CHEMICAL ENGINEERING TRANSACTIONS
VOL. 114, 2024

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Yee Van Fan, Xuechao Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114155

Potential of Producing Green Hydrogen Using Solar Power Plants: The Role of PEM Technology in the Improvement of Photovoltaic Schedule Keeping in Hungary

Gábor Pintér[a], Virág Mészáros*[,b], Nóra Hegedűsné Baranyai[a], András Vincze[a], Henrik Zsiboracs[a]

[a]Renewable Energy Research Group, University Center for Circular Economy, University of Pannonia, Zrínyi Miklós u. 18, 8800 Nagykanizsa, Hungary
[b]Széchenyi István University, HUMDA Plc, Dávid Ferenc u. 4-6, 1113 Budapest, Hungary
virag.meszaros@zalazone.hu

Similarly to many countries of the world, photovoltaic systems play an increasingly important role in electricity generation in Hungary, contributing greatly to the climate, environmental and sustainability goals of the energy transition. As a result of numerous factors, photovoltaic technology is used not only more and more widely but also in increasingly decisive quantities and proportions. Due to the intermittent nature of solar energy, photovoltaic generation varies both in space and over time and consequently poses a serious challenge to system management, especially due to dynamically developing capacities. The imbalances caused by uncertainty cannot be addressed by scheduling alone without the possibility of energy storage, which, with its numerous services and applications, is able to provide the flexibility necessary for the smooth operation of the system. Among the available energy storage systems, power-to-gas technology (i.e. converting electricity produced from renewable energy sources into a gaseous energy carrier) is emerging as a practical solution with high potential for the integration of variable renewable energy sources. The gas produced in this way, which can be stored and transported, can be used in many areas and sectors of energy use, such as transport, home heating and cooling and industrial processes, and can now also provide an effective solution for grid stability and scheduling. The aim of the present research is to present the potential amount of green hydrogen that can be produced by proton-exchange membrane technology (PEM) in connection with schedule-related downregulation, considering the climatic conditions and the total photovoltaic power plant capacity in Hungary. The novel, practical benefit of the research lies in the fact that it determines practically relevant characteristics in relation to the interconnections of solar power plants in Hungary and power-to-gas technology for transmission system operators, the key players of the energy market and decision-makers. This knowledge will not only help companies investing in solar power plants and power-to-gas technology from an economic point of view but can also contribute to the market-related development of hydrogen production solutions related to photovoltaic technology. Overall, P2G offers the ideal potential to convert the electricity produced by solar power plants that need to be downregulated, i.e. comprises a surplus in terms of scheduling, into green hydrogen, which is also suitable for long-term seasonal storage.

1. Introduction

Variable renewable energy sources (VRES) play a key role in the global energy transition process. Their deployment, however, calls for practical solutions in the field of energy storage for both short-term and long-term storage, spanning several weeks or even months (Zsiborács et al., 2019). Although pumped hydro storage (PHS), the currently most widely used technology for the storage of electric energy boasts the highest storage capacity, such plants can be built and used only in locations with suitable topography (Ali et al., 2021), which also means that the capacity of the existing facilities cannot satisfy seasonal heating needs. It is due to these reasons that power-to-gas (P2G) technology, which uses water electrolysis to store renewable electric energy, has recently come to the fore, promising great potential for use, especially when utilising the existing natural

Paper Received: 15 June 2024; Revised: 27 July 2024; Accepted: 9 November 2024
Please cite this article as: Pintér G., Meszaros V., Hegedűsné Baranyai N., Vincze A., Zsiboracs H., 2024, Potential of Producing Green Hydrogen Using Solar Power Plants: The Role of PEM Technology in the Improvement of Photovoltaic Schedule Keeping in Hungary, Chemical Engineering Transactions, 114, 925-930 DOI:10.3303/CET24114155

gas systems (Nelabhotla et al., 2021). The power-to-hydrogen process, by which hydrogen is produced by the electrolysis of water with the help of electric power, forms the basis of all power-to-gas technologies. Of the three main processes of hydrogen production, this study focuses on proton exchange membrane (PEM) electrolysis, as this is the most developed technology with commercially available equipment (Böhm et al., 2019; Cihlar et al., 2020).

In the energy industry, several types of hydrogen are known according to the technology of their production, and they are designated by different colours. As for the official nomenclature used in the European Union, the European Council's legislation on hydrogen and the decarbonised market, which was passed at the end of 2021, provides guidelines. According to these, the new terminology refers to the sources of the different types of hydrogen and their impact on CO_2 emissions. The thusly defined classes of hydrogen are renewable hydrogen and low-carbon hydrogen. According to the European Council, hydrogen is deemed renewable if the energy needed for its production comes from some renewable source other than biomass, and it results in the emission of 70 % less greenhouse gas than the production of hydrogen using fossil fuels. So-called low-carbon hydrogen has to satisfy the latter condition, but it does not need to be produced by using renewable energy (Inside Energy & Environment, 2022). All in all, however, in international usage, the various names based on colour are still common, such as grey, blue, green, black/brown, yellow, turquoise, aqua, white, and pink. The present work focuses on green hydrogen.

In the case of green (carbon-free) hydrogen, hydrogen is produced using renewable energy (Velazquez Abad and Dodds, 2020). Its advantage is that it is considered the most environmentally friendly of all hydrogens, but its disadvantage is that its production costs are high, so only a few per cent of the hydrogen produced globally is green hydrogen (Shiva Kumar and Himabindu, 2019). Projections show that green hydrogen will play an increasing role in the supply of energy in the future. As green hydrogen plays an important role in the EU's energy transition strategy to clean and sustainable energy sources, the Union has launched a number of support programs and initiatives to encourage the development of green hydrogen technologies and infrastructures and promote its widespread use. The role of this type of hydrogen in the energy industry is projected to increase in the future. Prices are expected to fall with the growing penetration of new technologies and mass production, making green hydrogen more competitive with conventional energy sources. Growing interest and investment in green hydrogen research and development could lead to further technological advances and efficiency gains. This will allow for a wider use of green hydrogen, which can contribute to reducing greenhouse gas emissions and ensuring a sustainable energy supply. As part of its Green Deal, the EU has set targets to reduce carbon emissions and improve energy efficiency. The EU's hydrogen strategic objective is to build at least 40 GW of water-splitting capacity by 2030 (European Commission, 2020), which is intended to be facilitated by changing the regulatory environment (European Commission, 2021a, 2021b). Projections show that hydrogen will account for 10-23% of primary energy consumption in the EU (Joint Research Centre of the European Commission, 2019). The ongoing decarbonisation process is further enhanced by the expected additional systemic benefits of converting the hydrogen produced into synthetic methane (Blanco et al., 2018).

The aim of the present research is to present the potential amount of green hydrogen that can be produced by proton-exchange membrane technology (PEM) by using electric energy from schedule-related downward regulation of photovoltaic power plants, considering the climatic conditions and the total solar power plant capacity in Hungary (Pintér and Zsiborács, 2023).

2. Material and methods

This study investigates the amount of green hydrogen that can be potentially produced in connection with the downward regulation of PV power plants based on the average negative regulatory demand related to the annual energy production, which was determined earlier for Hungary's total capacity of all scheduled PV power plants (first quarter 2024) (Pintér and Zsiborács, 2023). Using the data obtained thusly, the amount of green hydrogen that could be produced using PEM technology was calculated.

For the purposes of modelling in this research, the data of the Global Solar Atlas (World Bank Group - ESMAP - SOLARGIS., 2023a) were used because it is a 22 y old database (1999 - 2021) (World Bank Group - ESMAP - SOLARGIS., 2023b) working with climate data from real weather data series. In the study, 36° was taken as the optimal tilt angle (slope) for PV modules, and 180° was used as the value of the optimal orientation (azimuth). On the basis of the GSA platform data, it can be concluded that the average annual amount of PV energy that can be produced by a 1 kWp grid-connected PV power plant ranges between 1,200-1,300 kWh/kWp in most of Hungary (Solargis.com., 2023). In the research the average of the two values, 1,250 kWh/kWp, which is the typical average for the Hungarian cities of Budapest and Debrecen and Szombathely, was used.

All commercial producers of electric power in the EU are required to submit so-called day-ahead and, in some cases, intraday schedules of power generation to the transmission system operators (TSOs). The TSOs are responsible for operating power grids and transmitting electric power via the high-voltage power grid. The scheduling responsibility of power plants means that they must produce and feed electricity into the power network at predetermined times and in set quantities to ensure a stable and balanced power supply (Hu et al., 2021). In the course of schedule keeping, both downward and upward regulation may become necessary. A need for upward regulation arises when the solar power plant does not reach the production projected in the schedule, in which case the so-called balance group manager has to feed additional power (balancing energy) into the grid, for which it charges a surcharge. The main objective of the balance group manager (in Hungary, the local TSO) is to maintain the balance of the electricity system. On the other hand, demand for schedule-related downward regulation transpires when the actual power generation of the power plant is higher than what was forecast in the schedule. In this case, the manager of the balance group compensates for the discrepancy by withdrawing electric energy from the power system, for which it also demands a surcharge. This condition of the market necessitates the further development of solutions to enhance schedule keeping, in which P2G technology could be successfully deployed for the purpose of downward regulation (Zsiboracs et al., 2023; Zsiborács et al., 2021). The excess power could be utilized to produce hydrogen or even methane, especially because Hungary's excellent natural gas infrastructure, outstanding even in the whole of Europe, would be suitable for storing and making good use of the excess electricity once it is thusly converted into methane. Thanks to this natural gas storage capacity, it would be possible to store this energy even seasonally (Csedő et al., 2021; Pintér, 2020; Pörzse et al., 2021).

A 2023 study (Zsiboracs et al., 2023) surveyed the ratio of the annual downward and upward regulation demand relative to the electric energy production of PV power plants in 19 European countries. In the case of Hungary, the results showed that the ratio of the annual downward regulation compared to the actual power generation varied between 5.6 % and 7.3 % in the case of the day-ahead forecast. The use of intraday scheduling did not cause any improvement in accuracy, i.e. the average downward regulatory demand related to the scheduling of the annual energy production of PV power plants in Hungary was 6.5 %. This value was taken into account in the calculations in the research to determine the potential amount of green hydrogen that could be produced by PEM technology using the electric energy from the downward regulation related to schedule keeping.

The work is based on the technical data of the PEM technology developed by the company NEL ASA (NEL). NEL is a global hydrogen technology company providing solutions for the production and distribution of hydrogen from renewable energy sources. NEL offers containerised PEM electrolyser solutions, which are ideal for situations where space is limited or the electrolyser needs to be placed outdoors. The solutions below are currently available from NEL:

- Model MC250, 1.25 MW containerized electrolyser;
- Model MC500, 2.5 MW containerised electrolyser (Nel ASA., 2023, 2020).

The piece of information that is key from the point of view of operation is the amount of electric energy that is needed to produce a kg of hydrogen, which is 50.4 kWh/kg for this solution. This value was used as a basis for further calculations in the research project. The aim of the simulations carried out in the study was to determine how much green hydrogen can be produced without losses using the PEM technology under consideration with the available electricity defined above. A more precise insight is given into the realistic potential of producing green hydrogen based on the PV power plant capacity presented in the methodology chapter. A schematic representation of the process described above can be seen in the flowchart below (Figure 1).

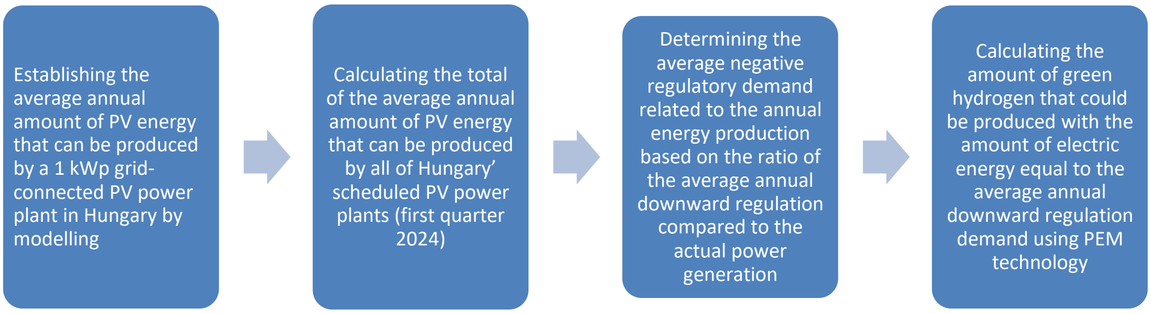

Figure 1: The process of investigation used in the research

It needs to be mentioned here that the model does not consider losses in hydrogen production. This was a necessary limitation as every project has individual characteristics, technical specifications and loss values. As for the hydrogen produced, several storage and transportation alternatives are available, such as chemical storage, physical storage, and adsorption; and road, sea and pipeline. The loss of energy and hydrogen varies, which also requires the limitations of the study to be set clearly (Pintér and Zsiborács, 2023).

3. Results and discussion

The approximate requirement of Hungarian PV power plants for downward regulation related to schedule keeping is 6.5 % of the annual PV power generation, which is the same percentage in the cases of both daily and intraday forecasts. Considering the 1250 MWh/y energy production of a 1 MW Hungarian PV power plant, this means a downward regulation demand of 81.3 MWh of electricity annually. Using the PEM technology introduced earlier to handle this negative regulatory demand, the 81.3 MWh of electric power could enable the production of 1.6 t of green hydrogen (taking no loss into account). Keeping PV power plant schedules always involves some downward and upward regulation, the amount of which depends on various factors, mostly related to weather and its predictability, creating difficulties for TSOs. The quantity of the average downward regulation need arising in the course of the annual aggregate energy production of all scheduled Hungarian PV power plants together with the potential amount of green hydrogen produced with its help by using PEM technology are both very important to know. To acquire this information, this study used the following data: the capacity of all Hungarian PV power plants obligated to submit schedules, the average demand for downward regulation caused by schedule keeping in the course of average annual power generation and the quantity of electric energy needed to produce 1 kg of hydrogen when using the PEM technology introduced above. Table 1 summarises the results.

Table 1: Potential green hydrogen production in Hungary using electric energy from the downward regulation of PV power plants subject to scheduling, considering a PV system of 3.4 GW aggregate capacity and the energy consumption of the MC250 and MC500 electrolyzers of NEL

Description	Value
Aggregate PV power plant capacity in Hungary, second quarter of 2024 (GW)	3.4
Average annual PV energy generation (GWh/GWp)	1,250
The average percentage of the annual downward regulation relative to the energy production in the case of day-ahead and intraday forecasting (%)	6.5
The downward regulation demand of the PV capacity examined (GWh)	276.3
Average power consumption of MC250 / MC500 at stack per a kilogram of H_2 gas produced (kWh/kg)	50.4
Total green hydrogen that can be produced with the electric energy from downward regulation, taking no losses into account (t)	5 481

Obviously, the green hydrogen produced thusly has great potential to be used for a variety of purposes ranging from applications in grids and energy systems to usage in the transport sector. An interesting aspect can be explored if the above results are combined with the consumption data of fuel cell buses determined by Caponi et al. (2023), where it was found that such vehicles in European cities consumed 15 kg of hydrogen per day on average. In terms of hydrogen supply for fuel cell buses in Hungary, the electric energy from the downward regulation of the Hungarian PV system coupled with the examined containerised PEM electrolyser solution could hold great potential. The PEM solution presented here could provide 1,100 buses with enough fuel for 332 days per year if no losses are considered. The results clearly suggest that deploying P2G technology could represent a great potential for the more efficient operation of the power system and the PV power plants. The current solution introduced could also become a progressive move toward an energy market that is both stable and sustainable.

4. Conclusion

The increasing grid impact of variable renewable energy sources must also be dealt with by the domestic regulatory system, which will pose great challenges to the Hungarian electricity system in the near future. In light of these developments, TSOs will have to rely more and more on balancing capacities of increasing volumes, the difficulty of which is further exacerbated by the current trend of decreasing or phasing out capacities based on fossil fuels. These projected changes in the supply and demand of balancing capacities will definitely call for new and novel answers. According to the authors, energy storage will be the increasingly dominant solution that will enter the regulatory market instead of, or in addition to, fossil power plants facing phasing out. As a result, energy storage has become an unavoidable issue in Hungary as well, and it has become an alternative to traditional network development and gas power plants, so its strong spread is expected in the future.

The findings of the above investigation of PV power plants confirm that among potential advanced solutions of high efficiency to tackle the challenges of schedule keeping, P2G technology could play a prominent role as an energy storage solution. It has also been established that a total of 5.48 Mt of green hydrogen annually could be produced, with no losses taken into account, when deploying the PEM technology presented herein if the whole electricity production of all Hungarian PV power plants obligated to submit schedules were utilised.

Overall, P2G offers an ideal opportunity to convert the electricity produced by PV power plants that need to be regulated, as it is a surplus in terms of scheduling, into green hydrogen, which is also suitable for long-term seasonal energy storage. With the approach described in the study, PV power plants would not only produce electric energy but also contribute to the production of green hydrogen, an increasingly important energy storage and fuel alternative for a sustainable future.

Acknowledgement

We acknowledge the financial support of 2021-1.2.6-TÉT-IPARI-MA-2022-00025 financed from the National Research, Development and Innovation Office (NRDI) Fund.

References

Ali S., Stewart R.A., Sahin O., 2021, Drivers and barriers to the deployment of pumped hydro energy storage applications: Systematic literature review. Clean Eng. Technol., 5, 100281, DOI: 10.1016/J.CLET.2021.100281.

Blanco H., Nijs W., Ruf J., Faaij A., 2018, Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization. Appl. Energy, 232, 323–340, DOI: 10.1016/J.APENERGY.2018.08.027.

Böhm H., Goers S., Zauner A., 2019, Estimating future costs of power-to-gas – a component-based approach for technological learning. Int J Hydrogen Energy, 44, 30789–30805, DOI: 10.1016/J.IJHYDENE.2019.09.230.

Caponi R., Monforti Ferrario A., Del Zotto L., Bocci E., 2023, Hydrogen refueling stations and fuel cell buses four year operational analysis under real-world conditions. Int J Hydrogen Energy, 48, 20957–20970, DOI: 10.1016/J.IJHYDENE.2022.10.093.

Cihlar J., Villar Lejarreta A., Wang A., Melgar F., Jens J., Rio P., van der Len K., 2020, Hydrogen generation in Europe, DOI: 10.2833/122757.

Csedő Z., Zavarkó M., Vaszkun B., Koczkás S., 2021, Hydrogen Economy Development Opportunities by Inter-Organizational Digital Knowledge Networks. Sustainability, 13, 9194, DOI: 10.3390/SU13169194.

European Commission, 2021a. Proposal for a Regulation of the European Parliament and of the council on the internal markets for renewable and natural gases and for hydrogen (recast). COM/2021/804 final, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A804%3AFIN>, accessed 10.11.2024.

European Commission, 2021b. Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen. COM(2021) 803 final, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0803>, accessed 10.11.2024.

European Commission, 2020. A hydrogen strategy for a climate-neutral Europe. <https://ec.europa.eu/commission/presscorner/api/files/attachment/865942/EU_Hydrogen_Strategy.pdf>, accessed 10.11.2024.

Hu Y., Armada M., Sanchez M.J., 2021. Potential utilization of Battery Energy Storage Systems (BESS) in the major European electricity markets. Applied Energy, 322, 119512.

Inside Energy & Environment, 2022, New Definitions for Blue and Green Hydrogen: The European Commission's Package on Hydrogen and Decarbonized Gas Markets <https://www.insideenergyandenvironment.com/2022/01/new-definitions-for-blue-and-green-hydrogen-the-european-commissions-package-on-hydrogen-and-decarbonized-gas-markets/>, accessed 11.11.2022.

Joint Research Centre of the European Commission, 2019, Hydrogen Use in EU Decarbonisation Scenarios.

Nel ASA., 2023. PEM Electrolyser <https://nelhydrogen.com/product/m-series-3/>, accessed 29.07.2023.

Nel ASA., 2020. MC Series Containerized Proton Exchange Membrane (PEM) Hydrogen Generation Systems<https://nelhydrogen.com/resources/m-series-containerized-pem-electrolysers/>, accessed 10.11.2024.

Nelabhotla A.B.T., Pant D., Dinamarca C., 2021, Power-to-gas for methanation. Chapter 8 in: Emerging Technologies and Biological Systems for Biogas Upgrading, 187–221, DOI: 10.1016/B978-0-12-822808-1.00008-8.

Pintér G., 2020, The Potential Role of Power-to-Gas Technology Connected to Photovoltaic Power Plants in the Visegrad Countries—A Case Study. Energies, 13, 6408, DOI: 10.3390/EN13236408.

Pintér G., Zsiborács H., 2023, Photovoltaic Energy Generation in Hungary: Potentials of Green Hydrogen Production by PEM Technology. Periodica Polytechnica Mechanical Engineering, DOI: 10.3311/PPME.23333.

Pörzse G., Csedő Z., Zavarkó M., 2021, Disruption Potential Assessment of the Power-to-Methane Technology. Energies, 14, 2297, DOI: 10.3390/EN14082297.

Shiva Kumar S., Himabindu V., 2019, Hydrogen production by PEM water electrolysis – A review. Mater Sci Energy Technol, 2, 442–454, DOI: 10.1016/J.MSET.2019.03.002.

Solargis.com., 2023. Solar resource maps and GIS data for 200+ countries. <https://solargis.com/maps-and-gis-data/overview>, accessed 28.07.2023.

Velazquez Abad A., Dodds P.E., 2020, Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. Energy Policy, 138, DOI: 10.1016/J.ENPOL.2020.111300.

World Bank Group - ESMAP - SOLARGIS., 2023a, Global Solar Atlas. <https://globalsolaratlas.info/map>, accessed 04.02.2023.

World Bank Group - ESMAP - SOLARGIS., 2023b, Data outputs. <https://globalsolaratlas.info/support/data-outputs>, accessed 12.02.2023.

Zsiborács H., Baranyai N.H., Vincze A., Zentkó L., Birkner Z., Máté K., Pintér G., 2019, Intermittent Renewable Energy Sources: The Role of Energy Storage in the European Power System of 2040. Electronics, 8, 729, DOI: 10.3390/electronics8070729.

Zsiborács H., Pintér G., Vincze A., Birkner Z., Baranyai N.H., 2021, Grid balancing challenges illustrated by two European examples: Interactions of electric grids, photovoltaic power generation, energy storage and power generation forecasting. Energy Reports, 7, 3805–3818, DOI: 10.1016/J.EGYR.2021.06.007.

Zsiboracs H., Vincze A., Pinter G., Baranyai N.H., 2023, The accuracy of PV Power Plant Scheduling in Europe: An Overview of ENTSO-E Countries. IEEE Access, DOI: 10.1109/ACCESS.2023.3297494.