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Photovoltaic Energy Generation in Hungary: Potentials of Green Hydrogen Production by PEM Technology

First Steps towards the Deployment of the Power-to-gas Technology

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Abstract

The dynamic spread of photovoltaic power plants in the global energy industry facilitates cost-effective and clean electricity generation. However, the intermittent nature of solar energy poses an increasing challenge from a system management point of view due to the fast-growing capacities. As a consequence, energy storage systems are increasingly important in this area, as they allow the efficient and flexible storage of excess electricity generated in the electricity system. Among various energy storage systems, the power-to-gas technology is becoming more and more important in the integration of weather-dependent renewable energy sources, as it can now provide an effective solution for increasing grid stability and scheduling efficiency, as well as enabling wide variety of application possibilities in the economy, for example in transport, industry or heating systems. The aim of the present research was to determine the potential amount of green hydrogen that can be produced by using the proton-exchange membrane technology, taking into account the climatic conditions in Hungary and the energy production potentials of photovoltaic power plants of given capacities. This is not only novel but also of practical use, as it provides important information about the integration of photovoltaic power plants and the power-to-gas technology to the actors of energy systems and the energy market and the decision-makers concerned. In addition to the vital economic aspects of the research, supporting the decisions of potential investors, it also contains important insights for market-related technological developments.

Keywords

PV grid integration, power-to-gas, green hydrogen, hydrogen generation system, PEM electrolyzers

1 Introduction

The four topics of the introduction cover the energy challenges related to weather-dependent renewable energy sources, the importance of the power-to-gas (P2G) technology, the role of green hydrogen and finally the presentation of the role of the European Union.

Increasing the share of electricity generated by using weather-dependent renewable energy sources (VRES) plays an extremely important role in humanity's decarbonization efforts. However, a related challenge is that technologies based on them necessitate electricity storage: on the one hand, short term storage, lasting for periods less than a day and, on the other hand, for longer ones, such as weeks or months, i.e., seasonally [1]. The systems with the highest storage capacity used today are the so-called pumped hydro storage (PHS) plants. The main disadvantage of these is that their installation and operation is possible only under certain topographical conditions [2], and even their capacity is far below the energy demand during heating periods. The recently increasingly well-known P2G technology is able to store the generated electricity with the help of water splitting in the form of hydrogen, and the potential of its future application is greatly increased by the fact that the already existing natural gas systems offer great opportunities in terms of its usability [3].

Another challenge is to ensure the reliable, stable operation and flexibility of the electricity system even with the integration of VRES with their ever-growing proportion. Energy storage can also provide a solution to this problem. Despite the fact that it has been used for this purpose for a long time, due to the pressure on evolving electricity systems in transition, the use of energy storage for

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this purpose needs not only to develop, but also to become more widespread [4, 5].

Taking into account the challenges outlined above, it can be stated that the increased interest in the P2G technology, both from policymakers and from science, is due to the significant potential role that this solution could play in the future in the storage of electric energy from variable renewable energy (VRE) [6]. The current expectations are supported by decades of operational experience [7, 8], however, P2G solutions have yet to become truly widespread. This latter fact is all the more regrettable, as it is now increasingly accepted that the target of 1.5 °C compared to pre-industrial levels, to mitigate the negative consequences of climate change, can only be met if the world economy achieves net-zero emissions by 2050, which is inconceivable without VRE [9] and a large increase in energy storage capacities [10].

All P2G projects are based on the so-called power-to-hydrogen process, which is the electrolysis of water to produce hydrogen, using electricity. Water splitting equipment today basically use three technologies: alkaline water electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC).

Of these, alkaline electrolysis is used most often today, and equipment based on this technology is not only easier to obtain than others, but also the most favorable in price per a unit of power [4, 11]. The acid electrolyte solution used in them, which has a highly corrosive effect on the elements of the system, however, is a significant disadvantage of this technology [12].

Today's most modern–and unfortunately still not easily available–water electrolysis technology is the so-called SOEC. Today, this new solution is mostly used only for research and development and special pilot projects [4]. An interesting feature of this novel type of water splitting is that it has a dual operation: it has both consumption and production modes. The advantage of this is that, in an integrated system, it can be used both for energy storage and for regenerating electricity from already stored energy [13].

Compared to alkaline electrolysis, the so-called PEM (proton-exchange membrane) water splitting technology also represents a more advanced level. Its operation is not only more dynamic, but its efficiency is also higher, since it consumes less electricity [14]. The other parameters of equipment using this technology, such as operating temperature and pressure values, are similar to those of alkaline electrolyzers [15, 16]. At the same time, the investment costs of PEM electrolyzers exceed those of the alkaline technology [11] due to the high content of rare earth elements in the equipment [17]. Nevertheless, PEM water splitters have often been deployed in various pilot projects in recent years, probably because of their beneficial properties, such as faster cold starts than those of alkaline water splitters, which allow them to contribute more reliably to maintaining the balance of the electricity system [18].

As a result of the search for a way forward in the transformation of energy systems, as interest in hydrogen and electrolysis technologies grows, increasing attention and resources are also focused on the related wide range of innovation, which includes not only production processes, but also system design, the research and development of the materials used and the possibilities of larger-scale production [19]. Today, it is an expectation supported by research that as a result of the developments of the next three decades, the electricity demand of hydrogen production will further decrease (by 3–7%, depending on the technology) [20], the service life of water splitting equipment will significantly increase (by up to 50%) [14, 20]. This process will hopefully lead not only to a reduction in unit investment costs, but also in the price of the final product [21]. Broken down by technology, this means that the investment costs per unit relative to performance of PEM and alkaline electrolyzers could decrease by at least 30% by the third decade of our century [16], and they may remain stably below EUR 1 million/MW by mid-century, while for SOEC water splitting technology this value may be permanently below the limit of EUR 2 million/MW [20, 21]. Overall, it can be stated that the most advanced electrolyzers currently commercially available use alkaline (AWE) and PEM technology [11, 20].

In the terminology of the energy industry, different names of colors are used to distinguish the types of hydrogen produced using different technologies. However, at the end of 2021, the European Council legislated names for hydrogen types, referring to the sources used by a given hydrogen technology and its impact on carbon dioxide emissions. According to this, there is so-called renewable hydrogen and low-carbon hydrogen. The former means that the energy needed to produce hydrogen is obtained from renewable energy sources (but not biomass) and that the technology used emits 70% less greenhouse gas than hydrogen produced from fossil fuels. The second type, low-carbon hydrogen, must also meet the latter requirement, although it is not expected to come from renewable energy sources [22]. Despite the official new nomenclature, people in the industry still prefer to use color-based designations, i.e., gray, blue and green, as well as black/brown, yellow, turquoise, aqua, white, pink hydrogen.

Green, i.e., carbon-free hydrogen, which this study focuses on, is produced using renewable energy [23]. Although it is the most environmentally friendly of all hydrogens of various 'colors', its production costs are unfortunately relatively high. This explains why only a fraction of hydrogen produced worldwide qualifies as green hydrogen [13]. Nevertheless, this type of hydrogen is expected to play a significant role in future energy supply and the transition to sustainable and clean energy, and thus in the EU's energy transition strategy. The European Union has already done a great deal to promote the use of green hydrogen and its development through various support programs and initiatives. As a result, on the one hand, the importance of green hydrogen in the energy industry will increase, and on the other hand, due to more modern technologies and higher production volumes, prices will decrease, making green hydrogen more competitive compared to conventional energy carriers. This trend, combined with technological innovation generated by increased interest and investment activities and the expected efficiency gains, could facilitate the increasing use of green hydrogen. As the EU has set strong targets in its so-called Green Deal to reduce carbon emissions as well as increase energy efficiency, greenhouse gas emission reductions due to the deployment of green hydrogen could be an important element in the transition to sustainable energy supply. In line with this, the EU's hydrogen strategy states that a minimum of 40 GW of electrolyzer capacity will be needed by 2030 [24], and this objective is also supported by adapting the regulatory environment accordingly [25, 26]. Various forecasts agree that the share of hydrogen in primary energy consumption in the European Union could reach up to 10–23% in the future [27]. This trend is greatly facilitated by the fact that hydrogen can be converted into so-called synthetic methane, which can open many new doors for utilization [28].

This study focuses on photovoltaic (PV) power generation and PEM technology in Hungary. The aim of the research is to determine the potential amount of green hydrogen that can be produced by using PEM technology, taking into account the energy production potential of PV power plant capacities in Hungary, under Hungarian climatic conditions.

2 The aspects examined in the study

The present work examines the potential amount of green hydrogen that can be produced by PEM technology based on three aspects related to PV power plants:

1. In the first step, the research examined the average annual energy production of a PV power plant with a capacity of 1 MW in Hungary, broken down by month. Based on the results obtained, the amount of green hydrogen that can be produced by PEM technology was determined.
2. In the second phase, the schedule-related average negative regulatory demand of the annual energy production of a PV power plant with a capacity of 1 MW was examined. Based on the data from this, it was determined how much green hydrogen could be produced with PEM technology.
3. At the third stage, the average demand for negative regulation related to the average annual energy production was determined for the aggregate capacity of all PV power plants subject to scheduling in Hungary. Based on the data obtained, it was determined how much green hydrogen could be produced by using PEM technology.

Due to the aspects examined, Sections 2.1 to 2.4 present the reasons for the selection of the PV power plant capacities studied herein as well as their average energy production characteristics, the average negative regulatory demand in Hungary, and the potentials of using P2G technology in the scheduling of PV power plants, as well as the characteristics of the specific PEM technology used in the research.

2.1 The reasons for selecting the given PV power plant sizes examined in the study

Establishing PV systems, similarly to other energy investments, not only requires significant capital, but is usually also for the long-term, so it requires great care, including the regulatory environment of the given country [29–31], as the rules for the use of renewable energies, support programs and opportunities not only vary greatly over time, but also vary considerably from country to country [32]. As a result, investors cannot afford not to monitor the changes or differences [33], so that they can make the best possible decisions in their investments [31]. The recent years have shown that investors prefer to build power plants of greater capacities, i.e., several MWs in their PV projects in Hungary [34]. It follows from this that the 1 MW capacity is excellent for modelling purposes, as it allows the easy proportionating of the results for PV systems of any size, which provides an opportunity for comparisons and interpretation of data even in the case of PV power plants of different capacities. This provided a good basis for extending the data obtained to include all the current PV power plant capacities subject to scheduling in Hungary (3 110 MW, third quarter 2023).

2.2 The energy production parameters of the examined PV power plants

The large number of PV system design-modeling software available in the world all have different simulation capabilities [35], so it was essential to choose the program that best suits the nature of the research. When it comes to calculating the annual electricity production of PV power plants, there are many free modelling options (e.g., the Photovoltaic Geographical Information System (PVGIS), PVWatts Calculator, Global Solar Atlas (GSA), etc. [36–38]), which are popular with both scientists and professionals in the industry [39–41]. The modelling and simulation carried out in the research project presented here used data provided by GSA [37]. which was chosen because the GSA database not only has a history of 22 years (1999–2021) [42], but its data is based on actual weather data series. The GSA online platform was established by the World Bank and the International Finance Corporation (IFC) within the framework of the Energy Sector Management Assistance Program (ESMAP) to support the establishment and spread of PV energy-based systems worldwide. Using data provided by Solargis and owned and maintained by the World Bank, the database contains a wide range of data and maps describing the average production potentials of solar energy and PV systems around the world, broken down by day, month and year [43]. Among other things, the database offers optimal slope and azimuth values tailored to the location of the PV system and the given radiation conditions, which were also used in this study, according to which the optimal tilt angle (slope) of the PV modules was 36° and the optimal orientation (azimuth) was 180°. Based on the data of the GSA platform, it can be established that in the vast majority of Hungary, the average annual amount of PV energy that can be produced varies between 1200–1300 kWh/kWp [44]. Based on this, the research calculated with the average of these two values, 1250 kWh/kWp. This average value is characteristic for the cities of Budapest Debrecen or Szombathely and their vicinities in Hungary.

2.3 The average amount of demand for negative regulation in Hungary: the potentials of deploying P2G technology in the scheduling of PV power plants

In order to put the average demand for negative regulation resulting from the operation of PV power plants and its magnitude into context, it is necessary to understand the importance of scheduling.

All installations operating in the European Union that generate electricity for sale are obliged to inform the transmission system operators (TSOs), which are responsible for operating the electricity network and transmitting electricity through the high-voltage electricity network, about their expected production by so-called day-ahead and, in certain cases, intraday schedules. The scheduling obligation means that power plants must generate electricity and load it onto the electricity grid at predetermined times and quantity, and compliance with this obligation can guarantee the reliability and balance of electricity supply. In the EU these forecasts must be produced for the local TSO no later than the day before, typically by 12:00, broken down into 15- or 60-minute periods [45].

The Hungarian rules stipulate that all market participants are obliged to take financial responsibility for any imbalances in the energy system arising as a result of their activities, the conditions of which have been continuously made stricter and stricter since 1 April 2020 [46, 47]. In the case of PV power plants, this responsibility is usually assumed by the so-called scheduling groups, whose services usually include the performance of scheduling activities (e.g., inverter monitoring, forecasting PV power plant energy production, etc.) for the operators or owners of PV power plants. Since natural conditions are constantly changing and it can be difficult to forecast them, it can be stated that a fully accurate PV electricity generation forecast cannot be made, which necessarily leads to costs that cannot be precisely planned in advance.

While power plants follow their schedules there may be demand for both upward and downward regulation. The former occurs when the output of the power plant falls short of the value forecast in the schedule. In this case, the balance group manager, who is typically the local TSO in Hungary, whose most important goal is to keep the system balanced, feeds so-called balancing electricity (i.e., extra energy) into the electricity system, for which the one causing the imbalance is charged a surcharge. In contrast, a demand for downward regulation occurs when the actual production of the PV power plant exceeds the value specified in the schedule. In such a case, the balance group manager withdraws energy from the electricity system, which it also charges a surcharge. This technological and market situation naturally stimulates research and development aimed at improving scheduling, in which P2G technology could play a prominent role regarding downward regulation [48, 49]. The surplus electricity produced above the forecast value can be used for the production of both hydrogen and methane, all the more so since the Hungarian natural gas infrastructure, which can be considered sophisticated and well-developed even by European standards, is excellent for storing (even seasonally thanks to the large natural gas storage capacity in Hungary) and utilizing the surplus electricity converted into methane in this way [6, 50, 51].

An earlier study [48] covering the relative upward and downward regulation needs of 19 European countries showed that the daily and intraday forecasting practices of PV electricity generation in Hungary can be considered quite accurate in international comparison. The inaccuracy compared to, for example, Germany or Spain can be explained by the fact that the latter two countries occupy significantly larger areas, so unexpected weather events do not affect the reliability of forecasts at the national level to the same extent as in the case of Hungary. The downward and upward regulation demand values in Hungary, compared to the energy production were as follows:

- the demand for downward regulation corresponded to 5.6 to 7.3% of the energy production annually in the case of daily forecasts, and intraday scheduling could not improve this situation, either;
- the demand for upward regulation ranged between 3.6 and 6.7%. And here the accuracy improving effect of intraday scheduling could also be detected, even if it remained rather small [48].

The results of the research [48] showed that the average negative regulatory demand related to scheduling of the annual energy production of all PV power plants in Hungary was 6.5%. The present study took this value into account in the calculations. Based on the data from this, it was determined how much green hydrogen could be produced by using the PEM technology in the case of scheduling.

2.4 The PEM technology used for the purposes of the study

Although both AWE and PEM technologies are now commercially available, this paper examines and discusses the potentials of the latter.

The technical specifications of NEL ASA (NEL) PEM technology were relevant during the investigation. The main field of activity of the global NEL company is various technological solutions related to the production and distribution of hydrogen produced using green energy. The company is a market leader not only in PEM but also in AWE technologies and has built more than 3500 electrolyzers around the world. For example, NEL's containerized PEM electrolyzer is an ideal and popular solution for on-site hydrogen production alongside PV power plants. The company can boast of promoting sustainable energy production, efficient energy storage and more accurate scheduling, ultimately supporting the decarbonization of the energy sector [52–54].

NEL offers the following PEM-based container solutions today:

- Model MC250, container electrolyzer with a capacity of 1.25 MW;
- Model MC500, container electrolyzer with a capacity of 2.5 MW [52, 53].

The main technical data of NEL's PEM systems are summarized in Table 1. One of the most important pieces of information for operation is the amount of electricity required to produce a unit of hydrogen, which is 50.4 kWh/kg for this design. The research used this value as the basis for the calculations.

The goal of the modelling and simulations carried out during the research was to determine the amount of green hydrogen that can be produced by using the PEM technology examined, based on criteria 1–3 defined in Section 2. These results are important because they allow a more accurate understanding of the real potentials of green hydrogen production in the context of the PV power plant capacities mentioned in Section 2. At the same time, the data obtained do not take into account losses. This modelling limitation had to be applied because each project has different characteristics, technical parameters and losses, so each project has to be examined individually and further

Table 1 The main technical data of the PEM systems used for the purposes of modelling [52, 53]

Description		Model	
		MC250	MC500
Hydrogen production, net production rate	Nm^3/h (0 °C, 1 bar)	246	492
	kg/24 h	531	1 062
Average power consumption at stack per volume of H_2 gas produced (kWh/Nm^3)		4.5	
Average power consumption at stack per mass of H_2 gas produced (kWh/kg)		50.4	
Delivery pressure (barg)		30	
Start-up time, from off state (min.)		<5	
Ramp-up time, minimum to full load (sec.)		15	
Production capacity dynamic range (%)		10–100	

modelled. Once hydrogen is produced, there are several storage and transportation options. Storage options include physical storage, adsorption and chemical storage, while transport can take place by pipeline, road or sea. As a consequence, the energy characteristics, as well as the amount of hydrogen loss, are specific, which justifies the clear definition of the limitations of the modeling herein.

3 Result and discussion

3.1 Calculating the amount of hydrogen that can be produced by PEM technology based on the average annual energy production of PV power plants in Hungary

In the first step of the research, it was necessary to determine the average annual energy production of a 1 MW capacity PV power plant in Hungary, in a monthly breakdown. The GSA platform was used for this purpose (Table 2). Table 2 clearly shows the monthly distribution of annual energy production. The winter months, e.g., January and December, show lower energy production on average, with values of 51.0 MWh and 36.2 MWh, respectively, which is only 4.1% and 2.9% of the total annual production, respectively. At the same time, the summer months, such as June and July, have significantly higher production values of 141.7 MWh and 147.9 MWh, respectively, which is 11.3% and 11.8% of the total annual production, respectively. From the monthly distribution of average annual energy production, it can be seen that the months that make good use of the capacities of the PV power plants are in the summer period, while the rate of energy generation decreases in the winter period. This information can be an important aspect in the production of green hydrogen in terms of seasonality, as it offers the possibility to align energy use with the production cycles of PV power plants.

By comparing the monthly and annual PV power generation data in Table 3 with the energy consumption data of the MC250 or MC500 systems, it is possible to determine how much green hydrogen can potentially be produced by using the PEM technology. Table 3 shows that the green hydrogen production varies from month to month, following the seasonal changes in PV energy production. The data show that a total of 24.8 metric tons of green hydrogen can be produced in one year, without taking into account any losses, using the PEM technology studied, if the entire electricity production of a 1 MW PV power plant is utilized. This potential amount of green hydrogen offers opportunities for sustainable energy production and storage, contributing to an increase in green energy use and the reduction of carbon emissions.

The results provide further interesting perspectives when considering the consumption of fuel cell buses. Caponi et al. [55] analyzed data from six European cities in 2023, and they found that fuel cell buses consumed an average of 7 kg/100 km and consumed an average of 15 kg of hydrogen per day. A PV system with a capacity of 1 MW and a containerized PEM electrolyzer would have significant potential for the production and supply of hydrogen for fuel cell buses. The system studied in the research would be able to provide about 5–7 days of H_2 in January, 19–20 days in the summer months, and 165 days in total

Table 2 The average electric energy generation of a 1 MW PV power plant in Hungary, in a monthly breakdown

Month	PV power plant, monthly average energy production (MWh)	PV power plant, monthly average energy production (%)
January	51.0	4.1
February	74.9	6.0
March	116.0	9.3
April	131.4	10.5
May	141,3	11.3
June	141.7	11.3
July	147.9	11.8
August	144.6	11.6
September	114.7	9.2
October	95.7	7.7
November	54.6	4.4
December	36.2	2.9
Total	1250	100

Table 3 The annual potential for green hydrogen production by month in the case of a PV system of a capacity of 1 MW, considering the energy consumption of the MC250 and MC500 systems

Month	Amount of H_2 gas produced at stack (t)
January	1.0
February	1.5
March	2.3
April	2.6
May	2.8
June	2.8
July	2.9
August	2.9
September	2.3
October	1.9
November	1.1
December	0.7
Total	24.8

if 10 buses were produced per month (excluding losses). A PV system with a capacity of 1 MW and a containerized PEM electrolyzer could have a significant potential for the production and supply of hydrogen for fuel cell buses. The system studied in the research would be able to provide a monthly amount of H_2 enough for about 5–7 days in the winter months, and 19–20 days in the summer months, 165 days in total, for 10 buses (excluding any losses).

3.2 Determining the amount of hydrogen that can be produced in Hungary by using PEM technology, by modelling based on the annual demand for negative regulation of the PV power plants

The transformation of energy systems and the significant increase in the share of renewables require exact information on the accuracy of the daily and intraday scheduling of PV energy production in every EU country. This is primarily important to TSOs and provides insight into the limitations of the countries' PV energy production forecasting practices, which not only helps investors in terms of economic aspects but is also essential for the development of management systems for various energy storage solutions for the market.

The average amount of demand for negative regulation related to the scheduling of the annual PV power generation of PV power plants in Hungary was 6.5%. This proportion was the same for both daily and intraday forecasts. Based on this, taking into account the average annual energy production of a Hungarian PV power plant with a capacity of 1 MW, which is 1250 MWh/year, 81.3 MWh of electricity requires downward regulation during this time. If the PEM technology under consideration were to eliminate the negative regulatory demand, 81.3 MWh of electricity could be used for the production of 1.6 metric tons of green hydrogen, without taking into account any loss. For PV power plants, such regulatory practices are important because in this way they could contribute more effectively to a more reliable timing of energy production. They would also be able to better address their needs for negative regulation, which would contribute to increasing network stability and reducing the amount of surcharges resulting from deviations from schedules. In addition, based on the bus example shown in Section 3.1, 1.6 metric tons of green hydrogen could provide 10 buses with 11 days' worth of fuel in a year.

It is important to emphasize that the results described above apply to PV power plants with a capacity of 1 MW. In the scheduling of PV power plants, depending on the predictability of the weather, there is always a certain amount of demand for downward and upward regulation, which is a challenge for TSOs to manage. For this reason, it is necessary to establish the amount of the average demand for negative regulation related to the annual energy production by the aggregate capacity of all scheduled PV power plants in Hungary as well as the quantity of green hydrogen that could potentially be produced by it by using PEM technology. In order to determine these figures, the capacity of all PV power plants subject to scheduling in Hungary was taken into account, as well as the average demand for negative regulation related to the scheduling of the average annual energy production of the PV power plants, and thirdly, the electricity required for the production of 1 kg H_2 by deploying the analyzed PEM installation. The results are summarized in Table 4.

Referring back again to the study by Caponi et al. [59], in which it was established that the average hydrogen consumption of fuel cell buses in European cities was 15 kg per day, interesting conclusions can be drawn. From the point of view of the production and supply of the hydrogen needed for the operation of such vehicles, the aggregate capacity of the PV systems in Hungary, combined with the containerized PEM electrolyzers under consideration could have significant potentials. The PEM system studied herein could provide a total of 334 days' worth of fuel for the operation of 1,000 buses with the amount of H_2 produced, without taking into account any losses.

Based on the above results, it can be seen that the application of P2G technology could represent significant potentials for the more efficient operation of electricity

Table 4 The potential of green hydrogen production in Hungary in the case of the downward regulation of a 3.1 GW PV system, based on the energy consumption of the MC250 and MC500 systems

Description	Value
The aggregated capacity of all PV power plants in Hungary (GW)	3.1
Average annual PV energy production (GWh/GWp)	1250
The average proportion of the annual downward regulation requirement as a percentage of the annual energy generation in the case of day-ahead and intraday forecasting (%)	6.5
The amount of PV downward regulation in the case of the examined PV capacity (GWh)	252.7
MC250 or MC500 average power consumption at stack per mass of H_2 gas produced (kWh/kg)	50.4
The amount of green hydrogen that can be produced by downward regulation, without taking into account any losses (*t*)	5014

systems and PV power plants. The solution presented in the research would also be a significant step forward towards a sustainable and stable energy market.

4 Conclusion

Similarly to other countries, the Hungarian electricity system faces considerable challenges due to increasing pressure on the regulatory system by the growing share of VRE sources. In order to ensure system balance, TSOs need to rely on greater and greater balancing capacities, which is a growing concern in light of trends towards reducing or shutting down fossil fuel based capacities. The expected shrinking of supply, coupled with an increase in demand, will lead to the emergence of novel regulatory solutions in the market. Based on the results of research and considering the trends, it can be predicted that energy storage will increasingly be able to respond to this challenge and replace traditional fossil power plants in the regulatory market, and Hungary cannot not be an exception, either.

The results obtained for PV power plants highlight the need to apply innovative and efficient solutions to the challenges related to scheduling, for which P2G technology could be an excellent solution in terms of energy storage technologies. Based on the results, it can be concluded that a total of 24.8 metric tons of green hydrogen can be produced in one year, without taking into account any losses, by using the examined PEM technology if the entire electricity production of a PV power plant of a capacity of 1 MW is utilized. In the case of using the PEM technology for the optimization of the downward regulation of the 1 MW PV, 1.6 metric tons of green H_2 could be produced, excluding any losses. However, in terms of all PV power plants subject to scheduling in Hungary, in the context of regulation, this value could exceed 5 thousand metric tons.

Based on the above, it can be stated that P2G technology can be an excellent tool for utilizing the excess electricity generated during the operation of PV power plants which need to be regulated in order to keep schedules, while the green hydrogen thusly produced could also satisfy seasonal energy storage needs. In this way, PV power plants would no longer simply generate electricity, but would also play a prominent role in the production of green hydrogen, which offers great potentials as both a fuel and energy storage solution for the more sustainable energy systems of the future.

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