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LOW-COST ELECTROLYZER FOR EDUCATION IN RENEWABLE ENERGY

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Abstract. *This study aims to demonstrate the impact of basic water electrolysis knowledge using a low-cost electrolyzer and accessible materials. Challenges like high equipment costs and time constraints for teachers hinder practical renewable energy experiments in classrooms, crucial for student learning. With a CAD-designed prototype, an electrolyzer was constructed for around US$150. Active learning evaluated results of a practical experiment with engineering undergraduates, showcasing the low-cost electrolyzer's function and hydrogen production effects using different electrolytic solutions. 1 M concentration NaOH and KOH were used for testing, 39 g.L^{-1} and 64 g/L, respectively. Voltage of 12 V and current of 60 A yielded 0.025 Nm^3.h^{-1} hydrogen flow for both solutions. Temperature sensor data showed electrode temperature increase with current. KOH reached 55°C, NaOH 45°C. Higher temperature correlated with increased hydrogen production. Half of surveyed students lacked electrolysis knowledge; post-lesson, 96% stated the experiment improved understanding. Pre- and post-test averages showed 80% more correct answers regarding electrolysis among those unfamiliar. The experiment highlighted how classroom practical activities positively influence electrolysis comprehension and raise awareness about renewable energy processes.*

Keywords: *Renewable Energy Education, Hydrogen Production, Renewable Energy, electrolyzer.*

1. INTRODUCTION

Hands-on activities play a fundamental role in students' learning, enabling the development of skills such as problem solving, knowledge retention, and persistence. Despite the benefits, the implementation of practical experiments faces obstacles (Ecker, 2018) (Johnson et al., 2019).

The way a subject is presented by teachers in the classroom has remained virtually unchanged since the foundation of the first university in Europe over 900 years ago. While the theoretical part is emphasized for students to build their understanding, approximately 40% of students lack interest in fields such as mathematics, engineering, science, and technology due to the lack of hands-on activities during their coursework (Ecker, 2018).

Given the global climate changes caused by excessive CO_2 emissions, it becomes necessary to establish new ways of producing renewable energy. Therefore, attracting students through practical experiments early in their engineering careers can contribute to the advancement of clean energy development worldwide (Le Anh et al., 2013) (De Fátima Palhares et al., 2018).

The action learning methodology is defined as any alternative form of student engagement during the learning process. This methodology differs from the traditional mode of teaching, where the student is merely a listener. In practice, action learning also incorporates traditional methods but introduces practical tasks in the classroom with the aim of enhancing students' knowledge (Johnson et al., 2019).

Furthermore, cooperative work during experiments is encouraged, and the Advanced Product Quality Planning methodology is recommended to improve communication and student participation, ensuring the project steps are carried out according to the schedule. The author explains that they used this technique to develop an electrolyzer, minimizing faults and production time of the product (Mittal et al., 2012).

According to Göllei et al. (2014), the electrolyzer is the equipment responsible for carrying out the electrochemical process of electrolysis. This non-spontaneous reaction involves the passage of a direct current (DC) through a system using an electrolytic solution containing NaOH and KOH ions, thus generating the chemical reaction and gas production. The electrolytic solution is essential for achieving efficient hydrogen production.

According to Russel (1994), hydrogen production can come from various sources, whether renewable or not. Water electrolysis is the process by which hydrogen can be obtained from water and electricity. Hydrogen production through electrolysis is economically interesting and relatively simple, as it utilizes water as a raw material. Currently, hydrogen production through water electrolysis is still a rarely used process, representing only 4% of the global energy matrix, with the majority of hydrogen being produced through thermochemical processes using natural gas (Dos Santos *et al.*, 2017).

The hydrogen production from photovoltaic and wind systems can be the solution for clean energy production, utilizing solar panels and a series circuit electrolyzer to produce hydrogen gas with a purity of 99.99%. The use of hydrogen as a clean energy carrier has been widely proposed for future generations, considering the scarcity of fossil fuels and the emission of polluting gasses are among the greatest problems humanity currently faces. In order to bring about a change in current consumption patterns of society, it is necessary to promote investment in educational techniques for renewable energy production in the classroom (Aydin; Kenanoğlu, 2018).

The objective of this study is to demonstrate the construction of a low-cost water electrolyzer with a parallel circuit and the impact of using the prototype in educational experiments related to renewable energy research.

2. MATERIALS

The electrolyzer model used was the wet cell, where the electrodes remain immersed in water, and the prototype was composed of two reservoirs: (1) for hydrogen and oxygen gas production and (2) for filtering the water vapor produced during electrolysis. The gas reservoir, with a capacity to store up to 5 liters of water, was divided into two equal parts, with the gases produced directed to the filtering reservoir as can be demonstrated in Figure 1.

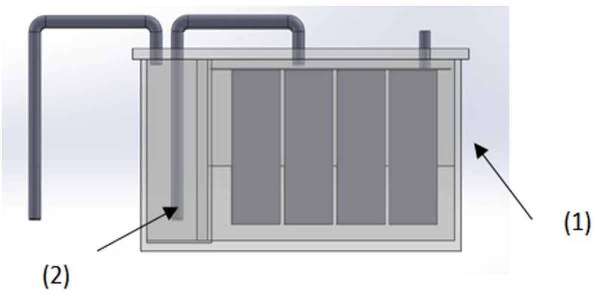

Figure 1. Wet cell electrolyser.

2.1 Construction Materials

The electrolyzer was constructed using acrylic plates according to the measurements specified in Table 1. The electrode arrangement for this selected electrolyzer was parallel. The electrodes (anode and cathode) were made of 316 L stainless steel and bent into an L shape with dimensions of 17 cm x 6 cm x 0.1 cm. Type 316 L stainless steel was chosen due to its low carbon content, making it more resistant to oxidation generated by the electrochemical reaction.

Table 1. Identification of acrylic plates used in the electrolyzer.

Plates	Area	Thickness	Units
A	31.6 cm x 18 cm	8 mm	2
B	18 cm x 12 cm	8 mm	2
C	30 cm x 12 cm	8 mm	1
D	17.2 cm x 12 cm	8 mm	1
E	17.2 cm x 4.8 cm	8 mm	1
F	23.2 cm x 4 cm	8 mm	1
G	35 cm x 17 cm	8 mm	1
H	3.5 cm x 1.5 cm	8 mm	6

The electrolyzer model was developed exclusively for bench testing in practical laboratory experiments. The electrolyzer can also be powered using a hydrogen production system from solar energy. The prototype was based on Michael Faraday's concept, where water electrolysis is performed through an electrochemical reaction.

2.2 External Materials

A 12/1s 12 DC 125/220 AC Hayonik transformer and a KBPC-2510 25A/1000V voltage rectifier bridge were used during the volumetric flow rate tests of the water electrolyzer as can be seen in Figure 2. In addition to the transformer, as flow meters (HHO), temperature sensors, and a digital multimeter were used to collect the data presented in the results. To compare the efficiency of the electrolyzer, different electrolyte solutions with KOH and NaOH salts were used at molar concentrations of 64 $g.L^{-1}$ and 39 $g.L^{-1}$, respectively.

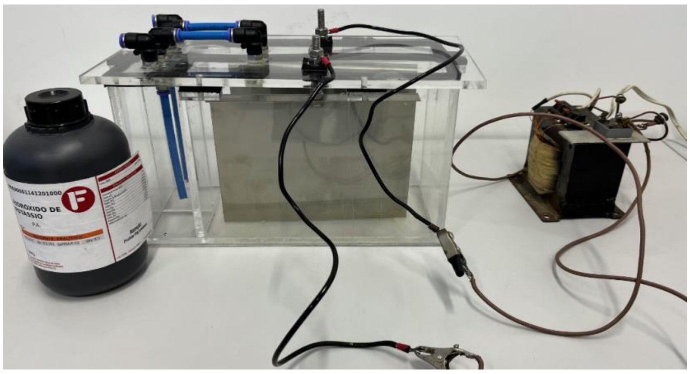

Figure 2. Electrolyzer and AC/DC transformer.

3. METHODS

In the construction of the electrolyzer, Eq. (1) from thermodynamic mathematical modeling and Eq. (2) from electrochemical modeling were used. These methodologies are essential for the functioning of the prototype, respecting the laws of alkaline electrolysis. After the construction of the low-cost educational prototype, the action learning methodology was employed to analyze the impact of the practical experiment on the understanding of undergraduate engineering students regarding renewable energies and hydrogen production by electrolysis.

3.1 Thermodynamic Model

According to Ulleberg (2003), to separate water molecules, a minimum amount of electrical energy is required to drive the electrolysis reaction. Under standard conditions, when the reaction starts and the transformation of liquid water into H_2 gas and ½ O_2 gas takes place, the Gibbs free energy for standard conditions becomes positive with a value of ΔG° + 237 $kJ \cdot mol^{-1}$. As a result, the electrical work required for the reaction to occur can be determined using Eq. (1).

$$\tau_{ele} = \frac{\Delta G°}{N_e.F}, \qquad (1)$$

where τ_{ele} is the electrical work under standard conditions [V], ΔG° is the Gibbs free energy under standard conditions [$kJ \cdot mol^{-1}$], N_e is the number of electrons consumed to produce the reaction [-], and F the Faraday's constant [96,485.332 $C \cdot mol^{-1}$].

3.2 Electrochemical Model

According to Spiegel (2008) there is a direct relationship between electrochemistry and thermodynamics. The operation of a hydrogen generator is based on the application of electric charge to the system. The Nernst equation allows calculating the value of the reversible electrical potential given a specific pressure and temperature level. The calculation of the standard electrical potential of the generator was performed, using Eq. (2).

$$E_{generator} = E^{\circ}_{generator} - \frac{R.T.lnQ}{N_e.F}, \qquad (2)$$

where $E^{\circ}_{generator}$ is the standard electrical potential of the generator [V], $E^{\circ}_{generator}$ is the standard potential of the generator [V], N_e the number of electrons consumed to produce the reaction [-], F is the Faraday's constant [96,485.332

C·mol^{-1}], R is the Universal gas constant [8.314 J]; T is the temperature [K], and lnQ is the Natural logarithm of the reaction coefficient [-].

According to Russel (1994) it is possible to calculate the mass of hydrogen by applying Eq. (3). To calculate the number of Faradays passing through the electrolyzer, it is necessary to determine the current applied to the electrodes within a certain time range.

$$m = F \cdot \frac{MA_{rel}}{F_{H2}}, \quad (3)$$

where m is the mass [g], F is the number of Faradays passing through the electrolyzer [C], MA_{rel} is the relative atomic mass of the element [mol], F_{H2} is the number of Faradays for the production of H_2 molecules or ½ O_2 [C].

3.3 Action Learning Methodology

The action learning methodology is characterized as an approach that actively involves students during the learning process. In practice, it combines traditional methods with the introduction of practical tasks in the classroom, aiming to enhance students' knowledge (Jara et al., 2011).

To investigate the effects of action learning in the educational process of engineering students, a practical experiment involving alkaline electrolysis was conducted. Some students from the Institute of Bioenergy Research (IPBEN-UNESP), Laboratory Associated of Guaratinguetá, underwent two tests on renewable energies in the IPBEN laboratory. A theoretical knowledge test was conducted, covering topics such as hydrogen characteristics and the use of salts in the electrolyte solution. After the completion of the practical activities, a new test on the basic concepts of electrolysis was also administered.

During the experiment, students had the opportunity to perform stoichiometric calculations, vary voltage and current, observe the effects in the electrolysis reaction, calculate the flow of hydrogen and oxygen, and measure the electrolyte temperature. The results obtained from the evaluations clearly demonstrated the positive impact of action learning on student learning. This innovative approach provided a practical experience that reinforced learning by establishing a direct connection between theory and practice, highlighting its potential in the field of engineering.

4. RESULTS AND DISCUSSION

From practical experiments using Eq. (3), it was possible to calculate the performance of the constructed electrolyzer. Among the salts used in electrolyte solutions, KOH achieves a hydrogen flow rate of 0.025 $Nm^3.h^{-1}$, as it is shown in Figure 3.

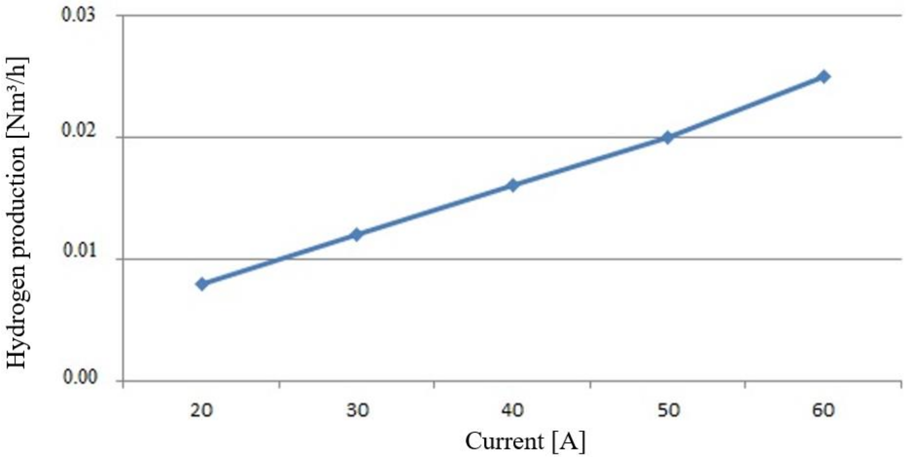

Figure 3. Hydrogen Gas Flow with electrolyte solution of KOH and NaOH.

According to Göllei et al. (2014) and Chi Yu et al. (2018) the volumetric flow rate is directly proportional to the electric current. Therefore, when there is a variation in voltage and current at the transformer output, there is also a variation in the production of hydrogen and oxygen, which was also observed in the prototype tests.

The maximum temperature reached by the NaOH electrolyte solution was 26°C during the experimental period, while the KOH solution reached 39°C, resulting in a 13°C variation between the electrolyte solutions. It was observed that an increase in current in the electrolyzer had a direct impact on the reaction temperature. Figure 3 shows that the production of hydrogen and oxygen was higher for the KOH solution, so as the current and voltage of the electrolyzer increase, the temperature also changes.

4.1 Experimental Analysis of Student Learning

In order to evaluate the performance of students during practical experiments, two knowledge exams on electrolysis were conducted. During the test grading process, a score was assigned for each question answered correctly, with a maximum score of 100 points. The initial exam consisted of seven questions with fundamental concepts of electrolysis.

The second exam included seven specific questions about electrolysis related to the practical experience. The first questions in both Exam 1 and Exam 2 were those that had the greatest impact on the assessment of learning, and the results are presented in the Figure 4 below.

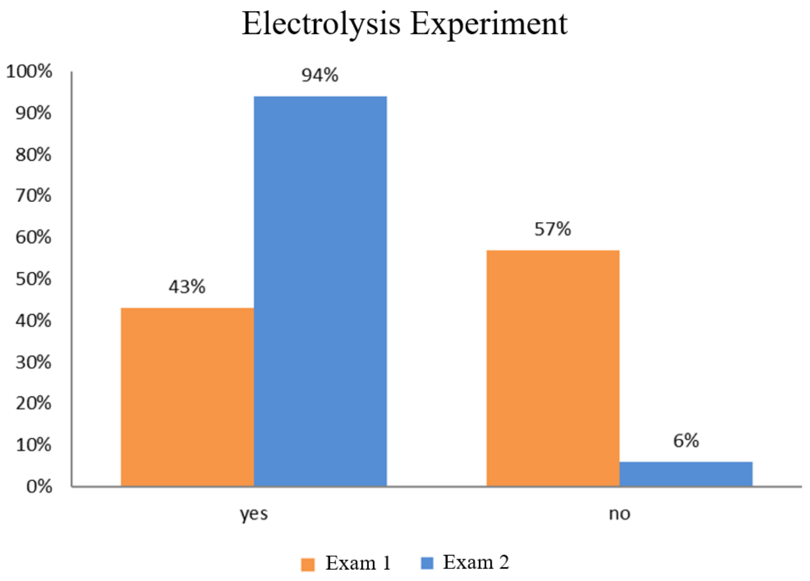

Figure 4. Exam results during the practical experiment.

In the first Exam, undergraduate engineering students were asked about their knowledge regarding water electrolysis. In this initial exam, 43% of the respondents stated that they were already familiar with the basic concepts of electrolysis. In the second test, the first question was about how much the practical experience had influenced the students' understanding of the basic concepts of electrolysis. For this second test, only 6% of the respondents answered that the practical experiences did not directly influence their understanding of the subject.

To validate that the students understood the concepts of the practical experiment, it was necessary for them to provide a written response to the last question of the second test. In the last question, they had to write everything they understood from the practical experiment, justifying it with the theoretical concepts presented during the class. Of all the interviewed students, 94% answered the last question correctly. The test scores of each student were recorded, as shown in Figure 5.

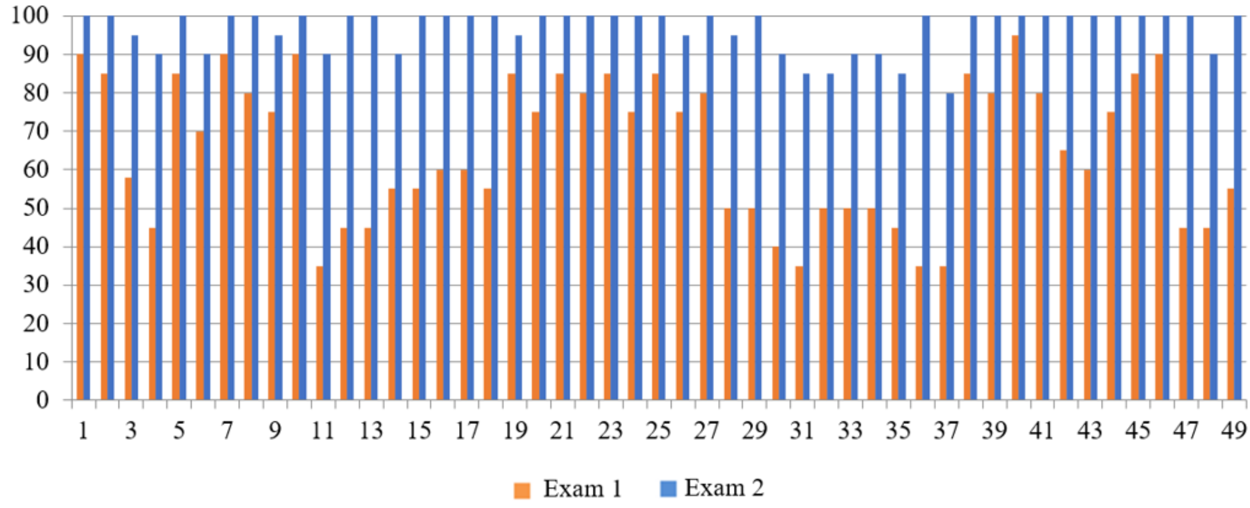

Figure 5. Scores of all students in the first and second tests.

By analyzing the scores of the two tests conducted during the practical experiment, it was possible to evaluate the performance of the students. Firstly, the students' scores were divided into three zones: Zone 1 (0 - 45pts), Zone 2 (45 - 80pts), and Zone 3 (80 - 100pts), as shown in Figure 6.

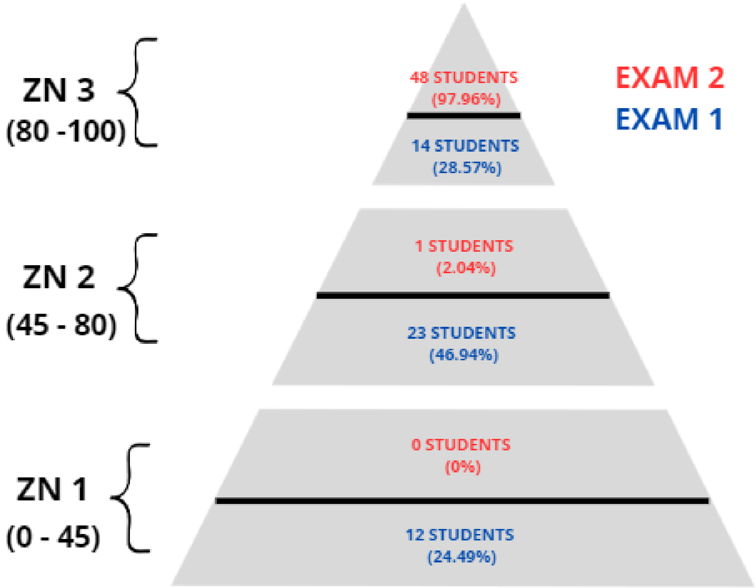

Figure 6. Test results during the practical experiment.

When comparing the distributions of the zones between the tests, there is an observed trend of improvement in the students' scores. The proportion of students in Zone 1 decreased significantly from 24.49% to 0%, while the proportion in Zone 3 increased considerably from 28.57% to 97.96%.

With the results obtained from these experiments, it became evident that the practical experiment had a positive impact on the students' knowledge, as well as promoting greater interaction between the teacher and the class after the conclusion of the experiment.

5. **CONCLUSION**

Based on the results of this study, it can be concluded that conducting a practical experiment on water electrolysis had a positive impact on students' learning performance. The construction of an electrolyzer using simple and low-cost materials was essential to enhance students' understanding during the experiment.

The results of the electrolyzer efficiency showed that variations in the electrolytic solution and current had a significant influence on the production of hydrogen and oxygen. Among the salts used in electrolytic solutions, KOH resulted in the highest gas production, reaching 0.025 $Nm^3.h^{-1}$. This difference in gas production is related to the superior electrical conductivity of one salt compared to the others. As discussed in the results, the maximum electrode temperature for the KOH solution was 39.8°C due to the higher gas flow produced during the experiments.

Regarding the results of the tests applied to undergraduate students, some important points were observed. There was a significant increase in the proportion of students who achieved higher grades, as represented by the migration from Zone 2 to Zone 3 in the second test. The absence of students in Zone 1 in the second test suggests that the practical experiment allowed for a better understanding and application of the theoretical concepts covered.

These results highlight the importance of including practical activities in postgraduate courses as they seem to contribute to improving students' performance. Future studies can explore other pedagogical interventions and analyze their effects on learning and performance in specific subjects.

6. ACKNOWLEDGEMENTS

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