20th International Conference on Renewable Energies and Power Quality (ICREPQ'22)
Vigo (Spain), 27th to 29th July 2022
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.20, September 2022

Hydrogen Technologies to Provide Flexibility to the Electric System: A Review

Á. Menéndez-Agudin[1], R. Rocca[1], G. Fernandez[1], L. Luengo-Baranguan[1], D. Zaldivar[1]

[1] CIRCE, Centro de Investigación de Recursos y Consumos Energéticos,
Parque Empresarial Dinamiza, Avda. Ranillas, 50018, Zaragoza, España
e-mail: amenendez@fcirce.es, rrocca@fcirce.es, gfernandez@fcirce.es, lluengo@fcirce.es, dzaldivar@fcirce.es

Abstract. Nowadays, the electric system is evolving towards a paradigm shift, with a constantly higher penetration of renewable generation, as well as the electrification of the transport and different industry sectors. This new scenario requires flexibility services to be provided to transmission and distribution grids, to allow their safe and reliable operation. From amongst the various options currently investigated, hydrogen technologies are demonstrating great potential in terms of lower energy costs for consumers/prosumers, lower emissions, and better levels of quality and security of supply. This paper provides a review of the latest state-of-the-art flexibility services that hydrogen-based technologies can provide to both DSOs and end-users. This review considers contributions from both academia and industry.

Keywords. Hydrogen, Grid Flexibility, Energy Storage, Power-to-Gas, Hydrogen Fuel Cells.

1. Introduction

To reduce the Greenhouse Gas (GHG) emissions resulting from electricity generation, governments are raising the share of Variable Renewable Energy sources (VREs) in their energy mix. This paradigm shift makes grid balancing more challenging, which, in turn, increases both the long-term and short-term flexibility demand.

Flexibility is a concept inherent to all electrical systems. The International Smart Grid Action Network (ISGAN) defines flexibility as the "*ability of power systems to manage changes*". Flexibility can be offered to Transmission and Distribution System Operators (TSOs and DSOs) from different products and markets, [1]. These include power balancing and frequency control, voltage, and reactive power control and, to a lesser extent, congestion management.

Flexibility has been historically provided by conventional, fast-response gas- and hydro-powered plants. However, these traditional technologies are currently supported and are expected to be partially or even fully replaced by energy storage systems (ESSs) and/or new energy vectors.

Many governments, including the EU, are moving within this framework by giving a major role to hydrogen as a flexibility provider, [2]. Indeed, hydrogen can provide flexibility with different technologies and in different ways, as it can be connected directly or indirectly to any electrical system. Electrolysers can provide flexibility by acting as flexible loads, [3]. Hydrogen can provide flexibility by acting as a short- or long-term storage system,[4]. Green Hydrogen, this is, hydrogen produced via electrolysis by renewable energy, can be injected directly into the gas grid, transferring renewable energy to sectors that otherwise could not be electrified (Power to Gas (PtG)), [5]. This type of flexibility can further improve the sector coupling between electricity and gas/hydrogen grids, [6]. As hydrogen can be directly used in heating, [7], transport, or industrial sectors there is no need to convert hydrogen to electricity again, improving the overall efficiency. Finally, Hydrogen can be re-converted to electricity using Hydrogen Fuel Cells (HFCs), [8], which can improve grid flexibility by generating electricity when needed and providing ancillary services, [9].

In this paper a review of each hydrogen technology is given to identify what type of flexibility service it can provide, adding references for each one of them.

2. Hydrogen Technologies

As discussed in the previous section, hydrogen can be used to provide flexibility with different technologies, each of them with some characteristics that make it more suitable for different types of services. In this section, an overview of the most common hydrogen-based technologies is provided.

A. Electrolysers

An electrolyser is an electrochemical device that converts electrical energy into chemical energy by splitting water into hydrogen and oxygen. During this process electrical energy is consumed, so not all the electrical energy gets converted into hydrogen, some of it is used in the process itself. In this way, in cases of surplus renewable energy production, this last can be stored in the form of hydrogen. Electrolysis technologies have reached their greatest commercial development in the last decade and there are currently three main types.

- Alkaline Electrolysers (AEC)[10]
- Polymeric Membrane Electrolyte Electrolysers (PEM), [11]
- Solid Oxide Electrolyte Electrolysers (SOEC), [12]

B. Hydrogen as Energy Storage

Hydrogen possesses a high mass-energy density but also a low volume energy density so that it must be compressed or stored in a concentrated state to achieve a high-volume energy density. For electricity generation, the most used method is to store it in pressurized steel tanks in the range of 350-700 Bar. Still, there exist more advanced technologies used today, such as cryogenic cooling systems, underground storage, or the so-called solid storage, where hydrogen is stored via intercalation into the structure of the material, either via adsorption into its surface, or with the formation of chemical compounds where hydrogen is weakly bonded. [13].

C. Power to Gas, [14]

In certain applications, it is better to use green hydrogen gas than using renewable electricity, for example in processes that cannot be electrified. To solve this issue, the concept of Power-to-gas was born. PtG allows massive electricity storage through the interconnection between the electricity grid and the gas grid, as renewable electricity can be transformed into hydrogen and stored in the gas grid. PtG, in turn, allows obtaining interactive benefits from both infrastructures. Hydrogen can also be blended with natural gas and injected into the gas grid up to certain amounts, several studies suggest that up to 15–20%, [15]. It can thereby contribute to reducing emissions related to natural gas combustion. Some of the technologies that could greatly benefit from PtG are as follows:

- **Gas Turbines,** [16]**:** hydrogen-powered gas turbines could provide the necessary stability to the grid while generating significantly less CO_2 emissions. since combined cycle plants offer one of the fastest responses to the variation in demand.
- **Combined Heat and Power (CHP) systems,** [17]**:** Similar to gas turbines, hydrogen can be used as a substitute fuel or combined with natural gas to produce heat and electricity, eliminating the emissions associated with current cogeneration.
- **Sector Coupling,** [18]**:** Integrating heating, transport and electricity sectors would allow better and more efficient use of them. Unified management of gas and electric grids, as seen in Figure 1, would provide flexibility and better adaptation to changes in demand or future technological innovations. This could make renewable energy used in processes that are difficult to electrify.

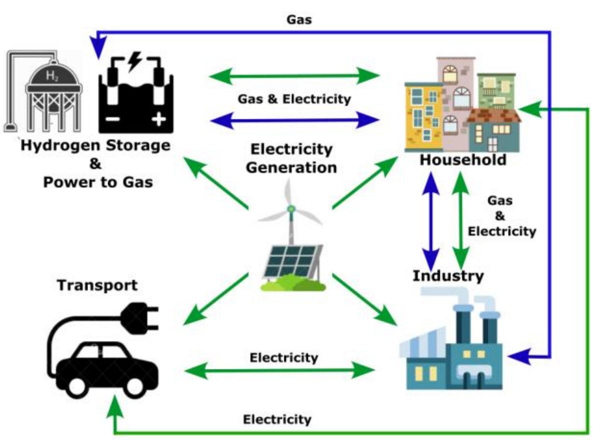

Figure 1. Sector Coupling through Power to Gas. Electricity (green) and gas (blue) exchanges.

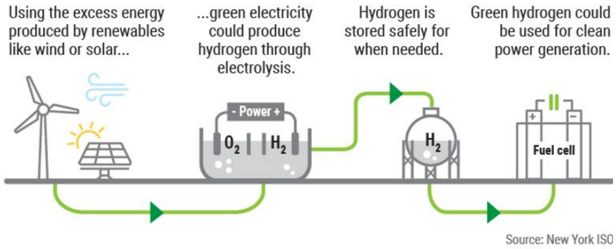

Figure 2. Green Hydrogen Value Chain (NYISO)

D. Hydrogen-Powered Boilers

Gas boilers that use renewable gases such as hydrogen mixed in different proportions can be used instead of electric heaters, [19]. Hydrogen could be mixed with natural gas or biomethane or even synthetic natural gas, or in the most extreme case boilers could run on 100% hydrogen.

The world's first hydrogen-based domestic boiler has been put into operation in a real situation in Rozenburg, the Netherlands, in 2019 by BDR Thermea Group, [20]. It was the first time that the use of pure hydrogen to power a high-efficiency condensing boiler to heat the central heating system of a residential building has been applied in a real-life situation.

E. Hydrogen Fuel Cells, [21]

A fuel cell is a device that makes it possible to generate electricity from the chemical energy of hydrogen and oxygen without combustion. The main advantage is that it has much higher efficiencies than combustion.

Currently, there are 5 main groups of fuel cells, classified according to their operating temperature, on the market. The output power of these fuel cells ranges from systems that allow a few watts to be obtained, to power plant-type systems that produce MW, although all of them are based on the same technology, an electrochemical cell.

Hydrogen fuel cells could be used as energy sources for domestic purposes and help with the implementation of distributed generation with renewable energy and PtG integration. A better hydrogen value chain, Figure 2, would be needed to bring closer hydrogen technologies to the end-user and reduce its overall cost.

3. Flexibility services

This section provides a more in-depth analysis of how hydrogen technologies can be used to provide flexibility to the grid. To this end, the most relevant flexibility services are analysed one by one. Moreover, Table I provides a useful recap of the flexibility services that each technology can provide and, should it be the case, caters to the most relevant references.

A. Grid Congestion

Saturation or congestion exists when power flows exceed the asset, lines or transformers, design threshold, either temporarily or permanently. [22]

Restrictions in the assets can be identified mainly due to non-compliance with the permanent security conditions, insufficient power or capacity reserve to balance the system, or a breach in the security conditions.

A relevant aspect of technical constraints is their predictability. In some cases, they are structural and therefore occur in a certain predefined time and are geographically stable, while others occur sporadically and are more difficult to predict.
The hydrogen technologies previously mentioned can help cope with renewable energy's inherent intermittency that can cause grid congestions. In [23] and [24], electrolysers are used to produce hydrogen to avoid curtailment in excess generation situations. These electrolysers can function as flexible loads, but when functioning with other technologies higher flexibility can be achieved. An Electricity Heat Hydrogen Multi-Energy Storage System (EHH-MESS) is used in [25] to improve flexibility. Hydrogen storage systems are usually combined with PtG systems, [26], [27] and [28] a combination of these two technologies is done to improve flexibility and avoid curtailment.
This increase in flexibility can bring also economic savings, [29] where a P2P energy market is enhanced with hydrogen storage, PtG, and the use of Fuel Cells.
This combination of technologies can also work to enhance the functioning of controllable power plants as combined heat and power cycle, as explained in [17].

B. Voltage Control

The reactive power in the grid must be always kept in equilibrium. Maintaining the reactive power under equilibrium means maintaining voltage inside restriction limits, [22].
The set of actions on reactive power generation and absorption resources and other voltage control elements are aimed at maintaining voltages at the nodes of the transmission grid within the specified margins to guarantee compliance with the safety and quality criteria of the electricity supply.
Similar to grid congestions, hydrogen technologies could help to solve voltage problems improving grid flexibility. In [30] a fleet of electrolysers is used to solve voltage fluctuations due to solar PV penetration by modifying its operating instructions. Hydrogen storage and PtG can also help in reducing voltage fluctuations. In [31], a PtG system combines the gas and electric grids to solve voltage deviations. A similar study is done in [32], although this time the PtG system is with natural gas instead of hydrogen. Usually, PtG systems rely on hydrogen fuel cells to provide this flexibility service [33].

C. Controlled island operation

The islands consist of isolated sections of the distribution grid where one or more generation facilities are supplying demand facilities that, for this reason, are separated from the rest of the system. Currently, the technology of power electronics has improved a lot making renewable energy easier to manage in distributed generation systems. This represents an opportunity for the DSO because it allows the creation of controlled islands, based on the installation of certain grid protection and control systems. These islands guarantee supply in the event of the unavailability of main grid sections.
Some studies focus on the optimization of the integration of PV generation with the use of hydrogen or battery, [34] while others focus on increasing renewable generation with hydrogen storage and Electric Vehicle batteries to function isolated from the network, [35].
Some studies made a similar approach but with a higher focus on maintaining energy quality in the grid, one emphasizes the maintaining of a stable power supply, [36] while the other aims at frequency control of the grid, [37].

D. Black Start

Restoration of electrical service is necessary after the electrical system, or part of it, has suffered a voltage collapse. This flexibility service aims to return to the normal operating status in the shortest possible time. This objective can be achieved by considering aspects such as the optimal location of resources capable of restoring the service considering aspects such as critical loads, maximizing restored loads and grid reconfiguration options.
Not all energy storage systems are suitable for Black Start's flexibility service. Thus, hybridization, this is, the combination of two or more energy storage technologies, should be developed, [38]. This hybridization mitigates the disadvantages of individual energy storage methods and makes possible the use of hydrogen technologies as storage, [39], where a Hydrogen Storage Power Plant can offer flexibility services like voltage and frequency control, as well as black start capabilities. The combination of hydrogen storage and Fuel Cell technologies can increase the ability to provide this service. In [40], an autonomous wind/hydrogen energy demonstration system located on the island of Utsira in Norway is prepared to offer black start capabilities in case of power loss, as well as operate in a controlled island mode thanks to hydrogen storage, a hydrogen engine, and a fuel cell. Although the system had also grid stabilizing equipment installed consisting of a flywheel (5 kWh) for frequency control and a master synchronous machine (100 kVA) for voltage control. In [41] a fuel cell is used for Uninterruptible Power Supply in case of blackouts in a telecommunications tower having also the ability to be used as a black start if needed.

E. Balancing Services

The balancing services fulfil the function of frequency/power regulation. Balancing services are purchased and managed by the System Operator. Currently, the following services are defined in the Spanish electricity system, functioning after a frequency offset:

- **Primary regulation reserve:** the power margin in which the generator sets can modify their generated power automatically in seconds.
- **Secondary regulation reserve:** the power variation margin in which the secondary regulator of the Spanish system can act automatically starting from the operating point where it is in every moment and actuate in 150 seconds.
- **Tertiary regulation reserve:** constituted by the maximum variation in power to go up or down of all the generating groups of the system that can be mobilized in a time not exceeding fifteen minutes.

Hydrogen technologies can contribute to the balancing services by either demanding power from the grid acting as a flexible load (electrolysers) or providing power to the grid acting as a generator (fuel cell). In [42] PEM electrolysers and Fuel Cells are examined to partake in European electrical ancillary services markets. A case

Table I. – Hydrogen Technologies to provide flexibility services

Hydrogen Technologies to provide flexibility					
Technology/ Flexibility service	Electrolysers, [3]	Hydrogen as Energy Storage, [4]	Power to Gas,[5] [6]	Hydrogen-Powered Boilers, [20]	Hydrogen Fuel Cells, [7] [8]
Grid Congestions	Yes, [23], [24]	Yes (**), [25], [26], [28], [29]	Yes, [24], [26], [27], [28]	Yes, [30], [33]	Yes, [17], [29]
Voltage Control	Yes, [3], [31]	Yes (**), [39]	Yes, [30], [33]	Yes, [30], [33]	Yes (*), [32]
Control Island Operation	Yes (*), [34], [35], [36], [37]	Yes (**), [34], [35], [36], [37]	Yes (*), [34], [35], [36], [37]	Yes (*)	Yes (*), [34], [35], [36], [37]
Black Start	No	Yes (**), [39], [40]	Yes (*), [39], [40]	No	Yes (*), [40], [41]
Balancing Services	Yes (*), [42], [43], [44]	Yes (**), [39], [46]	Yes (*), [16], [47], [47]	No	Yes (*), [9], [37], [45]
Inertia	No	Yes (**), [16], [47], [48]	Yes (*), [16], [47], [48]	No	No

Note: *"Yes" means that there is a direct capacity of the resource to provide the service; "No" means that there is no direct capacity of the resource to provide the service; "Yes (*) means that the capacity of the resource may be partial or conditioned to future technological developments, "Yes(**) means that it is conditioned how the energy storage is used, gas or electricity, and how it is converted.*

study based on a realistic representation of the transmission grid in the north of the Netherlands for the year 2030 aimed to ascertain the effectiveness of PEM electrolysers and fuel cells for the provision of primary frequency reserves.

Some other studies focused mainly on the use of electrolysers as a variable load to help regulate grid frequency, [43]. A dynamic model of the electrolysers stack, power-electronics interface, and downstream hydrogen process operational constraints is modelled to study the Fast Frequency Response capability of the system, [44].

As said before, Fuel Cells can also help regulate grid frequency. In [45], the feasibility and economics of using fuel cell backup power systems in telecommunication cell towers to provide grid services are studied.

Hydrogen technologies can also work in combination with other storage technologies such as batteries to improve their capability in providing frequency regulation. In [46] battery and hydrogen storage are hybridized for this purpose. The proposed control method was demonstrated to be able to control random changes in input and output power. The battery compensated for high-frequency fluctuations in power demand, whilst the electrochemical cell and fuel cell handled the remaining low-frequency ones.

F. Inertia

Proper levels of system (physical) inertia allow operators to maintain a stable frequency. However, with less synchronous generation connected to the system, the level of inertia available to the system decreases.

The inertial response provided by large rotating masses provides the response time for the system operator to take balancing actions. In the event of a power disturbance or imbalance, system operators with low (physical) inertia in their system would have less time to react due to a larger change in frequency.

Since inertia is provided to the system by the rotating masses of synchronous machines, technologies connected to the power system through power electronics converters are electrically decoupled from the grid and therefore do not naturally contribute to the inertia of the system. For this reason, all the technologies explained above cannot contribute to the system (physical) inertia, as they do not have rotatory parts, except Hydrogen Gas Turbines, which may function with green hydrogen obtained from renewable sources as part of the PtG concept. With the use of these turbines, a great amount of physical inertia can be sustainably added to the grid as hydrogen can be obtained with electrolysis with surplus renewable generation.

Various companies are working on hydrogen gas turbine prototypes. One of the most advanced ones is General Electric, [16], which currently has prototypes that can work with 100% hydrogen. Other companies such as Siemens, [47] or Mitsubishi, [48], are currently developing prototypes that can work with a 75% and 30% hydrogen-Natural Gas mix and are expected to be working with 100% hydrogen by 2030.

4. Conclusion

It could be said that hydrogen has a bright but uncertain future, as hydrogen competes directly with other energy storage technologies. Nonetheless, fossil-based hydrogen, hydrogen obtained by reforming natural gas, represents most of the hydrogen produced currently. To change this trend, global investments in electrolysers have recently increased considerably. On the other hand, renewable and low-carbon hydrogen are not yet cost-competitive compared to fossil-based hydrogen.

To solve this issue, Europe has developed "A hydrogen strategy for a climate-neutral Europe", [2], where present tendencies and future steps are analyzed. The priority of the EU is indeed to increase renewable hydrogen generation as much as possible in the coming years. To this cause, Europe has made considerable efforts and investments towards the improvement of the electrolysers, whose costs have already been reduced by 60% in the last ten years.

In addition to storing energy, hydrogen also possesses some unique characteristics that make it more suitable for certain situations and can help solving grid instability issues due to the intermittent nature of renewable energies. In this paper, a review of both academic and industrial works on hydrogen technologies, as well as flexibility services has been provided. Then, all references have been gathered in Table I, in such a way as to highlight the correlation between all hydrogen-based technologies and the flexibility services that they are capable of providing.

Acknowledgement

This research work is part of the PARITY project, which has received funding from the European Union's Horizon 2020 programme under grant agreement No 864319.

References

[1] J. Villar, R. Bessa, and M. Matos, "Flexibility products and markets: Literature review," *Electric Power Systems Research*, vol. 154. Elsevier Ltd, pp. 329–340, Jan. 01, 2018.

[2] "COMMITTEE AND THE COMMITTEE OF THE REGIONS A hydrogen strategy for a climate-neutral Europe." [Online]. Available: https://www.eu2018.at/calendar-events/political-events/BMNT-

[3] M. Mohanpurkar *et al.*, "Electrolysers enhancing flexibility in electric grids," *Energies (Basel)*, vol. 10, no. 11, p. 1DUMMU, Nov. 2017.

[4] S. Lazarou and S. Makridis, "Hydrogen Storage Technologies for Smart Grid Applications," *Challenges*, vol. 8, no. 1, p. 13, Jun. 2017.

[5] M. Ozturk and I. Dincer, "A comprehensive review on power-to-gas with hydrogen options for cleaner applications," *International Journal of Hydrogen Energy*, vol. 46, no. 62. Elsevier Ltd, pp. 31511–31522, Sep. 08, 2021.

[6] X. Li and M. Mulder, "Value of power-to-gas as a flexibility option in integrated electricity and hydrogen markets," *Applied Energy*, vol. 304, Dec. 2021.

[7] P. E. Dodds *et al.*, "Hydrogen and fuel cell technologies for heating: A review," *International Journal of Hydrogen Energy*, vol. 40, no. 5. Elsevier Ltd, pp. 2065–2083, Feb. 09, 2015.

[8] D. Akinyele, E. Olabode, and A. Amole, "Review of fuel cell technologies and applications for sustainable microgrid systems," *Inventions*, vol. 5, no. 3. MDPI Multidisciplinary Digital Publishing Institute, pp. 1–35, Sep. 01, 2020.

[9] G. Vuc, C. Barbulescu, S. Kilyeni, and F. Solomonesc, "Substation ancillary services fuel cell power supply. Part 2. case study," in *ICCC-CONTI 2010 - IEEE International Joint Conferences on Computational Cybernetics and Technical Informatics, Proceedings*, 2010, pp. 589–594.

[10] M. David, C. Ocampo-Martínez, and R. Sánchez-Peña, "Advances in alkaline water electrolysers: A review," *Journal of Energy Storage*, vol. 23. Elsevier Ltd, pp. 392–403, Jun. 01, 2019.

[11] B. Zhang *et al.*, "Advancing Proton Exchange Membrane Electrolysers with Molecular Catalysts," *Joule*, vol. 4, no. 7. Cell Press, pp. 1408–1444, Jul. 15, 2020.

[12] M. C. Tucker, "Progress in metal-supported solid oxide electrolysis cells: A review," *International Journal of Hydrogen Energy*, vol. 45, no. 46. Elsevier Ltd, pp. 24203–24218, Sep. 21, 2020.

[13] P. Breeze, "Hydrogen Energy Storage," in *Power System Energy Storage Technologies*, Elsevier, 2018, pp. 69–77.

[14] G. Hu *et al.*, "A Review of Technical Advances, Barriers, and Solutions in the Power to Hydrogen (P2H) Roadmap," *Engineering*, vol. 6, no. 12. Elsevier Ltd, pp. 1364–1380, Dec. 01, 2020.

[15] C. J. Quarton and S. Samsatli, "Power-to-gas for injection into the gas grid: What can we learn from real-life projects, economic assessments and systems modelling?," *Renewable and Sustainable Energy Reviews*, vol. 98. Elsevier Ltd, pp. 302–316, Dec. 01, 2018.

[16] "GE Hydrogen fueled gas turbines," *https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines?utm_campaign=h2&utm_medium=cpc&utm_source=google&utm_content=eta&utm_term=Hydrogen%20turbine&gclid=EAIaIQobChMI5uTDs4O09wIVNY9oCR0rNAXnEAAYASAAEgJgBPD_BwE*, May 2022.

[17] M. Daraei, P. E. Campana, and E. Thorin, "Power-to-hydrogen storage integrated with rooftop photovoltaic systems and combined heat and power plants," *Applied Energy*, vol. 276, Oct. 2020.

[18] H. C. Gils, H. Gardian, and J. Schmugge, "Interaction of hydrogen infrastructures with other sector coupling options towards a zero-emission energy system in Germany," *Renewable Energy*, vol. 180, pp. 140–156, Dec. 2021.

[19] M. Van, "DEMONSTRATION OF HIGH PERFORMANCE (LOW NO x) DOMESTIC HYDROGEN BOILERS." [Online]. Available: https://www.researchgate.net/publication/347445110

[20] "First real-life application of a Hydrogen boiler in the world," *https://www.bdrthermeagroup.com/en/stories/first-real-life-application-of-a-hydrogen-boiler-in-the-world#:~:text=ROZENBURG%2C%20THE%20NETHERLANDS%20%2D%20On%2025th,situation%20in%20Rozenburg%2C%20the%20Netherlands.*, May 2022.

[21] M. K. Singla, P. Nijhawan, and A. S. Oberoi, "Hydrogen fuel and fuel cell technology for cleaner future: a review.," *Environ Sci Pollut Res 28*, pp. 15607–15626, Feb. 2021.

[22] E. Hillberg *et al.*, "Flexibility to support the future power systems," 2019.

[23] D. Wang, M. Muratori, J. Eichman, M. Wei, S. Saxena, and C. Zhang, "Quantifying the flexibility of hydrogen production systems to support large-scale renewable energy integration," *Journal of Power Sources*, vol. 399, pp. 383–391, Sep. 2018.

[24] M. Greiml, F. Fritz, and T. Kienberger, "Increasing installable photovoltaic power by implementing power-to-gas as electricity grid relief – A techno-economic assessment," *Energy*, vol. 235, Nov. 2021.

[25] T. Yun, W. Zedi, L. Yan, M. Qian, H. Qian, and L. Shubin, "A multi energy storage system model based on electricity heat and hydrogen coordinated optimization for power grid flexibility," *CSEE Journal of Power and Energy Systems*, Jun. 2019.

[26] M. Jentsch, T. Trost, and M. Sterner, "Optimal use of Power-to-Gas energy storage systems in an 85% renewable energy scenario," in *Energy Procedia*, 2014, vol. 46, pp. 254–261.

[27] B. Xiong, J. Predel, P. Crespo del Granado, and R. Egging-Bratseth, "Spatial flexibility in redispatch: Supporting low carbon energy systems with Power-to-Gas," *Applied Energy*, vol. 283, Feb. 2021.

[28] S. Clegg and P. Mancarella, "Storing renewables in the gas network: Modelling of power-to-gas seasonal storage flexibility in low-carbon power systems," *IET Generation, Transmission and Distribution*, vol. 10, no. 3, pp. 566–575, Feb. 2016.

[29] A. Basnet and J. Zhong, "Integrating gas energy storage system in a peer-to-peer community energy market for enhanced operation," *International Journal of Electrical Power and Energy Systems*, vol. 118, Jun. 2020.

[30] S. Ghosh, R. Jain, S. Veda, and D. Terlip, "Improving Distribution System Operations Using Fleet Control of Electrolysers," 2020.

[31] Pengfei Zhao, Xi Lu, Zhidong Cao, and Chenghong Gu, "Volt-VAR-Pressure Optimization of Integrated Energy Systems With Hydrogen Injection," *IEEE Transactions on Power Systems*, vol. 36, no. 3, pp. 2403–2415, Mar. 2021.

[32] M. J. Vahid-Pakdel, H. Seyedi, and B. Mohammadi-Ivatloo, "Enhancement of power system voltage stability in multi-carrier energy systems," *International Journal of Electrical Power and Energy Systems*, vol. 99, pp. 344–354, Jul. 2018.

[33] N. A. Ahmed, A. K. Al-Othman, and M. R. Alrashidi, "Development of an efficient utility interactive combined wind/photovoltaic/fuel cell power system with MPPT and DC bus voltage regulation," *Electric Power Systems Research*, vol. 81, no. 5, pp. 1096–1106, May 2011.

[34] B. Nastasi, S. Mazzoni, D. Groppi, A. Romagnoli, and D. Astiaso Garcia, "Optimized integration of Hydrogen technologies in Island energy systems," *Renewable Energy*, vol. 174, pp. 850–864, Aug. 2021.

[35] A. Pfeifer *et al.*, "Building smart energy systems on Croatian islands by increasing integration of renewable energy sources and electric vehicles," Jul. 2017.

[36] S. Fukaume, Y. Nagasaki, and M. Tsuda, "Stable power supply of an independent power source for a remote island using a Hybrid Energy Storage System composed of electric and hydrogen energy storage systems," *International Journal of Hydrogen Energy*, vol. 47, no. 29, pp. 13887–13899, Apr. 2022.

[37] R. Mandal and K. Chatterjee, "Frequency control and sensitivity analysis of an isolated microgrid incorporating fuel cell and diverse distributed energy sources," *International Journal of Hydrogen Energy*, vol. 45, no. 23, pp. 13009–13024, Apr. 2020.

[38] Y. Zhao *et al.*, "Energy storage for black start services: A review," *International Journal of Minerals, Metallurgy and Materials*, vol. 29, no. 4, pp. 691–704, Apr. 2022.

[39] A. Nayeemuddin and W. Harald, *A Novel Hydrogen Storage Power Plant Structure for High RenewableEnergy Penetration*.

[40] Ø. Ulleberg, T. Nakken, and A. Eté, "The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools," *International Journal of Hydrogen Energy*, vol. 35, no. 5, pp. 1841–1852, Mar. 2010.

[41] K. Muthusamy, M. Muthusamy, R. Kaur, and V. Krishnasamy, "An intelligent hybrid interfacing converter of fuel cell powered telecom loads for efficient power conversion," *Computers and Electrical Engineering*, vol. 90, Mar. 2021.

[42] F. Alshehri, V. García Su arez, J. L. Rueda Torres, A. Perilla, and M. A. M M van der Meijden, "Modelling and evaluation of PEM hydrogen technologies for frequency ancillary services in future multi-energy sustainable power systems," *Heliyon*, vol. 5, p. 1396, 2019.

[43] Mitch Ewan, Richard Rocheleau, Karen Swider-Lyons, and Peter Devlin, "Development of a Hydrogen Energy System as a Grid Frequency Management Tool," *The Electrochemical Society*, vol. 75, no. 14, 2016.

[44] M. G. Dozein, A. Jalali, and P. Mancarella, "Fast frequency response from utility-scale hydrogen electrolysers," *IEEE Transactions on Sustainable Energy*, vol. 12, no. 3, pp. 1707–1717, Jul. 2021.

[45] P. Zhiwen Ma, J. Eichman, J. Kurtz, and Z. Ma, "Fuel Cell Backup Power System for Grid Service and Micro-Grid in Telecommunication Applications."

[46] D. Yamashita, K. Tsuno, K. Koike, K. Fujii, S. Wada, and M. Sugiyama, "Distributed control of a user-on-demand renewable-energy power-source system using battery and hydrogen hybrid energy-storage devices," *International Journal of Hydrogen Energy*, vol. 44, no. 50, pp. 27542–27552, Oct. 2019.

[47] "Siemens Zero Emission Hydrogen Turbine Center," *https://www.siemens-energy.com/global/en/priorities/future-technologies/hydrogen/zehtc.html*, May 2022.

[48] "Mitsubishi Modern Gas Turbine Technology," *https://power.widen.net/s/fn26z6c8db/mitsubishi-power_modern-gt-technology-remains-a-key-component-of-a-net-zero-power-sector*, May 2022.