M. A. Butturi & R. Gamberini, Int. J. of Energy Prod. & Mgmt., Vol. 7, No. 2 (2022) 151–163

THE POTENTIAL OF HYDROGEN TECHNOLOGIES FOR LOW-CARBON MOBILITY IN THE URBAN-INDUSTRIAL SYMBIOSIS APPROACH

MARIA ANGELA BUTTURI & RITA GAMBERINI
Department of Science and Methods for Engineering, University of Modena and Reggio Emilia, Italy.

ABSTRACT

The use of green hydrogen to power vehicles is recognized as contributing to the mitigation of the greenhouse gas (GHG) emissions responsible for climate change. On the other hand, the need for reducing GHG emissions is even more urgent in densely industrialized areas, traditionally located nearby highly populated zones. In these areas, road transportation is a relevant source of environmental pressures affecting air quality and the nearby communities' health: in Europe, private vehicles, vans, trucks, and buses produce more than 70% of the overall greenhouse gas emissions from transport, as well as particulate matter and nitrogen oxide. The European Hydrogen Strategy considers using green hydrogen as an energy carrier to de-carbonize industry and the transport sector, highlighting the need for the infrastructure to produce, store, and distribute hydrogen. The spatial configuration of the industrial sites and the existing infrastructure can facilitate the creation of hydrogen hubs serving both the logistics needs of companies and the public and private mobility in an urban-industrial symbiosis approach. Thus, this study aims at investigating the opportunities offered by the creation of synergies between industrial clusters and the nearby urban areas to improve the local sustainability by supporting the deploying of low-carbon mobility using green hydrogen. The available literature is reviewed in order to schematise and discuss the sustainability-related basis of adopting such a strategy, presenting an updated analysis of the latest research and application results suitable for future research applications and for supporting decision-making processes.

Keywords: climate change mitigation, green hydrogen, sustainable mobility, symbiosis, urban-industrial.

1 INTRODUCTION

According to the International Energy Agency (IEA) [1], transport accounts globally for 37% of CO_2 emissions from end-use sectors; moreover, it significantly contributes to air pollution, mainly through the release of particulate matter (PM), nitrogen oxides (NOx), and sulphur oxides (SOx), impacting urban air quality and communities' health [2, 3].

These issues require a shift to zero-emissions vehicles to reduce the environmental impacts of the transportation sector, as recognized by European [4] and global climate change mitigation strategies [5, 6]. In this effort towards a low-carbon mobility, hydrogen fuel vehicles (Fuel Cell Electric Vehicles – FCEVs) can be complementary to battery electric vehicles, opting for the most appropriate technology for each application and market segment [7, 8]. Also, the local railway sector, where diesel trains are mostly employed, can switch to hydrogen trains, supporting the sector's decarbonisation [9]. In fact, when used in fuel cells, hydrogen produces only water as a by-product and can be considered an alternative to fossil fuels [10].

Hydrogen is conventionally produced by fossil fuels using technologies like hydrocarbon reforming and hydrocarbon pyrolysis for industrial applications; to reduce the impacts of the production processes, many processes to obtain hydrogen from renewable resources are available, such as biomass-based technologies and approaches using water splitting [11]. Biomass-based technologies are thermochemical and biological methodologies that both release less CO_2 than conventional processes, producing the so-called "low-carbon"

ISSN: 2056-3272 (paper format), ISSN: 2056-3280 (online), http://www.witpress.com/journals
DOI: 10.2495/EQ-V7-N2-151-163

hydrogen [10]. The power to hydrogen process uses electrolysis to convert surplus electricity into hydrogen, splitting water molecules into dioxygen (O_2) and dihydrogen (H_2). When the employed electricity is only of renewable origin, e.g., produced by photovoltaic or wind systems, the produced hydrogen can be considered clean and is conventionally qualified as "green hydrogen" [5].

The deployment of renewable power-to-mobility hydrogen applications requires the development of hydrogen generation plants, distribution infrastructure, as well as refuelling and charging stations, posing techno-economic, security, and public acceptance issues [5]. On the contrary, the existing industrial areas can represent for the local communities a familiar industrial structure where facilities giving rise to perceived risks or disadvantages can be confined [12]. Thus, the industrial parks (IP) can create synergies with the adjacent urban areas, providing a suitable location for renewable power plants [13] to produce green hydrogen, for hydrogen storing and distribution facilities, and for exchange parking as a last-mile solution. In this approach, implementing the urban-industrial symbiosis model, the industries contribute to reduce both the emissions of the trucks, vans, and car traffic serving the commercial area and the environmental impact of the urban mobility. The urban-industrial symbiosis extends the industrial symbiosis concept to urban-industrial synergies, representing an integrated approach to the urban regeneration strategies that links the urban metabolism research field and the sustainable city planning [14]. The main advantages for the involved industries are related to eco-innovation, while the local communities benefit from the environmental restoration and improved well-being [15].

This paper aims at reviewing the scientific literature in order to analyse the green hydrogen solutions suitable to support local low-carbon mobility through the urban-industrial approach. The sustainability issues related to the adoption of this strategy are discussed to support future research applications and decision-making processes.

2 RESEARCH METHODOLOGY AND ANALYSIS FRAMEWORK

The more recent scientific literatures have been reviewed focusing on three main topics: the green and low-carbon hydrogen technologies, the low-carbon mobility solutions using hydrogen, and the hydrogen technologies employed in the energy hub context, suitable for the UIS context. The thematic analysis follows the outline illustrated in Fig. 1.

From the reviewed literature, the power-to-mobility applications of hydrogen suitable for the UIS context have been extracted and discussed.

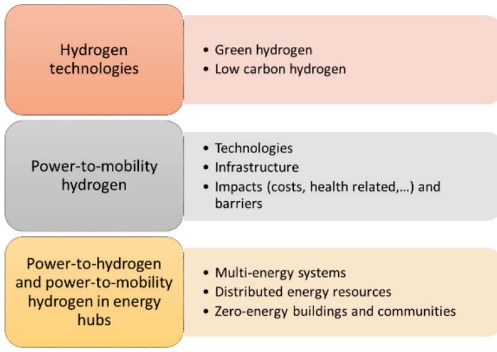

Figure 1: Thematic analysis framework for the reviewed literature.

2.1 Green and low-carbon hydrogen technologies

2.1.1 Green hydrogen

Green hydrogen is a power-to-hydrogen application, and it is obtained via electrolysis using renewable electric power; this is the lower emission process to generate hydrogen, producing high purity hydrogen [16]. Thus, green hydrogen is used when high purity hydrogen is requested or to reduce the peak loads on the grid and to stabilize the intermittent power supply from renewables [17], as hydrogen storage has proven to be an achievable option to support the increasing integration of power generation by renewable energy sources (RES) into the electricity grid [18].

Water electrolysis is a well-known endothermic process using electrical energy input to split water molecules into hydrogen and oxygen molecules. The typical electrolysis unit is the electrolyser, consisting of an electrolyte where a cathode and an anode are immersed. Three types of electrolysers are currently available commercially, each using different electrolytes and working under different conditions: alkaline water electrolyser (AEL), proton-exchange membrane electrolyser (PEM), and solid oxide electrolysis cells (SOEC) [5, 19]. The different technologies show different stages of development, performance, and cost [20].

The IRENA compared the key performance indicators for the different technologies in 2020 with 2050 projections, showing their large-scale applicability potential (Table 1).

Considering only the stack, PEM electrolysers have the smallest footprint, with an estimated footprint of 8 to 13 × 10^4 m^2 for a 1 GW PEM facility, compared to an estimated footprint of 10 to 17 × 10^4 m^2 for a 1 GW AEL facility [21].

The main renewable technologies employed or modelled for green hydrogen production are solar technologies, mainly photovoltaic (PV) systems [22]. Solar and wind-hydrogen coupling have been widely studied using case studies analysis, techno-economic assessment, and simulations [23–27], showing good economic potential depending on both local wind or PV electricity cost and the electrolysers technology maturity [16, 28].

2.1.2 Green hydrogen storage

Three are the main approaches to store hydrogen: it can be stored physically as a gas or liquid, or by adsorption and absorption on the surface or within solid materials, with different volumes, temperature, pressure, and storage duration characteristics.

The high-pressure gaseous hydrogen storage is the most common and mature technology; since the energy density of hydrogen by volume is low, it is necessary to compress it at up to 77 MPa to reduce the size of the storage tanks. Another way to increase the hydrogen density

Table 1: Hydrogen technologies' current costs and projections to 2050 (*adapted from IRENA* [21]).

	2020			**2050**		
	AEL	**PEM**	**SOEC**	**AEL**	**PEM**	**SOEC**
Cell pressure (bar)	< 30	< 70	< 10	> 70	> 70	> 20
System efficiency (kWh/kgH_2)	50–78	50–83	45–55	< 45	< 45	< 45
Lifetime (thousands hours)	60	50–80	< 20	100	100–120	80
Capital costs estimate for large stacks (>1MW; USD/kW_{el})	270	400	> 2000	< 100	< 100	< 2000

is to store it as a liquid at atmospheric pressure but at a very low temperature, about –253°C. Finally, solid-state storage, involving the combination of hydrogen with materials through physisorption or chemisorption, allows storing hydrogen at moderate temperatures and pressures [5, 10].

2.1.3 Low-carbon hydrogen

Besides the green hydrogen, the so-called "low-carbon hydrogen" can also support the low-carbon mobility. The low-carbon hydrogen can be produced using biomass which, under some conditions [29], is considered a renewable source of energy. On the contrary, the GHG accounting of hydrogen is recognized as a possible indicator for a general definition of clean hydrogen [30]. Biomass can be used to produce hydrogen, along with other byproducts, by thermochemical processes, namely, gasification and pyrolysis. In both technologies, the yield of hydrogen production depends on parameters such as the type of feedstock, the temperature, and the type of catalysts used [10].

2.2 Power-to-hydrogen mobility

According to the scenarios designed by IRENA [31], the transport sector could be the second largest user of renewable hydrogen by 2050. In the transport sector, hydrogen can be used in fuel cell electric vehicles (FCEVs). The use of clean hydrogen as a low-carbon transport fuel is going to take off as cars, buses, and commercial vehicles (trucks and vans) become available. The power-to-mobility configuration includes renewable electricity production, green hydrogen production, and the hydrogen supply network, including the refilling stations.

2.2.1 Technologies and impacts

The hydrogen can be used as fuel in internal combustion engines (slightly modified gasoline engines), but they have low efficiency and emit dangerous nitrogen mixtures [61]. Currently, the most efficient power-to-mobility hydrogen applications are the FCEVs, since they generate electricity by chemically combining the hydrogen and the oxygen from air into nonpolluting water. FCEVs were first introduced by car brands, like Honda, Toyota, and Hyundai, and are now being followed by other brands; in 2018, the market value of FCEVs was \$651.9 million, with a 66.9% increase predicted to 2026 [32]. Moreover, about 25,000 forklifts powered by hydrogen fuel cells are already in use worldwide, as well as more than 500 buses, 400 trucks, and 100 vans [33].

Due to the low-operating temperature (about 80°C), the most suitable fuel cells for FECVs are the proton exchange membrane (PEM) fuel cells, which include a solid polymer membrane electrolyte and carbon electrodes, with platinum used as a catalyst [3].

According to the LCA comparative study of Candelaresi *et al.*, a medium driving range of 600 km can be assumed for the FCEVs (0.76 kg of H_2 every 100 km) and they show an excellent transport decarbonization potential [34]. Moreover, when compared to battery-powered electric vehicles, FCEVs have a shorter refueling time and longer driving range [35]. Iannuzzi *et al.* [36] compared the conventional buses used in the city of Rosario (Argentina) and equivalent fuel cell electric buses by means of LCA analysis, finding that the logistics of raw materials and transport of hydrogen in a radius of 50 km from the use place are not relevant in terms of energy and greenhouse gas emissions.

Regarding the economic barriers to the FCEVs' deployment, the analysis performed by Ajanovic and Haas [33] based on the technological learning shows that the cost of the FCEVs is expected to reduce more faster than that of conventional fueled vehicles, making FCEVs competitive in the market.

2.2.2 Infrastructure

The need for expensive infrastructure, requiring common standards and regulations for safety and maintenance management, is considered an important barrier to the power-to-mobility application [35].

The hydrogen refueling stations (HRS) have different configurations depending on where hydrogen is produced. In the case of on-site production, HRS includes the hydrogen production unit, the compression system, storage tanks, the gas booster to regulate pressure during the refueling procedure, a cooling unit to guarantee safety during the fast vehicle's tank refill, other safety equipment (relief valves, sensors, and waterless fire suppression), mechanical and electrical components, and the dispensers. For off-site production, the hydrogen must be delivered from a central production unit (or a local storage hub) by road transportation or dedicated pipelines. Heavy-duty trucks transport hydrogen by means of tube trailers containing compressed (more than 180 bar) or liquefied gas (at a temperature –253°C); the pipeline transportation is a low-cost solution if existing ones can be used, since this kind of transportation does not require energy for compression or liquefaction nor the use of vehicles, but it must include a receiving station. On-site production requests a higher investment: HRSs with on-site water electrolysers can request an investment 1.5 times higher than a same capacity off-site station [37]. As far as concern, the cost of hydrogen distribution and dispensing into FCEVs, the use of on-board metal hydride storage tanks reduces the fueling costs with respect to the use of 700 bar tanks because of lower compression costs [38].

The refilling station network should be located through geo-optimization tools after accurately mapping the hydrogen consumption needs for light and heavy vehicles, considering urban areas and logistic centers, industries, and transport fleets [19].

Both for centralized and distributed hydrogen production, regulatory procedures include, among others, the environmental impact assessments and the urban planning acts' compliance. The HyLaw project, funded under the Horizon 2020 Programme, provides an online database including the applicable regulations in 23 European countries, while calling the attention of policymakers on legal barriers to be removed for the deployment of hydrogen applications [39].

Although the economic, safety, and regulatory concerns are addressed, the green hydrogen-to-mobility applications show great potential with the technological advancements. Robinius *et al.* [40] present a model for the analysis of the power-to-mobility application of the green hydrogen in Germany in 2050, considering the national renewable energy sources (RES) potential and the hypothesis of using the surplus renewable energy to produce hydrogen. The simulated scenarios include a distributed production that requires minimal hydrogen infrastructure, which is more cost-effective; a transmission network to connect the electrolysers to a number of secondary sources (hubs); and a distribution network connecting the hubs to the hydrogen fuelling stations located along the freeways. The economic analysis of the scenarios shows the cost-competitive potential of such a solution. The model applied by Fragiacomo and Genovese to a regional project deploying the power-to-mobility green hydrogen in Southern Italy demonstrates both financial performance and health-related economic positive impacts due to the reduction of carbon dioxide emissions [41]. Schitea *et al.* consider The development of the hydrogen mobility in Romania starting with urban agglomeration to be a reasonable choice to justify the initial investments, hypothesizing to revamp the available refuelling infrastructure [42].

The creation of a green hydrogen value-chain for the urban public transport (fuel cell buses) in Germany is proposed by Coleman *et al.* [43], considering near-site hydrogen production and short-distance pipeline infrastructure. Indeed, in the ramp-up phase of hydrogen infrastructure development, small-scale transportation strategies could be economically viable [44].

Beside the techno-economic and regulatory issues related to the implementation of the hydrogen distribution networks already mentioned, other main barriers to the large-scale deployment of green hydrogen applications can be the availability of water supply for electrolysis and the safety and public acceptance issues [17].

The main hydrogen safety research streams include three topics: storage and detection, combustion and explosion, and ignition and propagation [45]. In China, hydrogen is considered a dangerous chemical, making the installation of HRS possible only in chemical plant areas or far away from urban areas [17]. On the contrary, the EU-funded project Hydrogen Mobility Europe [46] reported, by March 2021, the monitoring data of 330 FCEVs, made by Daimler, Honda, Hyundai, and Toyota, 237 fuel cell range-extended electric vans, made by Symbio, and 39 hydrogen refuelling stations located in 8 EU countries; among other results, the FCEV have proven to be reliable, and there have been no vehicle or HRS safety issues. However, regarding the public's acceptance of HRS safety concerns, surveys show that there are high percentages of opponents to the building of stations near their residences, requiring more communication efforts and risk information to improve acceptance [47, 48].

According to the review by Emodi *et al.*, the engagement of local communities and local authorities in hydrogen projects, providing benefits and supporting infrastructure, promotes the social acceptance of the hydrogen industry [49].

2.3 Hydrogen in the energy hub context

The smart multi-energy systems (MES) combine different and complementary energy conversion technologies [50], including a share of renewable; when arranged as energy hubs [51], they support the energy-based industrial symbiosis, promoting the urban-industrial symbiosis approach [14].

Many studies have been conducted on the hydrogen technologies used in multi-energy and distributed energy systems [52], where hydrogen storage enables the coupling of different energy forms [53]. The analysis is performed at different scales (household, buildings, and current power plants) considering the hydrogen support to the high penetration of renewable sources (mainly sun and wind); with respect to end-use, the hydrogen used as fuel in vehicles, boilers, or CHP units, as a raw material for the industry are considered, and as a renewable energy storage medium [54]. In stationary applications, hydrogen energy storage systems can provide higher energy storage density and a longer life cycle compared to lead-acid or lithium-ion batteries [53, 55]. Moreover, it reduces the lifecycle carbon emissions of energy storage [56]. Fang *et al.* modelled the microgrid of an industrial park, showing that hydrogen-based energy storage can better achieve peak shaving and reduce grid connection fluctuations, as well as reduce the electricity cost of industrial parks, compared to conventional batteries [57].

Maroufmashat *et al.* [58] reviewed the common applications of energy hubs, including the use of hydrogen as an energy vector for storage and FCEV fuelling; they found that the distributed generation and delivery of hydrogen is more sustainable both from an environmental and economic point of view than centralized delivery. Moreover, Edwards *et al.* [44] observe that industrial clusters include suitable transmission and distribution infrastructure that can reduce the initial investment costs. Erikson and Gray [59] investigated the challenges of integrating hydrogen production, storage, and use into microgrid configurations with the aim of optimizing the hydrogen deployment within local hybrid renewable energy systems; their optimization model considers techno-economic, environmental and socio-political objectives, to allow a socially responsible evaluation of the hydrogen application to off-site or on-site FCEV filling stations. Bartolucci *et al.* [60] show that, though still not viable from an economic point of view, a significant penetration of hydrogen into the MES allows us to achieve a reduction of fossil primary energy up to 80%, implying a carbon footprint reduction, and higher levels of flexibility and resilience of the energy hubs. A trade-off between the high installation cost of small distributed hydrogen generation plants and the reduced cost of a local distribution network must be reached, taking into account the better coverage of the territory and the potential for higher emissions reduction [61].

The Hydrogen Valleys platform [62], promoted by the European Union, collects more than 30 hydrogen-based projects to be used as best practices for the deployment of hydrogen applications, including production, transportation, and various end uses such as mobility or industrial feedstock. A feasibility analysis for the implementation of the green hydrogen valley in the industrial area of Ravenna (Italy) has been performed by Guzzini *et al.* [63] showing that the design optimization is not sufficient to make the project economically competitive, so it is also necessary to design financial instruments to support the adoption of green hydrogen in local clusters. On the other hand, Mayyas *et al.* [64] demonstrated that renewable energy from large scale power hubs serving industrial consumers can be stored in the form of hydrogen with a competitive levelized cost of hydrogen production and levelized cost of energy storage in the United States, to be sold later as a fuel for FCEVs or converted back into electricity. As far as energy communities are concerned, Caramanico *et al.* [65] performed a life cycle assessment of the application of a fuel cell/photovoltaic hybrid micro-cogeneration heat and power system for a residential building with a detailed economic analysis, showing that annual savings can be obtained, but due to the high capital costs, some kind of incentives are needed to foster the deployment of such technologies. Liu *et al.* [66] modelled the planning of a distributed hydrogen-based MES and applied it to twelve typical cities around the world with different energy demand profiles and solar radiation, finding that this application can significantly reduce the operation cost of the energy system, except in high cooling demand and low solar radiation regions.

Zhang *et al.* [67] demonstrated the viability of a solar and biomass polygeneration system to satisfy cooling, heating, electricity, and hydrogen demand for vehicle fuelling in an urban context. Xu *et al.* [35] proposed a framework for electricity and hydrogen supply integrated with a PV power system at a local community level, considering both residential and non-residential vehicles; the numerical application of the model showed the feasibility of the proposed framework that ensures the power balance of the residential area and reduces its operational cost.

Genovese and Fragiacomo [68] presented a smart energy conversion system where the produced hydrogen is used both for the mobility and heat and power applications needed near the station; the analysis includes a fuel cell hydrogen fleet of 41 vehicles, 43 bicycles, and 28 fuel cell forklifts, as well as a cogeneration unit using a hydrogen 50 kWe PEM. This multi-service facility configuration allows us to distribute the on-site produced green hydrogen to serve the local economy.

Liu *et al.* [69] developed a hybrid renewable energy system combining stationary battery and mobile hydrogen vehicle storage for a campus, office, and residential buildings; their comprehensive techno-economic-environmental feasibility study shows the viability of this application for achieving zero-energy buildings and communities in urban areas. The integration of FCEVs into the local electricity network has been demonstrated to be technically and economically feasible; additionally, FCEVs can provide a flexible energy buffer to the local system: when parked, they can provide backup power and grid balancing [70]. Maroufmashat *et al.* [71] modelled and optimized a system including four interacting energy hubs in an urban context, where one acts as an HRS for forklifts and vehicles, and the others serve a food distribution center, a residential complex, and a school, considering that the hubs can exchange surplus energy. The results of the study showed that distributed hydrogen production is more preferable in environmental and economic terms than the hydrogen distribution infrastructure.

3 DISCUSSION AND CONCLUSION

As highlighted by the performed literature review, the most recent advances in fuel cell electric vehicle technologies and demonstration projects show the viability of adopting this low carbon mobility solution, once the economic barriers are overcome. Moreover, this solution contributes to provide storage systems suitable to support the increasing integration of power generation by RES into the electricity grid at the industrial park level and to recover heat for industrial applications.

Though the recovered literature does not specifically mention their use in the urban-industrial symbiosis, the benefits of such an approach are obvious from the prior research review.

The sustainability-related basis of adopting the green hydrogen power-to-mobility strategy in the UIS context and the advantages for the local communities are summarized and presented in Table 2.

Table 2: Sustainability aspects of adopting the green hydrogen mobility in the UIS context.

Sustainability dimension	**Advantage**
Economic	Possibility of taking advantage of the energy hub configuration of the industrial park/area energy system, where RES plants can be installed (no new installations needed and maintenance performed by the industrial park)
	Reduction of the costs of the hydrogen distribution infrastructure, since existing pipelines can be used and the near-site hydrogen production exploited
	Possibility of saturating the hydrogen production capacity through the private, public and industrial vehicles demand
	Reduced operational costs
	Hydrogen refueling stations managed by industrial partners
	Possibility of using the FCEVs as backup power units at the industrial facility, providing exchange parking as a last-mile solution
Environmental	Reduction of the local GHG emissions due to private, public, and industrial transportation (forklifts, trucks, vans)
	Promoting distributed hydrogen production is more environmentally benign than centralized production
Social	Safety issues related to the hydrogen production systems and HRS restricted to the industrial area
	Social acceptance due to perceived reduced risks
	Health-related positive impacts

The discussed issues demonstrate that the opportunities offered by the creation of synergies between industrial clusters and the nearby urban areas in an integrated urban planning perspective can allow us to fully exploit the sustainability potential of low-carbon mobility solutions using green hydrogen.

REFERENCES

[1] Online, https://www.iea.org/topics/transport, accessed on: 12 March 2022
[2] Online, https://www.eea.europa.eu/themes/transport/intro (European Environmental Agency - EEA), accessed on: 12 March 2022
[3] Salvi, B. L. & Subramanian, K. A., Sustainable development of road transportation sector using hydrogen energy system. *Renew Sustain Energy Rev*, **51**, pp. 1132–55, 2015. https://doi.org/10.1016/j.rser.2015.07.030
[4] Rostad Sæther, S., Mobility at the crossroads – Electric mobility policy and charging infrastructure lessons from across Europe. *Transp Res Part A Policy Pract*, **157**, pp. 144–59, 2022. https://doi.org/10.1016/j.tra.2022.01.010
[5] Lebrouhi, B. E., Djoupo, J. J., Lamrani, B., Benabdelaziz, K. & Kousksou, T., Global hydrogen development - A technological and geopolitical overview. *Int J Hydrogen Energy,* **47**, pp. 7016–48, 2022. https://doi.org/10.1016/j.ijhydene.2021.12.076
[6] Tsoi, K. H., Loo, B. P. Y., Tal, G. & Sperling, D., Pioneers of electric mobility: Lessons about transport decarbonisation from two bay areas. *J Clean Prod*, **330**, p. 129866, 2022. https://doi.org/10.1016/j.jclepro.2021.129866
[7] Robinius, M., Linßen, J., Grube, T., Reuß, M., Stenzel, P. & Syranidis, K, *et al.,* Comparative analysis of infrastructures: Hydrogen fueling and electric charging of vehicles, **408**, 2018.
[8] Tlili, O., Mansilla, C., Frimat, D. & Perez, Y., Hydrogen market penetration feasibility assessment: Mobility and natural gas markets in the US, Europe, China and Japan. *Int J Hydrogen Energy*, **44**, pp. 16048–68, 2019. https://doi.org/10.1016/j.ijhydene.2019.04.226
[9] Piraino, F., Genovese, M. & Fragiacomo, P., Towards a new mobility concept for regional trains and hydrogen infrastructure. *Energy Conversion and Management*, **228**, p.113650, 2021. https://doi.org/10.1016/j.enconman.2020.113650
[10] Nikolaidis, P. & Poullikkas, A., A comparative overview of hydrogen production processes. *Renew Sustain Energy Rev*, **67**, pp. 597–611, 2017. https://doi.org/10.1016/j.rser.2016.09.044
[11] COM, 301 final - A hydrogen strategy for a climate-neutral Europe, 2020.
[12] Côté, R. P. & Cohen-Rosenthal, E., Designing eco-industrial parks: a synthesis of some experiences. *J Clean Prod*, **6**, pp. 181–8, 1998. https://doi.org/10.1016/S0959-6526(98)00029-8
[13] Butturi, M. A., Lolli, F., Sellitto, M. A., Balugani, E., Gamberini, R., Rimini, B., Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis. *Appl Energy*, p. 113825, 2019. https://doi.org/10.1016/j.apenergy.2019.113825
[14] Butturi, M. A. & Gamberini, R., Urban-Industrial symbiosis to support sustainable energy transition. *Int J Energy Prod Manag*, **5**, pp. 355–66, 2020. https://doi.org/10.2495/EQ-V5-N4-355-366
[15] Van Berkel, R., Fujita, T., Hashimoto, S. & Geng, Y., Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. *J Environ Manage*, **90**, pp. 1544–56, 2009. https://doi.org/10.1016/j.jenvman.2008.11.010

[16] Maggio, G., Nicita, A. & Squadrito, G., How the hydrogen production from RES could change energy and fuel markets: A review of recent literature. *Int J Hydrogen Energy*, **44**, pp. 11371–84, 2019. https://doi.org/10.1016/j.ijhydene.2019.03.121

[17] Hu, G., Chen, C., Lu, H. T., Wu, Y., Liu, C., Tao, L., *et al.,* A review of technical advances, barriers, and solutions in the power to hydrogen (P2H) roadmap. *Engineering*, **6**, pp. 1364–80, 2020. https://doi.org/10.1016/j.eng.2020.04.016

[18] Wikramanayake, E., Acharya, P. V., Kapner, M. & Bahadur, V., Green hydrogen-based energy storage in Texas for decarbonization of the electric grid. *IEEE Green Technol Conf,* pp. 409–15, 2021.

[19] Vidas, L. & Castro, R., Recent developments on hydrogen production technologies: State-of-the-art review with a focus on green-electrolysis. *Appl Sci*, **11**, 2021. https://doi.org/10.3390/app112311363

[20] Buttler, A. & Spliethoff, H., Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renew Sustain Energy Rev*, **82**, pp. 2440–54, 2018. https://doi.org/10.1016/j.rser.2017.09.003

[21] IRENA, *Making the breakthrough: Green hydrogen policies and technology costs*, International Renewable Energy Agency, Abu Dhabi, 2021.

[22] Ramadan, M., A review on coupling Green sources to Green storage (G2G): Case study on solar-hydrogen coupling. *Int J Hydrogen Energy*, **46**, pp. 30547–58, 2021.

[23] Schnuelle, C., Wassermann, T., Fuhrlaender, D. & Zondervan, E., Dynamic hydrogen production from PV & wind direct electricity supply – Modeling and techno-economic assessment. *Int J Hydrogen Energy*, **45**, pp. 29938–52, 2020. https://doi.org/10.1016/j.ijhydene.2020.08.044

[24] Almutairi, K., Hosseini Dehshiri, S. S., Hosseini Dehshiri, S. J., Mostafaeipour, A., Issakhov, A. & Techato, K., A thorough investigation for development of hydrogen projects from wind energy: A case study. *Int J Hydrogen Energy*, **46**, pp. 18795–815, 2021. https://doi.org/10.1016/j.ijhydene.2021.03.061

[25] Karayel, G. K., Javani, N. & Dincer, I., Green hydrogen production potential for Turkey with solar energy. *Int J Hydrogen Energy*, 2021. https://doi.org/10.1016/j.ijhydene.2021.10.240

[26] Pal, P. & Mukherjee, V., Off-grid solar photovoltaic/hydrogen fuel cell system for renewable energy generation: An investigation based on techno-economic feasibility assessment for the application of end-user load demand in North-East India. *Renew Sustain Energy Rev*, **149**, 111421, 2021. https://doi.org/10.1016/j.rser.2021.111421

[27] Singlitico, A., Østergaard, J. & Chatzivasileiadis, S., Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. *Renew Sustain Energy Transit*, **1**, p. 100005, 2021. https://doi.org/10.1016/j.rset.2021.100005

[28] Ozturk, M. & Dincer, I., A comprehensive review on power-to-gas with hydrogen options for cleaner applications. *Int J Hydrogen Energy*, **46**, pp. 31511–22, 2021. https://doi.org/10.1016/j.ijhydene.2021.07.066

[29] Directive (EU) 2018/2001 of The European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

[30] Velazquez Abad, A. & Dodds, P. E., Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. *Energy Policy*, **138**, p. 111300, 2020. https://doi.org/10.1016/j.enpol.2020.111300

[31] IRENA, *Hydrogen from renewable power: Technology outlook for the energy transition*. International Renewable Energy Agency, Abu Dhabi, 2018.
[32] Sharma, S., Agarwal, S. & Jain, A., Significance of hydrogen as economic and environmentally friendly fuel. *Energies*, **14**, 2021. https://doi.org/10.3390/en14217389
[33] Ajanovic, A. & Haas, R., Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. *Int J Hydrogen Energy*, **46**, pp. 10049–10058, 2021. https://doi.org/10.1016/j.ijhydene.2020.03.122
[34] Candelaresi, D., Valente, A., Iribarren, D., Dufour, J. & Spazzafumo, G., Comparative life cycle assessment of hydrogen-fuelled passenger cars. *Int J Hydrogen Energy*, **46**, pp. 35961–73, 2021. https://doi.org/10.1016/j.ijhydene.2021.01.034
[35] Xu, X., Hu, W., Liu, W., Zhang, Z., Du, Y., Chen, Z, *et al.,* Optimal operational strategy for a future electricity and hydrogen supply system in a residential area. *Int J Hydrogen Energy*, **47**, pp. 4426–40, 2022. https://doi.org/10.1016/j.ijhydene.2021.11.085
[36] Iannuzzi, L., Hilbert, J. A. & Silva Lora, E. E., Life Cycle Assessment (LCA) for use on renewable sourced hydrogen fuel cell buses vs diesel engines buses in the city of Rosario, Argentina. *Int J Hydrogen Energy*, **46**, pp. 29694–705, 2021. https://doi.org/10.1016/j.ijhydene.2021.01.065
[37] Apostolou, D. & Xydis, G., A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. *Renew Sustain Energy Rev*, **113**, p. 109292, 2019. https://doi.org/10.1016/j.rser.2019.109292
[38] Frank, E. D., Elgowainy, A., Khalid, Y. S., Peng, J. K. & Reddi, K., Refueling-station costs for metal hydride storage tanks on board hydrogen fuel cell vehicles. *Int J Hydrogen Energy*, **44**, pp. 29849–29861, 2019. https://doi.org/10.1016/j.ijhydene.2019.09.206
[39] Online, https://www.hylaw.eu/database, accessed on 22 March 2022.
[40] Robinius, M., Otto, A., Syranidis, K., Ryberg, D. S, Heuser, P., Welder, L., *et al.,* Linking the power and transport sectors - Part 2: Modelling a sector coupling scenario for Germany. *Energies*, **10**, pp. 1–23, 2017. https://doi.org/10.3390/en10070957
[41] Fragiacomo, P. & Genovese, M., Technical-economic analysis of a hydrogen production facility for power-to-gas and hydrogen mobility under different renewable sources in Southern Italy. *Energy Convers Manag*, **223**, p. 113332, 2020. https://doi.org/10.1016/j.enconman.2020.113332
[42] Schitea, D., Deveci, M., Iordache, M., Bilgili, K., Akyurt, İ. Z. & Iordache, I., Hydrogen mobility roll-up site selection using intuitionistic fuzzy sets based WASPAS, COPRAS and EDAS. *Int J Hydrogen Energy*, **44**, pp. 8585–600, 2019. https://doi.org/10.1016/j.ijhydene.2019.02.011
[43] Coleman, D., Kopp, M., Wagner, T. & Scheppat, B., The value chain of green hydrogen for fuel cell buses – A case study for the Rhine-Main area in Germany. *Int J Hydrogen Energy*, **45**, pp. 5122–33, 2020. https://doi.org/10.1016/j.ijhydene.2019.06.163
[44] Edwards, R. L., Font-Palma, C. & Howe, J., The status of hydrogen technologies in the UK: A multi-disciplinary review. *Sustain Energy Technol Assessments*, **43**, p. 100901, 2021. https://doi.org/10.1016/j.seta.2020.100901
[45] Wei, R., Lan, J., Lian, L., Huang, S., Zhao, C., Dong, Z, *et al.,* A bibliometric study on research trends in hydrogen safety. *Process Saf Environ Prot*, **159**, pp. 1064–81, 2022. https://doi.org/10.1016/j.psep.2022.01.078
[46] Online, https://h2me.eu/ , accessed on 28 March 2022.

[47] Ono, K., Kato, E. & Tsunemi, K., Does risk information change the acceptance of hydrogen refueling stations in the general Japanese population? *Int J Hydrogen Energy*, **44**, pp. 16038–47, 2019. https://doi.org/10.1016/j.ijhydene.2019.04.257

[48] Han, S. M., Kim, J. H. &, Yoo, S. H., The public's acceptance toward building a hydrogen fueling station near their residences: The case of South Korea. *Int J Hydrogen Energy*, **47**, pp. 4284–93, 2022. https://doi.org/10.1016/j.ijhydene.2021.11.106

[49] Emodi, N. V., Lovell, H., Levitt, C. & Franklin, E., A systematic literature review of societal acceptance and stakeholders' perception of hydrogen technologies. *Int J Hydrogen Energy*, **46**, pp. 30669–97, 2021. https://doi.org/10.1016/j.ijhydene.2021.06.212

[50] Mancarella, P., MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, **65**, pp. 1–17, 2014.

[51] Eladl, A. A., El-Afifi, M. I., Saeed, M. A. & El-Saadawi, M. M., Optimal operation of energy hubs integrated with renewable energy sources and storage devices considering CO2 emissions. *Int J Electr Power Energy Syst*, **117**, p. 1105719, 2020. https://doi.org/10.1016/j.ijepes.2019.105719

[52] Shabanpour-Haghighi, A. & Karimaghaei, M., An overview on multi-carrier energy networks: From a concept to future trends and challenges. *Int J Hydrogen Energy*, 2021. https://doi.org/10.1016/j.ijhydene.2021.11.257

[53] Fonseca, J. D., Commenge, J.-M., Camargo, M., Falk, L. & Gil, I. D., Multi-criteria optimization for the design and operation of distributed energy systems considering sustainability dimensions. *Energy*, **214**, 118989, 2021. https://doi.org/10.1016/j.energy.2020.118989

[54] Fonseca, J. D., Camargo, M., Commenge, J. M., Falk, L. & Gil, I. D., Trends in design of distributed energy systems using hydrogen as energy vector: A systematic literature review. *Int J Hydrogen Energy*, **4**, pp. 9486–504, 2019. https://doi.org/10.1016/j.ijhydene.2018.09.177

[55] Shi, M., Wang, H., Lyu, C., Xie, P., Xu, Z. & Jia, Y., A hybrid model of energy scheduling for integrated multi-energy microgrid with hydrogen and heat storage system. *Energy Reports*, **7**, pp. 357–68, 2021. https://doi.org/10.1016/j.egyr.2021.08.037

[56] Capurso, T., Stefanizzi, M., Torresi, M., Camporeale, S. M., Perspective of the role of hydrogen in the 21st century energy transition. *Energy Convers Manag*, **251**, p. 114898, 2022. https://doi.org/10.1016/j.enconman.2021.114898

[57] Fang, J., Xu, Q., Tang, R., Xia, Y., Ding, Y. & Fang, L., Research on demand management of hybrid energy storage system in industrial park based on variational mode decomposition and Wigner–Ville distribution. *J Energy Storage*, **42**, p. 103073, 2021. https://doi.org/10.1016/j.est.2021.103073

[58] Maroufmashat, A., Taqvi, S. T., Miragha, A., Fowler, M. & Elkamel, A., Modeling and optimization of energy hubs: A comprehensive review. *Inventions*, **4**, 2019. https://doi.org/10.3390/inventions4030050

[59] Eriksson, E. L. V. & Gray, E. M. A., Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems – A critical review. *Appl Energy*, **202**, pp. 348–64, 2017. https://doi.org/10.1016/j.apenergy.2017.03.132

[60] Bartolucci, L., Cordiner, S., Mulone, V. & Pasquale, S., Hydrogen based multi energy systems: Assessment of the marginal utility of increasing hydrogen penetration on system performances. *Int J Hydrogen Energy,* **46**, pp. 38588–602, 2021. https://doi.org/10.1016/j.ijhydene.2021.09.108

[61] Cipriani, G., Di Dio, V., Genduso, F., La Cascia, D., Liga, R., Miceli, R, *et al.*, Perspective on hydrogen energy carrier and its automotive applications. *Int J Hydrogen Energy*, **39**, pp. 8482–94, 2014. https://doi.org/10.1016/j.ijhydene.2014.03.174

[62] Weichenhain, U., Kaufmann, M. & Benz, A. *Hydrogen valleys: insights into the emerging hydrogen economies around the world*. Brussels: FCHJU, 2021.

[63] Guzzini, A., Pellegrini, M. & Saccani, C., Green hydrogen valleys: a preliminary case study for the industrial area of Ravenna. *Proc Summer Sch Fr Turco*, 2021.

[64] Mayyas, A., Wei, M. & Levis, G., Hydrogen as a long-term, large-scale energy storage solution when coupled with renewable energy sources or grids with dynamic electricity pricing schemes. *Int J Hydrogen Energy*, **45**, pp. 16311–25, 2020. https://doi.org/10.1016/j.ijhydene.2020.04.163

[65] Caramanico, N., Di Florio, G., Baratto, M. C, Cigolotti, V., Basosi, R. & Busi, E., Economic analysis of hydrogen household energy systems including incentives on energy communities and externalities: A case study in Italy. *Energies*, **14**, 2021. https://doi.org/10.3390/en14185847

[66] Liu, J., Xu, Z., Wu, J., Liu, K. & Guan, X., Optimal planning of distributed hydrogen-based multi-energy systems. *Appl Energy*, **281**, 116107, 2021. https://doi.org/10.1016/j.apenergy.2020.116107

[67] Zhang, X., Yan, R., Zeng, R., Zhu, R., Kong, X., He, Y, *et al.*, Integrated performance optimization of a biomass-based hybrid hydrogen/thermal energy storage system for building and hydrogen vehicles. *Renew Energy*, **187**, pp. 801–18, 2022. https://doi.org/10.1016/j.renene.2022.01.050

[68] Genovese, M. & Fragiacomo, P., Hydrogen station evolution towards a poly-generation energy system. *Int J Hydrogen Energy*, 2021. https://doi.org/10.1016/j.ijhydene.2021.06.110

[69] Liu, J., Chen, X., Yang, H. & Shan, K., Hybrid renewable energy applications in zero-energy buildings and communities integrating battery and hydrogen vehicle storage. *Appl Energy*, **290**, p. 116733, 2021. https://doi.org/10.1016/j.apenergy.2021.116733

[70] Farahani, S. S., Bleeker, C., van Wijk, A. & Lukszo, Z., Hydrogen-based integrated energy and mobility system for a real-life office environment. *Appl Energy*, **264**, p. 114695, 2020. https://doi.org/10.1016/j.apenergy.2020.114695

[71] Maroufmashat, A., Elkamel, A., Fowler, M., Sattari, S., Roshandel, R., Hajimiragha, A., *et al.,* Modeling and optimization of a network of energy hubs to improve economic and emission considerations. *Energy*, **93**, pp. 2546–58, 2015. https://doi.org/10.1016/j.energy.2015.10.079