

USING A REMOTE LAB FOR ELECTROLYSIS EXPERIMENT AS PART OF RENEWABLE ENERGY COURSES

SANDA VOINEA^{1,*}, ADRIANA BALAN¹, R. MORGAN GREENE², LAURENTIU L. ANTON²,
RADU TIRCA¹, DANIEL COSTACHE¹, VICTOR T. DUMITRU³

¹ University of Bucharest, Faculty of Physics, 405 Atomistilor Street, 077125, Magurele, Romania

² Reykjavik University, Iceland School of Energy, Menntavegur 1, 102, 101 Reykjavík, Iceland

³ University of Bucharest, Faculty of Mathematics and Computer Science, 14 Academiei Street, 010014, Bucharest, Romania

* Corresponding author: sanda.voinea@unibuc.ro

Abstract. According to the European Renewable Energy Directive, by 2030, renewable energy must account for 32% of energy production. This goal requires specialists with interdisciplinary training in the field of renewable energy sources, who can integrate the concepts of sustainability and the zero carbon world into new technological solutions and develop new green energy policies. In this context, comprehensive, detailed and innovative training for green energy specialists is needed. This paper presents a modern remote lab tool as an open educational resource for training graduate students in renewable energy. The remote operated laboratory allows the establishment of working conditions and the download of data recorded following measurements made by users, through the website. The configuration of the laboratory transforms the water electrolysis experiment into a tool for further exploration of physical principles and the laws that govern them. Using remote connectivity, this experiment can be integrated in common study platforms for renewables.

Key words: electrolysis, hydrogen, remote laboratory, renewable energy.

1. INTRODUCTION

According to the Renewable Energy Directive 2018/2001/EU, renewable energy must account for 32% of energy production by 2030 [1]. In 2021, the European Commission adopted a set of proposals to reduce net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels, with goals for Europe to be the first climate-neutral continent by 2050 [2]. These new binding targets will have an impact on sectors such as energy, transport, construction, and will help create sustainable and skilled jobs across Europe. Additionally, the targets promote the adoption of renewable fuels, such as hydrogen in industry and transport. Achieving these targets will require the training of specialists with interdisciplinary instruction in the field of renewable energy sources who can integrate the concepts of sustainability and zero carbon world in new technological solutions and

facilitate the development of new green energy policies. The teaching of specialists requires the development of a sustainable education in this field, based on modern teaching methods and the exchange of good practices with institutions that have extensive experience [3].

The study of renewable energy is rather new, complex and inter-disciplinary with roots in physics, chemistry, economics and engineering. There is an increasing demand of renewable energy specialists that have a comprehensive understanding of renewable energy, as well as transversal skills that can help them easily adaptable to a fast-changing international environment.

Several studies have shown that specialized education on understanding the production and use of renewable energy in university and high school is needed to raise citizens' awareness of sustainability and environment issues [4-7]. In order for students to be able to obtain practical lectures on these aspects and to start innovating in this field, a modern curriculum and updated teaching methods are needed. In this way, education can lead to sustainable environmental development, which will be catalyzed by renewable energy solutions. Communications in the field of education reveal that modern teaching combines classical methods of information exposure with interdisciplinary approaches to experiments, modeling and simulations. [8-13].

This study disseminates the common experience gained by two European universities, the University of Bucharest and Reykjavik University, within a collaborative project for the development of a common educational platform for the master of renewable energies [14]. The development of a common philosophy on energy sustainability based on the exchange of students, professors and good practices between the two universities contributes to finding solutions for a zero carbon world. During this project, the emergence of the SARS-COV2 pandemic complicated the planned mobilities of students and professors between the universities. The collaboration partners had to develop new methods for disseminating knowledge, lessons and experiments originally planned in the initial project. An eMobility online course was built to provide the necessary educational materials in renewable energy using the respective Learning Management Systems of the two universities (Canvas and Moodle). Here, recorded lectures, readings and other educational material were distributed. Additionally, we designed remote laboratories to emphasize the possibility of hands-on learning during a period when in-person learning and mobilities were restricted. We developed a remote laboratory for producing hydrogen by electrolysis and understanding the principles of electrochemical cells that is presented in later sections of this paper. The paper also highlights the potential impact that an experimental means of learning has on students belonging to two different education systems and cultures. In addition, the experience of building and use of remote laboratories raises the level of education

in times of lockdown, related pandemic related restrictions and facilitates the continuation of the educational process. This experience will be an important lesson in the development of more advanced tools. These tools ultimately could allow a wider and more diverse audience to participate in learning about renewable energy technologies long after the pandemic has ended.

2. REMOTE LABORATORY

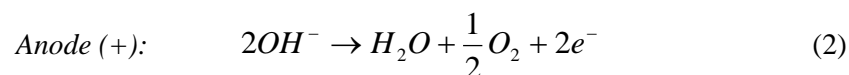
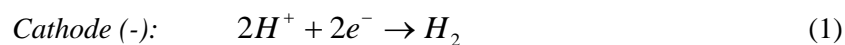
The aim of this remotely controlled experiment is to understand the phenomenon of electrolysis. The laboratory also highlights the role of electrolytic solutions in this process and the use of the reference electrode in electrochemical measurements.

2.1. THEORETICAL CONSIDERATIONS

The electrolysis process takes place when two electrodes are introduced in an electrolyte solution and connected to a current source. In the presence of an electric field, the migration of positive and negative ions to the electrodes takes place. At the cathode (-) the cations (positive ions) add electrons and reduce, while at the anode (+), the anions (negative ions) give up electrons and oxidize.

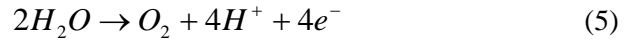
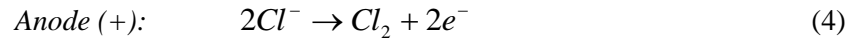
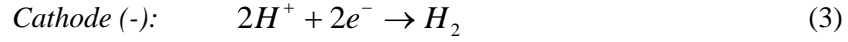
In the electrolysis process, the ions transported to the electrodes can be deposited on them or they can also react to form gas, liquid or solid, respectively by-products of electrolysis. The formation of these products depends on the nature and concentration of the electrolyte [15].

Electrolysis of water is the most common method to produce green hydrogen by splitting the molecule of water. When electrodes are connected to a current source, electrons move to the cathode where they combine with protons and form the hydrogen molecule as shown in equation (1). The hydroxide ions are transferred through the electrolyte solution to the anode, where electrons are released, according to equation (2) and these electrons return to the positive terminal of the current source [16].



In order to enhance the conductivity of the solution, electrolytes which generally consist of ions with high mobility are applied in the electrolyser [17]. In the alkaline electrolysis of water, the aqueous solution (KOH/NaOH) of about 20%-30% concentration, as the electrolyte are used. When NaCl solution is used, such as in our remote laboratory, the electrolyte Na^+ ions and water molecules can

be reduced at the cathode, while Cl^- ions and water molecules can be oxidized at the anode [18]. The equation (3) describes the cathode process while equations (4) and (5) depict the anode processes. At the cathode, only H_2 is formed because H^+ is less stable than Na^+ and H^+ is selectively discharged. Depends on the concentration of NaCl in solution, at anode the product formed is Cl_2 for high concentration and O_2 for the lower one.



In electrochemical measurements that have special applications in renewable energies, bioelectrochemistry, environmental protection, biomedicine, electrodes occupy the one of the most important places. For these applications, it is important to know the potential of each electrode, which, in practice, is very difficult. For this purpose, three electrodes are used: the electrode whose potential we want to determine, called the working electrode (WE), the auxiliary electrode that allows current to flow, the counter electrode (CE) and the reference electrode (RE), against which the potential is measured to WE [19].

2.2. SYSTEM ARCHITECTURE

The experiment is centered around a Raspberry Pi single-board computer, which governs all other elements of the setup and acts as a server. The robotic arm SCARA (Selective Compliance Articulated Robot Arm) is connected to an Arduino UNO microcontroller that controls the motion of the stepper motors. An Arduino board was programmed using PlatformIO [20], where the algorithm operating the stepper motors was written. The communication with the Arduino is ensured by a script implemented in Python version 3.8.7, which processes the user's commands, computes certain parameters and sends them to the board. The electrolysis setup is managed using an Arduino and GPIO interface. A voltmeter is built with Arduino hardware that reads the electrical tension on the reference electrode by utilizing a voltage divider. This allowed measuring the higher voltages of the experiment. A programmable power supply (Aim-TTi PL601-P) is connected directly to the Raspberry Pi via USB, its operating parameters being changed via a script that communicates with it. The electromagnetic valves are operated through the GPIO of the Raspberry Pi board, allowing them to open when electric current is applied (Fig. 1).

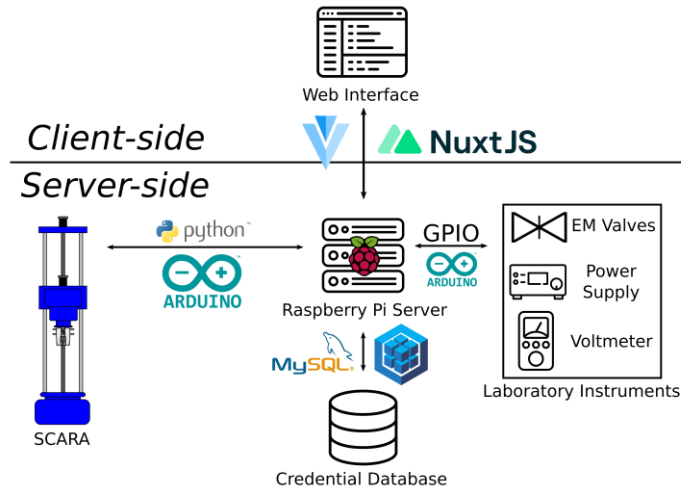


Fig. 1 – Architecture of the remote laboratory. The full color version can be accessed at <http://www.rrp.nipne.ro>.

The connection between the user and the experiment is aided by a web interface, hosted on the Raspberry Pi. In order to ensure proper data transfer between the client and the server, the following have been implemented:

1. Frontend: The interface has a menu that allows the user to log in using the credentials created upon registration. There is a page that contains instructions for operating the experiment and a page with the control dashboard of the experiment. There, the user can set the parameters of the experiment. Also, a live video feed of the experiment is produced. The frontend was developed using Nuxt.js and Vuetify. The login system is based on cookies and JSON web token.

2. Backend: The credentials of the users are stored on a database which uses MySQL and Sequelize ORM. The data is encrypted using SHA256 and RSA protocols. The access token is obtainable from the website. There are two UNIX pipes, linking the server and a Python process that communicates with the Raspberry Pi. Three endpoints for the experiment were implemented: (a) Start: receive the data and send via pipe a message towards Python, in order to start the experimental routine. (b) Status: a loop is started on the frontend that requests the status of the experiment via one pipe and receives the result via the other pipe. (c) Stop: a stop message is sent via pipe.

3. Python: The Python infrastructure ensures the communication with the Raspberry Pi via GPIO, and with the Node server via pipes. It handles the start-stop messages received from the server. It preprocesses the information so that the Arduino can understand and execute the commands (i.e., it transforms the commands into bit streams that are UTF-8 encoded).

4. Arduino: Two Arduino boards are used in this setup: (a) one of the boards controls the SCARA. The algorithm on the SCARA processes the bit stream received from Python and, by means of a CNC Shield V3, can communicate with the motors and send signals so that the robot can be put into motion. (b) The second board is used to measure the electrical tension on the reference electrode, by using a voltage divider.

2.3. DESIGN AND BUILDING PROCESSES

The original design of the robotic arm was created by How to Mechatronics [21]. The STL files were made available open-source via their website. The design of the actual built robot was based on said files and customized in order to suit the needs of the laboratory. The 3D models were processed using the software FreeCAD version 0.16 [22] and TinkerCAD [23], available online. The plastic parts that needed to be printed were sliced using Ultimaker Cura version 4.11 [24] and sent to two printers, a Creality Ender 3 Pro and a Tevo Tarantula Pro. The final design consists of: the frame of the robot, which was 3D printed; a base joint, rotated by a stepper motor; four support rods, supporting the arm; a lead screw, which enables movement along the vertical axis via a stepper motor; an arm, which has an elbow joint, rotated by a stepper motor; the operating end, which can hold different tools (Fig. 2). Due to the flexibility of the SCARA, it can be utilized in different practical scenarios by fitting different tools on the operating end, such as a gripper end, allowing it to grab and move objects, a laser tool, for cutting or engraving or a 3D printer hot end, making it possible to print other models.

The rest of the experimental setup is composed of two containers holding saturated electrolyte solution and distilled water, respectively, two graphite (working, counter) electrodes connected to a programmable power supply, a reference electrode (Ag – AgCl) connected to a voltmeter and electromagnetic valves, used to fill up and empty the main beaker (Fig. 3).

2.4. WEB INTERFACE

To perform the experiment, the operators first need to access the website hosting the platform. For that, they will need to register and log in, being granted control over the experimental setup. Upon logging in, the user is greeted by an informative page, explaining the effect of changing each parameter. The second page available is the control dashboard for the experiment. The parameters that can be set are (as shown in Fig. 4):

- concentration: sets the concentration by mass of the mixture of electrolyte and distilled water (the electrolyte is 25% NaCl by mass);

- time: sets the duration over which the experiment will take place;
- voltage: sets the electric tension applied between the working and the counter electrode;
- update interval: sets the time interval that passes between measurements.

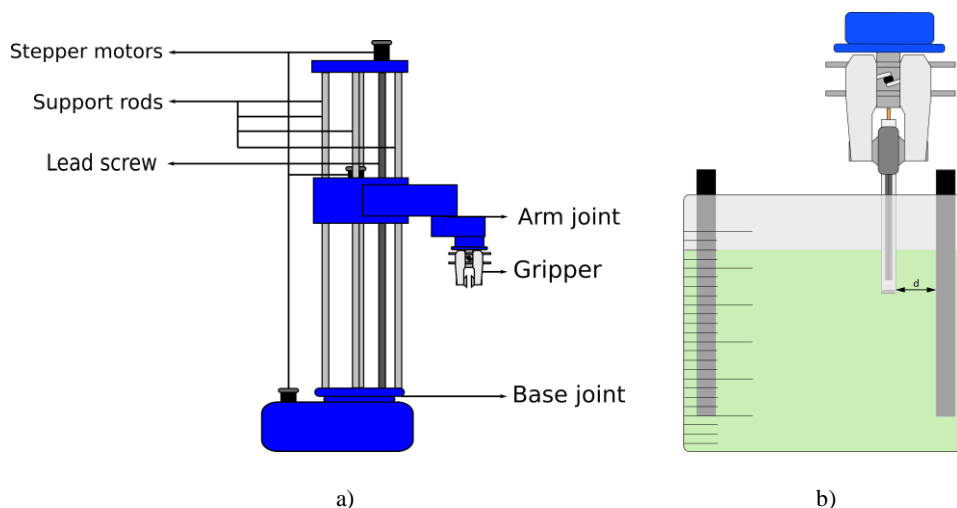


Fig. 2 – The robotic arm SCARA: a) components, b) SCARA used to move the reference electrode in electrolysis experiment. The full color version can be accessed at <http://www.rrp.nipne.ro>.

Two buttons are available, a **START** (starts experiment) and **STOP** (force stops the experiment). When **START** is pressed, the power supply begins applying tension. Through the video feed granted by the camera fitted on the setup, the user can see the water splitting and the hydrogen and oxygen bubbles forming around the anode and the cathode. The voltmeter measures the tension between the reference and the working electrode and makes it available to the server. While the experiment is running, the interface shows a table of values, appending data after each measurement. The parameters in the table are the time step, the input voltage and intensity of current and the output voltage. After the experiment is finished, the user can download the data in CSV format from the website.

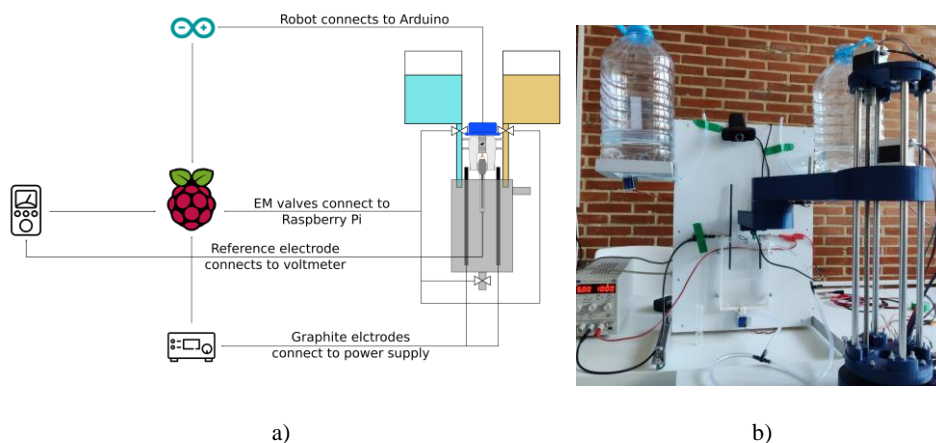


Fig. 3 – Experimental setup of the remote laboratory: a) scheme, b) functional lab. The full color version can be accessed at <http://www.rrp.nipne.ro>.

Welcome	Remote lab
Remote lab	Concentration (%) 50
	Time (seconds) 5
	Voltage (Volts) 8
	Update interval (seconds) 1

Fig. 4 – Web interface related to experimental set-up. The full color version can be accessed at <http://www.rrp.nipne.ro>.

3. RESULTS AND DISCUSSION

3.1. EXPERIMENTAL PROCEDURE

The remotely operated laboratory allows the setting of working conditions regarding the establishment of the electrolyte solution concentration, the applied

voltage, the distance between the working electrode and the reference one, the time interval of the measurements, respectively the time between two recordings. The quantities automatically registered by the system are the potential difference between the working electrode and the reference one, respectively the intensity of the electric current.

To establish a certain concentration of the electrolyte solution (NaCl solution), the valves from the two containers containing distilled water and the saturated salt solution are opened and are poured into the beaker from the respective containers.

The voltage is gradually varied until it can observe the split of the water and then it is varied by the user up to a maximum of 12V. The observation of the bubbles inside the beaker is done with the help of video cameras mounted around the assembly.

3.2. LEARNING OUTCOMES

The users download the data recorded after measurements in the remote laboratory and process them by calculating the concentrations of the used electrolyte solution and the average values of the voltage between WE and RE. Based on this data, graphs are constructed to establish the dependence of the working-electrode potentials with respect to reference electrode (U_2) at various applied voltages (U_1). Also, the students can analyze the influence of the electrolyte concentration on working electrode potentials with the reference electrode (Fig. 5). Using this remote laboratory, students are able to draw some conclusions about the influence of the electrolyte in the electrolysis process. They can establish a mathematical relationship between U_2 and U_1 to evaluate the overpotential of the experimental system. From the equation obtained by linear fit (Fig. 5d), one can calculate the working electrode potentials related to the reference electrodes using the theoretical electrolysis voltage (1.12V) and compare with the experimental values obtained for the input voltages set by them (e.g. 5V). The difference between these values (e.g. 0.53V) is the overpotential (which includes an electrochemical reaction overpotential, an electrolyte overpotential, and a diffusion overpotential). Students will evaluate the resistances correlated with these processes in the case of input current values set during the experiment [25].

3.3. SURVEY OF STUDENTS' EXPERIENCE

Based on the analysis of the questionnaires completed by the students of the two universities about the experience of using the laboratory, we found some

interesting features of the experience related to a remote experiment compared to a hands-on one.

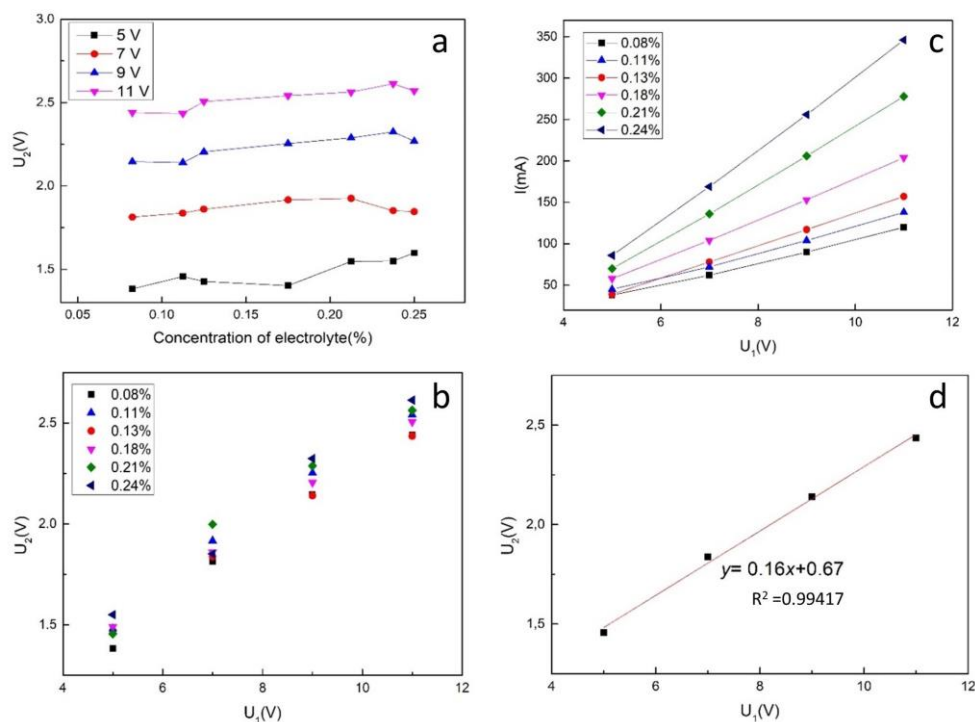


Fig. 5 – Dependence of working-electrode potentials with respect to reference electrodes: a - at various concentration of NaCl solution; b - at various applied voltages; c - characterization curve of electrolyzer for different concentrations of electrolyte solution; d - linear fit of working-electrode potentials with respect to reference electrodes at various applied voltages for 0.1% NaCl solution. The full color version can be accessed at <http://www.rrp.nipne.ro>.

The remote experiment is a useful experience because it opens up control and interaction with labs to more people in multiple locations. Also, under the conditions of travel restrictions, lockdown or reducing international travel due to GHG emissions, it is an important tool to conduct experiments to understand principles and laws, to deduce physical equations and to correlate them with the theoretical content of the courses.

The remote lab provides students with a comprehensive understanding of robotics and programming in order to develop applications for other experiments they could perform. However, several students considered that manual laboratories could not be completely replaced, as they provide a better understanding of the experiment itself due to the possibility of varying parameters and working conditions over a wider range, depending on knowledge and need.

4. CONCLUSIONS

Following the implementation of e-learning and distance laboratory methods combined with practical applications and hands-on laboratories, the students of the master of renewable energy, involved in the project have developed their knowledge about various types of renewable energy (geothermal and electrochemical). They have also improved their understanding of renewable energy production and sustainability.

The survey conducted among students from the two universities on the use of laboratory remote as a means of experimentation showed that they appreciated the experience in terms of being able to use the experimental setup in their own home and had more time to understand phenomena, interpretation and correlation of data obtained with the course material.

The configuration of the laboratory transforms the water electrolysis experiment, which was previously a very repetitive task, into a tool for further exploration of the physical principles and laws that govern them.

At the same time, the students pointed out that these types of experiments cannot completely replace hands-on laboratories because they are still attracted to these laboratories to act personally on instruments, on parameters that can be varied, can get a deeper knowledge of what is taking place and also any experimental error can be solved in time.

New learning outcomes can be assessed based on further development of the current configuration of the laboratory. The robotic arm can also be used in other hands-on or remote experiments and can be used as a learning tool about robotics, programming.

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