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Hy2Green: Remote laboratory of hydrogen technologies as an e-learning tool for training new professionals adapted to the new European energy model

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Abstract: This paper presents a prominent e-learning tool that is part of deliverable packages of Hy2Green Project (Ref. 2017-1-ES01-KA203-038302). The aim of the project is to develop an online training course that can help to improve new professional profiles in hydrogen technologies, in line with the energy transition model in Europe. As part of this training course and as result of a team collaboration, a remote laboratory based on hydrogen technology has been designed and implemented. Through the online platform, students from every part of the world can access remotely and in real-time, to a real laboratory built from a scaled green-hydrogen production plant. The green-hydrogen production plant has, in addition to hydrogen production and storage subsystems, a fuel cell, through which electricity is generated with the stored hydrogen. The developed remote laboratory offers technological and educational improvements. From the technological point of view, it allows handling a real installation, throughout the entire energy conversion process, being able to carry out laboratory tests, to characterize the different components. This remote laboratory is proposed as a multidisciplinary tool, where students develop their skills in automatic control, system modelling and renewable energy management. On the other side, from the educational point of view, this proposal contributes to democratization of education. That is nowadays equipment related to hydrogen technology is not cheap, so this implies that not all educational centres cannot afford to have a hydrogen laboratory. The remote laboratory presented in this work offers the possibility to carry out laboratory practices to whatever the student and the university are.

Keywords: Hydrogen Technology, Remote Laboratories, UE energy transition model, STEM skills Renewable energy systems, Energy management systems, Remote control, Hydrogen, Laboratory education, Control education.

1. INTRODUCTION

Europe must be prepared for the necessary energy change planned for the coming years. This new low carbon energy plan sets demanding targets in sustainability, energy efficiency and use of renewable energy. In this sense, hydrogen as energy vector produced by renewable way plays a key role in this new energy scheme (Commission, Portal and Commission, 2020).

On the other hand, EU in its Communication (COM (2018) 773 final) (European Commission, 2018) asserts that the transition is provided under the European Pillar of Social Rights, with its focus on supporting transitions with adequate social protection systems, inclusive education, training and lifelong learning. Skills development is essential. People will need specific, professional and “key competencies” from science, technology, engineering, mathematics (STEM) skills.

Additionally, according to FCH JU Hydrogen Roadmap 2019 (FCH-JU, 2019), EU hydrogen industry could provide employment for about 1 million highly skilled workers by 2030, reaching 5.4 million by 2050. These workers must have a specific qualification for the development, implementation and deployment of these technologies.

Regarding other educational projects focused on Hydrogen technology, the most important added value of the project NET-Tools (*NET-Tools*, 2019) consists of enabling cross-cutting interaction systems using future internet approaches with the evaluation of the quality and reliability of the existing knowledge and data sources. From primary schools, FCHgo (*Home | FCHgo! - EU project*, 2019) is a European project dedicated to fostering knowledge about fuel cells and hydrogen technology by delivering an educational model for 8 years. Inspired in secondary education, HySchools project (*HySchools*, 2019) is an Erasmus+ project that aims to create hydrogen educational and online resources for use in

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secondary schools. Promoting the training of teachers and awareness of students, the Ciro project (*Ciro*, 2019) develops an interactive program with game tools to reach a reduction of climate change with the use of hydrogen technology. Focused on higher education, TeacHy2020 (*TeacHy2020 project*, 2019) aims to serve as a repository of university grade educational materials.

Then, Hy2Green project sets the aim to meet with the training requirements by the EU in the new energy model. The overall objective of Hy2Green is to offer an online specific training program for new professionals adapted to the new energy models based on ICT and it is oriented to employment for these profiles. Hy2Green makes use of digital technologies besides facilitating the understanding of concepts, promoting accessibility to training, optimizing resources invested in training and allowing the realization of laboratory practices remotely using innovative techniques.

Hydrogen technology, addressed in this training module, is developed in all phases of production, storage and energy application of hydrogen (Fig. 1). To obtain sustainably hydrogen, one of the most widespread methods today is to obtain it by electrolysis of water. To obtain Green Hydrogen ('CertifHy pilot project issues green hydrogen Guarantees of Origin', 2019), defined as hydrogen produced with emissions lower than the Low-GHG-emissions threshold of 36.4 gCO_{2eq}/MJ_{H2} (Barth *et al.*, 2015), and as a renewable energy vector, electricity must come from renewable energies such as solar energy or wind energy, which are available many hours a day anywhere in the world. With energy excess, the hydrogen is obtained by electrolysis and stored in a tank, is therefore considered an energy vector, given its ability to store energy. When the energy input is required, a fuel cell is used, where the chemical process is inverse to that of the electrolyser. In the fuel cell, the input of hydrogen and oxygen is required, and the fuel cell produces in output electricity, water vapour and heat losses (de las Heras *et al.*, 2017). This electricity can have industrial, domestic and transport applications (Vivas *et al.*, 2018).

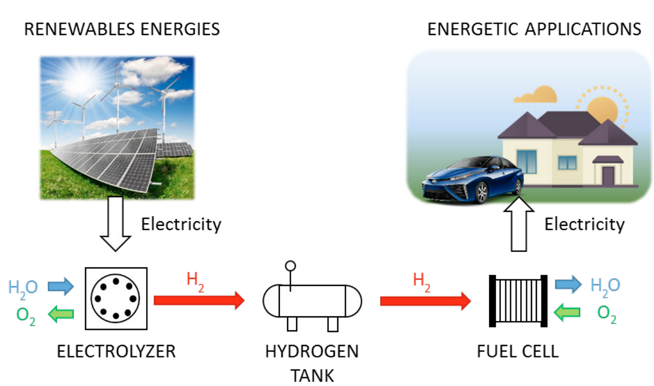

Fig. 1. Hydrogen technologies. Production, storage and consumption cycle.

Through the remote laboratory platform, the user (students from engineering degrees or similar academic profile) can access remotely and in real-time, to a remote hydrogen laboratory. There, it is possible to interact physically with all the phases included in solar-hydrogen technologies, from the generation of solar energy, through the production of hydrogen by electrolysis and its subsequent consumption and conversion again into electricity via the fuel cell. This allows to show the importance of automatic control for hydrogen technology development (Caparrós Mancera *et al.*, 2019). This remote laboratory (see Fig. 2) is made up by: (1)-a real plant based on a training kit (green-hydrogen production system), (2)-a communication interface that sends the video signal from the laboratory to a server and allows the communication between the students' computer and the remote laboratory facility, and (3)-a user interface integrated into Moodle. In this case Moodle is used as the Learning Management System (LMS). The experiment is available for students 24 hours a day, 365 days a year, by means of a reservation system, also integrated into the LMS.

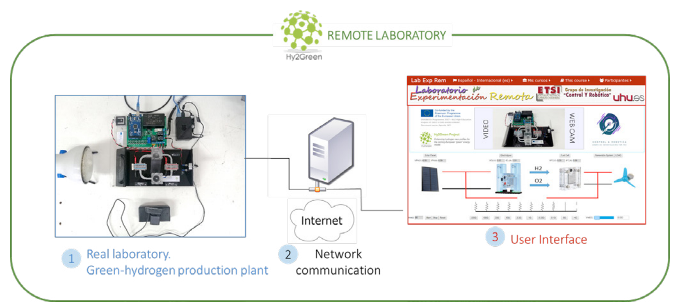

Fig. 2. Hy2Green. Remote Laboratory implementation.

Regarding the novelty of the paper, the main scientific contributions can be differentiated according to the following points of view:

- From the state of the art review, they have not been found European projects that offer a similar platform for e-learning in hydrogen technology.

- From a technological point of view, this paper presents a platform based on open-source hardware/software and low-cost devices. This gives the possibility to be replicated in any university and adapted to other matters. There is not known a hydrogen-based remote laboratory with characteristics comparable to this presented in the paper.

- From an educational point of view, the paper includes an analysis of educative experience that helps to understand the usability of the remote lab: comprehensiveness, autonomy and ease of use. It is difficult to find scientific papers that explore the dimensions underlying the usability variable and its relation to the perception of usefulness by students.

Next, in Section 2 the remote laboratory will be described in detail, from the plant components' explanation to the complete integration of the remote laboratory, including the user interface. In Section 3, the e-learning educational practice designed for the remote laboratory user is presented. In order to show the contributions and capabilities of the proposed system, in Section 4 a pilot study will be carried out to analyse the usability and educational usefulness. Finally in Section 5, the main conclusions are drawn.

2. HY2GREEN REMOTE LABORATORY

2.1 Description of the Green-Hydrogen production Plant

The developed remote laboratory is based on the Junior Basic J101 model educational kit from the manufacturer H-TEC Education. This kit includes a hybrid topology composed of renewable generation and the use of hydrogen, so it allows to put into practice all the knowledge acquired by students according to the topics addressed in the project.

The configuration of the plant is initially composed of a monocrystalline technology solar panel (item A, Fig. 3), which acts as the generator based on the incident light radiation. Subsequently, a PEM (Proton Exchange Membrane) electrolyser is available (item B, Fig. 3), which allows the production of hydrogen and oxygen gas by electrolysis of the water and stored in two auxiliary vessels (item C, Fig. 3). To produce the electrolysis reaction, the plant allows either a direct connection between the solar panel and the electrolyser or via a programmable power. The hydrogen and oxygen produced by the electrolysis process are stored in the auxiliary tanks. For the production of electrical energy from the hydrogen resource, a PE (Polymer Electrolyte) fuel cell is available (item D, Fig. 3), which receives the fuel supply thanks to the direct connection to the auxiliary vessels. Finally, there is a small fan (item E, Fig. 3), which acts as an electrical load for the fuel cell, and allows the students to visualize the conversion of chemical energy to electrical energy and subsequent mechanical energy. The main parameters of the plant are shown in Table 1.

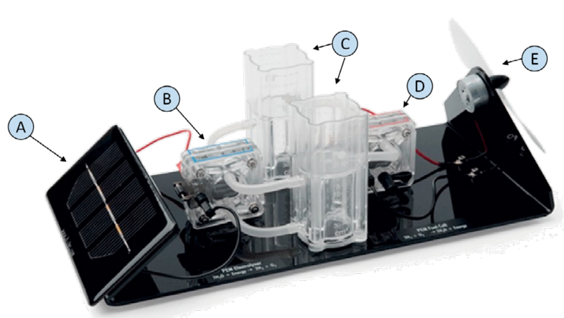

Fig. 3. Training kit (Green-hydrogen production plant)

Table 1. Training kit parameters

Element	Parameter	Unit
Solar panel	Surface	90 cm^2
	Open Circuit Voltage	≈ 2 V
	Short-Circuit Current	350 mA
	Maximum Power	500 mW
Electrolyser	Surface	4 cm^2
	H_2/O_2 generation ratio	5/2.5 cm^3/min
	Maximum Power	1.20 W
Vessel	Volume	30 cm^3
Fuel cell	Surface	4 cm^2
	Operating Voltage	0 – 0.96 V
	Maximum Power	500 mW
Fan	Power	100 mW

2.2 Remote laboratory implementation

According to the different didactic contents framed within the Hy2green project, the remote laboratory must allow the individual characterization of each element in the plant. Taking into account the technical characteristics of the educational kit, it is necessary to use auxiliary electronics that allow adapting the available hardware (item C, Fig. 4) to the different activities and tests proposed to the students.

To allow the characterization and control of the plant, as well as to define the communication hardware and software necessary for the remote laboratory implementation, a control unit is specifically used for the application (item B, Fig. 4). This control unit allows the interconnection between the different elements of the real plant, thanks to the use of discrete control variables, as well as the acquisition of the different electrical parameters. The core of the control unit is determined by a digital microcontroller, represented in this case by an Arduino Mega 2560 board.

To guarantee the data and order flow between the user interface and the plant-control unit system, a Raspberry Pi is used (item A, Fig. 4). The Raspberry Pi allows, through a Wi-Fi connection to the communications server, to establish the software interface between the final user and the control unit in a completely transparent way for the student. Thanks to the control software developed in the Easy Java Simulation (EJS) environment, each instruction associated with the user interface is encoded in C code programming so that it can be interpreted directly by the Atmel microcontroller. To allow the operation of the remote laboratory, there is a continuous bidirectional data flow between the Raspberry Pi and the control unit using a USB connection.

To visualize the operation of the system, an HD USB camera is available (item D, Fig. 4), which provides the video signal subsequently processed by the Raspberry Pi.

To allow the operation and characterization of the solar panel, a 150 W auxiliary lamp is used (item E, Fig. 4). The use of the lamp is subjected to the type of test to be performed, and therefore its use requires a discrete control signal from the control unit.

The communications server (item F, Fig. 4), is connected to the laboratory intranet as well as to the university's corporate network through the SARLAB (Remote Access Service for Labs) software platform, developed specifically for the application. This server guarantees the necessary connection between the remote laboratory and each student's computer resource (computer, tablet or mobile phone). Thanks to the use of the internet, the student can access the remote laboratory at any time, and make use of the resources with the developed user interface (item G, Fig. 4). The total cost of the hardware that made up the remote laboratory is about 200 €, without including the educational kit. The cost of the educational kit depends on the provider (it is around 300 €).

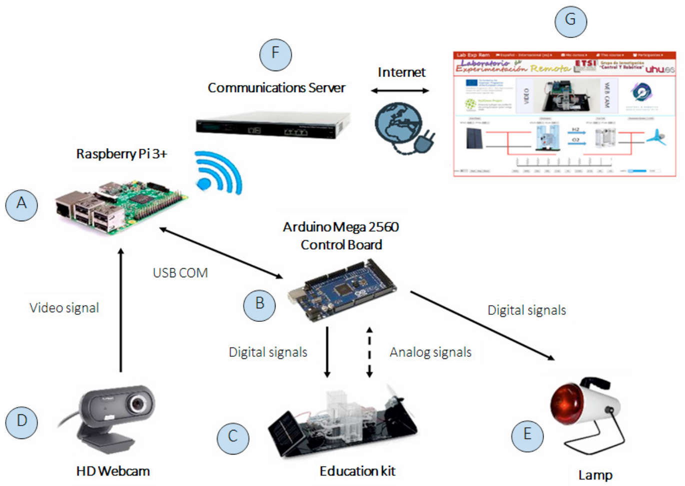

Fig. 4. System architecture.

Regarding the control and acquisition unit (item B, Fig. 4), it incorporates all the electronics necessary to acquire the main electrical variables of the plant, see operating voltage and current, as well as implementing all control actions for the interconnection and characterization of the different elements, according to the user's requirements. In this sense, for the solar panel characterization, the control unit allows the switching on/off of an auxiliary lamp, using a relay, which allows establishing fixed irradiation conditions. To obtain the polarization curve, the control electronics allow the connection and disconnection of an array of load resistors, by acting on relays and small power MOSFET transistor, whose values have been optimized to obtain a representative number of discrete points, which allow the polarization curve profile to be obtained significantly (Fig. 5).

Regarding the electrolyser, the characterization process is given by voltage control, which sets the operating voltage set point of the electrolyser, resulting in a discrete value of the electrolysis current. For this, a high-resolution programmable power source (PPS, Fig. 5) has been developed, using a resistor divider based on controlled variable resistance. This resistance is modelled by the use of a power MOSFET operating in the ohmic region, and the use of a closed-loop analog control circuit, defined by an error amplifier.

Similar to the case of the solar panel, the characterization of the fuel cell is carried out through the use of the resistor array, which allows obtaining discrete and significant points of the polarization curve. The connection and disconnection of the resistance array is carried out through the use of relays and small power MOSFETs (Fig. 5).

Finally, to illustrate the possibility of generating hydrogen from renewable energy sources, the control system allows making the physical connection between the solar panel, electrolyser, fuel cell and fan.

The remote laboratory composed of the plant described in section 2.1, and the control and communication electronics developed is shown in Fig. 6.

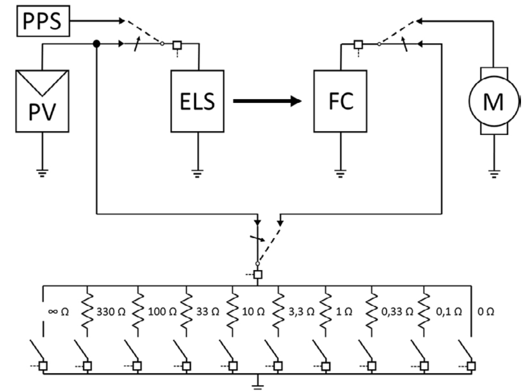

Fig. 5. Control unit electric scheme.

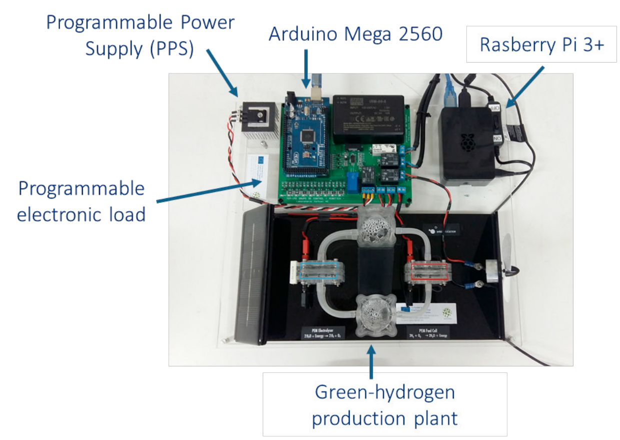

Fig. 6. Experimental system.

2.3 User interface

The developed user interface is shown in Fig. 7. This interface was developed within EJS software tool, and has been integrated into Moodle, which is used as Learning Management System (LMS). The user interface is accessible through a reservation management platform for 24 hours a day, 365 days a year.

Attending to the user interface designed, it is possible to distinguish two clearly differentiated parts.

In the first part, the video image taken from the USB camera is shown (item F, Fig. 7). From this image, students can easily check the operation of the plant. In this sense, from the video signal, the user has at his disposal multiple options: 1) to identify the hydrogen production option (solar or by the PPS), 2) to verify the lighting of the lamp, 3) to test the production of hydrogen and oxygen associated with the characterization of the electrolyser, through the visualization of gas bubbles and the hydrogen level according to the vessel volume indicator, 4) to calculate the hydrogen and oxygen consumption associated with the operation of the fuel cell, thanks to the variation on the vessel volume indicator, and 5) to see the fan movement once it is connected.

The second part of the user interface includes all controls from which the students are allowed to select the operating mode of the system (item A, Fig. 7), as well as displays in which are shown the main electrical variables, operating voltage and current, of each of the equipment that makes up the plant (item B, Fig. 7). Similarly, auxiliary controls are included for the selection of the load resistance value (item C, Fig. 7), as well as the selection of the electrolyser operating voltage (item E, Fig. 7), necessary parameters for the characterization of the solar panel, fuel cell and electrolyser respectively. Finally, there is a controlled timer (item D, Fig. 7), which allows the student to time those tests in which the calculation of time-dependent variables is necessary, such as the hydrogen and oxygen consumption/generation ratio by electrolyser and fuel cell respectively.

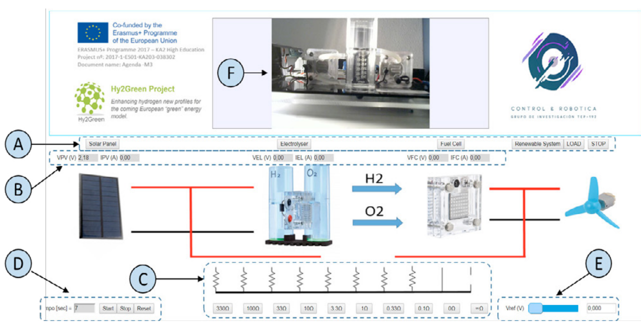

Fig. 7. User interface.

3. E-LEARNING TRAINING

The objective of the practice is to allow the student to operate remotely in the physical laboratory, interacting with the remote laboratory facility with the aid of a guideline document (available in the Moodle platform that hosts the connection to the project; see Annex: Hy2Green Moodle link). The guideline provides instructions and tables to be filled with experimental data, as the students were in a physical laboratory doing practices. The duration of the practice is around 1-2 hours. Access to the remote laboratory is done by means the Remote Access Service for Labs (SARLAB), see Annex. It is available 365/24 and it is ready for real use.

In the following section the laboratory practice activities are presented, reporting graphs of real measurements obtained during the testing phase of the remote laboratory facility. The obtained results are in line with the expected behaviour of the components and literature references for solar cells (Duffie and Beckman, 2013) and H_2 systems (Cassir *et al.*, 2013). The laboratory practice is developed in seven steps as follows:

Step 1. Measuring the solar cell operating current and voltage points (V-I curve, resolution of the measurement system of 0.01 A and 0.01 V, respectively) by connecting each resistor to the solar array (0.1-330 Ω) in isolated mode. The limit points will represent the open-circuit voltage V_{oc} and the short circuit current I_{sc}. From the V-I curve the V-P curve can be derived directly. An example of obtained curves is reported in Fig. 8.

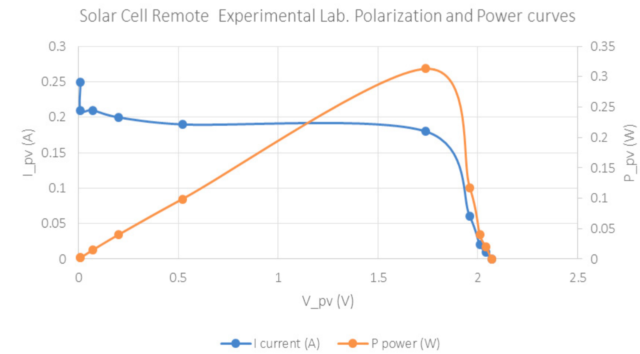

Fig. 8. Solar cell V-I and V-P experimental curves obtained from remote practice.

Step 2. Measuring the V-I curve of PEM electrolyser by acting on the PPS input voltage (from 0 to 2 V, with variation steps 0.1 V) the system is characterised and the voltage conduction range is defined. The I-P curve can be derived directly together with specific quantities such as current density and power density by knowing the active cell surface (Table 1). Fig. 9 shows a sample polarization obtained from the remote practice. From the voltage and current, the cell's equivalent ohmic resistance can be obtained.

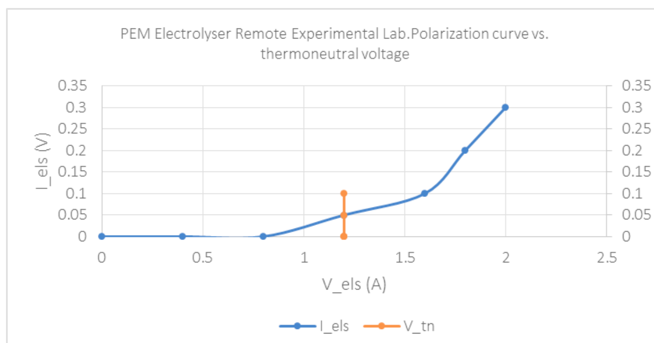

Fig. 9. PEM Electrolyser I-V polarization curve vs. thermoneutral voltage (V_{tn}).

Step 3. By reading the initial and final volume of gas (maximum storage volume 30 cm^3 with a resolution of 1 cm^3) the produced mass amount of hydrogen can be derived, applying the density in normal conditions, equal to 0.0898 kg/Nm^3 and considering near-atmospheric pressure conditions. In the test 5 cm^3 of H_2 were obtained producing for 2 minutes at 2 V (nominal conditions), with an average H_2 flow rate of 2.5 cm^3/min (the O_2 volume and flow rate is half, according to stoichiometry).

Step 4. Considering the Lower Heat Value (LHV) of 33.33 kWh/kg the energy content of the produced H_2 can be calculated. The ratio with the input energy (obtained from measured power and duration) gives the electricity-to-solar efficiency. The test shows around 0.015 Wh of H_2 versus 0.020 Wh consumed by the electrolyser giving an efficiency of 75% and specific electrical energy consumption of around 4 kWh/Nm^3.

Step 5. Connecting the solar cell directly to the electrolyser the student can check that the output voltage and current values from the solar cell are actually the ones applied to the electrolyser. From the electricity-to-hydrogen efficiency calculated in point 4 and knowing the solar cell nominal efficiency (15%), the incident radiation (W/m^2) can be calculated.

Step 6. Similarly, to the PEM electrolyser, the PEM fuel cell current and voltage are characterised against the resistance array (0.1-330 Ω) in isolated mode. The V-I curve is obtained and the P-I curve is derived directly along with specific quantities by knowledge of the cell active surface (Fig. 10).

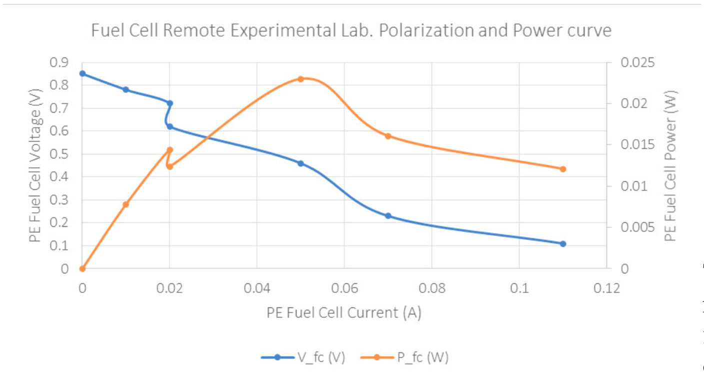

Fig. 10. PEM Fuel Cell V-I and P-I experimental curves obtained from remote practice.

Step 7. Connecting the fuel cell to the load type fan (100 mW) the current is small (0.05-0.1 A), therefore it is not possible to obtain a readable volume difference within feasible time. Instead, the nominal conversion efficiency is given (50-60%) and the student can calculate the autonomy time of the H_2 storage, by knowing the load power and stored energy in the form of H_2. Table 2 summarises the data collected from remote practice. The test gives an autonomy of around 4 h for the full storage volume, due to the limited load.

Table 2. Autonomy test

Element	Operating Point	Unit
Fuel Cell	Voltage (V)	0.46 V
	Current (I)	0.1 A
	Power (P)	0.046 W
	Efficiency	0.5
	LHV	33.33 kWh
Hydrogen consumed	Density	0.0898 kg/m^3
	Mass	2.69x 10^{-6} g
Vessel	Volume	30 cm^3
	Stored Energy	0.0897 Wh
Fan load	Autonomy [(H2_storedenergy/efficiency)/Power]	3.904 h

At the end of the remote laboratory practice, the student should produce a report of the laboratory practice that can be assessed for qualification by means Hy2Green Moodle platform.

The expected specific learning results with the remote laboratory practice are to:

- Understand and characterize a solar PV panel under various load ranges
- Understand the working principle and operation of the hydrogen systems in terms of power to gas conversion and gas to power conversion.
- Set up a workflow to obtain experimental data to draw the electrical characteristic curves of the hydrogen systems
- Compare different systems performances and derive experimental performance parameters
- Evaluate a solar hydrogen coupled system.

4. USABILITY AND EDUCATION USEFULNESS

To show the contributions and capabilities of the proposed remote laboratory, a pilot study has been carried out in the first semester of the academic year 2019-2020. The number of students involved has been 25 (20 from Energetic Engineering Degree and 5 from Master in Sustainability). The statistical study consists of an anonymous test completed by students after passing the corresponding of the matter. The questionnaire includes issues related to the remote lab features and its usefulness, Table 3 and Table 4. Students were required to rate the questions on a 5-point Likert scale (1—strongly disagree and 5—strongly agree).

Table 3. Usefulness of remote laboratory by the students

		AVG	SD
Q0	Your level on photovoltaic systems is high	2.40	0.45
Q1	This lab work allows strengthening the theoretical concepts	4.35	0.60
Q2	The remote lab work makes easier the theoretical-practice understanding	4.17	0.63
Q3	The overall assessment of the remote lab is positive	4.56	0.44

AVG: Average
SD: Standard Deviation

Based on students' answers, it can see the acceptance of the remote lab, in spite, most students did not have previous knowledge of hydrogen technology (Q0; average value, AVG = 2.40). Regarding the learning procedure (Q1 and Q2), students confirm that theoretical concepts are strengthened and improved by the use of the remote lab (Q1; AVG = 4.35), and working with remote lab makes it easier the theoretical-practice understanding (Q2; AVG = 4.17).

Table 4. Usability perceived by students

		AVG	SD
Q4	The interface allows the exercise to be carried out in the same way as in the classroom lab	4.37	0.45
Q5	The exercise can be carried out without the professor supervision	4.25	0.60
Q6	The time available to complete the tests is enough	4.75	0.54
Q7	The information available in LMS is suitable to perform the lab work	4.17	0.43
Q8	The use of the interface is easy	3.90	0.87
Q9	The access to the remote lab through the LMS is easy	4.56	0.54

AVG: Average

SD: Standard Deviation

Regarding the performing of the experiment (Q4, Q5, Q6 and Q7), students think it can be carried out in the same way as in the classroom lab (Q4; AVG = 4.37), and even without the teacher supervision (Q5; AVG = 4.25). Then, it can be deduced the great advantage of the remote lab over the classroom lab: the control by software substitutes the necessary teacher supervision to guaranty the correct use of lab devices. Besides, students consider that the time available to complete the tests is enough (Q6; AVG = 4.75). Additionally, there is also agreement in the suitability of instructions to perform the lab work (Q7; AVG = 4.75). Considering the aspects related to the user graphic interface, in spite, some students consider it could be improved (Q8; AVG = 3.90 and SD = 0.87), most of them think the access to the remote lab is easy (Q9; AVG = 4.56).

5. CONCLUSIONS

In this paper, it has been presented a hydrogen-based remote laboratory. The remote laboratory is part of the Hy2Green project. Hy2Green is an Erasmus+ funded project that has the aim to offer a specific training program for new professionals adapted to the new energy European model based on ICT, and regarding employment requirements for these profiles. The FCH Joint Undertaking foresees that the EU hydrogen industry employ about 1 million highly skilled workers by 2030, reaching 5.4 million by 2050. These workers must have a specific qualification for the development, implementation and deployment of these technologies. In basis on this, Hy2Green born with the objective to give responses to these expected requirements.

The developed remote laboratory integrates a hydrogen-based educational kit, a control unit based on an Arduino Mega 2560 board that allows the characterization and control of the plant. Additionally, a Raspberry Pi is used to guarantee the data and order flow between the software interface and the plant-control unit system, through a Wi-Fi connection to the communications server. To visualize the operation of the system, an HD USB camera has been used.

Additionally, the communications server is connected to the laboratory intranet as well as to the university's corporate network through the SARLAB (Remote Access Service for Labs) software platform, developed specifically for the application. This server guarantees the necessary connection between the remote laboratory and each student's computer resource (computer, tablet or mobile phone).

Regarding the novelty of the paper, the scientific contributions lay on three main aspects: 1) they have not been found European projects that offer a similar platform for e-learning in hydrogen technology. 2) The proposed remote laboratory is based on open-source hardware/software and low-cost devices; and 3) the analysis of educative experience has helped to understand the usability of the remote lab: comprehensiveness, autonomy and ease of use.

In conclusion, the hydrogen-based remote laboratory demonstrates reliability, as well as the remote communication system, through which students will be able to access 365 day/24 h. With the learning proposals through the remote laboratory, an interactive and real teaching methodology is achieved, where students will be able to train and develop skills within hydrogen technologies, energy management and automatic control.

Finally, according to the Technological Acceptation Model (TAM), the pilot test assessment shows that the developed platform meets with both usability and usefulness. These are dimensions that influence the users' attitude to the technology (very important in the challenge for STEM careers) and, therefore, over its use. Thus, this work shows that remote lab usability must be strengthened to integrate remote labs in the University. i.e., students consider remote labs as an instrument to be easily used in the practical classes.

List of Acronyms

EJS: Easy Java Simulation
ICT: Information communications technology
LHV: Lower heat value
LMS: Learning Management System
PE: Polymer Electrolyte
PEM: Proton exchange membrane
PPS: programmable power source
SARLAB: Spanish acronyms (remote access service for labs)
STEM: Science, technology and mathematics

ANNEX

Hy2Green project Moodle Platform: http://hy2green.h2athome.net/

Hy2Green Remote Laboratory service (SARLAB): http://sarlab3.uhu.es/sarlab/

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