% is a by-product coming from different production technologies (e.g., naphtha reforming). Therefore, hydrogen produced by low-emission technologies is less than 1 Mt (0.7%), with the majority of this coming from fossil fuels with CCUS (about 0.7%) and only 0.04% (35 kt H_2) coming from renewable electricity via water electrolysis. In 2021, the emissions associated with hydrogen production were more than 900 Mt CO_2 [59]. Hydrogen production costs by these processes are low, \$1-2/kg H_2 for SMR and \$1–1.5/kg H_2 for gasification, respectively.

The main challenge is how to produce hydrogen for today's and future uses at costs that are close to current ones, but without emitting CO_2 into the atmosphere. Within the sector today in the hotspot for green hydrogen application there are: heavy transport, district heating or the decarbonisation of certain industrial processes such as steelmaking.

The two approaches currently able to meet this challenge are “blue hydrogen” and “green hydrogen”.

Blue hydrogen comes mainly from methane steam reforming and, in small part, from gasification. There are a number of pilot plants at the industrial level for the production of blue hydrogen which, with different approaches, have demonstrated the possibility of achieving a total production cost of blue hydrogen at around \$2–2.5/kg H_2 by 2050, with around 90% as the maximum level of carbon dioxide capture generated in the process - corresponding to an emission threshold of around 5 t CO_2/t H_2 [60].

According to the current emission thresholds set by RED II (Renewable Energy Directive II - DIRECTIVE (EU) 2018/2001 [1]), clean hydrogen production must keep its emissions below 3 t CO_2/t H_2.

Under current conditions, blue hydrogen would not be able to meet the limits of RED II if it were produced by an energy mix with a high proportion of fossil fuels. The same is true for hydrogen produced by electrolysis of water not using just RES power, which would be classified as yellow instead of green.

The compliance to RED II is granted only by green hydrogen, including all carbon neutral cycles, processes like pyrolysis and gasification of biomass considered for the recovery of hydrogen from residual biomass and really interesting also as near zero pollution heat and power cogeneration systems with high efficiency. But the plants are complex, small plants are very expensive, the collection of suitable quantities of biomass could be a critical point, and the management of residual wastes is not simple [35–38]. Also steam reforming of biogas, bio-oils, bio-fuels and bio-alcohols is carbon neutral if we consider that the carbon content is coming from carbon bio-fixed through photosynthesis, i.e. if the whole carbon cycle is considered [55]. Moreover, if carbon capture and storage is applied after steam reforming also negative emissions could be obtained [61]. In this case the bio-feedstock comes from a previous treatment of biomass that introduces an additional step, then reducing efficiency and increasing costs. The approach could be interesting for industries where methane steam reforming is already applied for replacing it having a carbon footprint reduction, in this case one issue could be to grant a continuous bio-feedstock supply.

Regarding biological processes, today the mature technologies regard biogas, bio-alcohol production, and bio-fuels. While direct hydrogen production is under development and requires significant research efforts to become competitive.

The production of hydrogen by electrolysis of water using electricity produced from renewable sources, is to date the only technology on the market that can compete for maturity with the steam methane reforming, moreover it fully complies with the emission limits imposed by RED

II: green hydrogen is, therefore, the cornerstone on which the entire European Hydrogen Strategy is focused.

Maybe, in the long term other countries, including the natural gas and oil exporters, will converge on this approach.

3.2. *The essential technology for green hydrogen: the electrolyser*

There are different types of electrolysers, some of them are already on the market and others in the research and development phase. The technologies that are best known to date are listed in Table 2 on the basis of the Technology Readiness Level (TRL) and their current market penetration.

- ***Alkaline electrolyser (AEL)***

  Alkaline electrolysis has already been employed for many years in some industries, such as chlor-alkali production, and have proven to be very reliable.

  The advantages of AEL are their substantial reliability, their high service life (around 60,000 to 100,000 operating hours), and the use of inexpensive raw materials for their manufacture. The disadvantages are the inability to operate at low loads (<20%) - due to the problem of H_2/O_2 mixing, that could generate explosions -, the high footprint, and the high resistive losses in the electrolyte that limit the efficiency to 50-70%, i.e. in energy terms requiring around 50-78 kWh/kgH_2 [62].

  As for other types of electrolysers, the current value of CAPEX has a very wide range, given the low degree of dissemination and industrialisation, which is around $500-1,400 per kW of installed power [62,63].
- ***Polymer electrolyte membrane electrolyser (PEMEL)***

  PEM electrolysers have an electrolyte consisting of a thin polymer membrane that allows H+ ions to pass through it, while the electrodes consist of titanium coated with specific catalysts. PEM electrolysers have a much more compact design, can be operated at low and high loads (>100%), and have a sufficiently high service life (around 50,000 to 80,000 operating hours). However, they require very expensive materials (such as platinum or gold) as coatings to protect the materials from the strongly acidic environment in the cell and, above all, materials such as platinum and iridium for the catalysts. Iridium in particular, one of the rarest chemical elements in the Earth's crust, is feared to become a bottleneck for the entire technology. Today, its cost has risen by 400% compared to the 2015-2020 average, due to its importance in hydrogen production. The CAPEX value for a PEM electrolyser, also with a wide range, is around $1,100-1,800/kW, and is currently higher than AEL [62,63].
- ***Anionic exchange membrane electrolyser (AEMEL)***

  AEM electrolyser brings together the advantages of AEL and PEMEL technologies. The TRL level is still low, due, in particular, to the resistance and lifetime of the membrane. An AEM electrolyser is similar in concept to a PEMEL, but the polymer membrane allows the passage of OH- ions instead of H+. The environment in the cell is alkaline, greatly simplifying the material requirements for catalysts and for chemical corrosion resistance with respect to PEM [64,65]. AEM electrolysers are less evolved in respect to the PEMEL and a number of issues related to the polymeric membrane life and mechanical properties are remaining.
- ***Solid oxide electrolyser cell (SOEC)***

  SOECs, unlike the other electrolysers described above, operate at a high temperature, over 700 °C, with lower energy consumption. The technology is based on a solid oxide ceramic electrolyte, conducting the O^{2-} ions, and uses high-temperature steam to replace water. It is an interesting technology due to its low energy consumption, particularly for those user sectors that have high-temperature steam within their processes, but still suffers from a relatively low technology readiness level, particularly for the lifetime of ceramic oxides [66,67]. Although very promising, solid oxide electrolysis is the most problematic of the technologies related to fuel cells used in reverse mode. The issues are related to materials, lifetime, resilience to temperature fluctuations, number of on-off cycles. The CAPEX requirement for this technology ranges across $2,800-5,600/kW [63].

Based on the above considerations, the efforts for green hydrogen to become widespread and competitive are focusing on the AEL and PEMEL electrolysis technologies. The short- and medium-term goal is to lower the CAPEX – by using less expensive materials and components – and the OPEX – by mainly reducing consumption and electricity costs [59,63,68–70].

In particular, attention is paid to critical raw materials that will play a decisive role in the growth of production costs, especially for those technologies that depend on scarce materials or which are produced in limited geographical areas [17,70–72].

But putting electrolysis in the spotlight of current energy policies at global level brings out new queries related to the global impacts of large scale application of this technology and on the new equilibrium that will be created between countries [73].

4. Some geo-political considerations on the role of hydrogen in the energy transition

4.1. *The potential reshaping of global energy markets by hydrogen*

In recent years, there has been considerable discussion about the geopolitical implications of the energy transition. Researchers have studied how renewable energies and related technologies impact international relations and the economies of individual countries [74–77].

Much of the analysis focused on wind and solar energy, but there is growing interest in the geopolitical implications of large-scale adoption of green hydrogen. Some researchers argue that the growth of green hydrogen within the global economy could lead to such geo-economic and geopolitical changes, in which new scenarios and interdependencies will be shaped [19,78,79].

The consequences will be a different geography of energy trade with the emergence of new centres of geopolitical influence, based on the production and use of hydrogen. In this scenario, traditional oil and gas trade is expected to shrink.

According to the outlook drawn up by IRENA, green hydrogen will cover 12% of global energy consumption by 2050. This will be due to targeted investments in the sector that will increase economic competitiveness and change the current hydrocarbon-based relationships [17].

With regard to future value chains for the production of green hydrogen-based ammonia, methanol and green steel, according to Eicke & De Blasio [80], changes can be expected within the global market that

Table 2
Comparison of water electrolysis technologies.

	Alkaline electrolyser (AEL)	Polymer electrolyte membrane electrolyser (PEMEL)	Solid oxide electrolyser (SOEC)	Anion exchange membrane electrolyser (AEMEL)
TRL	8–9	8	5–6	3–4
Market penetration	Large scale	Rapid expansion	Limited development	Lab scale

will lead some countries to take other positions than they currently have.

With regard to green hydrogen ammonia, countries such as Russia and Egypt, among the world's leading producers, are limited in their ability to produce or distribute green hydrogen at scale; Russia because of infrastructure constraints, and Egypt due to limited freshwater availability. Whereas Mexico, Spain or Thailand, which have a good resource endowment and high economic potential, have a high capacity for growth.

Changes are also expected with respect to the production of green hydrogen-based methanol. Four countries - Saudi Arabia, Trinidad and Tobago, Oman and the United Arab Emirates - with a total world market share of 39%, are limited in their potential for green methanol production. The consequence of this will be that these countries will have to rely on imports to maintain their position in the future green methanol market. On the contrary, countries such as New Zealand, Norway or Chile, which currently do not have significant market shares in this sector, could, given their resources and economic conditions, sharpen their positions.

The production of green steel will also bring about changes in the world market for this product. China, the current largest producer globally, will continue to maintain its leadership. The other major steel producing countries, such as India, Japan and Russia, will face a considerable contraction of resources, increasing the import of green hydrogen. Furthermore, other countries such as the Baltic States, Morocco, Turkey and Thailand, which have good resource endowments and favourable economic conditions, could try to attract green steel production.

4.2. The issue of renewable fresh water

One issue that is at the centre of the debate on what the impacts of a widespread deployment of green hydrogen might be concerns water resources. Researchers from various scientific fields are comparing and assessing the effect of green hydrogen on the global water resource. The key question is: will there be enough water to meet our future demand for green hydrogen?

The views and scenarios that can be drawn from the literature and reports by various international bodies make different predictions. A research conducted by Newborough & Cooley [81] states that if all current fossil fuels used were converted to green hydrogen, the need for water for electrolysis would amount to 1.8% of the current global water consumption. Furthermore, they point out two aspects that need to be considered: i) the increase in demand would be outweighed by the water savings achieved by not having to produce fuels from oil or biomass and by reducing the use of conventional thermal power plants; ii) when green hydrogen is oxidised by combustion plants and fuel cells, the same amount of water as originally consumed by electrolysis is released into the environment.

A consensus on the low impact of green hydrogen production on water resources can be found in the work of Beswick et al. [82], as all future hydrogen will be produced using renewable energy sources such as wind and solar, which have little or no water consumption. However, even if the consumption of water to produce hydrogen is less than that required to produce energy from fossil fuels, concerns over the scarcity of fresh water call for a reduction in the use of water sources. They see a feasible and concrete solution in utilising the Earth's vast salt water resources, which can further reduce the water footprint of hydrogen.

Many researchers in the field believe that salt water is a potential optimal solution because it would prevent hydrogen production from contributing to the increase in demand for fresh water leading to the depletion of sources, along with other factors such as population growth and climate change.

Some of them, however, highlight the technical challenges that still need to be addressed in order for this technology to be fully deployed. From this point of view, Mohammed-Ibrahim & Moussab [83] focus on the need for robust and efficient electro-catalysts to prevent chloride corrosion and the formation of precipitates on the electrode surface. Gao et al. [84] emphasise the importance of developing highly active and selective catalysts for the electrolysis of seawater in the presence of contaminants such as metal ions, chloride and bio-organisms.

While, regarding seawater reverse osmosis (SWRO) coupled with proton exchange membrane (PEM) electrolysis, in addition to the presence of technical issues, Khan et al. [85] noted that there are limited economic and environmental incentives in pursuing R&D on the up-coming technology of direct seawater electrolysis.

The issues and development of these specific technologies will be addressed in more technical detail in the following paragraphs.

For Pflugmann & De Blasio [78] the issue of water resources is particularly important for countries where fresh water is scarce. The authors focus on the case of Saudi Arabia, which can rely on an abundance of renewable energy but limited water resources. It would be possible to address this shortcoming by desalinating sea water. To produce an amount of hydrogen equivalent to about 15% of Saudi Arabia's annual oil production, 26 million tonnes of renewable hydrogen would be required per year. This amount of hydrogen would require 230 million m^3 of fresh water. In order to obtain the freshwater Saudi Arabia's needs, at least five desalination plants would need to be added to its existing 31 large desalination plants.

Referring to Africa, the World Energy Council [86] also points out that, in the short term, access to water suitable for electrolysers might require upstream investments to desalinate water in some parts of the continent. This would entail further investments, particularly in water-stressed areas, and the improvement of suitable technologies.

Terlouw et al. [87] argue that the large-scale spread of hydrogen production in combination with other factors - such as additional water demand due to climate change, population growth, economic development and agricultural intensification - could lead to water scarcity. They refer to what is already happening on the islands of Crete and Tenerife. Lebrouhi et al. [88] also take the issue of water scarcity into account in their analysis, as it is one of the biggest problems in the world today. In their view, it is crucial that policies for the development of green hydrogen in some countries include an increase in the storage capacity of water flows (dams and local rainwater storage systems). At the same time, it is necessary to develop strategies for the optimal management of available stocks, create tools for recycling the resource to optimise its use and avoid waste, control water pollution and develop seawater desalination plants.

Woods and al. [89] suggest using wastewater effluents for water electrolysis, referring to the case of Australia. According to these authors, unused tertiary effluents have significant potential to lead to green hydrogen production at scale. Lower investments are required compared to seawater desalination systems. In addition, they constitute a security in water supply compared to stormwater. In this way, water for hydrogen is not in direct competition with existing needs and does not entail an additional water stress.

The World Economic Forum [90] carried out an analysis estimating what the impacts on water resources could be from the transition to a hydrogen economy. The research was carried out by analysing data, concerning energy demand and water withdrawal, from 135 countries. According to the estimates derived from the analysis, only nine of the 135 countries studied would need to increase their current freshwater withdrawal by more than 10% to fully switch to hydrogen-based energy, while 62 countries would need to increase their freshwater withdrawal by less than 1%. The average value for all 135 countries is 3.3%. The increased demand for water resources would affect desert countries with low annual rainfall, such as Qatar, Israel, Kuwait or Bahrain. Or, small island states, such as Singapore, Trinidad and Tobago or Malta, which would also experience difficulties due to limited freshwater reserves. For instance, Singapore, which is heavily dependent on neighbouring Malaysia for freshwater resources, is expected to increase the water it uses to convert energy into hydrogen by about 46.4%.

According to analysts at the World Economic Forum, the hydrogen economy can open up interesting prospects not only for the energy system, but also for addressing the issue of water scarcity. Countries with water shortages, such as Singapore and Qatar, are unlikely to be able to produce their own hydrogen and will therefore have to rely on imported hydrogen. This, which can certainly be seen as a disadvantage, will however allow these countries to use the water produced by the conversion of hydrogen back into energy, either through combustion or fuel cell technology, and to reuse this high-purity water locally.

4.3. The water-hydrogen-water cycle

As reported in the previous section, although nowadays hydrogen is largely used in a number of industrial processes only a small percentage of it is today produced by electrolysis. The transition to green hydrogen, obtained by RES electricity-based electrolysis or other green routes, will introduce a competitor to fossil sources of hydrogen used as feedstock, i.e. it will impact on the 82% of today's hydrogen production and, consequently, on the prices of fossil raw materials (oil, natural gas, carbon). In the same way, hydrogen is an energy vector, and it can partially or totally replace the conventional fossil fuels in transportation and home heating and cooking. In this last case, green hydrogen will be a totally new actor in a market today dominated by fossil fuels and under transition to electric mobility [91].

Hydrogen will therefore be both a market competitor and a market coupling actor, introducing a novel paradigm in market management and pricing. Based on this, a coupling mechanism between the green hydrogen market, carbon trading market, and electricity market has been formulated [92].

Green hydrogen production and diffusion are inevitable processes that will have both positive and negative impacts, as described in the literature we have cited. According to some researchers, the impact on water sources is one of these factors. This concern stems from the assumption that fresh water used to produce hydrogen will be diverted from other essential applications or sectors for social and economic well-being. In this situation, water sources could be managed unfairly, triggering speculation.

Based on this assumption, water is only and exclusively consumed. It does not take into account the by-product water resulting when hydrogen is used to generate electricity, as the World Economic Forum [90], for example, pointed out.

By burning hydrogen for energy generation pure water is obtained, both using fuel cells or direct combustion (internal combustion engines, turbines, heaters). As well as the fresh water used for electrolysis comes back as pure water (water-hydrogen-water cycle), more in general - whatever is the green hydrogen source (sea water, waste water, biomass) - the hydrogen applied as a fuel will return pure water. This water can be recovered and reused, although a part of it will be in the form of vapour and then it will be dispersed in the atmosphere.

In this way, by using green hydrogen it is possible to recover a part of the fresh water consumed for human activities, such as the water used for agriculture (irrigation) or urban purposes (Fig. 1).

Water can be recovered passing through hydrogen by pyrolysis and gasification of biomasses that are of great interest for valorising residual and waste biomass, and contributing also to waste management in a circular economy vision.

By producing bio-hydrogen with microorganisms, it is possible to treat waste water and create hydrogen at the same time. In addition, hydrogen combustion produces pure water.

Hydrogen by-products from some industrial production processes, such as chlor-alkali, or the steam reforming of biogas and bio-alcohol can also be a source of pure water.

In summary, not only does green hydrogen has no impact on the freshwater global availability, but it allows recovery of part of the fresh water coming from human activities in the form of wastewater or biomass.

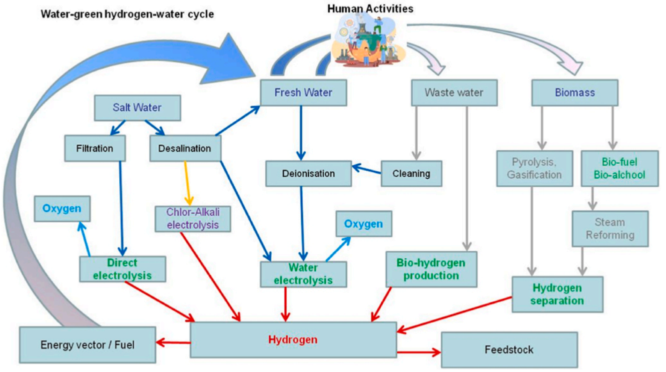

Fig. 1. The water-green hydrogen-water cycle. Only water (blue arrows), hydrogen (red arrows) and oxygen paths (light blue arrows) are reported.

Wastewater is a great opportunity for hydrogen production; nowadays, the possible approaches discussed are two. The first one is strictly related to the efficiency of the wastewater treatment plant, the second one is the approach to bio-hydrogen production. In particular:

a) the treatment of wastewater uses air as an oxidant agent; this because anaerobic treatment is a slow process, produces bad smells, and it needs post treatments of the exit water. Aerobic treatment can be done in open pools, it is faster, although it requires more energy, and the addition of oxygen to this air flow increases the treatment efficiency, reduces the treatment time and, consequently, the costs. So that it is preferred although in this case there is emission of CO_2, while in anaerobic digestion biogas can be produced. City water treatment plants are soil and energy consuming. By coupling an electrolyser for green hydrogen production, it is possible to use the by-product oxygen to speed up the water treatment, and treated water coming from the plant can be easily filtered, deionised and used as a feedstock for the electrolysers [81,93,94]. By this approach, green hydrogen production can be linked to the existing city wastewater treatment plants.
b) the bio-hydrogen approach is based on dark and photo-fermentation processes of the wastewater, or bio-supported electrolysis [95,96]. This approach is in the early stage of development and aims at reducing the energy cost of water treatment by valorising the by-products, in this case hydrogen. The main issue related to this approach is the control of the wastewater composition. This is because the microorganism needs substrate having compositions well inside defined ranges. So that this approach is more suitable for industry applications, especially the food industry, where the produced wastewater has sufficiently stable characteristics [97,98].

As already mentioned, another opportunity is the sea water. In conventional approach, the desalinated sea water can be used as a feedstock for electrolysis, but this creates a conflict with desalination addressed to other purposes [78,86,87]. Direct seawater electrolysis is under development, and a number of research papers proposed the possibility of applying it for producing hydrogen/oxygen [83–85,99], but this entails facing some technological challenges. Electrolysis applied to solutions of sodium chloride is a well-known industrial process for production of chlorine, sodium hydroxide and sodium hypochlorite, where hydrogen is a by-product. Industrial processes use high salt concentrations and different electrolyte solutions at anode and cathode to maximise the production of chlorine, sodium hydroxide and sodium hypochlorite. In direct seawater electrolysis to hydrogen/oxygen, oxygen evolution is in competition with chlorine evolution. Consequently, the challenge is to develop new catalysts for avoiding the evolution of chlorine, which is toxic, and obtaining exclusively oxygen evolution [83–85,99].

But there is also the possibility to apply electrolysis for producing hydrogen and sodium hypochlorite at low concentrations, without the necessity of producing oxygen [100]. Not the least, another alternative is to use the by-product of desalination. For example, about 70% of desalinated water is extracted from sea water by reverse osmosis [85, 101], a concentrated solution of salt is the waste of this process and, normally, it is not used and released in the environment. In principle, this brine can be used as chlor-alkali process feedstock, producing hydrogen and added-value chemicals (soda, chlorine, sodium hydroxide). Using this system, desalination for urban purposes and electrolytic hydrogen production do not "conflict". Coming back to previous geopolitical considerations, using Saudi Arabia as example, before planning the installation of new desalination plants for hydrogen production, it could be possible to apply the brine exit from the existing desalination utilities by an appropriate adaptation of the existing chlor-alkali technology.

Based on these considerations and looking at the future world trade market of hydrogen, it can be claimed that if the water-hydrogen-water cycle is implemented in the same location (local environment), no water consumption will rise up. On the contrary, the result will be different if hydrogen is moved from the production site to another side, especially for countries having a water stress issue. In this case, we have to rethink the "hydrogen transport" as "water transport" and, consequently, "world hydrogen trade" as "world water trade". As a consequence, for countries with existing (or planned) "water stress", importing hydrogen might be more attractive than exporting hydrogen. Indeed, by importing hydrogen, these countries will also acquire pure water, which has dual utility: energy and water.

This does not mean that "a hydrogen water issue" does not exist, but that a cunning management of the question will minimise the environmental impacts. Moreover, we need to be aware that moving billions of tons of water/hydrogen from one continent to another could have an effect on the environment. For example, coming back to the Arabic Gulf case, the realisation of many desalination plants dedicated to hydrogen production is requested, and these desalination plants will release waste concentrated brine in the local environment [102]. As evidenced in literature [102–104], this release is potentially harmful for the environment because it can has a negative impact on the aquatic ecosystem and related human activities.

In summary, if well managed, green hydrogen will not reduce the availability of the fresh water for urban uses. On the contrary, if pure water from green hydrogen oxidation is collected, freshwater availability will increase. This feature opens up new opportunities in local water scarcity management.

5. Distributed electrolysis and valorisation of by products

What we would like to emphasise is that much of the scientific literature and the institutional reports we have referred to - both in technical, economic and geopolitical terms - concern large-scale, centralised hydrogen production. The main R&D and financial efforts are focused on this category of systems and technologies.

These researches usually look at grid stabilisation, wind energy farms, electric market management and large scale hydrogen production for industry, transportation and fuel networks [105–107].

This centralised production approach creates an additional issue: hydrogen transportation and distribution, with related safety issues and cost increases. Moreover, as highlighted in the previous section, *trans*-continental hydrogen trade will move large quantities of water with possible unforeseen effects.

The cost increases due to transportation was already considered for car refuelling stations, and solutions like local generation, on Megawatts' scale, or the localisation of the refuelling station near wind farms or industries that have hydrogen as a by-product have been investigated [108–111].

More recently, several projects have been undertaken to transport hydrogen from production sites via existing natural gas pipelines or the construction of new "hydrogen pipelines". For instance, in Europe a large research project for this purpose was launched by IPCEI (Important Project of Common European Interest) funds. Looking at centralised hydrogen production (see **Fig. 2**), it also incurs energy and opportunity losses. In fact, long range transportation requires infrastructures and energy. The energy used for transportation reduces the system efficiency and increases the hydrogen costs. Moreover, centralised production could not be really useful for by-product valorisation, with a loss of market opportunities and, again, an increase in hydrogen cost. Not least, centralised green hydrogen production by electrolysis, as usually considered, requires large-scale clean water availability close to the production site.

Renewable electricity technologies, like PV and wind generators, allow distributed electricity generation. They are simple, can be applied widely and nowadays the produced energy has reached costs that are competitive with centralised production by fossil fuels also in small-scale applications. In the same way, distributed hydrogen production by electrolysis is an additional opportunity for hydrogen's wide applications.

Compared to centralized production, distributed hydrogen production offers a number of opportunities related to both the direct application of oxygen and/or heat by-products, increased efficiency through the absence (or limitation) of transportation requirements, and improved energy utilization through by-product valorisation.

5.1. *Oxygen valorisation*

As already highlighted, by water electrolysis for each kg of hydrogen we also produce 8 kg of high purity oxygen without any additional device and energy cost. In addition, there is no variation of the plant's CAPEX and OPEX. Obviously, if oxygen is not used in real time and its storage is requested, an additional expenditure - with respect to the case of the system with oxygen released in the atmosphere - is expected for the compression, or liquefaction, and storage of oxygen. As a result, at a very low oxygen price, the valorisation of this by-product will reduce hydrogen production costs.

This aspect was already considered by some authors in the financial analysis of electrolysis plants using photovoltaic roof installations as renewable electric power supply [23,48], and by Kato and al. [47] for reducing PEM electrolysis hydrogen production costs. This configuration is very interesting for distributed hydrogen production when the plant is dedicated to an oxygen user. This is because the user will become an "oxygen prosumer" (i.e. producer and user at the same time [112]) avoiding partially (or totally) buying oxygen and related transportation costs. This also reduces the oxygen storage costs because the user can store oxygen at a lower pressure and for a limited time. As expected, the higher the oxygen market price, the larger the advantage. So, for companies using low quality oxygen the advantage will be limited, while for

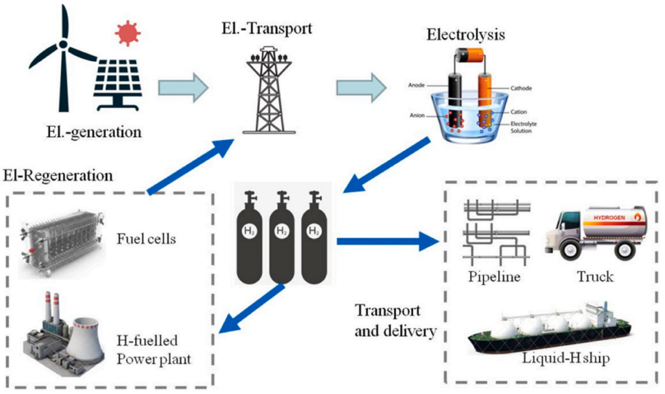

Fig. 2. Scheme for centralised hydrogen production and distribution. Picture realised by free images from VectorSquid.com and Vecteezy.com.

hospitals using high-quality oxygen the advantage will be very interesting. This is without quantifying the increased resilience against supply interruptions and sharp price variations due to self production, as well as the reduced footprint associated with oxygen production by conventional centralised methods and oxygen delivery to the user.

5.2. *Heat valorisation*

Electrolysers have limited energy conversion efficiency: 55-80% depending on technology and balance of plant optimisation. This means that there is waste heat that could be valorised. Unfortunately, excluding the solid oxide technology (700-800 °C), this heat is released at low temperatures (50-80 °C) and is not of real interest for industries. Again, in distributed hydrogen production, this low value heat can be used for home heating and district services, especially if this heat is coupled with the heat output of a combined heat and power (CHP) generation unit using hydrogen as a fuel (fuel cells or internal combustion engine based) [20,24,113,114].

Basically, we can envisage a homeowner producing electricity, heat and hydrogen. Thus, extending the current prosumer concept, often associated with electricity. In the same way, it is possible to foresee RES/hydrogen-based CHP services for renewable energy communities, supplemented by hydrogen refuelling infrastructures for the community's own cars and small service vehicles.

5.3. *Water recycling*

Water is not a by-product of hydrogen production, but a by-product of hydrogen applications for energy generation. Consequently, in distributed hydrogen production and application, water used for electrolysis can be recovered from fuel cells, internal combustion engines, CHP systems and hydrogen-fueled condensing boilers, according to the hydrogen application. This water can be reused in electrolysis after deionisation, thus no water is consumed in the cycle.

At city level, we can consider the utilization of a futuristic hydrogen city gas distribution network replacing today's natural gas distribution network. In this future hydrogen city we can foresee a distribution of hydrogen by pipelines, like for methane today. In this case, by condensing the water produced by hydrogen-fueled devices, it will be possible to cut the consumption of drinkable water applied for other purposes like home cleaning, cloth washing and watering houseplants. This reproduces in small scale the concept previously exposed for the world trade, moving hydrogen means moving water.

Not the least, it is possible to produce green hydrogen using city wastewater as previously discussed. Production of domestic (on-site) hydrogen from wastewater will also be possible in the near future.

5.4. *Polygeneration*

By unifying the previous points, it is possible to conceive a RES-based polygeneration concept involving power, heat, hydrogen and oxygen for distributed generation of energy and fuel, with oxygen valorisation and water recycling. A simple scheme is shown in Fig. 3. This distributed generation approach could be applied to industries, cities, neighbourhoods and energy communities for reducing, as close as possible to zero, the environmental impact of human activities.

As seen in Fig. 3, the proposed system arrangement considers RES power generation, a hybrid configuration of batteries/hydrogen for the energy storage system, and also the possibility to exchange both the electricity and hydrogen with the local grids. It can be envisaged that the system can work also in an island configuration. Water is recirculated between electrolysis and CHP units to minimise the freshwater use and, if of interest, also water condensed from heat/cool services can be reused in the electrolyser. The CHP unit is not necessarily based on fuel cells, it could also be based on a hydrogen-fueled internal combustion engine or turbine, depending on the user convenience in regards to desired energy balance. It should be noted that hydrogen could also be sold as fuel or feedstock for a local enterprise, although this path is not reported in the figure. If the oxygen is not used, it could be sold or reused in the CHP unit to increase its efficiency, but also released in the atmosphere.

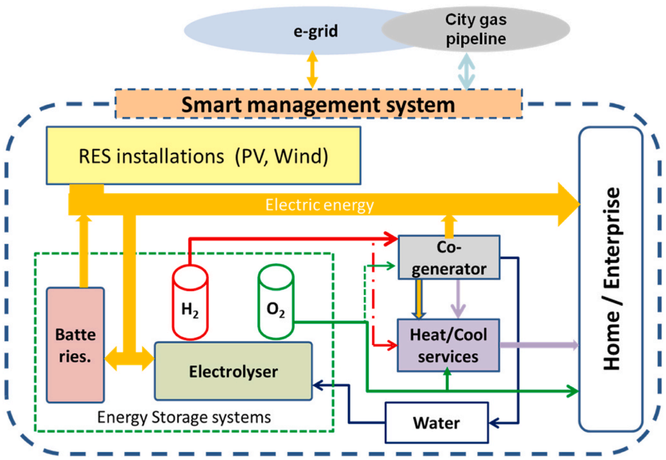

Fig. 3. Scheme of proposed polygeneration system with related energy and matter flows.

In summary, RES-based distributed generation of hydrogen is able not only to reduce the necessity of infrastructure for hydrogen transportation and distribution, but also to supply additional services/feedstocks. This approach allows to minimise the footprint and can be used by single industries, industrial districts, cities and small communities down to single homeowners, because it allows the local application of by-products and minimises emissions.

Technologies for distributed green hydrogen generation are ready. The remaining issues are mainly related to regulatory and economic aspects. In particular:

- High CAPEX - Like for large scale centralised production, a cost reduction for electrolysers is requested, this is more significant for small-scale electrolysis plants.
- Regulations about flammable gas storage in urban environments - In many countries, like Italy, there are strong limitations on the volume and pressure of flammable gases that could be stored (in liquid or compressed form) in, or near, a building. This is a strong limitation for energy communities, single homeowners and small craft enterprises.
- Regulation about refuelling points - Based on the information gathered, no country allows/foresees the installation of hydrogen/methane refuelling points close to residential buildings.
- Adaptation to hydrogen of gas-based home appliances - Natural gas cookers, boilers and other utilities admit just a few percentages of hydrogen blended with natural gas. New burners must be produced for hydrogen rich blends or pure hydrogen.
- City gas pipeline networks and related regulation - Regulation is needed both for methane/hydrogen blend distribution and for allowing prosumers to inject the produced hydrogen into the city gas network. Many pipelines are not suitable for hydrogen blends.

6. Conclusions

The aim of this research was to identify possible approaches and solutions for a broad deployment and applicability of green hydrogen, by looking at all the technologies today available and ready for large-scale applications.

Unlike other analyses conducted in the literature, the focus was not on the cost of hydrogen or the analysis of the necessary infrastructures.

Instead, an analysis of the possible technical-economic and social issues correlated with the green hydrogen economy was conducted.

Green hydrogen production technologies, the possibility of valorising by-products and wastes, and some geo-political aspects related to the water resource, the most abundant reserve of hydrogen on Earth, were examined.

Green hydrogen can be produced in different ways, not only by electrolysis. This introduces a revolution to existing energy and social policies as it links together markets and social issues that are currently only partially connected and apparently independent of each other. This is because hydrogen is not only energy but also a feedstock and also generate water by oxydation. When studying the hydrogen trade and related new economic international relationships and equilibriums, it is necessary to remember that hydrogen means "water former". Then, hydrogen is water neutral if locally generated and used, but it is not the same when hydrogen is produced for global trading and moved for thousands of kilometres for its application. Not least, by passing through hydrogen we can convert waste water and sea water into pure water, valorising these resources.

Therefore, in the political management of the transition from the current economy based on fossil fuels to that based on hydrogen and electricity from renewable sources, it is necessary to have a very broad vision of all the possible technologies and how these can correlate with each other.

Similarly, a narrow view of setting out the repercussions that might result from the hydrogen economy can lead to a focus on secondary problems while neglecting real and potential ones.

Based on the above considerations, the authors believe that a correct green hydrogen economy cannot be conducted without a balance between centralised and distributed production, and between global environmental interests and local social interests. Surely, centralised massive hydrogen production is necessary for industry decarbonisation and stabilisation of an electric grid dominated by RES power. Distributed hydrogen production is a powerful tool for maximising the social utility of the hydrogen economy, reducing household energy bills, increasing energy system efficiency and resilience, and reducing the environmental impact of city services. All these aspects must be considered in future energy policies.

We believe that energy policies based on concepts such as polygeneration, valorisation of by-products and waste, the balance between new and old technologies, without any a priori exclusions, could have a much more significant environmental, economic and social impact than policies based on a few technologies and which discredit a priori alternative solutions.

CRediT authorship contribution statement

Gaetano Squadrito: Conceptualization, Investigation, Methodology, Resources, Writing – original draft. **Gaetano Maggio:** Conceptualization, Investigation, Methodology, Formal analysis, Writing – review & editing. **Agatino Nicita:** Conceptualization, Investigation, Methodology, Resources, Writing – review & editing.

Declaration of competing interest

G. Squadrito, G. Maggio, and A. Nicita, submitting the paper **"The green hydrogen revolution"**, declare that there are not conflict of interest and that no funding has been received for this work from third parties.

The authors declare also that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, Orkesterjournalen L 328 (2018) 82–209, 21.12, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN.

[2] DNV, Energy Transition Outlook 2022 - a global and regional forecast to 2050, Report available at: https://www.dnv.com/energy-transition-outlook/index.html, 2022.

[3] Communication from the commission to the European parliament, the European Council, the Council, May 18, 2022, COM, the European Economic and Social Committee and the Committee of the Regions 230 (2022). final – REPowerEU Plan, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0230.

[4] J. Lui, W.-H. Chen, D.C.W. Tsang, S. You, A critical review on principles, applications, and challenges of waste-to-hydrogen technologies, Renew. Sustain. Energy Rev. 134 (2020), 110365.

[5] T. Lepage, M. Kammoun, Q. Schmetz, A. Richel, Biomass-to-hydrogen: a review of main routes production, processes evaluation and techno-economical assessment, Biomass Bioenergy 144 (2021), 105920.

[6] IEA, Renewables 2022 (Updated January 2023), IEA, Paris, 2022. https://www.iea.org/reports/renewables-2022.

[7] IEA, Renewable Electricity, IEA, Paris, 2022. https://www.iea.org/reports/renewable-electricity.

[8] IEA–PVPS, Trends in Photovoltaic Applications 2021, 2021. Report IEA-PVPS T1-41:2021, https://iea-pvps.org/wp-content/uploads/2022/01/IEA-PVPS-Trends-report-2021-4.pdf.

[9] L. Gan, P. Jiang, B. Lev, X. Zhou, Balancing of supply and demand of renewable energy power system: a review and bibliometric analysis, Sustain. Futures 2 (2020), 100013.

[10] C. Kockel, L. Nolting, J. Priesmann, A. Praktiknjo, Does renewable electricity supply match with energy demand? – a spatio-temporal analysis for the German case, Appl. Energy 308 (2022), 118226.

[11] O. Smith, O. Castel, E. Farcot, R.D. O'Dea, K.I. Hopcraft, The effect of renewable energy incorporation on power grid stability and resilience, Sci. Adv. 8 (2022) 6734.

[12] G. Plessmann, M. Erdmann, M. Hlusiak, C. Breyer, Global energy storage demand for a 100% renewable electricity supply, Energy Proc. 46 (2014) 22–31.

[13] M. Stecca, L. Ramirez Elizondo, T.B. Soeiro, P. Bauer, P. Palensky, A comprehensive review of the integration of battery energy storage systems into distribution networks, IEEE Open J. Ind. Electron. Soc. 1 (2020) 46–65.

[14] A. Hiesl, A. Ajanovic, R. Haas, On current and future economics of electricity storage, Greenhouse Gas. Sci. Technol. 10 (6) (2020) 1176–1192.

[15] A.R. Dehghani-Sanij, E. Tharumalingam, M.B. Dusseault, R. Fraser, Study of energy storage systems and environmental challenges of batteries, Renew. Sustain. Energy Rev. 104 (2019) 192–208.

[16] Hydrogen Council, Path to hydrogen competitiveness: a cost perspective, California. www.hydrogencouncil.com, 2020.

[17] IRENA, Geopolitics of the Energy Transformation: the Hydrogen Factor, International Renewable Energy Agency, Abu Dhabi, 2022. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf?rev=1cfe49eee979409686f101ce24ffd71a.

[18] Hydrogen Council, Hydrogen Insights 2022 - an Updated Perspective on Hydrogen Market Development and Actions Required to Unlock Hydrogen at Scale, McKinsey & Company, 2022. September 2022, https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf.

[19] M. Noussan, P.P. Raimondi, R. Scita, M. Hafner, The role of green and blue hydrogen in the energy transition – a technological and geopolitical perspective, Sustainability 13 (1) (2021) 298.

[20] G. Squadrito, L. Andaloro, M. Ferraro, V. Antonucci, Hydrogen fuel cells technology – chapter 16, in: A. Basile, A. Iulianelli (Eds.), Advances in Hydrogen Production, Storage and Distribution, Woodhead Publishing Limited, Cambridge, UK, 2014.

[21] G. Squadrito, G. Giacoppo, O. Barbera, F. Urbani, E. Passalacqua, L. Borello, et al., Design and development of a 7kW polymer electrolyte membrane fuel cell stack for UPS application, Int. J. Hydrogen Energy 35 (18) (2010) 9983–9989.

[22] G. Maggio, A. Nicita, G. Squadrito, How the hydrogen production from RES could change energy and fuel markets: a review of recent literature, Int. J. Hydrogen Energy 44 (23) (2019) 11371–11384.

[23] A. Nicita, G. Maggio, A.P.F. Andaloro, G. Squadrito, Green hydrogen as feedstock: financial analysis of a photovoltaic-powered electrolysis plant, Int. J. Hydrogen Energy 45 (20) (2020) 11395–11408.

[24] G. Squadrito, G. Maggio, A.P.F. Andaloro, A. Nicita, Distributed hydrogen generation & energy communities for a zero-emission energy economy, in: E-Book of Abstracts of HYdrogen POwer THeoretical and Engineering Solutions International Symposium - HYPOTHESIS XV, On-Line Conference, 2020, pp. 18–19. June 3-5.

[25] A. Kovac, M. Paranos, D. Marcius, Hydrogen in energy transition: a review, Int. J. Hydrogen Energy 46 (16) (2021) 10016–10035.

[26] I. Dincer, Green methods for hydrogen production, Int. J. Hydrogen Energy 37 (2) (2012) 1954–1971.

[27] L. Mosca, J.A. Medrano Jimenez, S.A. Wassie, F. Gallucci, E. Palo, M. Colozzi, et al., Process design for green hydrogen production, Int. J. Hydrogen Energy 45 (2020) 7266–7277.

[28] M. Yu, K. Wang, H. Vredenburg, Insights into low-carbon hydrogen production methods: green, blue and aqua hydrogen, Int. J. Hydrogen Energy 46 (41) (2021) 21261–21273.
[29] E. Meloni, M. Martino, V. Palma, A short review on Ni based catalysts and related engineering issues for methane steam reforming, Catalysts 10 (3) (2020) 352.
[30] T.L. LeValley, A.R. Richard, M. Fan, The progress in water gas shift and steam reforming hydrogen production technologies - a review, Int. J. Hydrogen Energy 39 (30) (2014) 16983–17000.
[31] A. Haryanto, S. Fernando, N. Murali, S. Adhikari, Current status of hydrogen production techniques by steam reforming of ethanol: a review, Energy Fuel. 19 (2005) 2098–2106.
[32] A. Iulianelli, S. Liguori, J. Wilcox, A. Basile, Advances on methane steam reforming to produce hydrogen through membrane reactors technology: a review, Catal. Rev. 58 (1) (2016) 1–35.
[33] A. Midilli, H. Kucuk, M.E. Topal, U. Akbulut, I. Dincer, A comprehensive review on hydrogen production from coal gasification: challenges and Opportunities, Int. J. Hydrogen Energy 46 (50) (2021) 25385–25412.
[34] A.W. Bhutto, A.A. Bazmi, G. Zahedi, Underground coal gasification: from fundamentals to applications, Prog. Energy Combust. Sci. 39 (1) (2013) 189–214.
[35] L. Cao, I.K.M. Yu, X. Xiong, D.C.W. Tsang, S. Zhang, J.H. Clark, et al., Biorenewable hydrogen production through biomass gasification: a review and future prospects, Environ. Res. 186 (2020), 109547.
[36] H. Song, G. Yang, P. Xue, Y. Li, J. Zou, S. Wang, et al., Recent development of biomass gasification for H2 rich gas production, Appl. Energy Combust. Sci. 10 (2022), 100059.
[37] M. Prestipino, A. Piccolo, M.F. Polito, A. Galvagno, Combined bio-hydrogen, heat, and power production based on residual biomass gasification: energy, exergy, and renewability assessment of an alternative process configuration, Energy 15 (2022) 5524.
[38] M. Prestipino, F. Salmeri, F. Cucinotta, A. Galvagno, Thermodynamic and environmental sustainability analysis of electricity production from an integrated cogeneration system based on residual biomass: a life cycle approach, Appl. Energy 295 (2021), 117054.
[39] R.W. Breault, Gasification processes old and new: a basic review of the major technologies, Energies 3 (2) (2010) 216–240.
[40] S. Heyne, T. Liliedhal, M. Maklund, Biomass Gasification – A Synthesis of Technical Barriers and Current Research Issues for Deployment at Large Scale, Technical report, Energy Technology Data Exchange (ETDE) World Energy Base (ETDEWEB), 2013, https://www.osti.gov/etdeweb/biblio/22138974.
[41] Y. Yun (Ed.), Gasification for Low-Grade Feedstock, IntechOpen, London, UK, 2018, 2018, https://www.intechopen.com/books/6349.
[42] T.Y.A. Fahmy, V. Fahmy, F. Mobarak, M. El-Sakhawi, R.E. Abou-Zeid, Biomass pyrolysis: past, present, and future, Environ. Dev. Sustain. 22 (2020) 17–32.
[43] X. Hu, M. Gholizadeh, Biomass pyrolysis: a review of the process development and challenges from initial researches up to the commercialisation stage, J. Energy Chem. 29 (2019) 109–143.
[44] S.A. Grigoriev, V.N. Fateev, D.G. Bessarabov, P. Millet, Current status, research trends, and challenges in water electrolysis science and technology, Int. J. Hydrogen Energy 45 (49) (2020) 26036–26058.
[45] E. Zoulias, E. Varkaraki, N. Lymberopoulos, C.N. Christodoulou, G.N. Karagiorgis, A review on water electrolysis, Cyprus J. Sci. Technol. 4 (2) (2004) 41–71.
[46] M. Chatenet, B.G. Pollet, D.R. Dekel, F. Dionigi, J. Deseure, P. Millet, et al., Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments, Chem. Soc. Rev. 51 (11) (2022) 4583–4762.
[47] T. Kato, M. Kubota, N. Kobayashi, Y. Suzuoki, Effective utilization of by-product oxygen of electrolysis hydrogen production, Energy 30 (2005) 2580–2595.
[48] G. Maggio, G. Squadrito, A. Nicita, Hydrogen and medical oxygen by renewable energy based electrolysis: a green and economically viable route, Appl. Energy 306 (2022), 117993.
[49] N. Akhlaghi, G. Najafpour-Darzi, A comprehensive review on biological hydrogen production, Int. J. Hydrogen Energy 45 (43) (2020) 22492–22512.
[50] H. Argun, F. Kargi, Bio-hydrogen production by different operational modes of dark and photo-fermentation: an overview, Int. J. Hydrogen Energy 36 (13) (2011) 7443–7459.
[51] P. Mishra, S. Krishnan, S. Rana, L. Singh, M. Sakinah, Z. Ab Wahid, Outlook of fermentative hydrogen production techniques: an overview of dark, photo and integrated dark-photo fermentative approach to biomass, Energy Strategy Rev. 24 (2019) 27–37.
[52] M.G. Walter, E.L. Warren, J.R. McKone, S.W. Boettcher, Qixi Mi, E.A. Santori, et al., Solar water splitting cells, Chem. Rev. 110 (11) (2010) 6446–6473.
[53] S. Chu, W. Li, Y. Yan, T. Hamann, I. Shih, D. Wang, et al., Roadmap on solar water splitting: current status and future prospects, Nano Futures 1 (2017), 022001.
[54] L. Yuan, Y. Chen, C. Song, T. Ye, Q. Guo, Q. Zhu, et al., Electrochemical catalytic reforming of oxygenated-organic compounds: a highly efficient method for production of hydrogen from bio-oil, Chem. Commun. 41 (2008) 5215–5217.
[55] A.A. Lemonidou, P. Kechagiopoulos, E. Heracleous, S. Voutetakis, Steam reforming of bio-oils to hydrogen – chapter 14, in: K.S. Triantafyllidis, A. A. Lappas, M. Stöcker (Eds.), The Role of Catalysis for the Sustainable Production of Bio-Fuels and Bio-Chemicals, Elsevier, Amsterdam, 2013, pp. 467–493, 978-0-444-56330-9.
[56] D. Zhang, C. Rong, T. Ahmad, H. Xie, H. Zhu, X. Li, et al., Review and outlook of global energy -use under the impact of COVID-19, Eng. Rep. (2022), e12584.
[57] L. Fernández, Global renewable energy industry – statistics & facts, February 9, https://www.statista.com/topics/2608/global-renewable-energy-industry/#topicOverview, 2023.
[58] D. Parra, L. Valverde, F.J. Pino, M.K. Patela, A review on the role, cost and value of hydrogen energy systems for deep decarbonisation, Renew. Sustain. Energy Rev. 101 (2019) 279–294.
[59] IEA, Global Hydrogen Review 2022, IEA, Paris, 2022. September 2022, https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.
[60] J.F. George, V.P. Müller, J. Winkler, M. Ragwitz, Is blue hydrogen a bridging technology? - the limits of a CO2 price and the role of state-induced price components for green hydrogen production in Germany, Energy Pol. 167 (2022), 113072.
[61] L. Thomson, Carbon capture from bio-oil steam reforming. https://www.azocleantech.com/article.aspx?ArticleID=1554, May 27, 2022.
[62] J. Brauns, T. Turek, Alkaline water electrolysis powered by renewable energy: a review, Processes 8 (2) (2020) 248.
[63] IEA, Electrolysers, September 2022, IEA, Paris, 2022, https://www.iea.org/reports/electrolysers.
[64] C. Li, J.-B. Baek, The promise of hydrogen production from alkaline anion exchange membrane electrolyzers, Nano Energy 87 (2021), 106162.
[65] E. López-Fernández, C.G. Sacedón, J. Gil-Rostra, F. Yubero, A.R. González-Elipe, A. de Lucas-Consuegra, Recent advances in alkaline exchange membrane water electrolysis and electrode manufacturing, Molecules 26 (2021) 6326.
[66] M.A. Laguna-Bercero, Recent advances in high temperature electrolysis using solid oxide fuel cells: a review, J. Power Sources 203 (2012) 4–16.
[67] A. Nechache, S. Hody, Alternative and innovative solid oxide electrolysis cell materials: a short review, Renew. Sustain. Energy Rev. 149 (2021), 111322.
[68] IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, International Renewable Energy Agency, Abu Dhabi, 2020.
[69] J. Proost, State-of-the art CAPEX data for water electrolysers and their impact on renewable hydrogen price settings, Int. J. Hydrogen Energy 44 (9) (2019) 4406–4413.
[70] DNV, Hydrogen forecast to 2050. https://www.dnv.com/news/hydrogen-at-risk-of-being-the-great-missed-opportunity-of-the-energy-transition-226628, 2022.
[71] C. Minke, M. Suermann, B. Bensmann, R. Hanke-Rauschenbach, Is iridium demand a potential bottleneck in the realisation of large-scale PEM water electrolysis? Int. J. Hydrogen Energy 46 (46) (2021) 23581–23590.
[72] S. Kiemel, T. Smolinka, F. Lehner, J. Full, A. Sauer, R. Miehe, et al., Critical materials for water electrolysers at the example of the energy transition in Germany, Int. J. Energy Res. 45 (7) (2021) 9914–9935.
[73] I. Staffell, D. Scamman, A. Velazquez Abad, P. Balcombe, P.E. Dodds, P. Ekins, et al., The role of hydrogen and fuel cells in the global energy system, Energy Environ. Sci. 12 (2019) 463–491.
[74] R. Vakulchuk, I. Overland, D. Scholten, Renewable energy and geopolitics: a review, Renew. Sustain. Energy Rev. 122 (2020), 109547.
[75] M. Blondeel, M.J. Bradshaw, G. Bridge, C. Kuzemko, The geopolitics of energy system transformation: a review, Geogr. Compass 15 (7) (2021), e12580.
[76] IRENA, A New World: the Geopolitics of the Energy Transformation, IRENA, Global Commission on the Geopolitics of Energy Transformation, Abu Dhabi, 2019, 2019.
[77] M. Bazilian, M. Bradshaw, A. Goldthau, K. Westphal, Model and manage the changing geopolitics of energy, Nature 569 (7754) (2019) 29–31.
[78] F. Pflugmann, N. De Blasio, The geopolitics of renewable hydrogen in low-carbon energy markets, Geopolit. Hist. Int. Relat. 12 (1) (2020) 9–44.
[79] T. Van de Graaf, I. Overland, D. Scholten, K. Westphal, The new oil? The geopolitics and international governance of hydrogen, Energy Res. Social Sci. 70 (2020), 101667.
[80] L. Eicke, N. De Blasio, Green hydrogen value chains in the industrial sector - geopolitical and market implications, Energy Res. Social Sci. 93 (2022), 102847.
[81] M. Newborough, G. Cooley, Green hydrogen: water use implications and opportunities, Fuel Cell. Bull. 2021 (12) (2021) 12–15.
[82] R.R. Beswick, A.M. Oliveira, Y. Yan, Does the green hydrogen economy have a water problem? ACS Energy Lett. 6 (2021) 3167–3169.
[83] J. Mohammed-Ibrahim, H. Moussab, Recent advances on hydrogen production through seawater electrolysis, Mat. Sci. Energy Technol. 3 (2020) 780–807.
[84] F.-Y. Gao, P.-C. Yu, M.-R. Gao, Seawater electrolysis technologies for green hydrogen production: challenges and opportunities, Curr. Opin. Chem. Eng. 36 (2022), 100827.
[85] M.A. Khan, T. Al-Attas, S. Roy, M.M. Rahman, N. Ghaffour, V. Thangadurai, et al., Seawater electrolysis for hydrogen production: a solution looking for a problem? Energy Environ. Sci. 14 (9) (2021) 4831–4839.
[86] World Energy Council, World energy insights working paper: regional insights into low-carbon hydrogen scale up, May 2022, https://energycentral.com/system/files/ece/nodes/548904/world_energy_insights_working_paper_regional_insights_into_low-carbon_hydrogen_scale_up.pdf, 2022.
[87] T. Terlouw, C. Bauer, R. McKenna, M. Mazzotti, Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment, Energy Environ. Sci. 15 (9) (2022) 3583–3602.
[88] B.E. Lebrouhi, J.J. Djoupo, B. Lamrani, K. Benabdelaziz, T. Kousksou, Global hydrogen development - a technological and geopolitical overview, Int. J. Hydrogen Energy 47 (11) (2022) 7016–7048.
[89] P. Woods, H. Bustamante, K.-F. Aguey-Zinsou, The hydrogen economy – where is the water? Energy Nexus 7 (2022), 100123.
[90] World Economic Forum, Will a Transition to a Hydrogen Economy Affect Water Security?, 28, 2022. September, https://www.weforum.org/agenda/2022/09/how-a-transition-to-a-hydrogen-economy-will-affect-water-security.
[91] IEA, Electric Vehicles, IEA, Paris, 2022. September 2022, https://www.iea.org/reports/electric-vehicles.

[92] H.-R. Wang, T.-T. Feng, Y. Li, H.M. Zhang, J.-J. Kong, What is the policy effect of coupling the green hydrogen market, national carbon trading market and electricity market? Sustainability 14 (21) (2022), 13948.
[93] D. Chauhan, Y.-H. Ahn, Alkaline electrolysis of wastewater and low-quality water, J. Clean. Prod. 397 (2023), 136613.
[94] R. Donald, R. Saunders, Green Hydrogen Production and Wastewater Treatment Enabling the Delivery of the UN Sustainable Development Goals, Australian Water Association's Queensland Conference, Twin Waters, 2020. November.
[95] M. Mahmoud, A.S. El-Kallinyi, G. Squadrito, Stacked titanium dioxide nanotubes photoanode facilitates unbiased hydrogen production in a solar-driven photoelectrochemical cell powered with a microbial fuel cell treating animal manure wastewater, Energy Convers. Manag. 25415 (2022), 115225.
[96] M. Mahmoud, Electricity-driven microbial factory for value-added resources recovery from waste streams, in: P. Kumar, C. Kuppan (Eds.), Bioelectrochemical Systems, Springer, Singapore, 2020, pp. 119–138.
[97] C.F.F.A. Costa, C.L. Amorim, A.F. Duque, M.A.M. Reis, P.M.L. Castro, Valorization of wastewater from food industry: moving to a circular bioeconomy, Rev. Environ. Sci. Biotechnol. 21 (2022) 269–295.
[98] M.C. Castro-Villalobos, J.L. García-Morales, F.J. Fernández, By-products inhibition effects on bio-hydrogen production, Int. J. Hydrogen Energy 37 (8) (2012) 7077–7083.
[99] H.K. Abdel-Aal, K.M. Zohdy, M. Abdel Kareem, Hydrogen production using sea water electrolysis, Open Fuel Cell. J. 3 (2010) 1–7.
[100] H. He, Y. Huang, A. Nakadomari, H. Masrur, N. Krishnan, A.M. Hemeida, et al., Potential and economic viability of green hydrogen production from seawater electrolysis using renewable energy in remote Japanese islands, Renew. Energy 202 (2023) 1436–1447.
[101] M. Qasim, M. Badrelzaman, N.N. Darwish, N.A. Darwish, N. Hilal, Reverse osmosis desalination: a state-of-the-art review, Desalination 459 (2019) 59–104.
[102] W.J.F. Le Quesne, L. Fernand, T.S. Ali, O. Andres, M. Antonpoulou, J.A. Burt, et al., Is the development of desalination compatible with sustainable development of the Arabian Gulf? Mar. Pollut. Bull. 173 (2021), 112940.
[103] D.A. Roberts, E.L. Johnston, N.A. Knott, Impacts of desalination plant discharges on the marine environment: a critical review of published studies, Water Res. 44 (18) (2010) 5117–5128.
[104] G.O. Vaughan, N. Al-Mansoori, J.A. Burt, The arabian gulf – chapter 1, in: C. Sheppard (Ed.), World Seas: an Environmental Evaluation, second ed. II, Academic Press, Cambridge, 2019, pp. 1–23, the Indian Ocean to the Pacific.
[105] C. Wulf, P. Zapp, A. Schreiber, Review of power-to-X demonstration projects in Europe, Front. Energy Res. 8 (2020), 00191.
[106] O. Ruhnau, How flexible electricity demand stabilizes wind and solar market values: the case of hydrogen electrolyzers, Appl. Energy 307 (2022), 118194.
[107] A. Al-Sharafi, A.Z. Sahin, T. Ayar, B.S. Yilbas, Techno-economic analysis and optimization of solar and wind energy systems for power generation and hydrogen production in Saudi Arabia, Renew. Sustain. Energy Rev. 69 (2017) 33–49.
[108] Y. Li, S. Kimura, Economic competitiveness and environmental implications of hydrogen energy and fuel cell electric vehicles in ASEAN countries: the current and future scenarios, Energy Policies 148 (2021), 111980.
[109] K.J. Tu, Prospects of a Hydrogen Economy with Chinese Characteristics, October, Études de L'Ifri, Ifri, 2020, 979-10-373-0248-9.
[110] H. Hao, Z. Mu, Z. Liu, F. Zhao, Abating transport GHG emissions by hydrogen fuel cell vehicles: chances for the developing world, Front. Energy 12 (2018) 466–480.
[111] Z. Wang, D. Wang, F. Zhao, F. Han, Y. Ji, W. Cai, Hydrogen refueling stations and carbon emission reduction of coastal expressways: a deployment model and multi-scenario analysis, J. Mar. Sci. Eng. 10 (2022) 992.
[112] first ed., in: F. Sioshansi (Ed.), Consumer, Prosumer, Prosumager: How Service Innovations Will Disrupt the Utility Business Model, 2019, Academic Press, London, San Diego, Cambridge (MA) and Oxford, 2019, 978-0-12-816835-6.
[113] G.P. Hammond, A.A. Titley, Small-scale combined heat and power systems: the prospects for a distributed micro-generator in the 'net-zero' transition within the UK, Energies 15 (2022) 6049.
[114] P.E. Dodds, I. Staffell, A.D. Hawkes, F. Li, P. Grünewald, W. McDowall, et al., Hydrogen and fuel cell technologies for heating: a review, Int. J. Hydrogen Energy 40 (5) (2015) 2065–2083.