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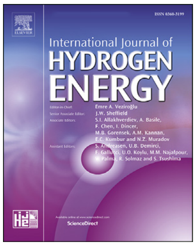

Hydrogen in energy transition: A review

Ankica Kovač[*], *Matej Paranos*, *Doria Marciuš*

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10000, Zagreb, Croatia

HIGHLIGHTS

- Hydrogen is the flagship of the green energy transition.
- National policies and directives are focused on supporting carbon-neutral society based on hydrogen.
- Progress of hydrogen usage is evident in the expansion of hydrogen infrastructure.
- Social acceptance of hydrogen technology is steadily increasing.
- The hydrogen economy is expected to grow by carrying out current energy strategies.

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ABSTRACT

The energy transition is not something that awaits us in the next decade. On the contrary, it is a process in which we are already deeply enrolled. The main step towards the creation of a carbon-neutral society is the implementation of renewable energy sources (RES) as replacements for fossil fuels. Given the intermittency of RES, energy storage has an essential role to play in this transition. Hydrogen technology with its many advances was recognized to be the most promising choice. As multiple hydrogen applications were researched relatively recently, the current development of its technology is not yet on the large-scale implementation level. With the increasing number of studies and initiated projects, the utilization of hydrogen's immense ecological potential is to be expected in the next few decades. New innovative solutions of hydrogen technology that includes hydrogen production, storage, distribution, and usage, are permeating all industry sectors. In a rapidly changing world, technological advances bring forth public discussions, that are a deciding factor whether society will be able to adapt and accept those new contributions or reject them. Currently, hydrogen is the best associated with fuel cell electric vehicles which emit only water vapour and warm air, producing no harmful tailpipe emissions. As various scientists are stressing the gravity of climate change effects that are reaching the physical environment, ecosystems, and humanity in general, concern for the future is becoming the main global topic. Consequently, governments are implementing new sustainable policies that promote RES as a substitute for fossil fuels. Increasing progress in hydrogen technology instigated nations worldwide to incorporate hydrogen in their energy legislations and national development plans, which resulted in numerous national hydrogen strategies. This work shows the progress of hydrogen taking its place as a key factor of the future green energy society. It reviews recent developments of hydrogen

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[*] *Corresponding author.*
E-mail address: ankica.kovac@fsb.hr (A. Kovač).

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technologies, their social, industrial, and environmental standing, as well as the stage of transitioning economies of both advanced and beginner countries. An example of the ongoing energy transition is Croatia, which is in the process of implementing a hydrogen strategy with the ambition to be able to one day equally participates in the rapidly emerging hydrogen market.

Introduction

Today's world is in the process of an energy transition. Human development so far in the last century was tied to fossil fuels, so dependence between the two was created. The utilization of fossil fuels irrefutably led to significant technological advancement in a short time spawn. One of the major downsides was increasing pollution on such a scale, that Earth couldn't withstand any more without considering consequences. Presently, these negative effects are visible in many forms, the most notable ones being connected to climate change. In the eyes of society, climate changes represent the main argument for an energy transition, which is often perceived as financially unprofitable, but a necessary change for the benefit of humanity. Even in time before climate change had visible effects on everyday life and global warming was 'just a scenario', scientist's warnings about the world's dependency on fossil fuels undoubtedly influenced the development of RES-based technology systems. Additionally, it set the stage for the exponential increase in numbers of research and studies exploring new ideas and solutions for the growing concerns, and consequently, research and development (R&D) of RES-based technology. We are currently witnessing a global climate crisis and public discussions are nowadays directed towards the mitigation of its consequences and adaptation to new scenarios. That being the case, it is certain that various researches and product developments were actualized as a direct result of an ongoing fight against climate change. On the other hand, global development could be a natural step in evolution, driven by human curious nature, unrelated to climate change. It is argued based on the premise that humans have always strived for innovations and improvements. Truth is presumably somewhere in between and regardless of reasons why it directed the course of global development towards the energy transition [1]. The present situation isn't suggesting that we are in the middle of the process, as a large portion of the global economy is still driven by the power of fossil fuels. Nevertheless, it also cannot be stated that we are at the start of the energy transition, since it had probably begun a few decades ago with the implementation of new energy sources such as wind and solar, even before the increased expansion of RES. Technological advances from that period resulted in numerous research and studies that were well analyzed [2]. The hydrogen role in this progression was recognized from the start, both by the scientific community and the International Energy Agency (IEA). The strongest support to the idea of hydrogen playing a substantial part in energy transition was received at the beginning of the 21st century [3]. Hydrogen as an almost unique technological trademark of energy storage with zero carbon dioxide (CO_2) and greenhouse gasses (GHG) emissions, continuously evoked curiosity and hope for future development. Despite the long and costly path of development towards utilizable and stable technology, hydrogen proved to be a risk-worth taking choice [4]. For this reason, hydrogen today has an essential place in the sector of energy storage. Electrolysis is recognized as a key process with the highest potential for decarbonisation and therefore, towards building a carbon-neutral society if applied to technologies on a large scale. The main obstacle remains to be the financial aspect of the development so the fundamental role still lies in the R&D sector to decrease the costs of production. When the techno-economic aspect of technology's future be positive, as history teaches us, large scale implementation will take place by inertia [5].

More often than not, hydrogen technology is being compared to lithium-ion batteries, where, due to the nature of the system operation (such as electrolyzers and fuel cells), the problem of its efficiency is emphasized. That sometimes leads to unnecessary competition between the supporters of these two principles of energy storage. This wrong placed debate is often presented through the comparison of the battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). However, the main setback for achieving a carbon-neutral society through the energy transition is a fossil fuel, or in particular, an engine with internal combustion. Since both hydrogen and batteries are more environmentally friendly, together they present a solution for reducing the negative impact that the sector has on the global environment. In some aspect, batteries are superior to hydrogen, while in other are vice versa. An example of it is that hydrogen has the potential of reaching a completely decarbonized vehicle fleet [6]. Only by smart planning and implementation of both, coupled with RES for that matter, can a carbon-neutral society be achievable. Hydrogen integration into smart grids solutions, although still facing many challenges, will become an indispensable part of smart grid development in the future [7]. Development strategies for forming 100% renewable smart cities are unattainable without smart energy systems where hydrogen zero carbon emission plays a crucial role in mitigating the variability of RES production with long term electrical energy storage solutions [8]. A big advantage of fuel cell implementation is in its co-generative capabilities, where heat energy, sometimes perceived as efficiency loss, can be utilized for residential and industrial heating purposes [9]. Hydrogen technology is essential in terms of the current understanding of future development. Despite its disadvantages, it is integral for long-term carbon-neutral energy storage solutions that enable the unique diversity of RES technologies. To fully recover after the post-pandemic economic crisis, governments worldwide are forced to establish new policies, which can be seen as a chance to support the green energy transition [10].

Hydrogen technology development

A requirement for hydrogen to assure its place in the energy transition, which also applies to any technology based on RES, is sufficient development of the technology itself. The potential for achieving a carbon-neutral society means little if efficiency, reliability, and scale of production are not adequate for the world's standards and needs. Therefore, decades of R&D of hydrogen technology seem to finally pay off. Hydrogen regarding efficiency can positively cope with concurrent technologies in most applications, and at the same time undoubtedly offer better commodities. Cost parity has not been reached yet in every aspect, but learning from the experience of other RES-based technology development trend, it is to be expected. With the production scale increased, production costs will reach economical profitability.

Hydrogen production

The main goal of the hydrogen energy transition, the carbon-neutral hydrogen society, is based on green hydrogen, i.e. hydrogen production via water electrolysis using RES. Its share is growing, and just in a decade, it is expected to be price competitive to the grey hydrogen production, i.e. hydrogen produced using fossil fuels followed by harmful emissions. To achieve cost parity, technical efficiency should be increased, equipment cost production and material price lowered, and finally, manufacture scaled up. These processes are already in progress for quite some time [11]. Hydrogen production via alkaline water electrolysis is now a mature technology with megawatt (MW) scale installations commercially available. Systems based on proton exchange membrane (PEM) and solid oxide (SO) electrolyzers also advanced to an enviable level. Their mutual comparison of operating UI characteristics is given in Fig. 1.

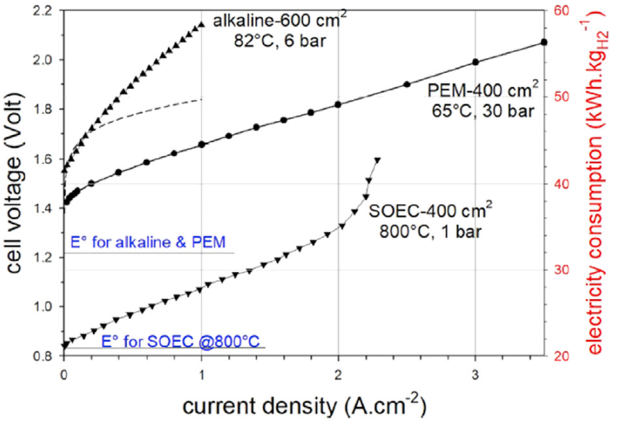

Fig. 1 – Comparison of conventional alkaline, PEM, and SO electrolyzer operating UI characteristics [12].

Various research points up towards wind and solar energy for hydrogen production since these two RESs are considered the best-suited energy sources for hydrogen production. Lately, scientists are proving that compatible RESs are not limited only to wind and solar. Multiple studies of the systems that combine RESs, for example solar and geothermal energy, were conducted, expanding the base of production. Their achievements set an example for a new direction where RES-based multigeneration energy systems are equipped with hydrogen production units. They are designed and analyzed for heating, cooling, domestic water preparation, power, and hydrogen production [13]. Multigeneration systems, in general, proved effective for fossil fuel technology in a way that raised its efficiency. Therefore, it could certainly boost the development of RES-based systems. Another approach to hydrogen production is via a biological process. So-called biohydrogen is produced when microorganisms convert water molecules and organic substrates into hydrogen by the catalytic activity of two key enzymes (hydrogenase and nitrogenase). Biological processes are proving to be a promising alternative for sustainable hydrogen production using RES, especially if placed in the context of waste management. The possibility to use waste resources, such as wastewater, for sustainable hydrogen production from low-cost substrate sources and solar energy, could contribute to another big environmental issue of waste management [14].

For the transition period towards a carbon-neutral society with a share of RES, exploitation of already built non-renewable based facilities could be essential for hydrogen production. The utilization of such infrastructure for hydrogen production is not in the line with green hydrogen production values, but could nonetheless significantly reduce costs of the capital investment in power production facilities. Reducing initial investment is especially important in the first phase of encouraging hydrogen production. A study that explored the utilization of thermal power plants, done by Urška Novosel, Marija Živić, and Jurij Avsec suggests combined production of electricity, heat, and hydrogen, as well as the implementation of other RES-based technology for the more efficient renovation of the facility and environmental benefits [15]. Other base-load facilities with the same exploitation potential are nuclear power plants. Given that opinions in the world about nuclear technology are divided, combined nuclear-renewable based systems are a more appealing option. One of the important obstacles in combining two technologies is that nuclear power generation has to be adapted according to the RES power production values [16]. However, the bigger challenge for green hydrogen production will probably not come from the utilization of non-RES for water electrolysis, but from current dominant hydrogen technology which is based on hydrocarbon reforming [17]. But the use of grey hydrogen is only justified in an extremely short transition period in teh next decade. Implementation of carbon capture and storage, or carbon capture and sequestration, i.e. carbon control and sequestration (CCS) technology can lead towards lower GHG emission overall [18]. In recent years, novel methods of chemical looping technology with high efficiency of CO_2 separation were explored [19]. Research conducted by

Dongqiang Zhang, Runhao Duan, Hongwei Li, Qingchun Yang, and Huairong Zhou, about the integration of the chemical looping air separation and chemical looping hydrogen technology in the conventional coal-to-methanol process, demonstrated achieved improvement in energy efficiency [20]. Different CCS technologies are shown in Fig. 2.

Hydrogen storage and application

Hydrogen storage solutions represent a key element in hydrogen systems, due to the nature of hydrogen molecule. This is especially emphasized when it comes to the utilization of large-scale projects and operations. They are generally divided depending on their purpose, to those more suited for the mobile application, and those for stationary facilities. The second division is based on the method of storage with physical-based and material-based designs as shown in Fig. 3 [22]. All variations of hydrogen storage have developed according to the determent conditions, operating time, and needs of users. On the example of metal hydrides, we can see the differences in stages of development for different cases. Metal hydrides are ranging from mature systems in specific designs, as is the case with submarines where they were used for quite a long time, to the devices with experimentally obtained results only a few years old, which have not yet entered the market [23]. Metal hydride hydrogen storage systems and compression technologies have proven to be efficient in small-to-medium scale energy storage systems [24]. For the accurate choice of the best available storage, adequate consumption calculations should be calculated. A group of scientists, led by Juan Aurelio Montero-Sousa, have conducted extensive research about the hybrid intelligent approach with a combination of clustering and modelling techniques, that when applied on a real dataset, predict the consumption of hydrogen in fuel cell stacks [25].

An often overlooked segment of compressed hydrogen storage units is the compression process itself. The main division in the compression technology is between mechanical and non-mechanical compression. Both have several different systems that create diversity in hydrogen compression technologies. This diversity creates a positive effect on the development of new innovative solutions which are big contributions to energy transition [26].

Hydrogen has many purposes, from fuel to non-energy related industries and households. Its electrical energy storage potential is to be realized in fuel cell applications. Those systems can be in stationary facilities such as heat and power co-generation (CHP), and mobile, like in FCEVs. One of the main advantages compared to the lithium-ion battery applications in CHP is that fuel cells increase CHP efficiency. Heat energy obtained can be used in residential, commercial, and industrial sectors, and therefore, can lower GHG emissions both from households and industry [27]. When talking about mobile units, FCEVs are the most notable example of hydrogen technology application. According to one conducted study, vehicles with hydrogen-fuelled internal combustion engines when compared to conventional, hybrid, classical electric, and biofuel, FCEVs have the highest average performances. Variables that were compared were emissions of CO_2 and SO_2, the social cost of carbon, energy and exergy efficiencies, fuel consumption, fuel price, and driving range. Even when used as fuel for internal combustion engine vehicles,

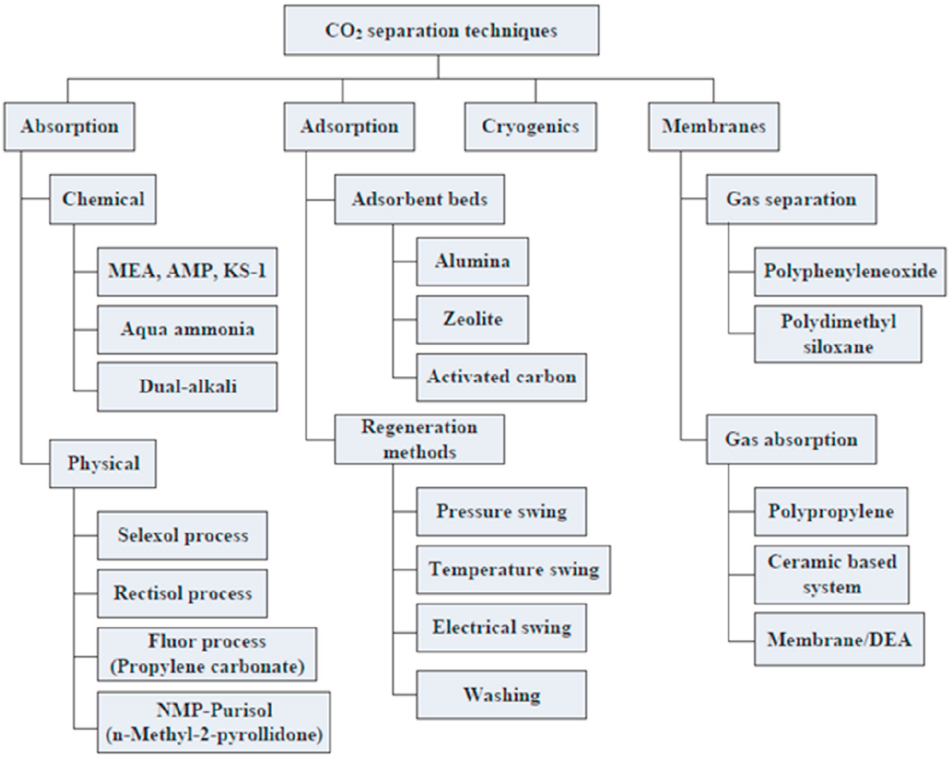

Fig. 2 – Different CCS technologies [21].

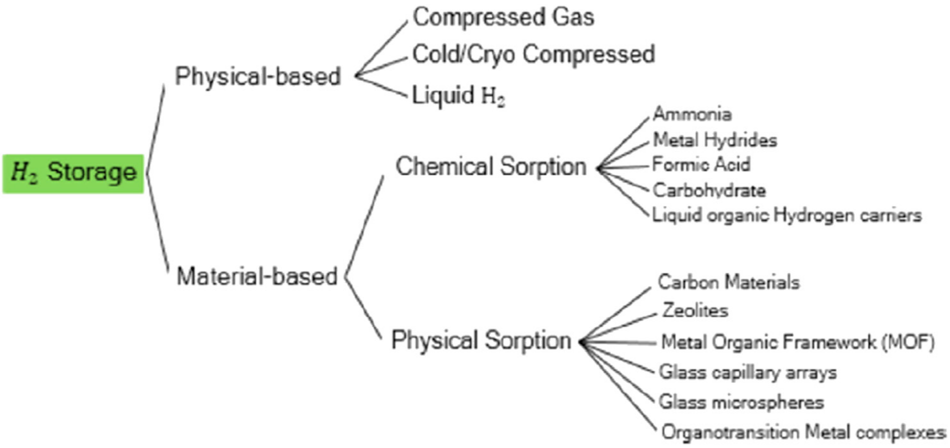

Fig. 3 – Hydrogen storage methods [22].

due to its high heating value, hydrogen proves itself as the quality solution, especially in comparison with conventional internal combustion engine vehicles [28]. Fuel cells are especially well suited for utilization in local transport systems, like public city buses. This is vital in the first stage of hydrogen expansion, where the hydrogen refuelling stations (HRS) network is not yet branched enough. With one well located HRS, many passenger FCEVs can be sustained, since they are always in the range of HRS. For that reason, a lot of projects are involving city buses and many studies are conducted on the subject, such as the one carried out by Teng Teng, Xin Zhang, Han Dong, and Qicheng Xue on energy management optimization strategies for FCEVs [29]. When considering the pollution of CO_2 and GHG in the transport sector, aviation is often overlooked, although it presents a significant pollutant, responsible for 2–3% of the overall world's emissions. Therefore, an investigation on hydrogen technology application in the aviation sector was conducted by Ahmad Baroutaji, Tabbi Wilberforce, Mohamad Ramadan, and Abdul Ghani Olabi. Their research presents an ideal opportunity for further hydrogen development and its integration in the aviation sector. Improvements in hydrogen storage tanks and fuel cell design make technology more suitable for aerospace applications [30].

Public views on hydrogen in energy transition

The success of hydrogen technology, as an essential segment of the energy transition, will not depend only on technical parameters, such as efficiency and production cost, but on the acceptance of final users as well. For hydrogen to be able to take part in the energy system's future, its technology must be simple enough to use for a part of the population that knows little if anything about it. An example of it is that lots of people today don't know the principle of engines with internal combustions, but regularly drive their car to work. Focusing only on entrepreneurs, environmentally conscious groups, industrial and scientific societies, will not be enough to build-up hydrogen society. Education and recognisability should play a significant role in reaching this ultimate goal. Therefore, the automobile industry is probably the best ticket for upgrading hydrogen status and reputation in the whole world.

Hydrogen infrastructure

The increased existence of hydrogen technologies in the world is perhaps most evident in the up growing number of installed HRSs. Data analyzed from annual reports of Ludwig-Bölkow-Systemtechnik and TÜV SÜD, regarding the number of newly installed HRSs, as well as their overall number, indicate that in the last 5 years, the total of HRSs more than doubled (Table 1) [31–35].

Statistics indicate that the main areas of development are in the northern hemisphere since there are only a few stations in the rest of the world. Fact is that the main development so far is focused on three countries: Japan with 114 stations, Germany with 87 (almost half of the total installed in Europe) and the United States of America (USA), where most of the HRSs are (especially in California with 48 operating HRSs) [35]. Hydrogen infrastructure is not limited to those strong centres of development; moreover, it is increasingly spreading to other countries. Examples of it are newly opened first hydrogen stations in Malaysia and Saudi Arabia, as well as in Dubai [36]. The most evenly dispersed picture regarding the HRS network represents Europe, where most countries from the European Union (EU) have developed basic hydrogen infrastructure, making the travel between Norway and Italy possible [33]. One of the newly added countries to that list is Croatia, where the project of the First Croatian Hydrogen

Table 1 – Number of installed HRSs in the world [31–35].

	2015	2016	2017	2018	2019
Europe	95	106	139	152	177
Asia	67	101	118	136	178
North America	50	64	68	78	74
Overall	214	274	328	369	432
- of which public	121	188	227	273	330
Newly installed worldwide (in that year)	54	92	64	48	83

Refuelling Station was successfully realized. This HRS currently serves for refuelling hydrogen bikes of 30 bar [37]. The infrastructure of HRSs is also renewing since notable differences can be seen between the newly installed HRSs and the real increase in the overall number of HRSs, which indicates that some older facilities are being closed. Most of the newly installed HRSs are results of national plans of two countries, Japan and Germany. Japan has strongly increased its network of HRSs in 2015 and 2016. In those two years, 73 new HRSs were installed [31,32] after which the trend continued with a slower rate of expansion, while Germany took the lead in the number of newly installed stations, counting 63 newly opened in the later 3 years [33–35]. The rapid growth of hydrogen infrastructure will continue in the next years with 226 additional HRS projects in the planning or building stage. In years to come, big growth is expected in Korea, France, and Netherland [35]. By the end of 2019, out of 432 HRSs, 330 had public access which represents around 76% of all the HRSs. When compared to the year 2015, whereby its end, 121 out of 214 HRSs were public, which amounts to around 57%. This data shows a clear change in a general view about how hydrogen is to be used. The idea that the population should have greater access to hydrogen is becoming dominant in oppose to the previous doctrine where hydrogen supply was secured for covering needs in closed-industry transport areas.

The global natural gas network has extensive transport and storage capacities (>100 GWh), which is the reason why lots of studies are investigating the possibilities of injecting hydrogen into existing infrastructure [38]. Another significant benefit of mixing hydrogen with natural gas is a reduction of GHG emissions, especially if added hydrogen is green. Blending hydrogen into the natural gas pipeline is a practical solution for increasing the output of RES-based systems such as large solar parks and wind farms. On the same note, extracting hydrogen from the natural gas mixture near the point of end-use is proposed as a method of delivering pure hydrogen. Using the existing infrastructure presents significantly lower investment compared to the construction of new hydrogen pipelines, which is especially important in this development stage of energy transition [39]. However, various modifications of the system network, investigations of possible risks, safety measures, purification, blending, and extraction of hydrogen are all additional costs that have to be made. The method of bringing hydrogen to consumers utilizing blending is very reliant on natural gas and pipeline specific characteristics and should, therefore, be thoroughly investigated for each case. Another aspect to be cautious about is the volume of hydrogen added to natural gas, as it affects the safety aspect. Furthermore, hydrogen injection should be carefully controlled to avoid its sudden increase in concentration (e.g. speed of change <2% per min) [40]. The mixture ratio also determines the amount of produced hydrogen for energy storage needs. Lots of recent studies agree that a mixture of 5–10% of hydrogen volume to natural gas is potentially optimal for the natural gas system, as it does not require modification of the current infrastructure or the equipment of domestic and industrial end-users [41,42]. However, as the percentage varies between 0 and 80 vol %, even more research is needed to achieve the technical feasibility and viability of proposed solutions [43]. The experiments conducted on the important characteristics of the mixture observed that hydrogen injection increases the upper and lower flammability limits and compressibility factor, while both lower and higher heating values, lower and higher Wobbe indices, along with the relative density, decrease. If more than 10 vol % of hydrogen should be injected, the measuring instruments, control stations, and compressors have to be changed [44]. It was also found that the addition of hydrogen into natural gas results in a decrease in mass flow rate throughout the pipeline and hence in the transmitted energy [45]. Nevertheless, even with an optimal small amount of hydrogen, the network should present a safe system of delivering, storing, and utilization that is achievable from both engineering and economical standing. Recently, lots of relevant research regarding hydrogen implementation effects, such as material properties of hydrogen/natural gas pipelines [46–49], safety issues [50–53], economical standpoint [54–56], and flow performance [57,58] were published, contributing to the hydrogen role in the energy transition. Given that immediate changeover from natural gas to hydrogen is not a realistic scenario, both for the distribution and the transport grid, a transition period with mixtures is widely considered [59]. Various researches suggest that the method of storing and delivering clean energy to markets through hydrogen/natural gas pipelines does not significantly increase risks associated with end-user devices, public safety, or the durability of the existing network if appropriate precautions are taken beforehand. Regardless, blend concentration should be assessed in detail as it may vary depending on the pipeline network system and natural gas composition. To conclude, any progressive step towards the implementation of hydrogen to natural gas infrastructure first requires extensive study, testing, possible modifications, monitoring, and maintenance practices.

Hydrogen in industry

The biggest representative for promoting hydrogen in the European business sector is the association of Hydrogen Europe. It consists of over 160 companies, 78 research organisations, and 25 national associations, in a partnership in innovation with Fuel Cells and Hydrogen Joint Undertaking (FCH JU). The FCH JU goal is to ease the hydrogen technologies market's arrival and boost its competitiveness with a fund of €1.3 billion. With Hydrogen Europe Industry, various industries, large and medium-sized enterprises (SMEs), which support the green energy transition, are brought together [60]. The widest spread industrial hydrogen utilizations are in steel-making, chemical, glass, and electronic industries. The present European steel industry is competing with the Chinese, and as steel production is still coal-based, will need to support carbon-neutral processes to be able to keep pace on a global level. Hydrogen is also used in the refining industry for hydrocracking and desulfurization, and for chemical product synthesis to form ammonia and methanol. Other uses are for agricultural fertilizing, metal production and fabrication, methanol production, food processing, and cosmetics. About 55% of the global hydrogen demand is for ammonia synthesis, 25% in refineries, 10% for methanol production, and 10% for others [61]. Another explored potential application for hydrogen in the industry is for high and low-temperature heat generation. Alkaline and PEM electrolyzers as well as PEMFCs, generate heat at low-medium temperature, which can be supplied for residential applications, district heating, and some industrial applications, while SOFCs are useable for high-temperature applications such as metal industries. Moreover, industries are beginning to use the electrolysis by-products to their advantage. Electrolysis with heat and oxygen recovery could lower the cost and increase the total energy efficiency of the hydrogen production, as about 15–30% of the energy is lost. Sweden researchers have studied the integration potential for a pulp and paper national industry. They concluded that by utilization of by-products oxygen and heat, the possibility to sell hydrogen produced from electrolysis is greater. In Sweden, of the total oxygen demand, about 65% is used by the metal processing industry, approximately 15% is used by the pulp and paper industry, and another 15% by the chemical [62].

Additionally, increasing the use of hydrogen in transport is expected to create a market with significant investing potential. According to some researches, hydrogen vehicles will form the greatest economy up the growing market between 2020 and 2030 [63]. Consequently, a need for hydrogen infrastructure e.g. HRSs and pipelines will increase, as will the demand for hydrogen systems such as fuel cells and electrolyzers. Europe with its growing clean hydrogen-based systems manufacturing is highly competitive and well-positioned in marketing sales. Cumulative investments in green hydrogen in Europe could be up to €180–470 billion by 2050, and in the range of €3–18 billion for low-carbon fossil-based hydrogen. Combined with the EU global leadership in RES-based technology, the emergence of a hydrogen value chain serving a multitude of industrial sectors and other final uses could employ up to 1 million people. It is estimated that green hydrogen could meet 24% of energy world demand by 2050, with annual sales in the range of €630 billion. Presently, green hydrogen is not yet cost-competitive enough when compared to fossil-based hydrogen. In ordered to be able to exploit all the opportunities associated with hydrogen, the EU needs a strategic approach that highlights coordinated investments and policies urging cooperation across private and public stakeholders [64]. Given the hydrogen role as an energy vector, use for energy storage and transport over far-reaching distances is considered to grow as well. Currently, around 5000 km of hydrogen pipelines are present in the world [65] compared to 2.91 million km of natural gas pipelines [66]. For further possibilities and industry expansion of hydrogen applications, the construction of new hydrogen infrastructure is crucial as well as the utilization of existing infrastructure (e.g. partial injection or conversion of existing gas networks) [67]. Alongside with automotive industry, shipbuilding and aircraft companies have the potential to gradually start implementing hydrogen solutions, turning towards a climate-neutral economy. Forming two lead markets, industry and mobility sectors can add to the development of hydrogen technology and its application to reduce their carbon footprint, given that they both produce the highest amount of emissions. The EU is dedicated to financially support and provide standards and methodologies to establish a global hydrogen market, which will contribute to sustainability, circular economy, and climate goals.

From the business perspective, the industry has the largest potential, while the profit margins are expected in transport. Energy industry is the biggest hydrogen consumer today that is also highly price-sensitive and globally competitive. Almost all of the hydrogen utilized is a grey one, produced using fossil fuel, which is understandable, as companies are not inclined to pay a higher price for green hydrogen without a constructive initiative. Large-scale deployment might bring down the cost of electrolyzers [68]. Blue hydrogen with relative climate safeguards, could potentially speed up industrial transformation by bringing down prices through economies of scale. Currently, grey hydrogen price amounts to €1.50 per kg, blue hydrogen €2–3 per kg, and green hydrogen €3.50–6 per kg [69]. Costs for green hydrogen are going down quickly, as electrolyzer costs have already been reduced by 60% in the last ten years, and are predicted to halve in 2030 compared to today with economies of scale. Electrolyzers are expected to compete with fossil-based hydrogen in 2030 when electricity generated by RES becomes cheaper and the EU industry planned to reach 40 GW capacities. A joint endeavour of Connecting Europe Facility for Energy and the Connecting Europe Facility for Transport resulted in the funding of hydrogen infrastructure, repurposing of gas networks, carbon capture projects, and HRSs. Besides, the EU Innovation Fund will support low-carbon technologies with €10 billion, over the period 2020–2030 [70].

The green hydrogen market perspective is founded on European industrial strength in electrolyzer production, where around 280 companies are active in the production and supply chain. There is currently more than 1 GW of electrolyzer projects in the process of making, while the total European production capacity for electrolyzers is below 1 GW per year. For hydrogen to become cost-competitive, a coordinated effort with the European Clean Hydrogen Alliance, Member States, and already developed regions is crucial. As the technology matures and the costs of its production decrease, hydrogen should progressively be deployed at a larger scale, which will bring the investors certainty in energy transition and further increase the number of hydrogen-related businesses [71]. Examples of a successful hydrogen technology deployment can be seen in South Korea and Japan, where large corporations work together with the government to upgrade hydrogen energy systems by conducting standards across the manufacturing and installation industry [72]. Another example is the USA Department of Energy, which provided loans or grants to companies with hydrogen applications, provided tax credits, and supported the development with the Recovery Act, which included refuelling point's demonstration projects [73]. The growth of the USA hydrogen economy will create new job openings as businesses expand to compete in the new market, and the industry continues to undergo restructuring. The EU, particularly France and Norway, have acknowledged hydrogen as an industrial feedstock, and therefore, have directed their strategies towards the industry sector [74]. By investing in hydrogen technology and bringing together academic institutes, service providers, suppliers, innovative start-ups, SMEs, and larger companies, Europe's industry becomes greener and more competitive on the fast forming hydrogen market, as the economy becomes more circular and countries more energy-autonomous, making Europe closer to the climate-neutral stage.

The social aspect of hydrogen

One of the challenges presented in hydrogen technology development is financial support. As governments realize the potential and necessity of hydrogen technology development more money will be invested in R&D, education, product manufacturing, etc. Even though private corporations bring significant contributions, the government's finances are public property. Society's willingness to support such big investments must be taken into consideration. Research conducted in South Korea by Joseph Kim, Hye-Jeong Lee, Sung-Yoon Huh, and Seung-Hoon Yoo tackles the question of household's willingness to pay for the development of marine bio-hydrogen technology, which is a project proposed by their government [75]. Likewise, projects must be clear about the ultimate motive that is carbon-neutral society, direct about the possibility of reaching it, and convincing enough to receive support. A new aspect that concerns people is the way hydrogen implementation will affect their lives. The introduction of new technology on a larger, global scale will have a big effect on energy equality and social practices [76]. Many research exploring socio-technical scenarios models will surely increase [77]. Unanimously in decision-making is sometimes pushed aside, even though development on a global scale often draws different approaches since diverse communities do not share the same view on the implementation of innovative technologies [78]. All these questions are still mostly unexplored from the aspects of scientists and engineers, which are committed to the development of hydrogen technology. However, that does not make them any less important than innovation, since energy transition cannot be perceived as completely techno-economic transition, but social as well. Hydrogen is often perceived as a dangerous explosive gas. Therefore, its reputation is reflecting on the development and usage of hydrogen technology worldwide, especially in the areas that have not yet fully developed any form of infrastructure nor have experience with the industrial application of hydrogen. That ungrounded fear originates back in 1937 when the hydrogen-filled Hindenburg Zeppelin exploded in a catastrophic accident. Blame felt on the highly flammable hydrogen although it was officially proved that the explosion was caused by the material coating. That was a time of newly introduced mass media, so the story reached global proportions. Today, the possibility of an accident containing hydrogen is no bigger than with any other fuel commonly used in everyday practice. Numerous studies are committed to security issues considering hydrogen production, transport, and usage. Problems of hydrogen equipment loss of integrity are analyzed to increase safety [79]. Accidents in the past which include hydrogen have been thoroughly studied and concluded with defining solutions to prevent further mishaps [80]. Moreover, simulation and analysis of hydrogen leakage accidents have been conducted to indicate the scale of damage that would occur in the case of an actual accident, so that adequate repercussions and safety measures can be installed to minimize the consequences [81]. Therefore, fear of explosion with catastrophic consequences will presumably not present an obstacle in social acceptance of the technology. An example of a recently occurred accident points out in that direction. On June 1st, 2019, the accident happened at the hydrogen chemical plant in Santa Clara, California [82]. Because of it, a major hydrogen production facility in California was out of operation for enough time to cause a delay in the supply of hydrogen for FCEVs owners in the region. Every problem creates unsatisfied users and lowers the reputation of technology reliability. Consequently, by investing in new emerging technology, inadequately developed infrastructure will be improved and hydrogen positive social standing solidified.

The safety aspect of hydrogen

Hydrogen is an odourless, colourless, tasteless, and non-toxic gas 14 times lighter than air, with rapid diffusion (diffusion coefficient in NTP air is 0.61 cm^2/s) and buoyancy. It has a low density of 0.08987 kg/m^3 at 0 °C and 1 atm, which conditions storages to very high pressures, and is highly flammable with a lower flammability limit (LFL) of 4.1% and an upper flammability limit (UFL) of 74.8% in the air conditions of 25 °C temperature and 1 atm. Between the lower and upper limit there is an explosion range [83]. Safety procedures include detection systems and portable monitors with alarms usually set at 20% and 40% LFL. When mixing hydrogen with other gasses, those characteristics change according to the volume percentage, thermodynamic properties, and ambient conditions. For example, a mixture of hydrogen/methane in 70/30 vol % in comparison to pure hydrogen has lower flame speed (142 cm/s) and detonation of the explosive mixture with air (20%), lower UFL, and slightly bigger LFL (34% and 4.5%, respectively), and higher ignition temperature [84]. Hydrogen/air mixture has eight times greater maximum burning velocity from natural gas/air and propane/air mixture [85]. Experiments with methane/hydrogen/air mixtures show that with appropriate hydrogen and methane ratio, the LFL of the mixture is lower than that of each gas component [86]. By adding more hydrogen to a mixture, laminar burning velocity increases, while laminar flame thickness decreases. In the case of the pressure increase, the fundamental burning velocity decreases, and laminar flame thickness [87]. Research Center Jülich in Germany experimented with hydrogen/oxygen and hydrogen/air mixtures at initial pressures up to 200 bar and concluded that UFL decreases with the increase in pressure, which is opposite to the behaviour of other flammable gases like hydrocarbons [88]. In comparison with today's characteristic fuels, hydrogen supplies more energy per unit mass (higher heating value (HHV) is 141.6 MJ/kg and lower heating value (LHV) is 119.9 MJ/kg) and burns with a colourless flame. Regarding safety, important chemical-physical properties at 101.3 kPa to take precaution for are autoignition temperature of 585 °C, the relatively high flame temperature of 2045 °C and flame velocity ranging from 265 cm/s to 325 cm/s, detonation limits, and low ignition energy [89]. With pressure decrease, minimum spark energies of hydrogen in air lower as follows: 0.017 mJ at 101.3 kPa, 0.09 mJ at 5.1 kPa, and 0.56 mJ at 2.03 kPa. In comparison to other gases, the minimum hydrogen ignition energy in the air is considerably less than that for methane (0.29 mJ) or gasoline (0.24 mJ). However, all three amounts indicate a high possibility of ignition. Potential ignition sources according to NASA Safety Standard For Hydrogen And Hydrogen Systems, could be personnel smoking, electrical short circuits, sparks, flames, metal fracture, shock waves from tank rupture, static electricity, fragments from bursting vessels, heating of high-velocity jets, lightning, welding, explosive charges, generation of electrical charge by equipment operations, friction and galling, resonance ignition (repeated shock waves in a flow system), mechanical impact, tensile rupture, mechanical vibration, exhaust from a thermal combustion engine [90].

When mixed with air, combustion can start either as detonation or deflagration that can transit to a detonation after the flame has travelled for some distance. What will occur depends on the hydrogen volume percentage, the power of the initiator, confinement of the reaction (complete or partial), and the presence of structures that induce turbulence in the flame front. The composition range in which a detonation can take place is from 18.3 to 59 vol % of hydrogen, which is narrower than that for deflagration [91]. Detonation in the form of a supersonic wave propagates a thousand times faster than the initial reactions, which makes its consequences more perilous than deflagrations [92]. When combined with oxygen, especially under significant pressure and temperature increase, explosion limits must be taken into consideration and defined according to databases [93]. Liquid hydrogen must be treated carefully due to possible hazards associated with fire and difficulties caused by critically low temperatures (hydrogen boiling temperature at 1 atm is −253 °C). In the case of skin contact, it can cause burns by frostbite or hypothermia, while inhaling cold vapour could lead to respiratory problems and asphyxiation. Regarding equipment damage, flow-through vents, valves, and storage vessels may be hindered by ice formed from moisture in the air, which consequently leads to material rupture if added extensive pressure, and finally, hydrogen release [91]. Generally, dangers associated with hydrogen usage are grouped as physiological (frostbite, respiratory ailment, asphyxiation), physical (phase changes, component failures, and embrittlement), and chemical (ignition and burning) but most often the realistic cases present a combination of mentioned. Three types of hydrogen embrittlement, caused by its diffusion, can be differentiated. Environmental embrittlement in metals and alloys causes surface cracks, deformations, losses in ductility, and decreases in fracture stress, while internal embrittlement creates internal cracks. Hydrogen reaction embrittlement is a side effect of the chemical connection of absorbed hydrogen and a metal constituent which results in a brittle hydride (e.g. hydrogen can form methane with the carbon in steels). Some methods of preventions include adding titanium and aluminium alloys with the base material, choosing amorphous structure material, plating techniques such as zinc and nickel plating, and coating techniques with graphene and niobium. Additionally, oxide, nitrogen, and carbon diffusion layer can be added to create a barrier for hydrogen penetration [94].

Scientists essentially agree that a crucial problem presents leakage of a flammable or detonable mixture, which can lead to a fire or detonation. As previously mentioned, gas leakage when ignited can lead to deflagration and detonation hazards, which amplitude depends on various factors such as the amount of hydrogen released, the air conditions, space limitation, as well as the location and strength of the ignition source [95]. In open areas, the risk is slightest as hydrogen rapidly rises and disperses before it could ignite. The problem occurs in enclosed, unventilated spaces, where gas cannot easily escape from, which leads to much higher overpressures. The final protection measure that can be used to reduce the consequences of deflagrations in confined systems is explosion venting (e.g. pressure relief panels). Various initiatives (e.g. European Hydrogen Safety Panel – EHSP [96]) and projects (e.g. Hydrogen Safety for Energy Applications - HySEA) are developing recommendations based on pre-normative research, to improve international standards for hydrogen safety procedures such as the design of explosion venting devices [97]. The effect of vent size on vented hydrogen/air explosion was analyzed by Sihong Zhang and Qi Zhang [98]. Research conducted on hydrogen/air flammable gas cloud formation due to hydrogen leaks into confined spaces has shown two diverse gas-dynamic patterns, depending on the speed of the gas release at a constant flow rate. The low speed of hydrogen outflow initially forms a thin layer of flammable cloud at the ceiling, which then expands via concentration front downward. The high speed of hydrogen outflow results in the uniform flammable cloud formation throughout the whole volume above the discharge point [99]. In case that the accident does occur, risks from fire hazards could include personnel injuries, facility, and equipment damage due to high air temperatures, radiant heat fluxes, or contact with hydrogen flames, while explosion consequences encompass blast wave overpressure effects, the heat effects from subsequent fireballs, the impact from fragments, and the structure collapse. J. LaChance et al. presented a survey of harm criteria that can be utilized in Quantitative Risk Assessments (QRA) for hydrogen hazards and risks [100], while D. A. Crown and Y.-D. Jo compared them to the hazards and risks associated with conventional fuel sources (gasoline and natural gas) [101]. C. Shen et al. made a consequence assessment of high-pressure hydrogen storage tank rupture during fire test, where damage patterns and destruction radius range were analyzed considering the intensity of the blast wave, thermal radiation, and flying fragments [102].

To ensure safe operation and detect a leakage on time, reliable safety sensors should be used. National Fire Protection Association (NFPA) obligates the use of hydrogen detectors for indoor fuelling operations [103]. Presently, there is a broad range of safety sensors on the market that are crucial for the successful deployment of hydrogen technology. To prevent hazards, integrated use of Failure Mode and Effect Analysis (FMEA), HAZard OPerability Analysis (HAZOP), and Fault Tree Analysis (FTA) are strongly advised. FMEA lowers the possibility of deficiencies, identifying the areas that are more prone to failures. In the case of failure occurrence, FMEA minimizes its effects, applying the appropriate corrective actions. HAZOP analysis helps with the identification of incidents and potential scenarios, whereas FTA analysis evaluates their happening probability [104]. Incorporating these well-established practices in future projects, as well as personnel training and education in hydrogen safety, are becoming standard in hydrogen safety engineering.

Development strategies

Energy transition of any kind can't happen without implementing the political solution, development of national strategies and action plans with clear agenda, the methodology of development, adequate legislation, and the finance structure. Due to the rapid advancement of hydrogen technology, the realization that its development is an essential part of any future carbon-neutral society was formed. Lots of countries and political entities started developing national plans for the implementation of hydrogen into an energy transition, in the form of the upgrade of current energy national plans with RES and clean energy production. Additions are a clearer focus on energy storage and exploitation of hydrogen's full potential. Development strategies, national plans, or the current state of technological progress of a few selected countries are presented in more detail in the following chapters. The aim is to present and compare different approaches to hydrogen technologies, from leading countries such as Japan and Germany, through some holding weaker reputation considering hydrogen development, to the countries at the very beginning of the true implementation of hydrogen. Almost every country in the world is conducting projects, as well as creating new ones. In the last few years, hydrogen spread out across the globe from most urban places to places with quality hydrogen development far away from the main R&D centres, like is the case with Patagonia [105].

EU

Most of the breakthroughs in hydrogen technology development happened in Europe, which has become the ground for strong innovations regarding hydrogen infrastructure. EU recognized its country's efforts and formed the EU Hydrogen Strategy for a carbon-neutral Europe. The document confirms the growing progress of hydrogen technology and its potential in reaching the 2050 goals of decarbonisation. Its priority is the evolvement of renewable, i.e. green hydrogen, using RES for its production via water electrolysis. The strategy defines three phases of progression. In the first phase from 2020 to 2024 objective is the installation of at least 6 GW of electrolyzers in the EU with the production of up to 1 million tons of green hydrogen. The second phase anticipates hydrogen becoming integrated into the energy system, with the goal of 40 GW of electrolyzers and the production of up to 10 million tons of green hydrogen. The third and final phase is from 2030 to 2050 when green hydrogen technology is to be deployed at such a large scale to reach all hard-to-decarbonize sectors. Boosting demand and scaling up the production are recognized as a vital factor in achieving these objectives, which will require a supportive policy framework. Adequate hydrogen infrastructure and further investment in R&D are necessary preconditions for any breakthrough. Hence, the transparent expenditure agenda will be devolved through European Clean Hydrogen Alliance [106]. Furthermore, the European Commission is implementing the concept of Smart Specialization for the development of European county's regions and cities for financial distribution and development [107].

Croatia

The hydrogen technology implementation plan considers the Croatian economy's dependency on tourism and the necessity for technological advances to keep up with the rest of Europe. Currently, hydrogen projects are conducted at several Croatian universities and institutes [108]. Croatia has relatively high solar energy potential, especially along the seaside, which is why PV systems are incorporated with hydrogen technology [109]. During the past decades, studies were conducted on alkaline [110] and PEM electrolyzers [111], its characteristics such as electrolyte ohmic resistance, the electrode overvoltage, and the electrode active surface [112] were discussed and related mathematical models developed. The solar-hydrogen power system was also proposed for supplying isolated passive houses with utility power energy and hydrogen for personal transport [113]. Research-based in Croatia proposes these types of systems be connected to the Croatian electricity distribution systems alongside the top tourist's traffic routes [114], which could present a possible solution for the peak loads in the system and grid balance. Croatia's 1244 islands are also popular destinations that can be integrated into hydrogen technology projects, where hydrogen as an energy vector combined with intermittent RES forms the islands communities' autonomous energy supply [115]. Medium to small-sized passenger transportation boats that are connecting islands with the mainland, present the opportunity for fuel cell application. Marine engine emissions that are products of fuel oil combustion are polluting the diverse Adriatic ecosystem and population well-being. As an alternative fuel, hydrogen can be stored as liquid ammonia that can be used for propulsion, either by the combustion of ammonia or by its use in fuel cells [116]. Hybrid ships have electric power produced by diesel engines driving electric generators, a fuel cell, and a battery, which makes them environmentally friendlier than conventional systems. Besides, they produce less CO_2, SO_x, NO_x, and can achieve zero-emission in ports [117]. Croatia with its developed shipbuilding industry could potentially take a lead in new green generation ship construction [118]. The Government has also changed its energy legislation and has put forward a framework for the systematic development and increased use of RES and cogeneration, where the use of hydrogen in fuel cells is supported [119]. Given that Croatia is an important European tourist destination, the estimated number of hydrogen FCEVs operated by foreign tourists in Croatia up to 2030 reached 84 000. Therefore, the hydrogen infrastructure, incorporated into the national grid power system and European hydrogen highway network, is needed. With that in mind, the fundamental concept of autonomous HRS and the Croatian roadmap strategy of HRSs were developed. Additionally, the required hydrogen to supply the tourist's FCEVs was calculated. Divided into 3 phases, installation of 3 HRSs by 2020, 7 by the end of 2025, and 12 by 2030 was suggested, with proposed locations as shown in Fig. 4 [120].

The first Croatian HRS was designed to secure the autonomy of the first Croatian fuel cell powered bicycle and boost hydrogen urban mobility. It has an innovative design that has been protected as intellectual property on the international level and as the trademark on the national level [121]. The HRS is designed concerning future upgrades, so those new innovative solutions can be implemented. As follows, the first Croatian HRS can be enhanced in a way that it provides hydrogen for remote areas regardless of extreme climate conditions it is subjected to. One of the most important parameters for the smooth operation of thermodynamically sensitive devices inside the HRS is the air temperature inside the housing itself. New research is initiated where the thermal management system is being introduced to maintain an optimal temperature distribution throughout the year. The thermal management of HRS housing is a great example of how to improve the functions of HRS in general [122]. Another research currently in progress is an experimental analysis of autonomous emergency micro-grid based on the solar system and hydrogen energy core. Electric energy produced from PV modules is used to cover the needs of consumers and when production exceeds consumption, electricity is used via electrolyzer to produce green hydrogen, which is then compressed and stored. The project is planned to develop the energy core of mobile and stationary so-called emergency systems based on hydrogen technology that will secure energy supply in case of shorter duration hazards. An auxiliary system installed this way is a potential foundation for the industrial development of Croatian large and medium-sized enterprises. Multiplication of micro-grids will reduce fossil fuel import, and thus dependence on the third countries.

Croatia's hydrogen infrastructure development will potentially encourage border countries (Italy, Slovenia, Hungary, Serbia, Bosnia and Herzegovina, and Montenegro) to connect with the progressive part of Europe and join the hydrogen economy. Presently, according to the Ludwig-Bölkow-Systemtechnik, out of 6 surrounding countries, only Italy has HRSs in operation, as shown in Fig. 5. Analysis of non-economic barriers for the deployment of hydrogen technology and infrastructures in European countries made by Davide Astiaso Garcia shows countries development such as that of Slovenia and Hungary is mostly hindered by complex procedures among involved authorities and lack of government's initiatives for increasing the transmission and distribution networks and the use of hydrogen vehicles [123]. Given the complexity of national directives and administrative procedures, end-users and investors are choosing transparent solutions already established on the market. Moreover, survey results have shown that the majority of citizens are not properly informed about hydrogen technology and therefore opt for known fuels. The number of applicants is additionally reduced by the lack of information and assistance to hydrogen experts for submitting project proposals. Despite those circumstances, prospective organizations similar to Croatian Hydrogen Association (CroH2) such as Hungarian Hydrogen and Fuel Cell Association, Hungary Chapter of Hydrogen Energy, Hydrogen Serbia, H2IT Italian Hydrogen and Fuel Cell Association, and Slovenian Hydrogen Association are all making efforts that bring countries closer to hydrogen implementations. For example, the initiative Spreading hydrogen mobility in South-East Europe (HYSEE) is planned to connect Serbia, Hungary, Bulgaria, Romania, and Greece. Also, a recent study shows that there is a large hydrogen storage potential in a salt cavern in Bosnia and Herzegovina [124].

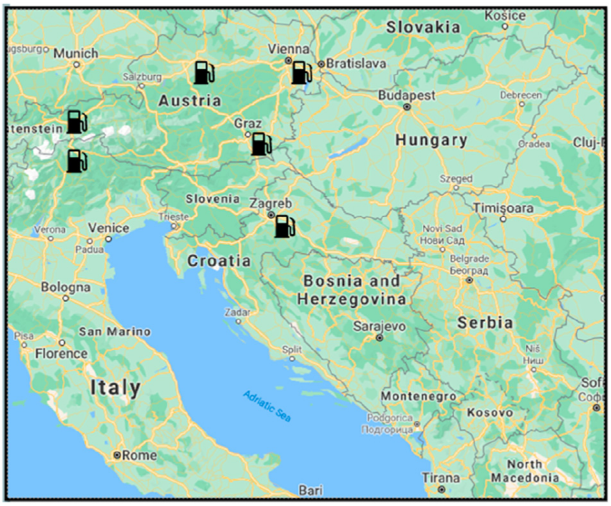

Fig. 5 – Map of HRSs in Croatia and surrounding countries.

Considering that the EU (and the establishment of the European Clean Hydrogen Alliance) recently published the European Hydrogen Strategy, Croatia is in the process of making its own National Hydrogen Strategy. With it, Croatia will be able to equally participate in the energy transition through various European programs and developing mechanisms. The initiative for the National Hydrogen Strategy was born within the CroH2 and was presented to the Minister of Economy and

Fig. 4 – Proposed development of hydrogen infrastructure in Croatia [120].

sustainable development of Croatia. The initiative has been accepted and the official announcement of the members of the working group is underway. The CroH2, with Prof. Frano Barbir, PhD as president and Assist. Prof. Ankica Kovač, PhD as vice president, has become a member of Hydrogen Europe, the umbrella association of the European hydrogen-related industry and associations from individual countries. Ultimate goals of the new professional association are the creation of a positive social, educational, political, and economic climate for the development and acceptance of hydrogen technology, bringing together Croatian industry (e.g. INA - multinational oil company), scientific (e.g. the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture as a member of European Clean Hydrogen Alliance) and R&D community, as well as including hydrogen in national energy strategies [125]. Croatia has taken the initiative and made a lot of effort to be able to one day join the leading countries in hydrogen technologies applications in transportation, stationary power generation, production, and cogeneration.

How to shape Croatia's hydrogen strategy?! — novel approach

For a long time, there have been a lot of signs that apart from hydrogen, there is no better or more comprehensive solution for both the short-term (until 2030) or long-term (until 2050) period. A three-pillared Croatian Hydrogen Strategy that leans on hydrogen production, utilization, and the education of the relevant community needs to be formed.

(i) The first pillar involves defining a broader strategy than the one based on grey hydrogen, i.e. a development strategy that progressively turns towards the green hydrogen by slowly reducing the amount of grey from the beginning, following EU guidelines. The duration of this short period of grey hydrogen in the Republic of Croatia has to be defined in detail. Several pilot projects will be realized while waiting for the drop in electrolyzer prices (which are already 60% lower than initial), needed for green hydrogen production. The needed quantities of green hydrogen can potentially be provided from large private producers of green electricity and/or state wind turbines and solar power plants, or public-private partnerships. However, if hydrogen were to be produced by domestically produced equipment as well, and not just imported, domestic production of low-power equipment could be launched and thus increase employment. If such a focused production were accompanied by a strategy of multiplication of micro-networks with solar-hydrogen energy cores, Croatia would stop relying on fossil fuel imports and become a country with a more flexible and robust electricity network. Moreover, it would be ready for climate extremes and their consequences that will follow in the coming decades.

(ii) The second pillar of the strategy is going to cover the question of who will use and buy hydrogen. In the first instance, public city transport (e.g. hydrogen-powered buses, truck transport, and railways) comes into consideration, and over time, car owners, vans, and even 3- and/or 2-wheel vehicles such as motorcycles and hydrogen-powered bicycles. Hydrogen will also be purchased by owners of stationary energy cores of local micro-networks in larger buildings or neighbourhoods.

(iii) The third pillar of the strategy is formed by the community who created the policy and are ensuring its efficiency and safety. Relevant faculties and educational institutions will provide professional people in both hydrogen production and usage and will offer curricula, various research, development, and guidance centres. Educated people are crucial for the energy transition involving hydrogen technology, as well as its implementation in large, medium, and small businesses. If such a basic concept of a hydrogen strategy is adopted, it would not be a problem to develop each pillar separately, defining the participants, their responsibilities, and the time and financial framework for individual actions.

Now, it is certain that the Republic of Croatia has to start investing in hydrogen.

Germany

As Europe's leading country in deploying and investing in hydrogen technology, Germany's Hydrogen National Strategy can serve as a guideline for other European countries. It is deeply incorporated with the EU vision of the hydrogen future. The goals and ambitions of their national strategy are focused on the integration of hydrogen in their industry and society. The recognized potential of the production of equipment can create numerous new jobs and bring new value to the economy. Ensuring a carbon-free society, with the right strategy, is no weight on the economy, but the flywheel of development and economic growth. The strategy is consisting of two phases. In the elaborated first phase, Federal Government will take 38 measures considering hydrogen production, transport, industrial sector, heat, infrastructure/supply, research, education, innovation, and focus on co-operation on European and international levels considering the market and economic partnership. It is supposed to last until 2023, when the second phase will be initiated with goals of stabilizing the new domestic market, moulding the European and international dimensions of hydrogen, for the benefit of the German industry [126]. To ensure the balanced development of hydrogen technology throughout the country, adequate delivery and distribution systems must be included. Studies regarding pipeline networks backed up with truck transport are good initiatives ensuring the diversity of possible solutions [127,128].

Benelux

As the objective of the energy transition towards the carbon-free society is not just a part of the few leading countries in the world, but a joint global undertaking, projects in the rest of the countries are to be conducted as well. A good example of how the energy transition is planed can be found in Netherland. Their main goal is to decrease the use of natural gas in the energy transition, investing, among others, in hydrogen.

Government Hydrogen Strategy has recognized hydrogen as a technology that will be strongly researched and applied in the next decade and adjusted its policy so that Netherland should enter the market and development sectors as soon as it is realistically possible. Their agenda is based on four pillars: the creation of quality and effective legislation and regulation cost reduction and scaling up production of green hydrogen, the sustainability of final consumption, and supporting policy ranging from international cooperation to regional development. The timeline is not set, but the basic conditions for the growth of hydrogen are to be shaped by 2025, including the formulation of the National hydrogen program [129]. As Netherland has excellent wind potential, the idea of exploiting that particular RES with a consistent infrastructure was explored. Nikolaos Chrysochoidis-Antsos, Miguel Rodríguez Escudé, and Ad J.M. van Wijk research was conducted on already installed refuelling stations in Netherland. Results indicate that 132 out of 3021 refuelling stations in the Netherlands, which amounts to around 4,6%, are suitable for the installation of a wind turbine for hydrogen production. Wind turbines are suggested to be installed on the location of the refuelling station with an electrolyzer unit to produce hydrogen on the spot [130].

Netherlands neighbour, Belgium, does not have the reputation of being a frontrunner in hydrogen development. As it is surrounded by France, Netherland, and Germany that are engrossed in this sector, the idea is for Belgium to stay connected in the regional hydrogen roadmap development. However, some conditions that place Belgium in quite a unique position. Belgium's huge advantage, the port city of Antwerp, is one of Europe's centres of hydrogen production, where one of the largest underground pipeline transport networks of hydrogen begins. Also, many companies connected with hydrogen development are located in Belgium. With the vision of implementing hydrogen in Belgian transport, H2-Mobility Belgium was developed with the main goal of creating a National Implementation Plan for hydrogen in Belgium and preparation of Belgian's market for FCEVs. Based on the prediction of neighbouring counties, the development of HRSs and FCEVs on the road was calculated. It is anticipated that by the end of 2020, 25 HRSs will be installed, 75 by the end of 2025, and 150 by the end of 2030, covering the needs of 30.000 FCEVs. The achieved results for 2020 suggest overestimation in the predicted numbers. Belgium's hydrogen strategy needed for further development is shown in Fig. 6 [131].

Iceland

The use of hydrogen as energy storage in remote locations is often emphasized as an environmentally friendly, quality solution that can secure electrical power for inhabitants. That is why the idea of the hydrogen economy on the island state of Iceland is not new [132]. The ambitious goal to transform Iceland's national economy through energy transition towards the hydrogen economy by 2050 is a testament to long-term planning and policy-making [133]. Therefore, a few research and case studies were conducted regarding progress and sociotechnical effects on people and the state [134]. Since Iceland is a country with great RES production of electricity and potential for further electrification with the main objective being lowering dependency on petrol fuel, transport is the right sector for the hydrogen implementation. Although it requires energy supply systems development and further investments, hydrogen is an attractive alternative in reducing the import of petroleum products, consequently reducing consumer total fuel costs [135]. Therefore, Iceland's energy transition will continue with hydrogen as one of the main factors.

Central and Eastern Europe

For countries of central and Eastern Europe, hydrogen development, which started around the 1960s, came to a halt, by the end of the 20th century, due to a change of political regime, which significantly slowed down their research and national development plans [136]. In the Czech Republic, by the founding of the Czech Hydrogen Technology Platform (HYTEP) in 2007, interest in hydrogen started growing and new projects were created. This has resulted in an increase in hydrogen production locations as shown in Fig. 7 [137]. By investing in the development of hydrogen technology, they expect to create an impact on lowering emissions of produced CO_2, improve adoption of legislation considering the application of hydrogen and achieve a positive impact on economic growth [137]. A similar situation is in countries like Poland, Romania, and Ukraine where organizations promoting hydrogen started to appear at the begging of the 21st century. All are directed towards RES and dedicated to including hydrogen in their energy transition [136].

In the Russian Federation, hydrogen technology development started during the Second World War, and considering the strength and importance of the former USSR, it is not surprising it had great progress. Hydrogen technology was used in space exploration. In the 1980s FCEVs were designed and even hydrogen aircraft engine was constructed. Development continued in the following centuries with the establishment of the National Hydrogen Energy Association of the Russian Federation (NHEA RF) in 2003 [136]. Many fundamental R&D projects are being conducted. Due to Russian geography, research concerning the application of hydrogen technology in the Arctic region proved to be promising. Significant improvements in hydrogen infrastructure could solve the energy availability problem of isolated and remote societies located in the Artic [138].

Japan

It can easily be said that Japan is the world's champion in hydrogen power. As an economically and technologically advanced country without many natural resources, the national direction towards RES and hydrogen was the most obvious way of securing energy independence, long-term sustainability, and stable foundations for future development. Japan's Hydrogen Strategy from 2018 set the groundwork for further development of research and industry. Furthermore, the economic and geopolitical implications energy transition will bring are discussed. With an ambitious ultimate goal of becoming a carbon-free hydrogen society short after 2050, their strategy is reliably backed up with a

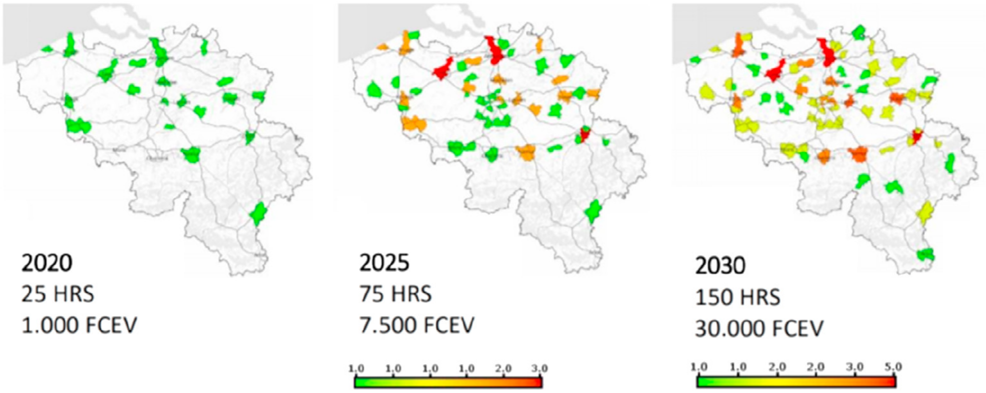

Fig. 6 – Projection of hydrogen infrastructure development in Belgium [53].

Fig. 7 – Hydrogen production locations in the Czech Republic [137].

financial background. Japan's hydrogen concept is not narrowly directed only on an electrical energy storage solution, but on all integral parts of many economic sectors. If succeeded, hydrogen will become the main fuel for the economy drive. Hydrogen production is founded on the combination of petroleum steam reforming and coal gasification with CCS and green hydrogen production via water electrolysis. The next major sector is transportation, where the focus is set on the technology of liquefied hydrogen, hydrides, ammonia as a hydrogen carrier, compressed hydrogen, and reliance on a domestic network of pipelines and trucks. Applications in industry, power generation, and stationary fuel cells for residential CHP are primary solutions for implementing hydrogen into society. However, the main application is in transportation sector. Two out of three leading world car manufacturers of FCEVs are from Japan (the third being from the Republic of Korea). It is of big importance to raise global awareness and international cooperation on a higher level because, without market and hydrogen acceptance in the rest of the world, investments will be wasted money. Experience with hybrid sales, which have a relatively well-spread refuelling station network around the globe, indicates that Japan's predictions of 800 000 FCVEs in 12 years is ambitious and will be hard to achieve without joint global cooperation. Although they have strong FCEVs car-making companies, they don't sell a majority of the cars in Japan, which has the most developed hydrogen infrastructure, but most of the FCEVs are sold in the USA, more precisely California [139].

Republic of Korea

As one of the leaders in hydrogen technology advances, Korea has proven to be committed to the cause of reaching a carbon-free society. The rapid growth of population and economy strongly impacted the country's standing in the second half of the 20th century. With the economy skyrocketing and industry spreading with the exponential growth of the transport sector, pollution started to be a significant problem. Korea than shifted their focus towards RES and better living

Table 2 – Predicted number of FCEVs in Korea [140].

	2019	2022	2030	2040
Passenger cars	6.395	65.000	810.000	2.750.000
Taxis	–	–	10.000	80.000
Buses	–	2.000	20.000	40.000
Trucks	–	–	10.000	30.000

conditions for its citizens, that brought hydrogen role upfront national transformation process. In the last few years, Korea started to see the results of investments and development programs, which seems to follow the path of Japan considering the number of HRSs installed. Plans for HRSs are predicting the rapid growth of FCEVs on Korean roads in the next two decades, as given in Table 2. Considering the increase of FCEVs, a detailed analysis of needed HRSs development was necessary. Relevant research was conducted by Hyunjoon Kim, Myungeun Eom, and Byung-In Kim. Authors attempted to realistically present challenges in real conditions for projected demands and propose an optimized plan for national wide deployment of HRSs as given in Table 3 [140].

China

One of the world's largest national economies is still in the process of rapid growth with no indications that will stop any time soon. Rapid development and an increase of standard lead, consequently, led to increased pollution as well. With this in mind, China is strongly enforcing larger implementation of RES-based technology, in conjunction with hydrogen, as their environmental problem, especially in big cities, is dangerous for human wellbeing. Therefore, many projects and studies on national strategies were conducted, considering hydrogen. As they proved on the example of solar technology, China is more than capable to drastically impact the hydrogen market and with innovative solutions to decrease the cost of production. According to some of their earlier predictions, they expect to have around 1 million FCEVs on their roads by the end of 2030. For that number, around 1000 HRS is suggested. Although estimations like that might sound optimistic, China's ambition towards the strong development of hydrogen proves that it is on the right path to success. One of the key suggestions in hydrogen policy is further research encouragement since the cost is still the main obstacle in large-scale production, greater attention on the development of commercial vehicles fleet as is the case with passenger vehicles, detailed infrastructure planning, and focus on system integration [141].

Table 3 – Calculated numbers of HRSs in Korea for the proposed number of FCEVs [140].

	2022	2030	2040
General roads	186	336	801
Expressways	58	60	78
Bus	69	211	290
Overall	313	607	1169

Conclusions

The increasing growth of green hydrogen role in forming a future carbon-neutral society is discussed and reviewed, as well as the transitioning stage of both small and larger countries. The framework of analysis is formed by the advances in the technological, social, and industrial aspects of hydrogen. As societies are directed toward a future where RESs are a dominant figure in the energy sector, energy storage, and its utilization are becoming key factors for achieving the next step. It became obvious that without incorporating hydrogen technology in energy transition strategies, there will not be enough potential to completely submerge in a carbon-neutral future. The advancement and development of hydrogen technology are already at a satisfactory level for its complete involvement in the national strategies. Presently, the number of ongoing R&D projects is a record high, with estimations predicting an even more rapid increase shortly soon. The hydrogen market's significant growth proves that trust in hydrogen technology development was well placed. Primary focus is set on solving legislation, securing adequate markets, preparing industries and economics for the growth of hydrogen-based systems, and promoting global interconnection and cooperation. The main challenges of the energy transition with hydrogen future essential role in it, might not be problem of cost or efficiency as it were a few decades ago but preparing society and users for the presence of hydrogen in normal application and life. According to the strategies and predictions of several governments, hydrogen-based systems and applications could, in a relatively short time spawn, significantly expand their presence on the market, from occasional cutting-edge technology of the future to everyday occurrence. Fear of hydrogen, which is dating back to the Hindenburg Zeppelin explosion in 1937, labelled hydrogen as dangerous. Thus, every incident has a greater impact on the public compared to the accidents of other technologies, even if they occur more often with more severe consequences. However, understanding that the current situation is unsustainable is pushing the world towards RES and hydrogen as a clean version of a better society. Health and living difficulties caused by air pollution in a densely populated area, constant natural disasters caused by evident climate changes, inefficient waste management, and global pollution in general are topics that do not worry just scientists anymore, but the whole world. Therefore, the situation has matured for governments and investors to institute proceedings for scaling up investments in green technologies. Today's leading countries in hydrogen utilization are Japan, Germany, and the USA since they first recognized not only an environmental necessity but economic potential as well. Given their positive developing trends, other countries that started investing in new projects will eventually reach the current state of the earlier mentioned trio, establishing a global market and easing the way for the rest of the countries, which are at the beginning of the transition or didn't yet start. Their development will be accelerated by the existence of a well-developed, cheaper, and stabilized technology. The relevant example is Croatia, which is currently undergoing the process of the energy transition, implementing its hydrogen strategy. The future research scopes will be directed towards the appropriate means of carrying out this directive. If even a quarter of various national and global strategies will be actualized by 2030, the impact on the population will be extensive and the direction of the energy transition towards a green hydrogen society fixated. Ultimately, hydrogen will solidify its place as an essential part of the future green, carbon-neutral energy society.

Declaration of competing interest

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

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