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# Perspectives on Hydrogen

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**Abstract:** Humankind has an urgent need to reduce carbon dioxide emissions. Such a challenge requires deep transformation of the current energy system in our society. Achieving this goal has given an unprecedented role to decarbonized energy vectors. Electricity is the most consolidated of such vectors, and a molecular vector is in the agenda to contribute in the future to those end uses that are difficult to electrify. Additionally, energy storage is a critical issue for both energy vectors. In this communication, discussion on the status, hopes and perspectives of the hydrogen contribution to decarbonization are presented, emphasizing bottlenecks in key aspects, such as education, reskilling and storage capacity, and some concerns about the development of a flexible portfolio of technologies that could affect the contribution and impact of the whole hydrogen value chain in society. This communication would serve to the debate and boost discussion about the topic.

**Keywords:** hydrogen; decarbonisation; energy vector; implementation; education; reskilling; regulation

## 1. An Urgent Run for Decarbonization (of the Atmosphere)

The impact of anthropogenic activity has reached a level at which the alarm for an irreversible warming of our Earth's troposphere has been activated. Many authors provide forecasts about the temperature rise during next decades [1,2] showing how the atmosphere warming is really dramatic (>1.5 °C in optimistic scenarios), which suggests that fast changes should be implemented in our society to avoid the harmful effects of climate warming.

Hydrogen is proposed as an energy vector that would definitively contribute to decarbonization. Not only as an energy carrier, or decarbonized fuel for the mobility and industrial sector, but also as an energy storage media that will provide management capability for most renewable energy sources [3–6]. Hydrogen has been adopted as a critical issue at international level, bringing hydrogen to the front of the political agenda [7–9] and one of the pivotal options for the future energy sector [10,11].

Such a role was also analyzed during the previous deep energy crisis in the 1970s, when a big effort to find an alternative to oil was the challenge to solve. That decade produced a big step ahead in the development of renewable energies, including a potential role for the hydrogen economy [12–15]. Nevertheless, the role of hydrogen was declining at the end of the 1990s and early 2000s due to the risk perception of the population, the low intensity of public campaigns, the emerging impact of other energy technologies and the cost [16]. This aspect was particularly important for the mobility sector, the main reason for the development of the hydrogen economy that now is facing the increasing implementation of electric cars. On the other hand, this new energy crisis is much more complex in its roots, as it is not initiated by a particular energy availability (oil) but affected by much more complex impacts and constraints as the need of reducing the carbon footprint, costs and transforming the whole energy market in a global context. The need for decarbonized storage has also boosted the quest for technologies, such as hydrogen, or its derivatives as synthetic natural gas, ammonia or light hydrocarbons. Last but not least, energy security is another driven force that has boosted the search for alternatives such as hydrogen [17],

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which could substitute current fossil fuels and raw materials in hard-to-abate sectors, diminishing geopolitical dependencies.

Hydrogen developers, the industry and policymakers should use that hydrogen first-wave experience to propel this second great development opportunity to validate the integration of the hydrogen economy into the core of a decarbonized society. I will analyze in the next section some thoughts about the future of hydrogen from my point of view with the aim of providing a critical review to contribute to the future of this wonderful molecule in the energy sector ($H_2$).

## 2. From a Hope to Reality

Hydrogen is considered a very worthy commodity at the industrial level, mainly for the chemical industry, where it is produced and consumed on site. The role of hydrogen as a future energy vector, either as storage or as an energy carrier, requires the implementation of a capacity to generate, store, transport and use hydrogen many orders of magnitude of that of today. In some projections, hydrogen is predicted to manage 5% of the energy demand in 2050, with a production, storage, transport and utilization in the order of 240 MtonH2/y [18], equivalent to 28,800 PJ/y. Even if that is an enormous amount of energy, hydrogen will be coexisting with other energy vectors, such as electricity. In fact, it would serve as an add-on management capacity for electricity in the case of a future scenario based on hydrogen production via electrolysis. Energy efficiency and cost are much more favorable than using directly renewable-based electricity if possible, as there is no transformation involved. In that case, hydrogen will compete with the rest of the energy storage technologies to find a place in the energy sector, either in efficiency or in cost. Regarding cost, current hydrogen generation costs from renewables are in the range of 3.2–7.7 USD/kg$H_2$, [19] which in terms of energy is 96–231 USD/MWh in the form of molecules. Such a cost would be competitive versus fossil molecules in the future. Additional costs should be added for long-term storage capacity and a complete power-to-gas cycle. Nevertheless, hydrogen may serve as an excellent vector for sector coupling, linking the energy production based on renewables to the chemical industry, which requires the availability of raw materials, such as hydrogen itself or even carbon molecules. Hydrogen may play a role in energizing high-temperature processes or other heating demands.

The challenge for hydrogen development is scaling up from the up-to-date specific applications, mostly consumed at the site of production in the chemical industry, such as refineries or ammonia factories, to a general use as to be considered a practical energy vector. That is a path that electricity has completed since the beginning of the 20th century, with the development of the electric networks, generation plants and electric engines. Hydrogen must also clear the challenge of the distribution and utilization. In parallel, both electricity and hydrogen must run for distributed generation, safe high-capacity storage and decarbonization. Such transformation and implementation in society requires the establishment of a framework legislation and normalization, as well as qualified human resources to take over that mission. The transformation of the electricity market to manage the huge number of prosumers and renewable energy is a big challenge that may affect any parallel energy market, such as the one based on molecules such as hydrogen and its derivatives. There is still a long way to go to create suitable markets for the energy transition, including the definition of their infrastructures

## 3. The Chicken and Egg Dilemma

The development of the complete, coherent value chain of hydrogen is the key to the success of its implementation. The capacity of each step must be in harmony with the other. Those chain pieces—generation, transport, distribution and utilization—should be able to connect properly to each other, not only from a technological point of view but also from market structure, regulation and standards. It will make no sense to be able to produce huge amounts of hydrogen in a given form by a portfolio of technological alternatives if the market is not developed enough to consume such an amount. Hydrogen transport and storage may be one of the critical paths for such development [20,21]. In particular, the transport debate is open. Certainly, the decarbonized energy transport of molecules implies a flow of hydrogen molecules. Such an objective faces some technological problems, such as material embrittlement of the ducts and energy pumping. The transport of blending hydrogen and natural gas is a good alternative to use in the existing gas infrastructure until the viability of pure hydrogen pipelines is confirmed. It would also be very likely that hydrogen will travel accompanied by nitrogen (NH3), carbon (CH4) or a combination (LOCH), such as in nature, and produce "last mile" hydrogen near the consumption site.

It seems that a long path is still pending in the capacity of storage to replace current fossil fuel derivatives in some sectors such as the aviation and marine sectors, which are very important because of their carbon footprint contribution. The availability of huge hydrogen storage capacity is a requirement for the link between generation and utilization, as well as providing a reasonable service autonomy for hydrogen devices. A clear candidate for hydrogen storage for energy reserves are geological caverns [22], although some questions and practical issues should be solved before confirmation, such as the required pressure, hydrogen losses via interaction with the cavern material, and the requirements of the geological site. For mobility, compressed hydrogen seems to be enough for vehicles with a well-designed network of refueling stations. Nevertheless, some other long-range transportation systems, such as is the case for marine and aviation vessels, the situation is less optimistic for the moment as the current available technologies are far from fulfilling the requirements [23]. Such storage capacity (particularly limited in volume) is bringing consideration of hydrogenated compounds such as organic hydrocarbons, ammonia or synthetic natural gas. A similar argument may be applied to energy transport by ducts, where it is still not clear the type of hydrogenated compound that should be transferred.

As in every widespread technology implemented in society, standardization is a must to avoid compatibility problems. At the first stages, if the technology is scaled separately by competitors, there will appear several potential obstacles for market development, as well as higher environmental impacts. Fortunately, the huge, powerful alliances of industrial developers that have been established to boost and harmonize efforts for the deployment of hydrogen technologies increases the compatibility of the multiple types of equipment that is being installed.

## 4. The Risk of Putting All the Eggs in the Same Basket

A complex system, such as is the case for energy delivery and utilization, as well as the decarbonization goal, implies a deep integration of all the systems in a circular economy and will require a strong adaptation capacity for all the technologies that would be put into practice. A fast implementation of the technology in society may trend toward the concentration of all efforts in the technologies that are more mature from the point of view of results at small scale, blocking the growth of other alternatives that could be applicable in the long term. As an example, from the point of view of hydrogen generation, most of the commercial efforts are focused on the deployment of water electrolysis as the dominant technique for high-scale decarbonized hydrogen production. On the opposite side of the hydrogen value chain, fuel cells seem to be the dominant technology for hydrogen utilization. Both technologies are certainly valid and they are reaching a technology readiness level that has elevated them as winning horses for the first high-scale implementation of a decarbonized hydrogen economy (with the permission of fossil-based hydrogen technologies, such as natural gas steam reforming, which requires a deep implementation of carbon capture and sequestration, but that is another debate). Entrusting all the responsibility of hydrogen generation and the use of hydrogen to a few technologies is risky. Electrochemical technologies face some threats and risks, such as the availability of raw materials that are often classified as critical [24–26], with a potential impact on their role in the case of a very large scale deployment. Some voices are already advising about the possible geopolitical impact of such circumstances, stressed now by the global crisis induced by events such as the COVID pandemic and warfare. On the other hand, the risk is not negligible of the unbalances availability of such materials, increasing their cost, which would impact the viability of the implementation of hydrogen production. The other limiting issue is the availability of the main hydrogen source, water, which is expected to be scarce in the future in many places and requiring the development of specific recovery techniques [27], reducing the global efficiency of hydrogen production and its competitiveness in relation to its use as an energy vector. In this run for decarbonization, there will be no chance to rewind as global warming is becoming almost critical. Other technologies, such as pyrolysis [28–30] or hydrogen oxidation, deserve the chance for development, as they may reduce the energy demand for hydrogen production, the utilization of raw materials and their hydric footprint. In this respect, the accepted classification of hydrogen based on its technology and sources based on colors (green, blue, turquoise, etc.) is not contributing to a technology neutral approach to the energy transition, especially if such classification is used in regulation, affecting research and innovation. Such approaches need to be focused on the effective contribution to decarbonization and sustainability, for instance, improving and applying recognized standards for life cycle assessments, such as the ISO 14044 series. That is the case for other sectors, where labeling is based on efficiency. Such classification should provide a technology neutral vision on clear environmental and sustainability indicator thresholds that are clearly regulated for all present and future technologies (Figure 1).

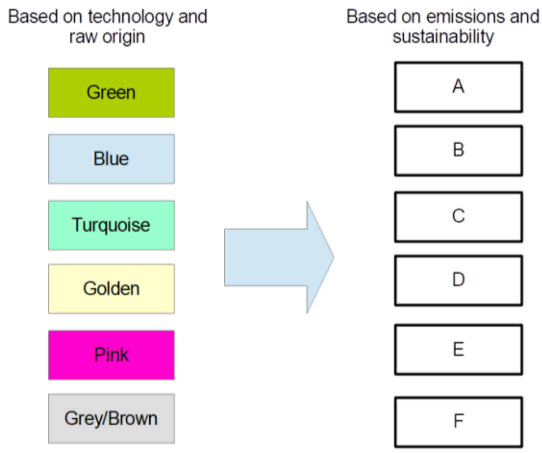


**Figure 1.** Hydrogen classification based on impacts instead of technologies.

Regarding hydrogen consumption, fuel cells and thermal engines complement each other. In this case, both solutions may have their market and applications that would depend on the type of service to be provided. In this respect, thermal engines may improve their performance with hydrogen as fuel, reducing NOx emissions as much as possible, as this is the main Achilles' heel of this technology. Regarding fuel cells, their operational lifetime should be extended and the need for platinum as a reference catalyst be reduced. In any case, I see the weaknesses of fuel cells being less critical with respect to the development of the hydrogen economy, as there are already some fields, such as light- and heavy-duty vehicles that are in good progress.

Energy solutions are not unique and are very much dependent on the final user and need. Different solutions should be provided for different countries and situations, depending on the climate, available resources, connectivity and type of application. Hydrogen will not be so different in that respect. The integration of the hydrogen economy into the circular economy will be a must and huge effort should be made to enhance material recovery in all the value chain of the technology.

## 5. Human Resources as a (Forgotten) Bottleneck

At present, there are in progress and projected, a huge number of hydrogen-related projects with billions of announced investments strongly supported by regional, national and international R&D and innovation public and private bodies. It is not possible to account here for a shortlist of selected projects because many of them will be missed. Nevertheless, the most ambitious are the hydrogen clusters that are proposed worldwide. Such projects will shed some light about the real potential and limitations of the hydrogen economy at a large scale and along its whole value chain, including the possibility of different technology integration. They likely may solve some of the questions posed in this perspective paper. In any case, society changes are implemented by people. A fast implementation of a new model for the energy system, and in particular, the development, manufacturing, and installation of the components of the hydrogen economy in its whole value chain requires a large number of human resources. On the other hand, building new human competence or re-skilling existing professionals from other disciplines requires a huge formation effort. In the particular case of hydrogen as an energy vector, it has scarcely been explained in general programs at school level compared with other energy technologies [31], resulting in a generally low knowledge about what is its realistic impact in current society and creates some doubts in public acceptance and perception [16]. The attraction and vocations for hydrogen careers is jeopardized. In fact, the approach of many higher education students to the hydrogen sector is mainly driven now, in the 2020s, by the perspective to find a good job, more than for a previous deep knowledge, as is the case for other energy technologies. Therefore, an effort has to be made to include knowledge of hydrogen technologies and their role in our society in every stage of the education process, from basic schools to specific higher education programs, at a similar level to other energy technologies.

The availability of skilled workers at every level of the hydrogen economy is one of its main risks, as it is estimated that hydrogen-related job demand would be as large as millions of new jobs. The scarcity of human resources is observed at every level, from technicians to engineers [32], and there is a general concern about how to provide specific professionals [33]. In addition, those jobs should be covered by skilled workers in a record time. The scarcity of skilled manpower would certainly limit the successful implementation of the hydrogen economy. Such manpower is also needed for the adaptation and monitoring of safety rules that are required to handle hydrogen at every level of its value chain, as for regulation with the utilization of natural gas or any other flammable material. Such safety regulation regarding periodic inspections, especially for equipment not directly affected by industrial occupational hazard prevention services (appliances), implies credentials for skilled personnel in the matter.

## 6. Let Hopes Shape the Future

Decarbonization of our activities in the atmosphere is one of our main objectives, as our anthropogenic impact on the Earth's climate is threatening our future. Hydrogen is called for to contribute to achieve such an objective, integrated into a system with other pieces, such as renewable sources and material circularity. Even if hydrogen's practical impact in our society is limited now, huge expectations and hopes are placed on the topic. We (as society) have to convert those expectations and hopes into reality, identifying the weaknesses and threads of such a path (now storage and distribution, the reduced number of technological alternatives, education reskilling and the discussion on the perspective paper about regulations). Hydrogen has a lot of strengths and implies a lot of opportunities to tackle global warning, making possible the energy transition. I am convinced that the future has a place for hydrogen, may be as it is or as hydrogenated compound as in nature (do not forget that is very rare to find hydrogen molecules on Earth). We have time to clear the weaknesses and threats, some of them expressed here, and comply with the expectations of this second hydrogen wave. *Science has the ability to transform society and convert the hope for the development of hydrogen society into reality.*

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