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Assessment of Solar Hydrogen Production in an Energetic Hybrid PV-PEMFC System

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***Abstract*—**This paper discusses the design and analysis of a hybrid PV-Fuel cell energy system destined to power a DC load. The system is composed of a photovoltaic array, a fuel cell, an electrolyzer and a hydrogen tank. HOMER software is used in this study to calculate the optimum capacities of the power system components that their combination allows an efficient use of solar resource to cover the hourly load needs. The optimal system sizing allows establishing the right balance between the daily electrical energy produced by the power system and the daily electrical energy consumed by the DC load using a 28 KW PV array, a 7.5 KW fuel cell, a 40KW electrolyzer and a 270 Kg hydrogen tank. The variation of powers involved into the DC bus of the hybrid PV-fuel cell system has been computed and analyzed for each hour over one year: the output powers of the PV array and the fuel cell, the input power of the elctrolyzer system and the DC primary load. Equally, the annual variation of stored hydrogen produced by the electrolyzer has been assessed. The PV array contributes in the power system with 82% whereas the fuel cell produces 18%. 38% of the total energy consumption belongs to the DC primary load while the rest goes to the electrolyzer.

***Keywords*—**Electrolyzer, Hydrogen, Hydrogen Fueled Cell, Photovoltaic.

I. Introduction

THE depletion of fossil fuels (coal, oil, natural gas), climate change, gradual deterioration of the ozone layer, biosphere and biodiversity balance disturbance are all factors that have promoted new environmental and energy policies based partly on reducing pollutant emissions [1], as required by the Kyoto Protocol signed on 11th December 1997 and on exploiting other renewable or/and clean energies [2], [3].

The emission of greenhouse gases (GHG) is directly related to the technology chosen to produce electrical energy as well to consumers' habits. In this context, renewable energies (solar, wind, hydraulic, biomass, geothermal) know today a particular interest and are seen as a vector of sustainable development and as an alternative solution of fossil fuels since they have the merit to be clean and inexhaustible whatever the consumption [4].

Solar energy (SE) in its photovoltaic branch is the most abundant among all. The intensity of solar radiation received at the ground on an annual average is estimated at about 75000GToe which is equivalent to 0.9 billion of TWh. This energy is 6000 times the current annual global energy consumption [5]. In PV applications, electrical energy is directly obtained from solar radiations using the main power generating unit namely PV module. Using PV systems is interesting as far as ecological and economic aspects are concerned when local conditions are favorable from a viewpoint of solar energy availability.

However, high investment costs of PV installations and the stochastic nature of solar resource are curbing its integration in power plants. Thus, the hybridization of SE with other sources allows exploiting their benefits, both from technical and economic viewpoints. The awareness of the dangerous circumstances of massive use of fuels (depletion, CO2 Emission) urged concerned sectors to swing to other fuels with lesser or none carbon dioxide (CO_2) emission. The hydrogen, produced independently of oil and associated with the fuel cell is one of those alternatives [6]. It can be produced from a variety of sources: natural gas, biomass, water, and easily stored in different forms, liquid or gaseous. Nowadays hydrogen energy is seen as one of the solutions to meet challenges of sustainable development: reducing GHG, local pollution in cities and dependence on petroleum fuels.

The Hybridization of solar resource with hydrogen technology has aroused great interest in view of numerous studies performed in this field focusing on integrating this technology in power generation systems by studying technical, electrical and economic aspects [7], studying methods of producing and storing hydrogen [8], and the integration of intelligent strategies and controllers for an optimized management of electrical energy produced within the system [9]-[11].

The aim of this work is to determine the optimal design of a PV-fuel cell hybrid power system used to power a household on a daily profile corresponding to its electrical energy needs, and to study the variation of powers and hydrogen produced and consumed by the system during one year. In this system, solar energy is the main source of energy.For a continuous supply of electrical energy to the load, the PV system is coupled to an electrolyzer to produce hydrogen that's used by the fuel cell (FC). The FC must meet all the load demand during the period where solar resource is not available. Thus we can establish equivalence between the daily electrical energy produced by the power system and the daily electrical energy consumed by the DC load while taking advantages of using both clean and renewable energies: solar and hydrogen. Both, the analysis and the design of the system have been performed using Hybrid Optimization Model for Electric Renewables (HOMER) software developed by National Renewable Energy Laboratory (NREL) in the United States (USA). It simplifies the task of evaluating the design of off-

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grid and grid-connected electrical power systems. HOMER runs simulations with different energy systems (PV modules, wind turbines, hydroelectric dams, biomass generators, power systems, fuel cells…….) and also offers a wide range of energy storage devices (batteries bank, hydrogen…). It searches for the combination of sources meeting the load and then finds the system achieving the goal with minimum costs. This article is organized as follows: introduction, description of the system components, input data and finally simulation results and discussions.

II. System Description

A. Photovoltaic Generator

A photovoltaic solar module is a direct electric current generator comprising a number of solar cells electrically interconnected. It's the basic module in photovoltaic power plants. Depending on the required power of the load, PV modules are connected in series and/or in parallel.

The power produced by a PV module depends on the intensity of the solar radiation received on its surface as well as the temperature of the junction. It is given by (1):

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{\overline{G_{T,STC}}}\right)\left[1+\propto (T_C - T_{C;STC})\right] \quad (1)$$

P_{PV}: rated capacity of the PV array (output power under standard test conditions [kW]);f_{PV}:PV derating factor [%]; $\overline{G_T}$: Solar radiation incident on the PV array;$\overline{G_{T,STC}}$:Incident solar radiation at standard conditions [1Kw/m^2];$\propto$: Temperature coefficient of power [%/C°]; T_C: PV cell temperature [C°]; $T_{C;STC}$: PV cell temperature at standard test conditions [25C°].

B. Electrolyzer and the Hydrogen Tank

Water electrolyzer consists of several cells connected in series. Its principle of operation is based on the decomposition of water into hydrogen and oxygen. It is made possible by passing a direct current through two electrodes immersed in a liquid or solid electrolyte according to the reactions:

$$\text{Reaction at anode: } H_2O \rightarrow {}^1/_2\, O_2 + 2H^+ + 2e^- \quad (2)$$

$$\text{Reaction at the cathode: } \quad 2H^+ + 2e^- \rightarrow H_2 \quad (3)$$

The hydrogen produced by water electrolysis is stored in the hydrogen tank in the form of compressed gas to be used later by the hydrogen fueled cell.

C. Fuel Cell

A fuel cell (FC) allows direct conversion of chemical energy of combustion (oxidation-reduction) into electrical power, heat and water. A FC is composed of three basic components, two electrodes: an oxidizing anode (electron emitter) and a reducing cathode (electron collector) separated by an electrolyte.

The electrolyte has the ability to lead ionized molecules from one electrode to the other directly and to block the electrons to pass through the external circuit of the FC where electromotive energy can be used.

In the case of a Proton Exchange Membrane Fuel Cell (PEMFC), the electrolyte is a solid polymer membrane that operates at low temperature (20°C-100°C). It selectively transmits to the cathode hydrogen ions (H+) formed by catalytic oxidation of hydrogen injected directly on the anode. The PEMFC has a power ranging from few watts to hundreds of kilowatts.

The electrochemical reactions occurring at the electrodes of a PEMFC are given by equations:

Reaction at the anode, couple H^+/H_2:

$$2\ H_2 \rightarrow 4\ H^+ + 4\ e^- \quad (4)$$

Reaction at the cathode, couple O_2/H_2O:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (5)$$

Over all cell reaction:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{electrical energy} + \text{heat} \quad (6)$$

The expression of the FC voltage is expressed as follows:

$$E_{FC} = E_{Nernst} - \eta act - \eta ohm - \eta conc \quad (7)$$

ηact,ηohm, $\eta conc$are the activation losses, the Ohmic losses and the Mass transport losses.

To calculate the voltage (E) of (n) unit cells connected in series forming an assembly we use the following equation:

$$E = n * E_{FC} \quad (8)$$

$$E_{Nernst} = 1.229 - 0.85T^{-3} * (T - 298.15) + 4.311 * 10^{-5} * T * [ln(P^*_{H2})] + 10ln(P^*_{O2}) \quad (9)$$

P is the effective pressure in atmospheres of oxygen and hydrogen, and T is the temperature in Kelvin.

The power delivered by the FC (P) is expressed as the product of the cell voltage and cell current:

$$P_{FC} = I_{FC} * E_{FC} \quad (10)$$

III. System Operation and Input Data

The hybrid energy system is composed of a PV array, a fuel cell, an electrolyzer and a hydrogen tank as represented in Fig. 1. The PV system feeds the load when solar radiation is available. In situations where there's an excess of the PV power it goes to the electrolyzer that's considered as a second load. The electrolyzer generates hydrogen which is stored in the hydrogen tank as a compressed gaz. The fuel cell generates electricity using the stored hydrogen as a fuel to feed the load when the PV system can't generate the required energy due to low levels of irradiation and/or during the night.

HOMER software simulates a one-year operation of the power system, for this reason two annual profiles are used: the solar radiation and the load profile:

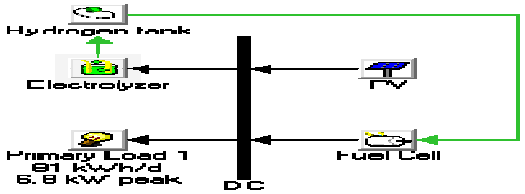


Fig. 1 Power system structure

A. Solar Radiation

The solar radiation profile is an important element that influences greatly the design and the cost of the power system. The solar radiation profile used in this study is that of UDES site situated at 36.39° latitude and 2.42° longitude. Fig. 2 depicts the monthly averages solar radiation data, we can notice that the highest levels of solar radiation are observed from April to September and the lowest levels are observed from October to March. Table I presents the daily radiation data in (kWh/m^2/d) and the clearness index values for the proposed location.

B. Load Profile

The optimal sizing of the power system depends on the amount of electrical energy requested by the household. The description of the household profile consists to define the electrical energy consumed by all electrical appliances: lightning, air conditioning, washing machine, refrigerator, computers, TV, ... The time of maximum solicitation of electrical energy by the load varies from a season to another. Thus in this study, three different profiles, are used, which reflect the seasonal variation of electricity consumption; we have considered a load profile for winter another for summer and a third profile for autumn and spring. The load profiles to supply with electrical power are depicted in Fig. 3. We note that the consumption profiles have the same shape for the three concerned periods of the year (fall, autumn/spring, summer).

TABLE I
DAILY RADIATION DATA AND CLEARNESS INDEX VALUES

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.481	2.313
February	0.506	3.117
March	0.523	4.199
April	0.528	5.203
May	0.545	6.039
June	0.588	6.798
July	0.597	6.743
August	0.618	6.353
September	0.589	5.085
October	0.537	3.598
November	0.491	2.504
December	0.483	2.121

The first phase situated between 00h:00 and 06h:00 is a period of low activities and therefore low consumption of electrical energy. From 06h:00a.m, an increase in electrical energy consumption is observed and reaches its maximum at about 9h:00. Just after there's a fall in the electrical energy demand from 13h:00 to 16h:00 which corresponds to a period of slowed activities rate. For the third phase between 16h:00 and 22h:00, a strong demand for electrical energy is observed, during this period all the members of the family are present at home so the number of electrical appliances used in this time increases and electrical energy consumption increases as well to reach a peak at about 08h:00p.m then the demand for electrical energy falls again.

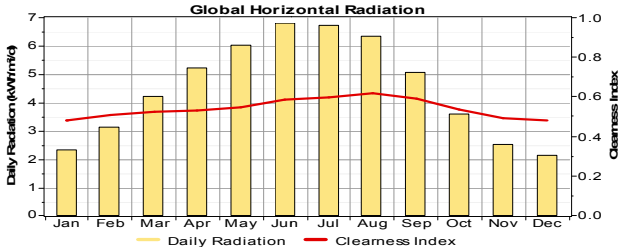


Fig. 2 Monthly averages solar radiation data and clearness index

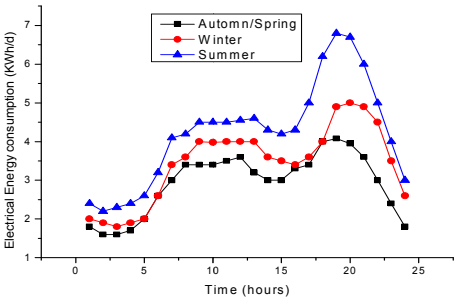


Fig. 3 Load daily profiles

IV. Simulation Results

In addition to the radiation data and load profile, the technical and economic characteristics of the hybrid energy system components [PV modules, FC, electrolyzer and the hydrogen tank] are required to identify the optimal configuration (optimal sizing and optimal cost) of the system that would achieve the right balance between daily needs of electrical energy demand and the daily electrical energy produced by the power system. The technical and economic characteristics of the HES components are given in Table II.

TABLE II
TECHNICAL AND ECONOMIC CHARACTERISTICS OFTHE HES COMPONENTS

Component	CAPITAL COST ($/KW)	Replacement cost ($/KW)	Size (KW)	Lifetime (years)
PV modules	5678	5678	20-30	15
Fuel cell	3000	3000	5-10	40000 hrs
Electrolyzer	2100	2100	20-45	15
Hydrogen tank	1600 ($/Kg)	1600 ($/Kg)	150-300	25

The simulation results of the system are represented in Table III. The optimal configuration of the system comprises a 28 KW cPV array, a 7.5 KW rated power FC, a 40 KW electrolyzer and a 270 Kg hydrogen tank.

The primary DC load is satisfied at 100%. For both the electrolyzer and the load, the PV array ensures 82% of the required electrical energy while the remaining 18%, are

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ensured by the FC; the monthly average electric energy produced by the PV array and the FC are represented on Fig. 4; the output power of the PV array achieves its highest levels from May to September and therefore the FC operates less compared to other months of the year where the output power of the PV array is lower due to low radiation levels which could be clearly observed from November to February.

TABLE III
TECHNICAL AND ELECTRICAL CHARACTERISTICS OF THE SYSTEM

Optimal System	Production (KWh/Yr)	Consumption (KWh/Yr)
28KWcPV array	PV array: 64510 (82%)	DC primary load: 29151 (38%)
7.5 KW Fuel Cell	Fuel Cell: 13871 (18%)	Electyrolyzer Load: 46891 (62%)
40KW elecytrolyzer	Total: 78382(100%)	Total: 76041 (100%)
270 Kg Hydrogen Tank		Electricity excess: 2340 (2.99%)

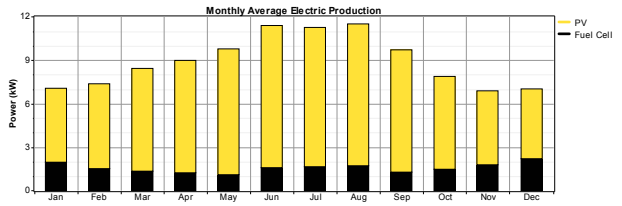


Fig. 4 Monthly average electric energy produced by the PV array and the FC

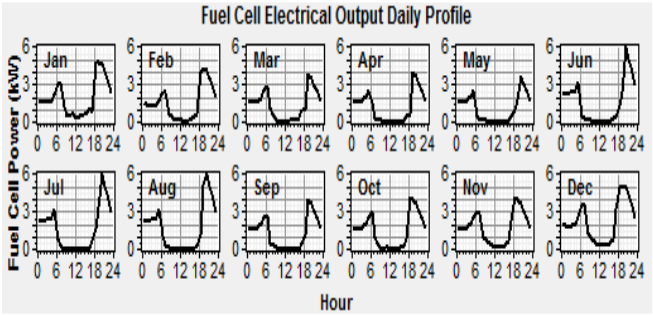


Fig. 5 The FC electrical output daily profiles

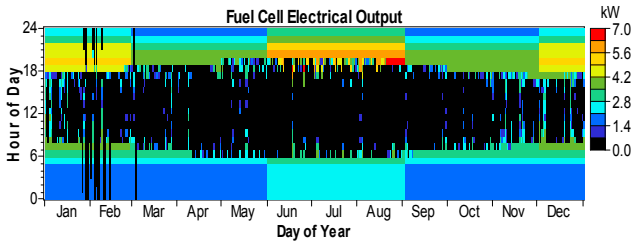


Fig. 6 The yearly output power of the FC

The PV plant operates 4367hrs/Yr to produce 35711 KWh/Yr of electrical energy with a capacity factor of 26.3%. Its average daily output power is about 177 KWh/d. The energy consumed by the electrolyzer is used to produce about 1010 Kg/Yr of hydrogen with a capacity factor of 13.4 %.

Regarding the FC, it produces 13871 KWh/Yr of electrical energy with a capacity factor of 21.1% which is equivalent to 5380 Hrs of operation. The number of starts of the FC is about 486 starts/Yr, so the FC operates almost 11Hrs for each start. If we consider that 365 starts correspond to the number of nights per year where the FC should work, it means that the FC intervened 121 times during the day over all the year to compensate for the lack of electrical energy that the PV array was not able to provide. The electrical output power daily profiles of the FC are represented by Fig. 5. To produce this annual amount of electricity, the FC consumes about 832Kg of hydrogen per year with a rate of 0.06Kg/KWh of electricity, which is equivalent to 27743KWh/Yr of energy. Thus, the efficiency of the FC is 50%.

The annual output power of the FC is represented on Fig. 6, the FC operates during the night when there's no solar radiation or during the day to supplement the load demand when the PV power is not enough to meet demand.

A close inspection of Fig. 6 shows that the output power of the FC is lower in the morning (00h: 00 to 06h: 00) than in the evening from 18h:00; this is due to low demand for electrical energy during this time range of the day.A direct relation between the operation time of the FC, the day duration and the solar radiation intensity is observed: in winter, which corresponds to short day duration and low levels of solar irradiation, the operation time of the FC is the highest compared to other seasons where the FC starts functioning approximately at 18h00p.m until 08h:00. This time is reduced in spring and autumn where the FC starts functioning at about 19h:00p.m and stops at about 07h:00 so the operation time is reduced by about two hours. In summer, where high solar radiation levels are observed, the operation time of the FC is reduced by about three Hours compared to winter. However, the output power of the FC achieves its highest level in summer where the peak demand of the load is observed, this power is reduced in winter and then it achieves its lower level in autumn and spring which coincides with load profiles of Fig. 3.

The FC contributed during the day in supplying the load with electrical energy when the PV power is not enough to cover the load needs, but the rate of contribution is higher in winter than in the other periods of the year, in this period the output power of the PV array is low due to low solar radiation levels and therefore not enough to cover the total energy needed by the load.

The lowest levels of stored hydrogen are observed in the period from January to March due to the increased dependence on the FC. During this period, the output power of the PV array is the lowest compared to the rest of the year due to low levels of solar irradiation and short day duration. In this case, the PV array does is not only lacks of excess power for storage but it's also unable to meet the load demand for electrical energy Fig.7.The hydrogen produced annually by the electrolyzer is equal to 1010 Kgs/Yr which results in an energy storage capacity of 33678 KWh/Yr and an autonomy of 2660 hrs. The extreme capacity of the hydrogen storage tank (270Kg) is observed from August to November. In this period the tank is filled with hydrogen produced using the excess of electrical power produced by the PV array. As we can see from Fig. 8, the tank is 100% filled with hydrogen for

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18% of the year which corresponds to the period from September to November, see Fig. 9.

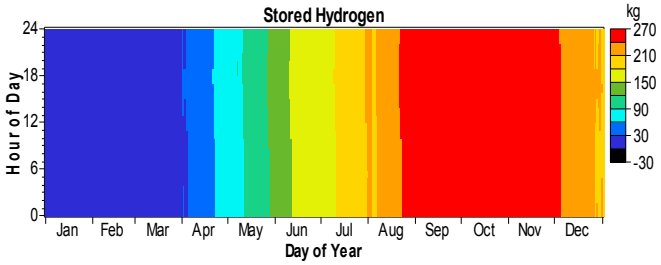


Fig. 7 The yearly hydrogen tank storage level

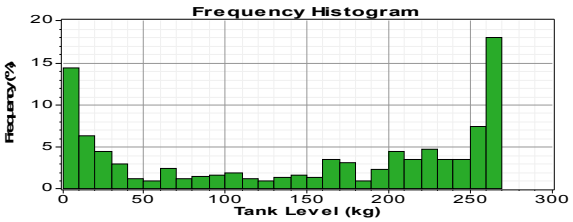


Fig. 8 The frequency of yearly storage tank levels

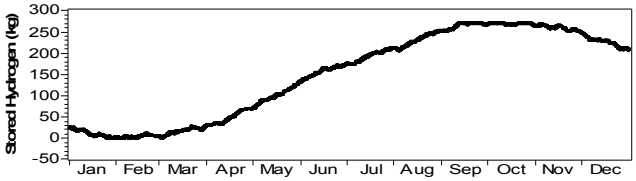


Fig. 9 Annual variation of stored hydrogen

For each component of the power system, the input and output powers are computed. Fig. 10 shows the evolution of powers involved in the DC bus of the PV-FC system for a typical day.

In this case, the FC operates only during the night, from 00h: 00a.m to 06h: 00, the FC supplies the load with the required electrical energy. From 06h: 00, the PV array takes over the production during the day and the excess of energy is consumed by the electrolyzer to produce hydrogen. At about 17h:00, the output power of the PV array is not enough to cover the load demand, then the FC starts providing the additional power and finally at 19h:30it provides the entire amount of electrical energy to the load when the there's no more solar radiation.

Fig. 11 shows a particular case of the system operation where the power produced by the PV system is less than the power required by the load during the day, in this case the FC intervenes all over the day to produce the additional or the entire amount of electrical energy. As we can see, from 00h:00 to 08h:00 the FC powers the load, then at 08h:00 the PV array starts feeding the load however this energy is less than the required , the deficit of energy is then ensured by the FC.This situation lasts all the day until 18h: 00p.m where the FC takes over the total production.

The input power of the electrolyzer system is equal to zero throughout the day the moment there is no energy excess. The stored hydrogen level in its turn has fallen down during the day for it has been consumed by the FC. This situation appeared during winter season where the radiation levels are low or on partly sunny days.

Another case that may appear during the system operation is shown in Fig. 12. We observe from 6h: 00 am to 11h:00a.m that the surplus of energy produced by the PV array is used by the electrolyzer. Around 11h: 00a.m, the excess of energy is no longer consumed. This is because the output power of the PV array exceeds largely the load demand and a high excess of energy produced by the PV system is observed which allows filling the tank with hydrogen and reaching quickly its maximum value (270KGs), this level is maintained since the FC is not used during the day. Once the tank is filled to its maximum, the electrolyzer doesn't consume any more the energy produced by the PV array in excess and consequently this energy is wasted. The energy excess produced by the system is equal to 2.99%, this situation occurs in September and October see Fig. 9.

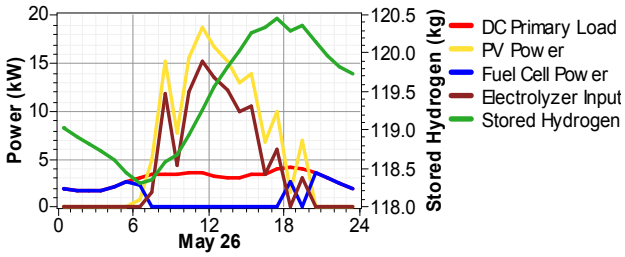


Fig. 10 Input and output powers involved in the DC bus of the power system for a typical day

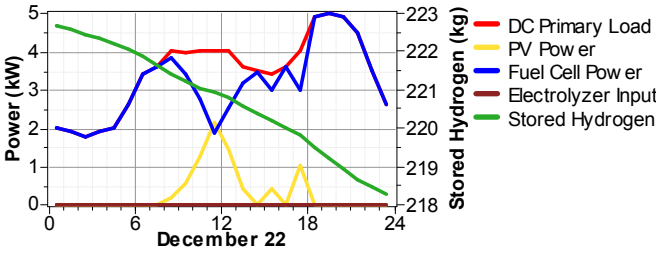


Fig. 11 Input and output powers involved in the DC bus of the power system when output PV power is less than the load demand

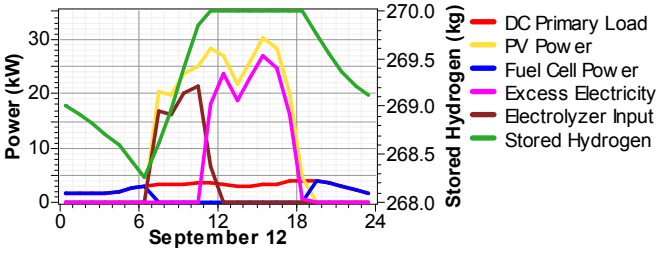


Fig. 12 Input and output powers involved in the DC bus of the power system in the case where the hydrogen tank is filled

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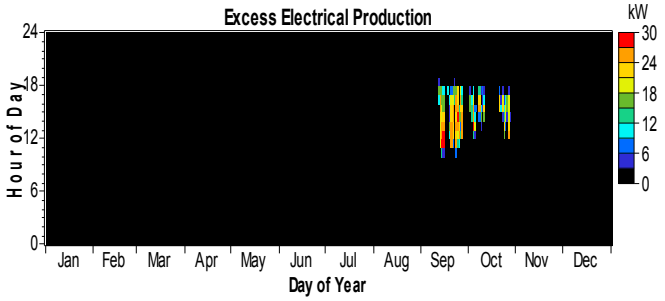


Fig. 13 Annual excess electricity

V. Economic Results

The system under study presents a net present cost (NPC) of 826065 ($) for an annual real interest rate of 6%. As we can see from Table IV, the hydrogen tank presents 50% of the total cost of the system, followed by the PV system with 25% then the FC and electrolyzer with about 25% for both. Thus, from a financial viewpoint, systems using hydrogen as mean of energy storage is not a favorable solution compared to systems using batteries especially for systems of high capacities.

TABLE IV
Economic Characteristics of the System

Component	NPC ($)	Cost of Energy C.O.E ($/KWh)
PV array	212,975	
Fuel Cell	100,922	
Elecytrolyzer	107,168	2.217
Hydrogen Tank	405,000	
System	826,065	

VI. Conclusion

In this article, the design and optimization of a renewable hybrid PV-fuel cell system is presented. The system has been optimally sized using Homer 2.68 beta Software of NREL and considering a number of constraints and input data (load and solar radiation profiles, technical and economic data). The system comprising a 28 KWc PV array, a 7.5KW rated power fuel cell, a 40 KW electrolyzer and a 270 hydrogen tank was found optimal and achieved the imposed design criteria. The simulation carried out in this study showed how the input and output powers of the system are affected by the season period and consumers' habits (load).

The study allowed us to reap the benefits of PV-FC systems for a sustainable development in the future; first the hydrogen is a clean fuel produced locally independently of fuels and exploiting a clean resource which is in our case solar energy: no costs related to fuel transportation or harmful substances released in the atmosphere, secondly the products generated during the process of producing hydrogen out from water or generating electricity from hydrogen (oxygen gas, heat, water) are clean, safe and they don't present any hazard effects on the environment.

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