Torun International Studies

2023, No. 1 (17), pp. 5–15

Published online June, 2023

DOI: http://dx.doi.org/10.12775/TIS.2023.001

Majka Andrzej*
0000-0002-5033-0054

Klimczyk Michał**
0000-0003-4004-182X

Kucharski Kamil***
0000-0002-3187-3571

Muszyńska-Pałys Jagoda****
0000-0002-1743-5495

HYDROGEN VALLEY AS A HUB FOR TECHNOLOGICAL COOPERATION BETWEEN SCIENCE, BUSINESS, LOCAL GOVERNMENT AND NGOS. AN OVERVIEW OF APPROACHES IN EUROPE

ABSTRACT

Considering the deepening geopolitical and climate crisis, more attention is systematically being paid to the development of alternative energy technologies. It is important to note that economically important energy sovereignty can be achieved through methods that simultaneously meet climate neutrality objectives. Therefore, the current period is a historic opportunity to enable the development of green, renewable energy, as this has comprehensive justification. In the ongoing circumstances, one of the fastest growing branches of science and economy is hydrogen technology. Numerous hydrogen projects of varying territorial scope are being developed in Europe. They are characterised by different organisational approaches. Therefore, the authors have undertaken to review and evaluate different hydrogen valley

* Rzeszów University of Technology (Poland), e-mail: andrzej.majka@prz.edu.pl
** Rzeszów University of Technology (Poland), e-mail: m.klimczyk@prz.edu.pl
*** Rzeszów University of Technology (Poland), e-mail: k.kucharski@prz.edu.pl
**** Rzeszów University of Technology (Poland), e-mail: j.muszynska@prz.edu.pl

concepts using the SWOT method. The conducted work reviews leading European hydrogen projects and identifies the strengths, weaknesses, opportunities and threats of different types of hydrogen valley organisational concepts. The results of the work carried out will support the construction and development of new hydrogen valleys, which, in line with the objectives of the European Union, will be systematically created in the coming years.

Keywords: hydrogen; valley; decarbonization; energy sovereignty; climate neutrality; economy

1. INTRODUCTION

In 2019, the European Commission published the European Green Deal, which sets out tasks for improving the climate situation in the European Union (European Commission, 2019). The document's objectives included reducing greenhouse gas emissions and protecting health and well-being of citizens. One of the ways the European Green Deal is being implemented is through the announced hydrogen strategy for a climate-neutral Europe in 2020. The European Union's strategy notes that the use of hydrogen involves no CO2 emissions and almost no air pollution. From this perspective, hydrogen can be a climate- and health-safe energy carrier (European Commission, 2021). Accordingly, the strategy assumes the formation and development of local hydrogen clusters called "hydrogen valleys". The idea of hydrogen valleys involves local production of hydrogen from decentralized renewable energy sources, short-distance transportation, and the use of hydrogen for industrial, transportation, energy, and residential and commercial heating purposes.

In recent months, additional circumstances have emerged requiring urgent development of energy sector technologies. The war on Ukrainian territory is linked to several economic sanctions and has necessitated the search for alternative energy sources. Due to the experience of the war, the need to strengthen energy sovereignty at the continental, national and local levels is recognized. An expression of the above insights is the REPowerEU Plan announced in 2022. It specifically assumes diversifying energy sources, replacing fossil fuels, accelerating the clean energy transition, and conducting investment and reform activities (European Commission, 2022). Among others, REPowerEU aims to accelerate the development of technologies for the production and use of hydrogen from renewable energy sources. Accordingly, it plans to take investment measures to double the number of existing hydrogen valleys by 2030.

As can be seen above, contemporary circumstances favor the development of hydrogen technologies, especially through the formation and development of local clusters called hydrogen valleys. An important step on this path is the March 1, 2023, Joint Declaration on Hydrogen Valleys by Hydrogen Europe, Hydrogen Europe Research, S3 H2 Valleys Platform and the European Commission. The declaration assumes reinforcing the research and innovation agenda for clean hydrogen, continuing investments for clean hydrogen technologies, maximising funding impact by working in synergy, promoting knowledge sharing and partner matchmaking, stimulating the development of education and training and spearheading the development of hydrogen valleys (Hydrogen Europe et al., 2023). The declaration defines hydrogen valleys as "steppingstones to incubate and grow a European – and by extension global – hydrogen economy".

Consequently, the way in which hydrogen valleys emerge and the extent to which they operate is becoming increasingly important. As this process is very dynamic and has been going on for a relatively short period of time, it is seen as very important to review it and to draw conclusions as to the opportunities and threats facing selected types of hydrogen valleys. To this end, a selection of the most recognisable hydrogen projects in Europe needs to be reviewed and analysed.

2. LITERATURE REVIEW

According to the current state of knowledge, hydrogen technologies can play an important role in the energy economy as well as in heat supply and transport (Staffell et al., 2019). It is believed that hydrogen will play a key role in replacing fossil fuels since its conversion to heat or power is relatively simple and environmentally clean (Panwar et al., 2011). It will play an important role in deep decarbonisation (Parra et al., 2019) and the entire energy transition (Kovač et al., 2021). As research shows, the hydrogen economy in the 21st century will systematically develop (Barreto et al., 2003). It is estimated that there will be a systematic increase in global hydrogen consumption until at least 2070 (Rissman et al., 2020).

What is very important, hydrogen is an energy carrier complementary to the system of renewable energy sources. It can be produced, among others, from solar (Hosseini & Wahid, 2020; Koumi Ngoh & Njomo, 2012) and wind energy since its production is based primarily on electricity (Osman et al., 2022), which can also be recovered in the reverse process. Due to the production of hydrogen in the electrolysis process (Chi & Yu, 2018), it can be considered a relatively universal process, in which different energy sources can be used.

Hydrogen can be used for heating purposes in domestic and industrial applications (Dodds et al., 2015). It can be used in land (Ale & Bade Shrestha, 2009; T-Raissi & Block, 2004), sea (Balcombe et al., 2019) and air (Hoelzen et al., 2022) transport. It can be used in industrial production processes, metallurgy, to produce fertilizers, biofuels, synthetic fuels, as well as for pharmaceutical applications (Osman et al., 2022).

The hydrogen economy fits well into the environmental policy and responds to the challenges faced by modern civilization (Clark & Rifkin, 2006; Demirbas, 2017; Pandev et al., 2017). To produce hydrogen, a possible solution is to create hydrogen valleys providing multiple consumers (Ficco et al., 2022; Petrollese et al., 2022). As presented in the introduction, this is also a solution supported by the policy instruments of the European Union (Bonciu, 2020). The use of hydrogen technologies is also increasingly socially accepted, which is an important factor in their development (Maack & Skulason, 2006).

The above review of the current state of knowledge and contemporary views of researchers proves that the development of hydrogen technologies is deeply justified. Factors that should be considered include: a wide range of hydrogen applications, relatively high production versatility and complementarity with the system of renewable energy sources. It should be noted that the development of hydrogen technology is deeply justified by climatic and economic circumstances (including the war in Ukraine, which strengthens the need to develop energy sovereignty at the continental, national, local and subject level), and also strongly supported by political instruments. The concept of local hydrogen clusters is indicated as the most prospective way of developing the hydrogen economy. It is worth noting that the idea of the hydrogen valley allows for the creation of a community of production, storage, transport and use of hydrogen in individual and industrial applications of various scales.

3. METHODOLOGY

To determine the strengths and weaknesses, as well as the opportunities and threats facing various types of hydrogen valleys, a SWOT analysis of selected hydrogen projects in Europe was carried out. Projects whose publicly available description allowed for a reliable comparison were selected for the analysis. What is very important, hydrogen valleys with different specificities were selected. Among the selected hydrogen valleys there were: Subcarpathian Hydrogen Valley (Polish hydrogen valley with a range of one province, located only on land), Green Hysland (Spanish hydrogen valley located on the island of Mallorca), BIG HIT (Scottish hydrogen valley located on the coast and two islands), Heavenn (Dutch hydrogen valley located on the territory of many cooperating regions), Hydrogen Valley Estonia (Estonian hydrogen valley with a national range). On the basis of the collected information, a SWOT analysis was performed, and the conclusions presented in further sections were made.

The following factors were considered as strengths: the possibility of more effective cooperation between entities, including the one with public authorities, close area (distance) of cooperation, self-sufficiency potential, no threat of competition, degree of redundancy, access to diverse energy sources, diversity of supply and demand, and other factors conducive to development of a given type of valley. The following aspects were assumed as weaknesses: limited ability to undertake large-scale solutions, limited number of potential members and partners, limited area, difficulty in establishing external cooperation, transport limitations, the need to cooperate with regions with different strategies and authorities, complexity of the valley structure, potential difficulties in management and others. The following factors were considered as opportunities: the possibility of independence and energy sovereignty, the potential for decentralization, the potential for development, the possibility of networking and cooperation, the ease of planning demand and supply, the predictability of the development of the area, the possibility of territorial development, correspondence with the strategy at the national level and others. The following aspects were assumed as threats: regional competition, difficulties in development, difficulties in increasing the area of operation, difficulties in establishing cooperation, limited possibility of increasing supply, risk of interrupting the supply chain, dependence on weather conditions, risk of collision with various policies of the entities involved, limited interest in cooperation, project time consumption and others.

4. RESULTS AND DISCUSSION

4.1. OVERVIEW OF SELECTED HYDROGEN VALLEYS

All of the selected hydrogen valleys are project consortia with the participation of science, business, local governments and non-governmental organizations. The valleys analyzed include:

1. Subcarpathian Hydrogen Valley (*Podkarpacka Dolina Wodorowa*, 2023) – Polish hydrogen valley with a range of one province, coordinated by Rzeszów University of Technology.

It associates 24 entities, including: 15 industry or business entities, 1 government agency, 2 universities, 1 science institute, 3 local government entities and 1 non-government organization. The project assumes the production of hydrogen from solar and wind energy, transport via pipelines, roads and the existing gas network, the use of hydrogen to produce electricity and heat, for road transport (including public transport) and for industrial applications.

2. Green Hysland (*Green Hysland – Deployment of a H2 Ecosystem on the Island of Mallorca*, 2023) – Spanish hydrogen valley located on the island of Mallorca. It associates 30 entities, including: 12 industry or business entities, 3 local government entities, 1 government administration entity, 3 universities and 8 non-governmental organizations. Green Hysland assumes the production of hydrogen from solar energy, transport by pipelines and road, and the use of hydrogen for hydrogen refueling stations, commercial and municipal fuel cells combined heat and power system, injection of H2 into the local gas distribution grid, free cooling and heating primary power system for a ferry terminal.
3. BIG HIT (*BIG HIT*, 2023) – Scottish hydrogen valley located on the coast and two islands. It associates 12 entities, including: 4 industry or business entities, 5 non-governmental organizations, 1 government administration entity, 1 local government and 1 university. The BIG HIT concept assumes the production of hydrogen from wind and tidal energy, storage of hydrogen in high-pressure tanks, transport by sea and the use in heat of local buildings, supplying heat and power for several harbor buildings, a marina and 3 ferries in Kirkwall, and to fuel the 5-hydrogen fuel cell road vehicles for Orkney Islands Council.
4. Heavenn (*Heavenn – H2 Energy Applications in Valley Environments for Northern Netherlands*, 2023) – Netherland hydrogen valley located on the territory of many cooperating regions. It associates 30 entities, including: 17 industry or business entities, 3 local government entities, 1 university and 9 non-governmental organizations. The project involves a hydrogen production from solar and wind energy, including offshore, distribution through road transport and pipelines, storage of hydrogen in the underground infrastructure and the use for hydrogen buses and cars, electricity production, as well as in other industrial, heating and transport applications.
5. Hydrogen Valley Estonia (*Hydrogen Valley Estonia*, 2023) – Estonian hydrogen valley with a national range. It associates 9 entities, including: 3 regions, 1 university and 5 energy or industry companies. The project is supported by 25 other organizations. The project assumes the production of hydrogen from solar and wind energy, including offshore sources. It assumes road transport of hydrogen and the use of hydrogen for public transport, heavy duty vehicles, railways, sea and air transport, as well as use in industrial processes and for heating.

4.2. SWOT ANALYSIS

Table 1
SWOT analysis of Subcarpathian Hydrogen Valley example

Subcarpathian Hydrogen Valley – voivodeship (region)	
Strengths	**Weaknesses**
• cooperation with one main regional government, • management by one leading university, • ease of practical cooperation – short distance between entities, • parallel cooperation of entities in other fields,	• limited possibility of undertaking large-scale solutions, • limited number of potential members, • land restrictions in the region,
Opportunities	**Threats**
• the possibility of creating regional energy independence, • decentralization of hydrogen production, • significant number of diverse industrial customers,	• competition with other regions of the country, • limited opportunities for area development,

Table 2
SWOT analysis of Green Hysland example

Green Hysland – island	
Strengths	**Weaknesses**
• cooperation with one main regional government, • closed, self-sufficient ecosystem, • Implementation of the supply chain in a small area, • no territorial competition,	• limited area of operation, • difficulties in establishing external cooperation,
Opportunities	**Threats**
• possibility of joint search for solutions with other islands – similar challenges, • ease of planning demand and supply, • predictable development strategy – independence,	• difficulty in integrating into the continental hydrogen network, • limited production capacity in a given area,

Table 3
SWOT analysis of BIG HIT example

BIG HIT – Group of islands and Coast	
Strengths	**Weaknesses**
• possibility of self-sufficiency of each island, • solution redundancy – excluding one infrastructure does not affect the others,	• the need to transport of hydrogen by sea – as a time-consuming and costly solution, • cooperation between different local governments,
Opportunities	**Threats**
• relative strong supply chain security, • the possibility of using the advantages of island and continental solutions,	• storage and transport failure may cause interruptions in the supply of hydrogen, • weather conditions as a source of supply disruptions,

Table 4
SWOT analysis of Heavenn example

Heavenn – group of regions	
Strengths	**Weaknesses**
• combination of multiple energy sources, • complete supply and demand chain, • the largest number of potential partners,	• high complexity of the project, • large area of activities, • the need to reconcile many local government strategies
Opportunities	**Threats**
• high potential of continental cooperation, • possibility of expanding to other regions	• multi-regional cooperation • the need to reconcile different regional strategies • interdependence of regions

Tab. 5. SWOT analysis of Hydrogen Valley Estonia example

Hydrogen Valley Estonia – Country Area	
Strengths	**Weaknesses**
• multiple energy sources • central source of funding • no country competition • one leading research center • several hydrogen production sites	• relatively large area • need of support for large-scale infrastructure • low probability of self-sufficiency • management difficulty
Opportunities	**Threats**
• cooperation at the international level • funding as part of the implementation of the national strategy	• lack of interest in participating in a large-scale project, • long time necessary to achieve the set goals

4.3. DISCUSSION

Regardless of the type and location of the hydrogen valley, each of them is a hub of cooperation between science, business, local government and NGOs. Hydrogen valleys are often supported by government institutions. The common features of hydrogen valleys are primarily the source of energy and the conditions for the receipt of hydrogen. All valleys focus on renewable energy sources, depending on the specificity of the region, they decide on a greater share of a more effective source in their climatic conditions. In areas located in the immediate vicinity of the sea, energy obtained from wind farms dominates, while in the case of valleys located closer to the equator, for obvious reasons, solar energy dominates. The common denominator of the hydrogen valleys are also the recipients, in each of the valleys, hydrogen is to be the only fuel for public transport, additionally it is to be used to heat buildings in combustion with natural gas, it should also be mentioned that industrial plants maximize the use of hydrogen in their processes. All these three elements, public transport, heating, industry generate mainly a carbon footprint, active development of the valleys in the long term, implementing the assumptions of its programs may completely exclude it.

In the context of different types of valleys, attention should be paid to the fact that a smaller area of operation favors the creation of energy autonomy and facilitates the management.

Valleys located on the territory of individual administrative units (island, province, country) are not susceptible to difficulties resulting from various regional strategies. Projects involving units from different administrative units (a group of islands, a group of regions) may encounter such difficulties. In the context of the area of operation, the size of the infrastructure is important. Large infrastructure in a large area is often associated with high costs and difficulty of operation. At the same time, there is a larger group of potential hydrogen suppliers and consumers in larger areas. The nature of the area is also a significant factor. Continental valleys are characterized by the simplicity of transport of hydrogen via pipelines and roads. Transporting hydrogen is more difficult by sea. From this perspective, a hybrid solution – connecting the coast with islands is perceived as the most universal one. Regardless of the above differences, it should be noted that hydrogen valleys can be implemented in regions of any type and size, as evidenced by the projects presented above.

5. CONCLUSIONS

The development of hydrogen technologies is deeply justified in environmental and economic needs. The targets of decarbonization and zero-emissions, as well as increasing energy sovereignty, can be effectively implemented by creation of local clusters – hydrogen valleys. This solution is strongly supported by the instruments and policy of the European Union.

Hydrogen valleys are hubs for technological cooperation between science, business, local government and NGOs. They consider the needs resulting from the implementation of the strategies of the regions, provide a market for correspondent enterprises and enable the implementation of the objectives of non-governmental organizations. The need to develop hydrogen technologies involves both scientific and educational institutions. Implementation of the hydrogen valley goals is also important for the development of national and international economies.

Hydrogen valleys constitute the complete value chain of the economy. Hydrogen production takes place in a centralized or distributed manner, mainly from renewable energy sources such as wind farms and photovoltaic power plants. However, it is also possible to use other energy sources, such as nuclear or conventional energy. Hydrogen transport is possible both through stationary infrastructure (pipelines), as well as by land and sea. Hydrogen can be used in many branches of the economy – electricity and heat production, public and private transport, as well as to stabilize the energy system as an energy store. In addition to the above, hydrogen is used in many industrial processes and ongoing research will lead to an increase in the number of its applications.

Hydrogen valleys can be implemented in any type of territory and area. Hydrogen projects in Europe have been established on islands, groups of islands, regions and countries. These solutions are diverse in nature, depending on the needs of a given project. It should be noted that the hydrogen valley concept is universal and flexible in terms of implementation.

However, it was noticed that hydrogen valleys have some common features even in such diverse areas. This type of features includes, above all, the fact that most of the analyzed valleys were created in areas far from the center of the countries, which is a significant opportunity for the development of a given region for starting a hydrogen economy. Hydrogen valleys can be formed in areas that have not been characterized by a high degree of industrial development. In this way, they can create new sectors of the economy. At the same time, if they are created in industrial areas, they can be effectively implemented there. In the context of creating a hydrogen economy, it is very favorable for the region to have at least its own road network and municipal infrastructure that allows the transport of hydrogen and its use in public transport and the heating network. Existing combined heat and power plants can be effectively adapted to hydrogen combustion. Considering the above, launching hydrogen valleys may be a special opportunity for areas far from the centers of countries and for areas that have their own, independent infrastructure or heating network. Attention is also drawn to the fact that in the analyzed regions, the hydrogen economy can be an energy store for renewable energy sources. It should therefore be noted that the development of hydrogen valleys may even be necessary in areas where there are no conventional energy sources.

Various aspects of selected organizational concepts have been indicated as a part of this study, but none of them is treated as the most prospective one. The most important conclusion from this work is the fact that hydrogen valleys, as socio-economic nodes, can be effectively launched in areas and communities of any range and type, but it is launched in particular in areas that are characterized by selected common features presented above. The universal nature of the concept of hydrogen valleys will support the dynamics of the development of the hydrogen economy, which should be the subject of further research and conclusions from the development of existing hydrogen projects. However, this study can be a valuable guideline when analyzing the launch of a hydrogen valley in each type of area and with a specific range and scale.

REFERENCES

Ale, B. B., & Bade Shrestha, S. O. (2009). Introduction of hydrogen vehicles in Kathmandu Valley: A clean and sustainable way of transportation. *Renewable Energy*, *34*(6), 1432–1437. https://doi.org/10.1016/J.RENENE.2008.10.015

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management, 182*, 72–88. https://doi.org/10.1016/J.ENCONMAN.2018.12.080

Barreto, L., Makihira, A., & Riahi, K. (2003). The hydrogen economy in the 21st century: A sustainable development scenario. *International Journal of Hydrogen Energy*, *28*(3), 267–284. https://doi.org/10.1016/S0360-3199(02)00074-5

BIG HIT. (2023). https://www.bighit.eu/

Bonciu, F. (2020). The European Union Hydrogen Strategy as a significant step towards a circular economy. *ROMANIAN JOURNAL OF EUROPEAN AFFAIRS*, *20*(2). https://ssrn.com/abstract=3756224

Chi, J., & Yu, H. (2018). Water electrolysis based on renewable energy for hydrogen production. *Cuihua Xuebao/Chinese Journal of Catalysis*, *39*(3), 390–394. https://doi.org/10.1016/S1872-2067(17)62949-8

Clark, W. W., & Rifkin, J. (2006). A green hydrogen economy. *Energy Policy*, *34*(17), 2630–2639. https://doi.org/10.1016/J.ENPOL.2005.06.024

Demirbas, A. (2017). Future hydrogen economy and policy. Energy Sources, Part B: Economics, Planning, and Policy, *12*(2), 172–181. https://doi.org/10.1080/15567249.2014.950394

Dodds, P. E., Staffell, I., Hawkes, A. D., Li, F., Grünewald, P., McDowall, W., & Ekins, P. (2015). Hydrogen and fuel cell technologies for heating: A review. *International Journal of Hydrogen Energy*, *40*(5), 2065–2083. https://doi.org/10.1016/J.IJHYDENE.2014.11.059

European Commission. (2019). *The European Green Deal*. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f01aa75ed71a1.0002.02/DOC_1&format=PDF

European Commission. (2021). *A hydrogen strategy for a climate-neutral Europe*. https://www.eu2018.at/calendar-events/political-events/BMNT-

European Commission. (2022). *REPowerEU Plan*. https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF

Ficco, G., Arpino, F., Dell'Isola, M., Grimaldi, M., & Lisi, S. (2022). Development of a Hydrogen Valley for Exploitation of Green Hydrogen in Central Italy. *Energies*, *15*(21). https://doi.org/10.3390/EN15218072

Green Hysland – Deployment of a H2 Ecosystem on the Island of Mallorca. (2023). https://greenhysland.eu/

Heavenn – H2 Energy Applications in Valley Environments for Northern Netherlands. (2023). https://heavenn.org/

Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B., & Hanke-Rauschenbach, R. (2022). Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps. *International Journal of Hydrogen Energy*, *47*(5), 3108–3130. https://doi.org/10.1016/J.IJHYDENE.2021.10.239

Hosseini, S. E., & Wahid, M. A. (2020). Hydrogen from solar energy, a clean energy carrier from a sustainable source of energy. *International Journal of Energy Research*, *44*(6), 4110–4131. https://doi.org/10.1002/ER.4930

Hydrogen Europe, Hydrogen Europe Research, S3 H2 Valleys Platform, & European Commission. (2023). *Joint Declaration on Hydrogen Valleys*. https://www.review-energy.com/fileuploads/user/2023.03.01_Joint-declaration-on-Hydrogen-Valleys.pdf

Hydrogen Valley Estonia. (2023). https://vesinikuorg.ee/

Koumi Ngoh, S., & Njomo, D. (2012). An overview of hydrogen gas production from solar energy. *Renewable and Sustainable Energy Reviews*, *16*(9), 6782–6792. https://doi.org/10.1016/J.RSER.2012.07.027

Kovač, A., Paranos, M., & Marciuš, D. (2021). Hydrogen in energy transition: A review. *International Journal of Hydrogen Energy*, *46*(16), 10016–10035. https://doi.org/10.1016/J.IJHYDENE.2020.11.256

Maack, M. H., & Skulason, J. B. (2006). Implementing the hydrogen economy. *Journal of Cleaner Production*, *14*(1), 52–64. https://doi.org/10.1016/J.JCLEPRO.2005.05.027

Osman, A. I., Mehta, N., Elgarahy, A. M., Hefny, M., Al-Hinai, A., Al-Muhtaseb, A. H., & Rooney, D. W. (2022). Hydrogen production, storage, utilisation and environmental impacts: a review. *Environmental Chemistry Letters*, *20*(1), 153–188. https://doi.org/10.1007/S10311-021-01322-8

Pandev, M., Lucchese, P., Mansilla, C., Le Duigou, A., Abrashev, B., & Vladikova, D. (2017). Hydrogen Economy: the future for a sustainable and green society. *Bulgarian Chemical Communications*, *49*, 84–92.

Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews*, *15*(3), 1513–1524. https://doi.org/10.1016/J.RSER.2010.11.037

Parra, D., Valverde, L., Pino, F. J., & Patel, M. K. (2019). A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. *Renewable and Sustainable Energy Reviews*, *101*, 279–294. https://doi.org/10.1016/J.RSER.2018.11.010

Petrollese, M., Concas, G., Lonis, F., & Cocco, D. (2022). Techno-economic assessment of green hydrogen valley providing multiple end-users. *International Journal of Hydrogen Energy*, *47*(57), 24121–24135. https://doi.org/10.1016/J.IJHYDENE.2022.04.210

Podkarpacka Dolina Wodorowa. (2023). https://www.dolinawodorowa.org/

Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S. A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E. D., de la Rue du Can, S., Helseth, J. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy*, *266*. https://doi.org/10.1016/J.APENERGY.2020.114848

Staffell, I., Scamman, D., Abad, A. V., Balcombe, P., Dodds, P. E., Ekins, P., Shah, N., & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy Environ. Sci*, *12*, 463. https://doi.org/10.1039/c8ee01157e

T-Raissi, A., & Block, D. L. (2004). Hydrogen: Automotive fuel of the future. *IEEE Power and Energy Magazine*, *2*(6), 40–45. https://doi.org/10.1109/MPAE.2004.1359020