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Achieving decarbonization: challenges and opportunities of green hydrogen

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Identified among the key pillars to achieve decarbonization, hydrogen, specifically the green one, will play a strategic role against climate change. Assessing the opportunities and challenges of its adoption, this work outlines the hydrogen (r)evolution in the transition agenda towards 2050, shifting from the global scale to the European one.

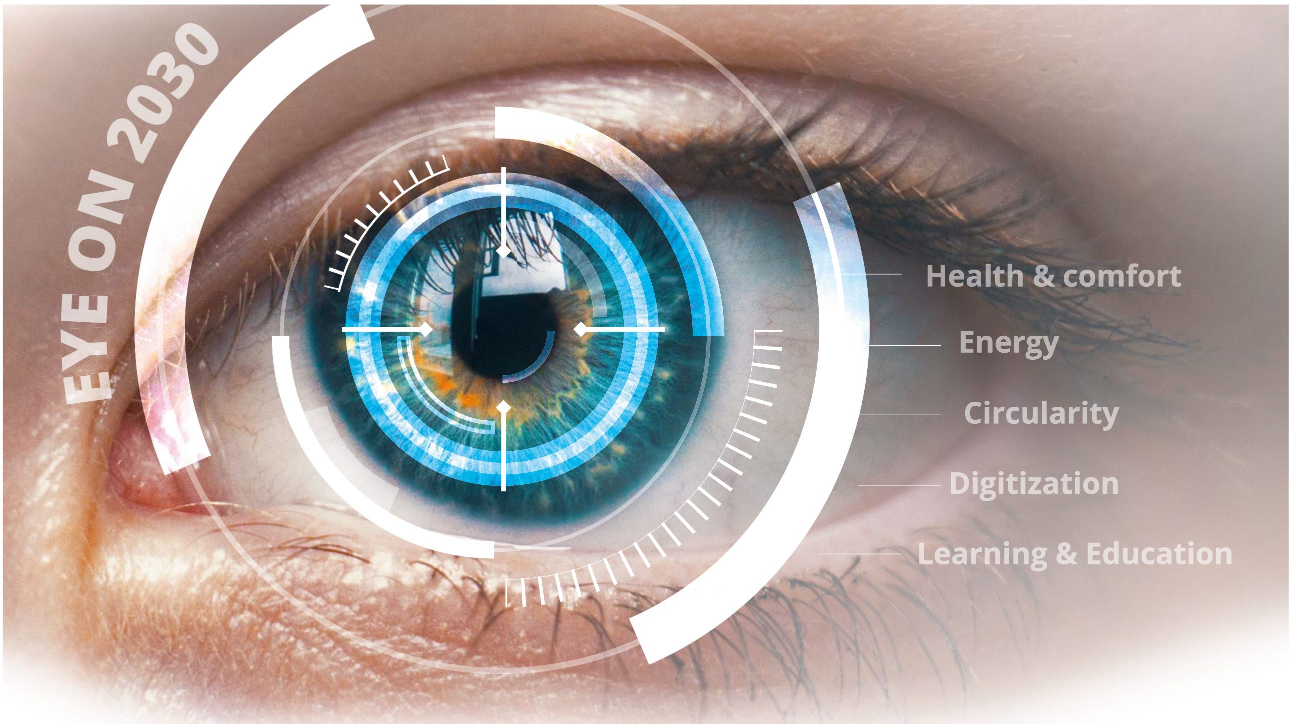
Keywords: energy transition; green hydrogen; long-term strategies; decarbonization.

Introduction

Several interventions, aiming to achieve the ambitious and urgent targets needed to actively and rapidly fight against climate change issues, are at the centre of worldwide policies and long-term strategies. Deepened by the recent COP26 at Glasgow [1], the goal of 1.5°C as limit for global temperature rising seems to require greater efforts, starting from energy systems and involving all other sectors. This desired changeover will affect both energy production and consumption, specifically concerning the diffusion of climate-neutral solutions and the development of new energy infrastructures, in parallel with the substitution of well-established sources like fossil fuels [2]. A transition away from fossils to climate-neutral solutions will play a crucial role, considering that energy-related carbon dioxide (CO_2) emissions represent three-quarters of the global greenhouse gases (GHG) emissions today [3]; in particular, the robust electrification of end uses and the decarbonization process are the two major developments that energy systems are experiencing [4]. This shift is not limited to energy aspects but involves transformations of "the broader social and economic assemblages that are built around energy production and consumption" [5]. In this context, it is of primary importance to identify the appropriate long-term strategies towards a carbon-neutral 2050, through the identification of the key pillars driving the decarbonization process. Specifically, renewable energy deployment, energy efficiency interventions, electrification of end uses, clean hydrogen adoption and sustainable bioenergy represent promising candidates to make the transition happen [6]. Among the key pillars of the transition, this paper concentrates on hydrogen exploitation. Identified as valuable energy carrier and chemical feedstock, hydrogen represents one of the irreplaceable drivers of the transition to tackle climate change issues, specifically if produced from renewable energy [7,8,9]. Hydrogen is experiencing "an innovation turning point", concerning its potentiality to decarbonize challenging sectors, specifically those that are harder to electrify (i.e., shipping, aviation, heavy industry, long-haul transport) [6,10]. One of the biggest opportunities, in terms of innovation concerns hydrogen electrolysers, which represent a technological option that can contribute to the CO_2 emissions reductions between 2030 and 2050 according to the net zero pathway [3]. In the light of the above, studying hydrogen, in the attempt of deepening its opportunities and criticalities, perfectly fits within the mentioned carbon-neutral view. Therefore, recognizing the crucial role of hydrogen in the complex energy transition framework, this work seeks to deepen the potentialities of this vector and to assess its main challenges, focusing on how countries worldwide are paving the way to its adoption. The paper underlines how the role of policy makers can become crucial for spreading innovative measures and technologies, through the development of informed interventions and strategic actions. Ad-hoc long-term strategies are required to drive the transition towards 2050, considering that now, reversing from the past, political systems have become a determinant of energy transitions [11].

Hydrogen through its main drivers and main barriers

This section aims to describe the different ways of hydrogen production that are already used, available or under study. Around 120 million tonnes of hydrogen are produced yearly, two-thirds of which are of pure hydrogen, while the remaining part is a mixture of other gases [12]. When analysing the commodity, it is important to distinguish the possible production modes; specifically, diverse colours (i.e., grey, brown, black, green, blue, pink) are used in literature, aiming to create a common language for hydrogen and to effectively select real carbon-neutral solutions. About 95% of hydrogen used worldwide (the same percentage is valid if considering the sole European Union) is produced using fossil fuels, generally classified as grey type [7]. Mostly exploiting the steam methane reforming process, grey hydrogen production causes an increase of CO_2 emissions, slowing down the pace of transition; similar considerations are valid for the so-called brown (or black) hydrogen, produced using coal, and representing 19% of the total hydrogen production [13]. Specifically, the term green hydrogen is used to indicate the commodity produced by water electrolysis exploiting renewable energy, which represent less than 1% of the global hydrogen production [6]. This typology is gaining interest, since, due to the negative environmental impacts that the production of grey and brown hydrogen has, it is widely recognized the



need to convert all the hydrogen based on fossil fuels to the green type. Moreover, attention is also devoted to the blue hydrogen; produced from natural gas as the grey one, the main difference relies on the possibility for the CO_2 emitted by the production process to be compressed and liquefied, then transported and stored (Carbon Capture and Storage, CCS) or also supplied to a process, reusing CO_2 in new products (Carbon Capture and Use, CCU) [14]. According to the net zero pathway [3], the role of blue hydrogen will be crucial to get the long-term targets, with a coverage of 40% of the total production of the energy carrier, while the remaining percentage will rely on renewable energy (i.e., green hydrogen) [3]. However, it is worth mentioning that, at present, the required CCS and CCU technologies for the blue hydrogen exploitation are still not technologically ready and economically competitive [13,15]. For the sake of completeness, also pink hydrogen is discussed in literature, which is associated to the exploitation of nuclear energy for the water electrolysis process. Recognizing the need to put strong effort in green hydrogen technological advancement, the most evident factor slowing down its adoption is of economic nature; specifically, at present, the price of grey hydrogen ranges from 0.5 to 1.7 USD/kg, while the adoption of CCUS technologies (blue type) increases the levelized cost of production up to around 1 to 2 USD/kg [16]. The use of renewable electricity to produce hydrogen costs from 3 to 8 USD/kg [16], clearly constituting a key barrier to its scaling up with respect to the hydrogen produced by fossil fuels, which is responsible of around 900 million of tonnes of CO_2 emissions each year [16]. However, the economic barrier is not the only one to be addressed; in detail, **Table 1** reports the main drivers and barriers concerning green hydrogen, adapted from [17].

Having set with undisputable certainty that the green option is the most effective choice among the alternative ways of hydrogen production, how to effectively use this clean hydrogen is still a remarkable challenge to be addressed. Today hydrogen is mostly exploited in industrial applications (i.e., oil refining, ammonia production, methanol production, steel production), with an increase of methanol and ammonia demand expected for the medium-term, while in the long-term steel and high temperature production can determine a huge growth for green hydrogen demand [18]. Specifically, hydrogen can give a contribution to the hard-to-decarbonize sectors, for which the direct electrification and use of renewable energy is not a viable solution as it is for other sectors [19]. Thanks to the possibility to shortly reach very high temperature levels, green hydrogen can substitute coke, leading to the decarbonization of the sector of iron and steel production, which currently determines 7.2% of the global CO_2 emissions [20]. For what concerns transport, hydrogen is a promising solution for decarbonizing railway, aviation and shipping sectors, even if an open debate is ongoing in relation to real opportunities and challenges [13]; moreover, according to the International Renewable Energy Agency (IRENA), in 2050, a request of about 46 million of tonnes of green hydrogen will come from the naval sector [21]. Finally, looking at the building sector and its potentialities to be decarbonized through end uses electrification, some promoters of hydrogen argues that the actual gas pipelines could be exploited for transporting blending hydrogen [13], while its percentage in the mix with natural gas is at the centre of debates and technological studies and advancements are ongoing.

The role of hydrogen in the long-term strategies: global and national insights

Hydrogen effectively contributes to the definition of energy transition scenarios; specifically, "the more ambitious the GHG reduction target, the greater is the amount of green hydrogen expected in the system" [17]. In fact, the first key recommendation from the International Energy Agency (IEA) to scale up hydrogen refers to the need to establish the role hydrogen must play in the long-term energy strategies

Table 1. Green hydrogen: main drivers and barriers, adapted from [17].

DRIVERS	BARRIERS
Low variable renewable electricity costs	High production costs
Technologies ready to scale up	Lack of dedicated infrastructure
Benefits for the power system	Energy losses
Government objectives for net-zero energy systems	Lack of value recognition
Broader use of hydrogen	Need to ensure sustainability
Interest of multiple stakeholders	High production costs

[18]. In particular, it in envisioned that the share of green hydrogen will be significant in the future energy mix if no fossil fuels subsidies will be guaranteed in the long-run; moreover, assumed that the variety of cost assumptions could lead to a wide range of different green hydrogen deployments, its spread will rely on economic challenges, but will be also strongly affected by political, social and environmental priorities [17]. Having set this, it is crucial to understand that geographical constraints and cross-border dynamics play a strategic role in defining the adequate hydrogen pathway, being tailored on several government priorities, opportunities, and strategies. In fact, the term "transition" in its common meaning must be able to capture also more widely changes in the spatial organisation of energy systems and economic activities, being dependent also on the relationships between one country/region and others [22]. Among the policy interventions proposed by IRENA [19], aiming to scale up the green hydrogen adoption with respect to different contexts of actions, four measures are highlighted: (i) acceleration of manufacturing capacity, tackling of high investment costs of electrolysers and enabling of infrastructure; (ii) reduction of renewable electricity costs; (iii) advancement in sustainability; (iv) enabling of demand and market entry for hydrogen [19]. Specifically, effective policy measures should concern capacity targets, fiscal incentives, auctions, green gas targets, international agreements, financing, planning, creation of standards, guaranteeing of origins, research and development [17]. The adoption of ad-hoc policies depends on how advanced each country hydrogen market is and on how governments intend to address the climate change issues and react to the related challenges with respect also to their possibilities. Pflugmann and De Blasio [23], taking care of (i) RES endowment, (ii) renewable freshwater resource endowment, and (iii) infrastructure potential, proposed five groups to classify countries according to their possibility to produce green hydrogen, grouped among "export champions", "renewable-rich but water-constrained with high infrastructure potential", "renewable-constrained with a high infrastructure potential", "resource-rich with high infrastructure potential", "resource-rich with low infrastructure potential" [23]. Despite the possible geographical constraints and barriers, the reaction of different countries to the "call for hydrogen" is encouraging. In fact, at the date of publication of the IEA report "The future of hydrogen" in 2019 [18], only Japan and Korea had developed national hydrogen strategies and France had announced an ad-hoc hydrogen plan. After that, Australia, Canada, Chile, the Czech Republic, France, Germany, Hungary, the Netherlands, Norway, Portugal, Russia, Spain, the United Kingdom, Colombia, together with the European Commission, had published their own strategies referred to hydrogen exploitation, while Italy and Poland had released their strategy for public consultation; meanwhile 20 other countries worldwide are developing their own plans [16]. Besides the specific proprieties of single countries, it is important to mention that there are also geopolitical implications that cannot be left behind: the creation of new dependencies between states in case of large-scale imports; (ii) the change in the interest and actors of the energy transition if hydrogen throws a lifeline to fossil fuels market; and (iii) the possible escalation of rivalry between countries [24]. In line with this, potential and established co-operation among countries is ongoing; specifically, not only bilateral coordination between governments but also international co-operation agreements have been established among governments and private entities [16]. The development of multilateral initiatives and projects can be a key enabler of knowledge-sharing, also promoting the elaboration of best practices to connect a wider group of stakeholders [16]. Focusing on European Union, the European Commission adopted its Hydrogen Strategy on July 2020 [25], aiming to study and strategically define the contribution of green hydrogen to a climate-neutral Europe for 2050 [26]. Covering the entire hydrogen value chain, the European Strategy explores how this vector can unlock investments supporting economic growth and job creation, which is a critical point to be addressed, mostly to encourage a faster recovery from the Covid-19 crisis [26,27]. Recognizing the need of developing an ad-hoc investment agenda, through the European Clean Hydrogen Alliance and proper recovery plans, other key actions aim to scale up demand and production, promoting hydrogen adoption in transport sector, introducing certifications, common standards and effective planning of infrastructure and adequate market rules, boosting research and development and strengthening the EU international leadership through new missions, cooperation and agreements [25]. It is widely recognized that hydrogen can represent a win-win option for the whole Mediterranean region; specifically, the well-established RES sector and the hydrogen production in the Northern shore of the Sea could support the installation of production sites in the Southern and Eastern coasts and promote a share of knowledge and activities among the interested countries [28]. Moreover, reinforcing hydrogen and its role as key pillar to achieve carbon neutrality, in the Fit for 55 Package, the European Commission has set the

objective of including a 50% of renewable hydrogen consumption in industry by 2030 [29]. As a result, Member States are planning to use for hydrogen on average 7% of the funds regarding the green transition pillar of their Recovery and Resilience Plans (RRP); in line with national priorities, it is interesting to note that the percentage increases up to 24% according to German plans, while the Italian percentage falls to 3% [30]. Despite the national peculiarities, hydrogen clearly represents a strong candidate to guide the energy transition process, identified as "an investment priority to boost economic growth and resilience, create local jobs and consolidate the EU's global leadership" [31]. **Figure** below summarises the overview conducted on green hydrogen, specifically fixing why, where [19], and how [17] to use it.

Conclusions

In the attempt to achieve the climate neutrality target for 2050, governments worldwide have planned and adopted strategic interventions involving hydrogen. Specifically, the exploitation of renewable energy for water electrolysis makes green hydrogen a perfect candidate to speed up the transition process, primarily allowing the decarbonization of hard-to-abate sectors.

The paper investigated the hydrogen (r)evolution, analysing the main drivers and barriers to the green hydrogen diffusion. It is undoubted that the role of hydrogen in the energy transition and the speed of technological advancements in this sector is dependent on the different long-term strategies adopted by single countries, in line with their priorities and potentialities, as well as on the possibility to exploit bilateral and multilateral agreements between countries and on the research and development progresses. The green hydrogen adoption must be a key priority in the next years, to favour its spread worldwide and to make the long-term pathways traced to achieve decarbonization more effective. ■

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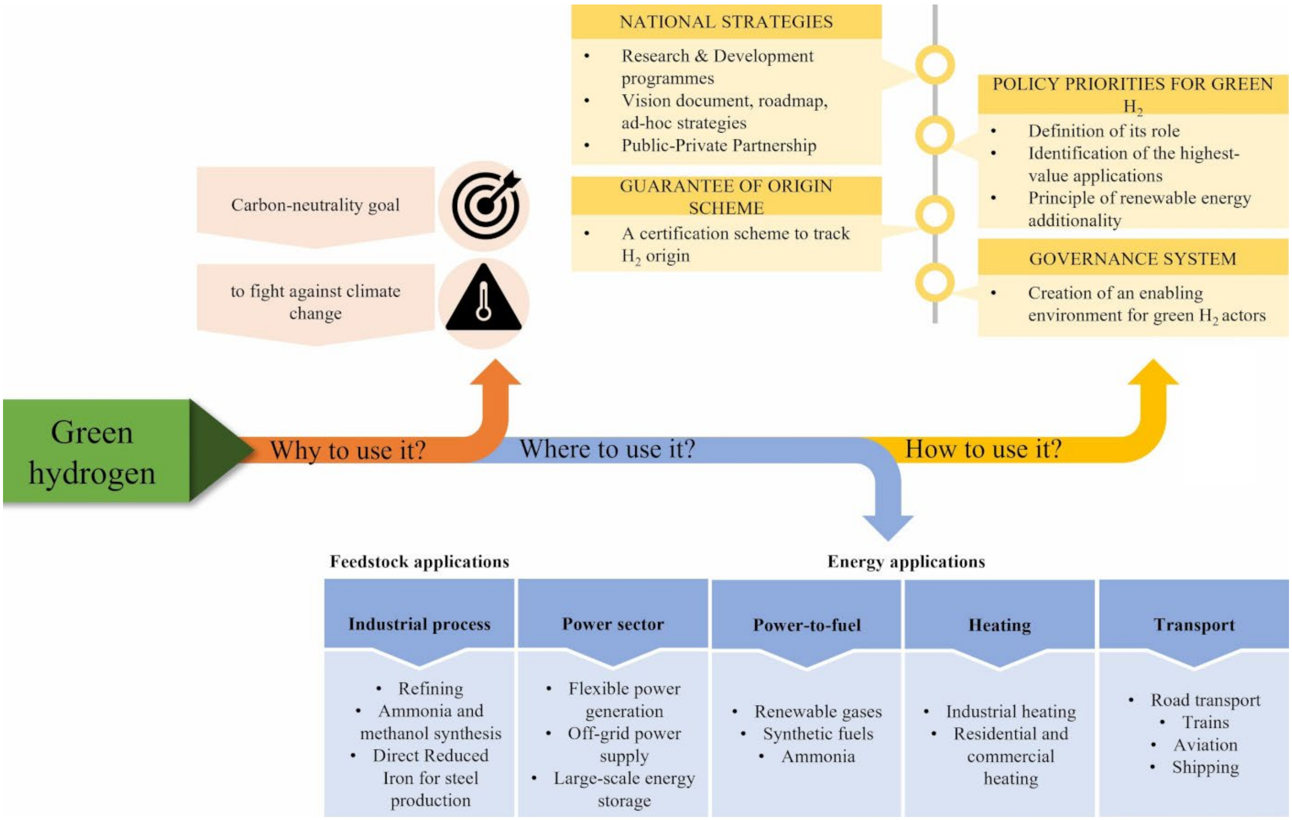

Overview on why, where, how to use green H_2.

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