Energy-Environmental Modelling of a PEM-Type Fuel Cell for Hydrogen Production

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***Abstract*– Hydrogen is being considered nowadays as a fuel for the future due to its multiple applications and also its potential contribution to carbon emission reduction. In this research, a preliminary energy-environmental modelling is carried out considering hydrogen production based on renewable energies and a PEM fuel cell for electricity production.**

In this case, hydrogen is produced by electrolysis using two 250-Wp solar photovoltaic modules and a 400-W wind energy converter for combined electricity generation under local conditions. Carbon emission reduction is estimated considering a partial potential substitution of fossil fuels by green hydrogen and using an overall carbon dioxide factor for the national electric grid.

Outcoming results show that 698.1 kWh/yr could be locally produced considering a solar radiation of 3825 Wh/m^2-day. Also, 188.9 kWh/yr could be locally produced considering a mean wind speed of 3.1 m/s measured at 10 m height. Besides, 56.1 kWh is needed to obtain 1 kg of hydrogen through electrolysis using a PEM fuel cell.

It is concluded that a combined daily solar-wind electricity production of 2.43 kWh could help to reduce 496 kgCO$_2$/yr due to a partial substitution of fossil fuels by green hydrogen.

Last but not least, a demonstrative module has been set up, for educational purposes, at the Environmental Engineering Department located on the main campus of the National University of Engineering, in Lima-Peru.

Keywords-- Hydrogen Production / Fuel Cell / Renewable Energy / Environmental Management / Sustainable Development.

I. INTRODUCTION

This work was carried out by the research group named “Energy and Sustainable Development”, with the participation of students and professors from the Environmental Engineering Department at the National University of Engineering, located in Lima-Peru, during the year 2020.

A. *Introduction*

The research group “Energy and Sustainable Development” has previously worked on hydrogen production based on solar photovoltaic electricity, in 2018, and hydrogen production based on wind electricity, in 2019.

The Environmental Engineering Department at the National University of Engineering is very interested in contributing to climate change mitigation. A particular area of potential contribution is related to carbon emission reduction for local electric grids.

In the early years of current century, electricity mix in Peru was about 90% hydropower and 10% thermal power. However, since the year 2005, natural gas started to play an increasing role in electricity generation, nowadays national electricity mix is about 48% hydropower, 48% thermal power, and 4% renewable energy (RER).

The term RER (Renewable Energy Resources) is locally used in order to include solar, wind, and biomass energy sources. Also, it includes hydropower plants but only up to 20 MW of installed capacity. With regard to introduction of RER, electricity produced by biomass started in 2010, by solar energy started in 2012, and by wind energy started in 2014. In the last 10 years, large scale RER-based projects have been implemented and interconnected to the national electric grid.

Nevertheless, one of the key barriers for increasing electricity produced by RER seems to be the variability of resource availability, namely solar and wind resources. On the other hand, hydrogen energy is seen as the “fuel for the future” due to its significant potential contribution.

B. *Background*

In Ref. [01], the whole world is running on energy, where there is exigency to shift toward renewable energy sources. As the commonly used sources of energy are endangered and about to deplete. Introducing renewable energy will improve the environment from adverse effects of greenhouse gases; also, it ameliorates the economy of the country by providing new jobs in that sector. It also improves energy security by decreasing the foreign import of oils and many other things related to energy production. Among different renewable sources, sun is the potential producer of the energy. Fuel cells on the other hand playing significant role in energy production. Significantly, Proton Exchange Membrane Fuel Cells (PEMFC) playing momentous role in power generation. PEMFC’s employs hydrogen and air to supply electricity and water through electro chemical reactions. In this paper, we integrated solar power generation with PEMFC’s for efficient and continuous power generation. We have modeled Fuel cell of 6kW and PV cell of 1kW separately. The solar photovoltaic and Fuel cell model were first simulated separately and combined analysis were carried out using MATLAB Simulink. The developed hybrid model was also validated and its power output graphs were also analyzed. Thus, the hybrid systems are very much useful in remote areas where there is difficulty to get electricity.

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In Ref. [02], this work aims to demonstrate the importance and usefulness of multiscale computational approaches and tools, as well as of reliable input data and verification procedures for fuel cells & hydrogen (FCH)technology applications. For that purpose, three typical case studies on the use of simulation models/tools at various scales for specific applications are examined. More specifically, these cases concern: (i) the optimization of materials design for Fuel Cells via a novel process-based methodology; particularly the stochastic reconstruction and accurate characterization of carbon fiber-based matrices, which are commonly used as Gas Diffusion Layers (GDL) in Proton Exchange Membrane Fuel Cells. The computational approach employs a rigorous model simulating the spatial distribution of the graphitized res in that is typically used to enhance the structural properties and thermal/electrical conductivities of the composite GDL materials; (ii) the investigation of hydrogen safety related issues and scenarios, where characteristic examples of Computational Fluid Dynamics (CFD) studies and associated benchmarking activities in particular applications are presented; (iii) the optimization of hybrid Renewable Energy (RE) – hydrogen systems at real scale in remote/isolated communities like off-grid islands where cost effectiveness with regard to the produced energy is a critical factor. Besides the scientific and technical aspects, we would like through these examples to stress how complementarities and synergies between numerical and experimental research can greatly assist in closing knowledge gaps & developing innovative designs, and may contribute toward defragmentation of relevant efforts, more effective collaboration between researchers and provision of validated simulation tools.

In Ref. [03], hydrogen is an energy carrier that can be used in industry, residences, transportation, and mobile applications. One of the main attractions for hydrogen is the environmental advantage over fossil fuels. However, Polymer Electrolyte Membrane Fuel Cells, (PEMFC), is an integral part of the future hydrogen economy, they are highly efficient and a low polluting technology. Numerous applications exist; one of the promising applications is the automotive industry. For this report a comprehensive literature survey is conducted.

The findings of the literature survey include hydrogen production and fuel cell models that fit into two broad categories, that is, analytical and empirical. This work is a presentation of our original research and development regarding the production and utilization of a solar hydrogen and its use in a PEM single cell. In order to facilitate the understanding of the charge transfer phenomena in the PEM single cell, a modeling tool with visual basic was developed. All the experiences and results were illustrated in this work.

In Ref. [04], modeling the corrosion behavior of Pd/Cu couple in acidic media (0.25 M HCl) at various operating conditions [(30, 50 _C) and (0, 300, 600, 900 RPM)] was considered as an ultimate goal of this work. Multiple regression analysis with respect to ANOVA was utilized to generate a mathematical correlation. The derived correlation and the surface response revealed that increasing temperature and speed of agitation affected the corrosion rate of Cu in the Pd/Cu couple. This result indicates that using copper in the hydrogen purification e Proton Exchange Membrane (PEM) fuel cell hybrid systems is not acceptable due to the degradation that might occur as a direct result from the galvanic action between Pd/Cu couple. In order to improve the resistance of Pd against corrosion and hydrogen embrittlement at elevated temperatures, it should be alloyed with Au or Ag rather than copper.

In Ref. [05], thanks to the independent sizing of power and energy, hydrogen-based energy storage is one of the very few technologies capable of providing long operational times in addition to the other advantages offered by electrochemical energy storage, for example scalability, site versatility, and mobile service. The typical design consists of an electrolyzer in charge mode and a separate fuel cell in discharge mode. Instead, a unitized regenerative fuel cell (URFC) is a single device performing both energy conversions, achieving a higher compactness and power-to-weight ratio. This paper presents a performance model of a URFC based on a proton exchange membrane (PEM) electrolyte and working on hydrogen and oxygen, which can provide high energy and power densities (>0.7 W/cm^2). It provides voltage, power, and efficiency at varying load conditions as functions of the controlling physical quantities: temperature, pressure, concentration, and humidification. The model constitutes a tool for designing the interface and control subsystem as well as for exploring optimized cell/stack designs and operational conditions. To date, only a few of such analyses have been carried out and more research is needed in order to explore the true potential of URFCs.

In Ref. [06], an analytical model for hydrogen alkaline anion exchange membrane fuel cell (AAEMFC) is developed in this study. The results show that due to both the electrochemical reaction and electro-osmotic drag, water in cathode is consumed faster than oxygen. Proper liquid humidification in cathode is favorable for performance improvement, especially at low operating temperatures; on the other hand, without liquid humidification, high reactant flow rate is needed. If there is no liquid humidification and the oxygen stoichiometry ratio is fixed, a higher operating pressure increases both the activation loss and ohmic loss, leading to lower cell performance. With the increment of catalyst layer (CL) thickness, the reactant concentration in CL decreases, and the ohmic resistance of electron and ion increases. Decreasing the membrane thickness reduces both the ohmic resistance and activation loss, because more water can transfer from anode to cathode.

In Ref. [07], fuel cell technology is one of the most promising, emissions free, energy conversion technology under renewable energy systems because of its wide ability in most of the commercial applications like electrical vehicles, building cogeneration and standby power supply. Mathematical models are trusted as important tools for designing and performance analysis of fuel cell -based systems. Many mathematical models based on thermal, electrochemical and electrical steady states as well as dynamic have been reported in literature to evaluate performance of Proton Exchange Membrane (PEM) fuel cell, but all these models are complex and needs huge amount of data for modeling and performance testing. The present paper proposes simple, but more realistic MATLAB SIMULINK model for PEM fuel cell to evaluate its performance under different operating conditions. The performance of the proposed model is compared with single practical, 25 cm^2 active area, PEM fuel cell for model validation. The presented model is also valid for a stack having any number of cells.

In Ref. [08], this study presents the performance of a proton exchange membrane (PEM) fuel cell in terms of its pressure and voltage parameters. The aim of this study is to improve the performance, efficiency and development of modeling and simulations of PEM fuel cells by experimental optimization. PEM fuel cell performance was researched using an open cathodic plate fuel cell, the effect of fuel cell's performance. PEM fuel cell efficiency was measured in terms of operating pressure and voltage parameters. The energy and exergy efficiencies of the PEM fuel cell were found to be 47.6% and 50.4%, herein. In this study, these results indicate that waste water of experimental work comprehends importance of the PEM fuel cell life-time.

In Ref. [09], this paper presents a sensor fault estimation scheme for polymer electrolyte membrane (PEM) fuel cells using Takagi Sugeno (TS) fuzzy model. First, PEM fuel cell systems with sensor faults are modelled by TS fuzzy model. Next, by adding a first order filter, an augmented TS fuzzy system with actuator fault is obtained. Then, for the augmented system, an unknown input observer (UIO) and a fault estimator are developed. The UIO gains are computed by solving linear matrix equalities (LMEs) and linear matrix inequalities (LMIs). The UIO convergence and stability are analyzed and the performances of the proposed fault estimation scheme is demonstrated by numerical simulations for a PEM fuel cell system with return manifold pressure and hydrogen mass sensors.

In Ref. [10], it is reported an analytical physics-based model for oxygen concentration perturbation spectra of a PEM fuel cell cathode side. An expression for the concentration impedance (CI) taking into account oxygen transport in the cathode catalyst layer (CCL) and the gas diffusion layer (GDL) is derived. In the static limit the CI gives the limiting current density due to oxygen transport in the GDL. The Bode plots of real and imaginary part of the CI have minima at the characteristic frequencies corresponding to oxygen transport in the GDL and the CCL, respectively. These features enable direct estimation of the respective oxygen diffusion coefficients without curve fitting.

According to Ref. [12], there are relevant interrelations among energy, environment, and sustainable development. The conceptual representation of exergy and the confluence of energy, environment and sustainable development is shown in Fig. 1. Here it is also suggested that the energy and material flow balance methods connect energy analysis with the environment.

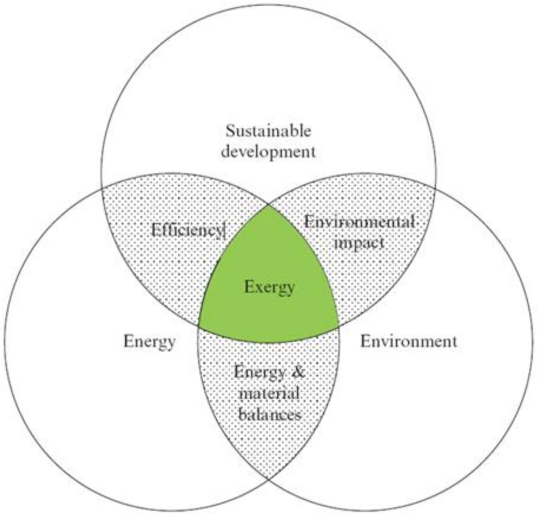

Fig. 1. National electricity generation during peak power demand.
Source: Dincer, I et al [Ref. 12].

II. METHODOLOGY

The methodology that was carried out for the present work focuses on hydrogen production based on renewable energies and its potential contribution for carbon emission reduction in local electrical grids.

A. *Electricity produced by solar energy*

In this case, electricity produced by solar energy focuses on the utilization of a solar photovoltaic system. According to a Solar Map for Peru, potential for solar energy applications may be high in certain regions, reaching solar irradiation levels up to 8 kWh/m^2-day. However, in other parts of the country lower levels can be around 3.5 kWh/m^2-day.

A peak-sun hour (PSH) is defined as the equivalent hours of solar irradiation at a rate of 1000 W/m^2. Thus, solar daily electricity production, SDEP, can be calculated as follows:

$$SDEP = kWp \times PSH \tag{1}$$

wherein:

kWp: Maximum Power Output for the PV Module

PSH: Peak Sun Hours

Also, the solar capacity factor, SCF, can be calculated as follows:

$$SCF = SDEP / (kWp \times 24h) \tag{2}$$

For illustration purposes, average daily solar electricity production for a 20-MWp plant installed in a southern region of Peru is shown in Table I, during the year 2020.

TABLE I
AVERAGE DAILY SOLAR ELECTRICITY PRODUCTION

Month	MWh/month	Days/Month	MWh/day	SCF
JAN	3852	31	124.3	0.26
FEB	4219	29	145.5	0.30
MAR	3869	31	124.8	0.26
APR	4113	30	137.1	0.29
MAY	3848	31	124.1	0.26
JUN	2927	30	97.6	0.20
JUL	3726	31	120.2	0.25
AUG	3589	31	115.8	0.24
SEP	4149	30	138.3	0.29
OCT	4567	31	147.3	0.31
NOV	5451	30	181.7	0.38
DEC	5369	31	173.2	0.36

Source: COES Report [Ref. 11].

B. *Electricity produced by wind energy*

In this case, electricity produced by wind energy focuses on the utilization of a wind energy converter system. According to a Wind Map for Peru, potential for wind energy applications may be high in certain regions, reaching wind speed levels up to 7 m/s measured at 10 m height. However, in other parts of the country lower levels can be around 3 m/s measured at 3 m height.

Wind power, WP, can be calculated as follows:

$$WP = Cp \text{ x } \rho \text{ x } g \text{ x } A \text{ x } V^3 \tag{3}$$

wherein:

Cp = power factor, no units
ρ = air density, kg/m^3
g = gravity acceleration, m/s^2
A = rotor blade area, m^2
V = mean wind speed, m/s

Therefore, wind daily electricity production, WDEP, can be calculated as follows:

$$WDEP = WP \text{ x } 24h \tag{4}$$

Also, the wind capacity factor, WCF, can be calculated as follows:

$$WCF = WDEP / (kW \text{ x } 24h) \tag{5}$$

wherein:

kW = wind energy converter installed capacity, kW

For illustration purposes, average daily wind electricity production for a 32-MW plant installed in a southern coastal region of Peru is shown in Table II, during the year 2020.

TABLE II
AVERAGE DAILY WIND ELECTRICITY PRODUCTION

Month	MWh/month	Days/Month	MWh/day	WCF
JAN	8824	31	284.6	0.37
FEB	13214	29	455.7	0.59
MAR	14025	31	452.4	0.59
APR	14076	30	469.2	0.61
MAY	12727	31	410.5	0.53
JUN	13641	30	454.7	0.59
JUL	16769	31	540.9	0.70
AUG	16138	31	520.6	0.68
SEP	16007	30	533.6	0.69
OCT	15991	31	515.8	0.67
NOV	13164	30	438.8	0.57
DIC	12281	31	396.2	0.52

Source: COES Report [Ref. 11].

C. *Hydrogen production*

According to Ref. [12], hydrogen may be produced by means of a wide variety of ways, including the use of fossil fuels and renewable energies. Two main energy conversion pathways do exist that lead to green (renewable energy, waste and process heat) or non-green (fossil fuels energy) hydrogen production

According to Ref. [13], hydrogen production processes include the following alternatives:

1. Chemical conversion

Chemical conversion processes designation is very broad, and it may be applied to both fossil fuels (coal and hydrocarbons) and renewable energy (biomass). Main processes are: reforming (steam water, partial oxidation, auto-thermal), pyrolysis, and gasification. In all the above processes, CO_2 is produced in more or less quantity, and its sequestration is possible. The forementioned sequestration is necessary if the process is applied to a fossil fuel in order to claim clean environmental attributes for hydrogen. If the process is applied to biomass, capturing CO_2 would produce a negative emission of CO_2 even though it may not be economically justified.

Reforming processes are the most common nowadays for hydrogen production. From a thermodynamic point of view, it may be classified in endothermal and exothermal. The first type requires heat supplied from an external source, as it is in steam water reforming, while the second one rejects heat in the reaction as it is in the partial oxidation case. In auto-thermal reforming, a combination of both processes is produced achieving a net zero heat balance. In the Peruvian case, special attention might be dedicated to reforming with steam water in view that it could be applied to a variety of hydrocarbons (natural gas, LPGs, liquid hydrocarbons, and others) and alcohol.

Pyrolysis consists of decomposition of a solid fuel (coal or biomass) through heat action (usually about 450°C for biomass and 1200°C for coal) in the absence of oxygen. Final products of the process depend on the nature of the utilized fuel, temperature and pressure of operation, and material permanence in the unit.

Gasification process consist of a combustion with oxygen defect wherein CO, CO_2, H_2, and CH_4 are obtained, in different proportions according to the primary source and process conditions. Oxygen is limited to 10% and 50% of the stoichiometric value, and temperature is between 700°C and 1500°C. Gasification can be applied to both biomass and coal.

2. Thermolysis

Thermolysis processes imply hydrogen extraction from its original molecule (hydrocarbon or water) by means of heat supply. Under such definition, reforming, gasification, and pyrolysis can be also considered as thermolysis processes. The consideration of theses processes as chemical or thermolytic methods depend on the heat source deployed. Thus, chemical processes are referred to the case when heat for the process is extracted from the same primary source by means of a combustion, on the other hand, thermolysis processes are referred to the case when heat comes from an external source, such as concentrated solar power or nuclear energy at high temperature.

3. Electrolysis

Electrolysis consists in the rupture of the water molecule by means of an electric current. When it occurs under normal environmental conditions (25°C and 0.1 MPa) the process is as follows:

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (6)$$

In case of electrolysis at low temperature, electricity consumption is very high. Therefore, it is recommended to obtain hydrogen in situ in small quantities and in the absence of other types of supplies. Another alternative could be the integration with renewable energy in search of a way to store excess or variable electricity. Operating temperature may actually be around 80°C in alkaline or proton exchange membrane electrolyzers. In the Peruvian case, special attention might be dedicated to solar and wind power electricity due to their high potential in certain regions.

In case of electrolysis at high temperature, electricity consumption becomes more acceptable. It is necessary to have steam water and a thermal source at high temperature. Electrolyzers have to be solid oxide type.

4. Fermentation

Hydrogen production based on biomass include alcoholic fermentation and anaerobic fermentation.

In case of alcoholic fermentation, solar energy is stored in the form of simple or complex carbon hydrates from which ethanol can be obtained by means of fermentation.

In case of anaerobic fermentation, also known as anaerobic digestion, it is a microbial fermentation in the absence of oxygen to produce a mix of gases (mainly CH_4 and CO_2) known as biogas.

5. Photolytic processes

Photolytic processes utilize solar light to produce water hydrolysis. Currently, there are two procedures: photobiologic and photoelectrochemical.

6. Photobiologic processes

A few organisms such green algae, cyanobacteria, photosynthetic bacteria, may act as biologic catalyzers to produce hydrogen energy from water and certain enzymes.

In this case, hydrogen production is based on the utilization of renewable energy electricity through an electrolysis process. Energy supply includes both electricity generated by the solar system and the wind system.

In this case, a Proton Exchange Membrane (PEM) fuel cell is considered for the electrolysis process.

Daily hydrogen production, DHP, can be calculated as follows:

$$DHP = \eta \text{ x } (SDEP + WDEP) \qquad (7)$$

wherein:

η = fuel cell efficiency, no units

D. *Energy-Environmental Modelling*

In this case, energy-environmental analysis focuses on potential carbon emission reduction due to expected contribution of hydrogen production as intended for partial substitution of fossil fuels usage associated with power generation for local grids.

Carbon emission levels depend on the actual mix of energy sources being used for power generation. For illustration purposes, an overall annual emission factor will be used.

Potential carbon emission reduction, PCER, associated with substitution of fossil fuels by hydrogen produced using renewable energy, can be estimated as follows:

$$PCER = ACEF \text{ x } (SDEP + WDEP) \text{ x } \eta \qquad (8)$$

wherein:

ACEF = average carbon emission factor, $kgCO_2/ kWh$

For illustration purposes, national electricity generation during maximum power demand is shown in Fig. 2. In December 2020, max. power demand was registered on

December 17th at 19h30. At that time, 95% was provided by hydropower (61%) and natural gas (34%).

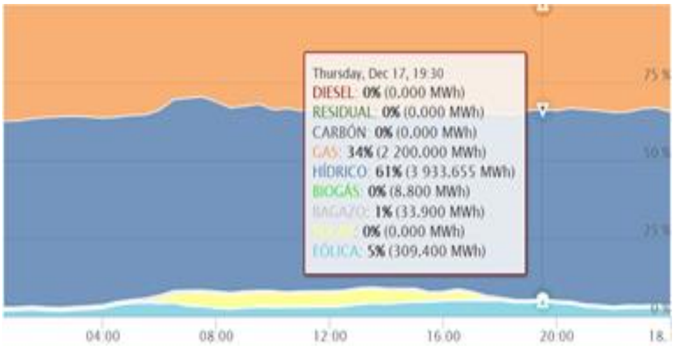

Fig. 2. National electricity generation during peak power demand. Source: COES Report [Ref. 11].

Also, electricity generation for December 17th at 12h00 (noon) can be shown in Fig. 3. An overall 0.56 tCO_2/MWh can be considered at present for the national electricity grid.

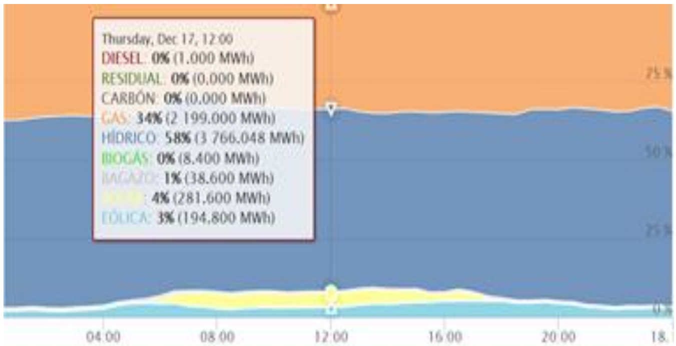

Fig. 3. National electricity generation at noon. Source: COES Report [Ref. 11].

E. Demonstrative module for educational purposes

An educational module that may be used for illustration purposes is proposed. In this case, hydrogen production is based on renewable energies, therefore it could be considered as “green” hydrogen. Also, partial substitution of fossil fuels by hydrogen would lead to potential carbon emission reduction in local electric grids. Even though, solar and wind resource availability is not uniform throughout the country, the educational module aims to provide students and lecturers with a first insight into potential environmental benefits of “green” hydrogen.

III. RESULTS

Results from this work include: solar photovoltaic electricity generation, wind electric power generation, hydrogen production by a PEM Fuel Cell, integrated energy-environmental modelling, and a demonstrative module for educational purposes.

A. Solar Photovoltaic Electricity Generation

The solar photovoltaic system utilized in this work was composed by two 250-Wp solar photovoltaic modules manufactured by SolarWorld. Each solar photovoltaic module contains 60 polycrystalline solar cells. Average local solar radiation was found to be 3825 Wh/m^2-day which is consistent with data provided by the Solar Map for Peru, as well as data used by commercial simulation software, including RETScreen from Canada and HOMER PRO from the United States. Average electricity production accounted for 1.91 kWh/day which is equivalent to 698.1 kWh/yr. Thus, the capacity factor for the solar photovoltaic system was found to be 15.9%.

B. Wind Electric Power Generation

The wind power system utilized in this work was composed by a 400-W wind energy converter manufactured by HY. The wind energy converter used in this work has a diameter of 1.6 m and five blades. Average local wind speed at the rotation center of the wind energy converted was found to be 3.1 m/s which is consistent with data provided by the Wind Map for Peru, as well as data used by commercial simulation software, including RETScreen from Canada and HOMER PRO from the United States. Average electricity production accounted for 0.52 kWh/day which is equivalent to 188.9 kWh/yr. Thus, the capacity factor for the wind energy system was found to be 5.4%.

C. Hydrogen Production by a PEM Fuel Cell

Hydrogen has been produced using electricity generated by solar and wind energy resources. Hydrogen has been obtained through an electrolysis process utilizing a PEM-type Fuel Cell. Under local conditions and average of 56.1 kWh was needed in order to obtain 1 kg of hydrogen.

D. Integrated Energy-Environmental Modelling

Overall energy-environmental modelling for hydrogen production based on solar and wind energy resources can be seen in Fig. 4. Electricity is generated at a rate associated with local conditions for solar irradiation (W/m^2) and wind speed (m/s). In this case, combined average daily solar-wind electricity production was 2.43 kWh. Then, the electricity generated is used in a PEM-Type Fuel Cell for hydrogen production. In this case, average annual hydrogen production was 15.81 kg. Local grid carbon emission factor is estimated as 0.56 tCO_2/MWh. Thus, carbon emission reduction might be computed as a result of the amount of equivalent electricity to be substituted by hydrogen produced by solar and wind resources. In this case, 496.7 kg/yr of carbon dioxide might be avoided.

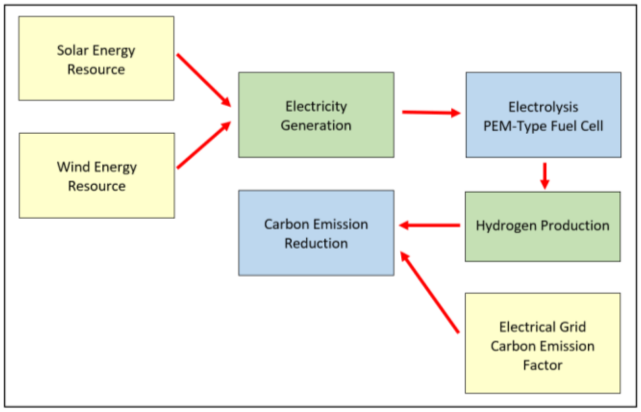

Fig. 4. Energy-Environmental Modelling of a PEM-Type Fuel Cell for Hydrogen Production

E. Demonstrative Module for Educational Purposes

As a result of this work, a demonstrative module composed by a solar photovoltaic system, a wind energy system, and a PEM fuel cell has been implemented at the Environmental Engineering Department in the National University of Engineering, in Lima-Peru for educational purposes.

The aforementioned education module is intended to be used by students and professors in order to learn about the use of renewable energies for hydrogen production and its potential contribution to carbon emission reduction under local resource availability.

IV. CONCLUSIONS

With regard to this work, the following preliminary conclusions can be outlined:

1. Electricity generated by a solar photovoltaic system is directly related to solar radiation locally available and measured in terms of W/m^2. At this particular site, it was determined a capacity factor of 15.9% which is reasonable for local conditions. In other regions of Peru, an equivalent system could reach up to a capacity factor of 30%.
2. Electricity generated by a wind energy system is directly related to wind speed locally available and measured in terms of m/s at the rotation center of the wind converter. At this particular site, it was determined a capacity factor of 5.4% which is reasonable for local conditions. In other regions of Peru, an equivalent system could reach up to a capacity factor of 45%.
3. Hydrogen produced by an electrolysis process using a fuel cell is directly related to the electric power input for the fuel cell. In this particular case, a PEM-type fuel cell has been used in order to produce 17.8 grams of hydrogen per kWh.
4. The energy-environmental modelling as applied to this particular case reflects the interaction among the use of renewable energies, hydrogen production, and potential contribution to carbon emission reduction for the local electric grid. Carbon emission reduction is associated by the electricity generation share coming from renewable energy, using hydrogen as an energy carrier, in order to substitute electricity generated by local power plants.
5. Last but not least, a suitable demonstrative module been set up, for educational purposes, at the Environmental Engineering Department located on the main campus of the National University of Engineering, in Lima-Peru.

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