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Teaching laboratory exercises for analyzing the performance of a proton exchange membrane electrolyzer in hydrogen generation systems

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Abstract. The progressive integration of renewable energy sources into the power system introduces significant challenges due to the inherent variability of their generation. Energy storage systems represent an effective solution to mitigate these challenges. Among small-scale storage technologies, battery-based systems and hydrogen fuel cell systems are the most widely adopted. Consequently, future engineers responsible for planning and operating power systems must be adequately trained in the principles, operation, and integration of these energy storage technologies. This paper presents an educational, hands-on kit developed by the research team, along with a set of laboratory activities designed to be carried out using the kit, with the objective of helping future engineers understand the fundamental principles of converting electrical energy into storable "green" hydrogen through a proton exchange membrane (PEM) electrolyzer. The kit enables testing of the electrolyzer under different operating conditions, assessment of its dependence on external factors, and evaluation of its performance. Its implementation in an elective course within the electrical engineering program during the final two years of study has achieved highly satisfactory results, enabling students to effectively apply the acquired knowledge in their future professional practice.

Key words. Energy storage systems, green hydrogen, engineering curricula, renewable energy integration.

1. Introduction

Ensuring the stability and aggregated inertia of power systems in the face of generation due to intermittent renewable sources has emerged as a paramount technical challenge within the framework of the energy transition. Energy storage for electricity generated by these sources has proven to be an effective solution for facilitating their integration into the power system [1], [2]. The main technologies used to store energy are hydroelectric systems (pumped-storage plants), batteries, and fuel cells, although only the latter two are available for small-scale storage systems. As these systems become more widespread in the future, engineers must be prepared to support their deployment, configure their operation, and manage their maintenance. Such preparation, however, requires incorporating the conceptual foundations underlying the operation of this energy storage equipment into engineering curricula. This is particularly true for fuel cell–based systems, in which engineering students must understand the operating principles of each component, including the electrolyzer, the device that converts electrical energy from a renewable source into storable "green hydrogen". In general, the study of hydrogen technology for energy storage and its subsequent conversion into thermal or electrical energy is scarcely included in university curricula beyond short-duration specialization courses [3], despite international level recommendations such as the European Union Strategy on Education for Sustainability [4] and the European Green Deal [5], which emphasize the importance of incorporating education on renewable and sustainable energy and, by extension, these types of systems, into university level educational programs. Despite the recognized future potential of hydrogen technology in the energy sector and its capacity to serve as a means of storing energy generated by renewable energy-based plants, relatively little attention has been given to the development of educational equipment that facilitates understanding of its operation.

Teaching laboratory exercises focused on the analysis of proton exchange membrane (PEM) electrolyzers in higher education are a valuable tool for connecting theoretical electrochemistry with renewable energy engineering. Didactic equipment incorporating transparent PEM electrolyzers enables students to directly observe water electrolysis processes and to evaluate hydrogen production efficiency, thereby facilitating the understanding of fundamental thermodynamic principles and mass transport phenomena [6]. The transparent PEM electrolyzer combined with real-time monitoring supports an interactive learning experience in which students can examine how operating parameters such as temperature, pressure, and current density, influence electrolyzer performance. This approach aligns with the growing demand for STEM curricula that emphasize sustainable and clean energy technologies and energy conversion systems. Although several initiatives in this area have been implemented as virtual laboratories [7], hands-on practice with real equipment provides a learning experience closely aligned with real-world conditions, thereby better preparing future engineers and researchers for the transition to sustainable energy systems.

This paper presents an educational kit and the instructional materials related to PEM electrolyzers developed to support hands-on teaching activities within a graduate-level electrical engineering course. The kit was developed by the research team to address specific training needs within an elective course focused on the integration of renewable energy–based generation plants into the electric power system. Designed according to principles of low cost and high scalability, the kit consists primarily of a commercial reversible proton exchange membrane (PEM) fuel cell, and includes a controllable power supply that enables the simulation of renewable energy generation, two small tanks for storing the generated gases, a distilled water reservoir that allows continuous operation of the electrolyzer, and a set of measuring instruments for monitoring the electrical parameters of the system. The equipment has been used for laboratory activities over the past academic year, achieving high level of satisfaction among both students and instructors.

The design of the device remains open, with the intention of integrating in the future a power supply capable of more accurately simulating highly variable generation such as that produced by photovoltaic systems [8], enabling the development of new experiments related to hydrogen storage and its conversion into electrical energy, or scaling the system to achieve higher power levels.

The article is structured as follows: Section 2 presents the operating principles of a PEM electrolyzer; Section 3 describes the equipment and its operation; Section 4 outlines a teaching laboratory activity carried out using the kit and discusses the results obtained; and finally, Section 5 presents the conclusions.

2. Operation of a PEM electrolyzer

A PEM electrolyzer is an electrochemical device capable of converting water into hydrogen and oxygen using distilled water and electrical energy supplied by an external source. Another technology available on the market is the alkaline electrolyzer, whose main drawback is the use of an aqueous solution of sodium or potassium hydroxide as the electrolyte. This electrolyte can lead to premature degradation of the equipment and results in poor dynamic response when coupled with highly variable energy sources. By contrast, PEM electrolyzers require electrodes coated with precious metals (e.g., ruthenium, iridium, and platinum), which constitutes an economic disadvantage. However, this drawback is partially offset by their superior performance under variable operating conditions, making PEM electrolyzers particularly well suited for large-scale green hydrogen production systems.

The operation of a PEM electrolyzer is analogous to that of a PEM fuel cell but in reverse mode. An external power supply drives electrons toward the hydrogen electrode, which therefore acts as the cathode, since the gain of electrons corresponds to a reduction process. Conversely, electrons are extracted from the oxygen electrode, where oxidation occurs, and which thus functions as the anode.

The active component of a PEM electrolyzer is the Membrane Electrode Assembly (MEA), which is constructed from two electrodes coated with catalysts to facilitate the electrochemical reactions, and a polymer membrane placed between them. The function of this membrane is to allow only protons to pass through while preventing electron transport, forcing electrons to flow through the external circuit. The membrane is made of a polymer commercially known as Nafion.

In a PEM electrolyzer, water dissociation into oxygen and protons occurs at the anode. To enable this reaction, catalysts based on ruthenium and iridium (e.g., IrO_2 or $IrRuO_x$) are required. A thin conductive layer (approximately 5–15 μm thick) containing the catalyst is deposited directly onto the Nafion membrane, forming the anode catalytic layer. On top of this layer, a thicker ultraporous carbon paper layer (referred to as the backing layer) is applied. Its function is to conduct electrons and to facilitate gas transport toward the catalytic layer.

Finally, the assembly is completed with a perforated metallic plate, known as the bipolar or end plate, which is electrically conductive and allows the flow of oxygen and water toward the anode. This plate is manufactured from titanium to prevent corrosion caused by the presence of water. The cathode has the same structural configuration; however, in this case the catalytic layer contains only platinum as the catalyst. The total thickness of the anode–membrane–cathode assembly is only about 0.2 mm. Figure 1 shows a schematic diagram of a PEM electrolyzer, in which all its components are clearly identified. Figure 2 shows the commercial PEM electrolyzer used to build the educational kit. The upper section contains the terminals for connecting the anode and cathode to the power supply, along with the gas outlet ports, while the lower section includes the inlet for distilled water.

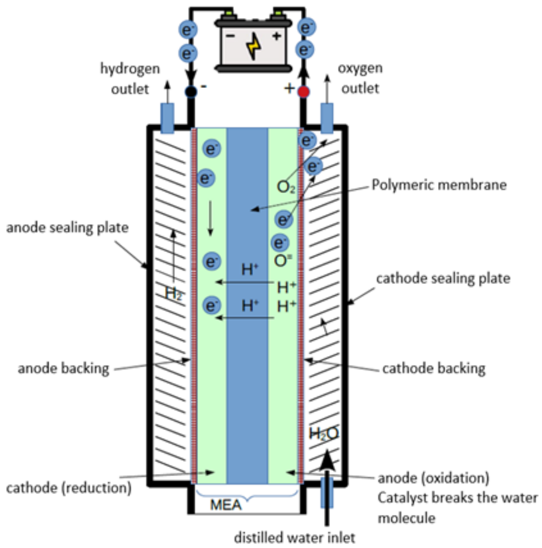

Fig. 1. Schematic diagram of a PEM electrolyzer.

On the oxygen side, a certain amount of water is supplied and brought into contact with the anode catalytic layer. Due to the action of ruthenium and iridium oxide catalysts (IrO_2 or $IrRuOx$), the water molecule dissociates into protons and oxide ions (1).

$$\boldsymbol{H_2O \rightarrow O^{=} + 2H^{+}} \qquad (1)$$

If electrons are extracted from the anode by an external energy source, the oxide ions are converted into atoms and subsequently combine to form O_2 molecules (2).

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^{+} + 2e^{-} \quad (2)$$

Fig. 2. Commercial PEM electrolyzer used in the educational kit.

The two electrons are extracted from the anode through the positive terminal of the power supply, leading to the generation of oxygen gas. Meanwhile, the polymer membrane allows only protons to pass toward the cathode while blocking electron transport; electrons must therefore be supplied through the external circuit via the negative terminal of the energy source.

At the cathode, a reduction reaction takes place: the protons that have crossed the membrane from the anode combine, with the assistance of the catalyst and the electrons provided by the external power supply, to produce hydrogen gas.

$$2H^{+} + 2e^{-} \rightarrow H_2 \quad (3)$$

The process continues as long as water and electrons are supplied to the electrolyzer. The higher the current provided by the external source, the greater the production of gases at both the anode and the cathode, since a larger number of electrons participate in the process, leading to an increased number of redox reactions.

Platinum and iridium oxide catalysts are essential to achieve acceptable reaction rates at both the anode and the cathode. These materials are very expensive but indispensable for the manufacture of this type of device. Proton transport occurs through the electrolyte membrane, whose effectiveness is limited to relatively low operating temperatures (typically below 80 °C), which are characteristic of PEM electrolyzers.

Each mole of water requires two moles of electrons, and since the Faraday constant represents the charge of one mole of electrons (96,485 C), the minimum theoretical voltage required for electrolysis is 1.23 V. At elevated temperatures this voltage decreases, potentially allowing electrical efficiencies above 100% when external waste heat is supplied. In practice, accounting for entropy effects and additional losses, voltages exceeding 1.48 V are generally required. This threshold voltage is known as the thermoneutral voltage.

For water electrolysis, the Gibbs free energy corresponds to the minimum electrical work necessary to drive the reaction, while the entropy term represents the additional energy that must be supplied to maintain the products at the same temperature and energetic state as the reactants. Under these conditions, a reactor operating at 1.48 V is considered to have a theoretical electrical efficiency of 100%.

3. Description of the educational kit

The educational kit, designed and manufactured by the authors, is shown in Figure 3. In the lower section, the PEM electrolyzer (L in the figure) is positioned between two reservoirs intended to collect the generated gases (K and M). These transparent reservoirs are equipped with light-emitting diodes (LEDs) of different colours to facilitate gas identification: red for the oxygen reservoir and blue for the hydrogen reservoir. The hydrogen reservoir collects the gas exiting through the port adjacent to the anode of the electrolyzer, whereas the oxygen reservoir is connected to the cathode side. The distilled water inlet is also located on the cathode side and is connected via a silicone tube to an upper reservoir (C), which is illuminated by a white LED to facilitate reading the volume measurement scales engraved on its surface. Distilled water is supplied continuously to the PEM electrolyzer by gravity. Below the distilled water reservoir, a manual valve (H) is incorporated to control the water flow supplied to the electrolyzer.

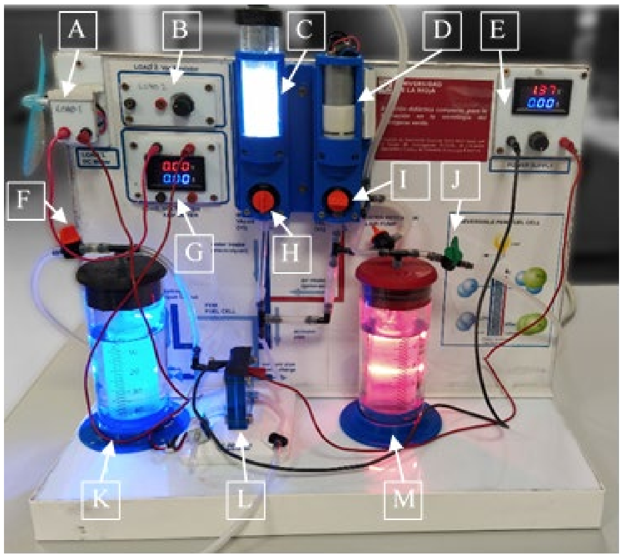

Fig. 3. Appearance of the fully assembled educational kit.

Two additional valves (F and J) are located adjacent to the gas reservoirs to enable the release of the generated gases. Gas collection is achieved using two graduated inverted bell jars submerged in water-filled glass containers, where the gas accumulates by displacing the water downward and remains trapped beneath the bell jars.

A low-pressure air pump (D) is installed to the right of the distilled water reservoir (C) to provide air to the electrolyzer during fuel cell operation. Additionally, two electrical loads (A and B) located in the upper left section dissipate the electrical energy produced by the PEM device in fuel cell mode; however, these elements are not considered in the analysis of electrolyzer operation.

An adjustable power supply (E) regulated by a potentiometer is also located in the upper right section of the kit and includes a display for real-time voltage and current measurements. The voltage and current displays (G) of the power supply are intended for indicative purposes only. Accurate performance of the laboratory experiments requires the use of a higher-precision voltmeter and ammeter, which are not included in the kit.

4. Execution of the laboratory teaching session

This section presents two laboratory experiments that can be carried out with the kit: the determination of the thermoneutral voltage and the electrolyzer operating curve, and the analysis of the stored energy and efficiency of the electrolyzer.
Prior to conducting the laboratory experiments, several preparatory steps must be performed. The upper distilled water supply reservoir, the glass containers of the gas collection reservoirs, and the interior of the PEM device must be filled with distilled water, using a syringe, if necessary, until the cathode is fully covered. After filling, a 5-minute stabilization period is required to ensure adequate hydration of the electrolyzer and to avoid its deterioration.
Before connecting the electrolyzer, the adjustable power supply is configured with a maximum current of 1 A by short-circuiting the terminals and adjusting the current potentiometer. The maximum voltage is then set to 3 V under open-circuit conditions using the voltage control potentiometer, thereby preventing potential damage to the electrolyzer due to excessive current or voltage.

3.1. Determination of the thermoneutral voltage and the electrolyzer operating curve.

This experiment aims to determine the electrolyzer operating curve. The current delivered by the regulated power supply is adjusted for each operating point. The current is initially set to its maximum value (1 A), followed by a two-minute stabilization period to ensure steady-state operation. Subsequently, the current is gradually decreased, and voltage and current measurements are recorded until zero current is reached. The voltage at which the current first becomes nonzero corresponds to the thermoneutral voltage. A large number of voltage and current measurements should be collected, especially in the vicinity of 1.5 V, as these values correspond to the onset of the electrolysis process.
Examination of the operating curve (voltage-current, Fig. 4) reveals that increasing voltage leads to the appearance of a small knee, followed by a linear region known as the ohmic region, where a fraction of the supplied energy is dissipated as heat owing to the resistance of the electrodes and their interfaces with the electrolyte. Based on these results, the polarization curve is modelled by a third-degree polynomial equation is showed in Fig. 4.

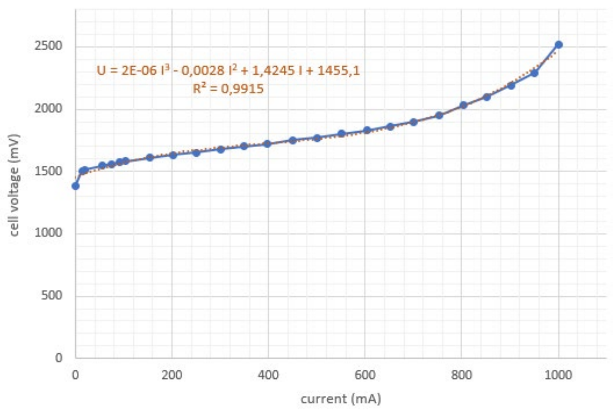

Fig. 4. Voltage-current function for the PEM electrolyser.

In addition to performing the experiment, the student's active role focuses on identifying the thermoneutral voltage point and the ohmic region over the curve.

3.2. Analysis of the stored energy and efficiency of the electrolyzer.

The second experiment is intended to determine the stored energy and the efficiency of the electrolysis process to different operation currents. The procedure begins by releasing the gases accumulated during the previous experiment through the discharge valves of the gas reservoirs. Thus, the volume of hydrogen produced is determined from the graduated scale on the reservoir. The electrolyser is operated at a fixed current of 1000mA, 750 mA, 500 mA and 280mA, consecutively. In each test the time required to produce successive 2 c.c. increments of gas are recorded with a stopwatch until a capacity of 12 cm^3 is reached.

The values of the voltage and current supplied by the power source at those times are also recorded. Using the recorded data, a table is constructed (Table 1).

Table I. – Experimental results.

Vol. H_2 (cc)	Time (s)	V cell (mV)	A cell (mA)	Power (mW)	Δt (s)	Energy (J)
test 1						
0	0	2942	1000	2942		
2	18	2950	1000	2950	18	53,10
4	38	3210	1000	3210	20	64,20
6	58	3310	1000	3310	20	66,20
8	75	3430	1000	3430	17	58,31
10	94	3440	1000	3440	19	65,36
12	112	3450	1000	3450	18	62,10
test 2						
0	0	2732	750	2049		
2	25	2740	750	2055	25	51,38
4	50	2830	750	2122,5	25	53,06
6	72	2880	750	2160	22	47,52
8	100	2940	750	2205	28	61,74
10	124	2960	750	2220	24	53,28
12	148	2970	750	2227,5	24	53,46
test 3						
0	0	2269	500	1134,5		
2	38	2280	500	1140	38	43,32
4	79	2340	500	1170	41	47,97
6	118	2390	500	1195	39	46,61
8	152	2430	500	1215	34	41,31
10	200	2480	500	1240	48	59,52
12	242	2520	500	1260	42	52,92
test 4						
0	0	1780	280	498,4		
2	85	1788	280	500,64	85	42,55
4	187	1794	280	502,32	102	51,24
6	274	1803	280	504,84	87	43,92
8	370	1814	280	507,92	96	48,76
10	499	1830	280	512,4	129	66,10
12	603	1853	280	518,84	104	53,96

This table is supplemented with the electrical power delivered by the source, the time interval between samples, and the electrical energy for each interval. The electrical energy is calculated as the product of the average power over the interval and the interval duration. By using the density of hydrogen at standard conditions (0.0899 $kg \cdot m^{-3}$) and its lower heating value (120.05 $MJ \cdot kg^{-1}$), the stored energy at each time point is determined: First, the mass of stored hydrogen and, then, the energy stored in the form of hydrogen. From the power supplied data and the elapsed time, the graph presented in Figure 5 is constructed. The area enclosed between the curves and the horizontal axis for zero power corresponds to the energy supplied by the power source in the corresponding test.

The ratio between the energy stored in the hydrogen reservoir and the energy supplied by the power source during the reservoir filling process corresponds to the efficiency of the electrolyzer (4),

$$\boldsymbol{\eta} = \frac{\boldsymbol{E_{H_2}}}{\boldsymbol{E_e}} = \frac{\boldsymbol{LHV_{H_2} \cdot \rho_{H_2} \cdot Vol_{H_2}}}{\boldsymbol{\sum_i V_i \cdot I_i \cdot \Delta t_i}} \quad (4)$$

where $\boldsymbol{E_{H_2}}$represents the energy stored as hydrogen, $\boldsymbol{E_e}$ is the electrical energy supplied during the experiment, $\boldsymbol{LHV_{H_2}}$is the lower heating value for hydrogen, $\boldsymbol{\rho_{H_2}}$ is its density, $\boldsymbol{Vol_{H_2}}$ represents its volume (12 cm^3 in this case), $\boldsymbol{V_i}$ is the average value of power source voltage in the interval i, $\boldsymbol{I_i}$ the current in interval i (1000, 750, 500 and 280 mA), and $\Delta \boldsymbol{t_i}$ is the duration of interval i. The number of intervals shown in Table I are six per test; the remaining points represented in Figure 5 are calculated by linear interpolation.

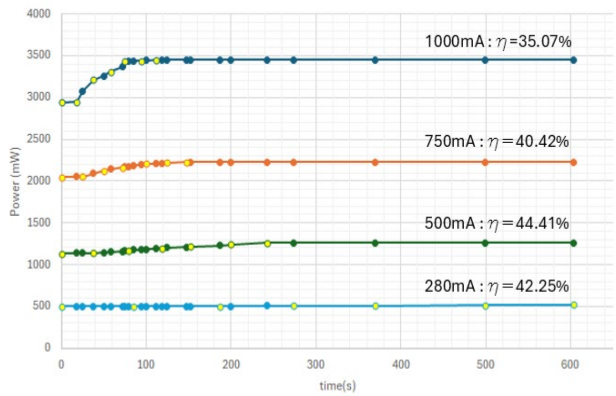

Fig. 5. Time-power curve for the PEM electrolyzer.

In our case, the efficiency obtained in the different tests performed with the educational kit was around 35% (1000mA), 40% (750mA), 44% (500mA) and 42% (280mA).

4. Skills and competencies developed by students

Effective integration of hydrogen technology into university-level educational programs should include laboratory activities designed to develop technical and analytical competencies based on previously acquired conceptual and theoretical knowledge. The two experiments developed using the educational kit and described in Section 4 are designed with this objective. For the proposed experiments to provide meaningful learning value, their execution must promote reflection, conceptual integration, understanding of the results, and critical analysis. These objectives are achieved by providing students, prior to conducting the experiments, with a clear laboratory guide accompanied by a set of tasks to be completed or questions to be answered, all of which are directly related to the experiments performed.

With a focus on the operation of a PEM electrolyzer, the prerequisite theoretical competencies include:

a) Understanding the components that constitute a proton exchange membrane (PEM) electrolyzer.
b) Comprehending its operation based on the electrochemical oxidation and reduction (redox) reactions occurring at the anode and cathode.
c) Identifying the role of noble metal catalysts (platinum, iridium, and ruthenium).
d) Understanding the behaviour and function of the polymer membrane (Nafion) in relation to process efficiency.

The technical and experimental competencies to be promoted include:

e) Developing the ability to operate laboratory instrumentation, such as adjustable power supplies, voltmeters, and ammeters, to monitor process conditions and record electrical parameters.
f) Developing the ability to safely modify process operating conditions in order to obtain results for analysis.
g) Applying critical maintenance and safety protocols for equipment preservation, including:
    - membrane hydration,
    - electrical operating limits,
    - equipment maintenance,
    - order and cleanliness,
    - working environment conditions, and
    - personal protective equipment (PPE).

Finally, the analytical and computational competencies to be encouraged include:

h) Interpreting characteristic parameters of the PEM electrolyzer, such as the thermoneutral voltage, membrane power density (power generated per unit membrane area), electrolyzer efficiency, and characteristic curves such as the polarization curve.
i) Quantifying physicochemical parameters, including:
    - thermoneutral voltage,
    - current density per unit membrane area,
    - mass of hydrogen produced, and
    - electron flow through the electrical circuit.
j) Identifying the ohmic region in which energy is dissipated as heat due to the internal resistances of the system.

The laboratory guide for conducting the experiments must be carefully designed so that students can acquire the aforementioned skills and competencies, and so that their learning progress can be assessed through instructor observation during the experimental work and through the evaluation of student-prepared reports, including the required tasks and well-reasoned responses to the questions posed in the corresponding guide.

5. Conclusions

A low-cost educational device has been developed for conducting experiments related to hydrogen generation as an energy storage system (without precluding its use in other applications). The device integrates all the components required for characterizing the operation of a PEM electrolyzer, testing its performance, and determining its efficiency. It has designed to enable undergraduate students enrolled in an elective course on the integration of renewable energy sources into the power systems to acquire a set of skills and competencies related to hydrogen production from renewable energy–based sources and its subsequent storage.

The device has been tested by the eleven students enrolled in the course during the previous academic year, and a higher level of student satisfaction compared to previous years was observed, as reflected in the teaching evaluation surveys conducted by the university.

The design of the device remains open, with the aim of developing a more comprehensive system that would allow, among other possible experiments, analysis of electrolyzer operation under different temperature conditions; operation powered by electricity directly supplied from a renewable source (e.g., a photovoltaic system); alternative storage configurations (including storage at pressures above atmospheric); automation of data acquisition and the generation of measurement tables; and an increase in storage capacity and hydrogen production rate. These improvements are planned to be developed in the coming years.

Acknowledgement

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