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Study and dimensioning of a Wind-Electrolyzer-Fuel cell system for the power supply of an isolated site.

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Abstract— ***The development of hybrid systems of renewable electricity generation with or without hydrogen storage, particularly in isolated sites, whose aim is to ensure power supply without interruption and minimize the environmental hazard, represents a viable and sustainable solution. It is in this context that this work was undertaken, it relates to the study and the dimensioning of a hybrid autonomous system Wind-Electrolyzer-Fuel Cell (WG-FC) to provide the energy needs of an isolated site in the deep south of Algeria. It is about the development of a model, in MATLAB SIMULINK, of a hybrid system of simultaneous production of electricity and hydrogen for power supply of this isolated site. The principal interest of this system is the clean production on the place of consumption (autonomous system) and the mutualisation of the resources.***

Keywords— ***Hybrid system, electricity production, renewable electricity, wind, autonomous, electrolyzer, fuel cell, storage, hydrogen, Matlab Simulink.***

I. Introduction

Until now, the electricity generation was mainly due to the nuclear industry and processing of natural resources fuels. These two modes of production pose problems whose importance is growing over the years. It is about the storage of the nuclear waste and the disappearance envisaged of the principal sources of fossil energy.

The environmental constraints concerning the rejections in the atmosphere of gases for purpose of greenhouse also reinforce the idea of a clean, sparing and durable production of electrical energy, thus, the modes of production resting on the renewable energy conversion (wind, solar, etc.) have to be used more and more within the framework of the durable development. Because of these upheavals and taking into account the nature distributed of wind layer, it is legitimate to imagine a policy of development of energy going in the direction of a decentralization of the means of production coupling several sources of complementary energy (wind, photovoltaic, fuel cell, diesel…).

In the field of the wind potential assessment and design of systems for converting wind energy, we can cite studies of Himri et al. in the assessment of wind potential in the South and South-West of Algeria **[1], [2]**. The work of Koussa et al. for Adrar region **[3]** and the work of Helal et al. for the region of Beni-Saf **[4]**. In this case, the recourse to hybrid systems integrating renewable energies presents a strategic choice which is justified by a positive incidence that is from the economic or environmental point of view. Some studies have been reported in the literature to model hybrid renewable energy systems, FC power plants, and other relevant area, among them, khan et al **[5],[6]** presented the model of a small wind-fuel cell hybrid energy system and analyzed life cycle of a wind-fuel cell integrated system. Delfino and fornari **[7]** investigated a grid integrated fuel cell-wind turbine system.

In Ref **[8],** power conditioning for a wind-hydrogen energy system has been reported. Bechrakis et al **[9]** investigated simulation and operational assessment for a small autonomous wind-hydrogen energy system. Barbir **[10]** proposed a system for the production of hydrogen from renewable energy sources using PEM electrolysis.

In Ref **[11],** a dynamic model of a PEM electrolyzer and a hydrogen storage model is produced. Mathematical modeling and simulation of dynamic systems are important in order to develop the best hybrid system.

The aim of the present study is the development of a model in Matlab simulink environment of a hybrid system of simultaneous production of electricity and hydrogen for the power supply of a remote site in southern of Algeria.

II. METHODOLOGY

The adopted step is based on two approaches, the first consists to use the software Matlab simulink to study the dynamic behavior of the system, and the second consists in using the software HOMER for the optimization of the system.

III. SITE SELECTION

The estimation of the wind power available on a given site is probably the most significant stage when it is a question of considering the establishment of an operating system of this energy **[12],** the various characteristics of the sites object of our study (Ghardaia, Tindouf, Hassi R'mel and Adrar) are illustrated in table 1.

The various characteristics of the studies sites (Ghardaia, Adrar, Tindouf and Hassi R'mel) are calculated at 10 m height compared to the level of ground.

The site of Adrar marks the first place with a mean velocity of the wind which reaches 6.3 m/s, a available wind power of 280.5 W/m², and an annual energy of 1458.6 Kwh/m².

TABLE I
SITES CHARACTERISTICS.

	Ghardaia	Tindouf	Hassi R'mel	Adrar
K	1.47	1.54	2.40	2.14
C (m/s)	2.62	5.77	6.89	7.12
<V> (m/s)	2.37	5.19	6.11	6.30
<V^3> (m^3/s^3)	37.33	365.98	370.74	448.80
<P> (W/m²)	23.33	228.74	231.71	280.50
<Pr> (KWh/m²)	13.82	135.55	137.31	166.21
E (KWh/m²)	121.32	1189.43	1204.91	1458.6

IV. WEIBULL DISTRIBUTION

Generally, the wind speed variation is not stable such as it is the case of Ghardaia and Tindouf.
Tindouf with 5.19 m/s mean wind speed is more favorable compared to Ghardaia with 2.37 m/s mean wind speed.
Hassi R'mel wind speed distribution is less symmetrical, that means that the wind is not really stable. Consequently, Adrar marks an advantage compared to Hassi R'mel with 6.3 m/s mean wind speed, and symmetrical wind speed distribution which meant the stability of this site.

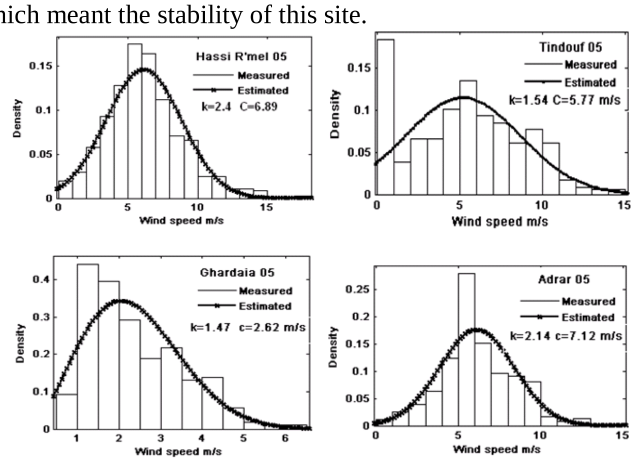

Fig.1: Weibull distribution

According to table 1, the fig 1, we note that the site of Adrar is more favorable for the establishment of our WG-FC hybrid system.

V. SYSTEM DESCRIPTION

The dynamic simulation model is described for the wind-fuel cell hybrid generation system, the model developed in Simulink environment consists on six main blocks: wind turbine, electrolyzer, PEM fuel cell, power control system, and two blocks for the P-I conversion. The bloc diagram is shown in fig 2.

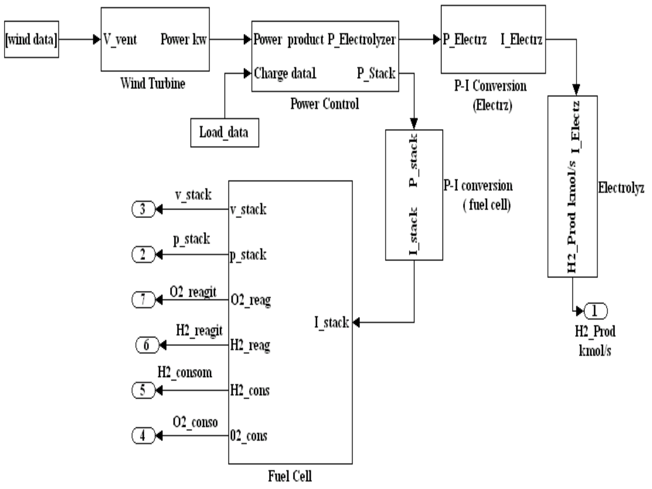

Fig 2: system components

When the electrical power produced by the wind generator is greater than the instant load requirement, the excess power is used for the power output is less than the load requirement, the extra power is delivered by the fuel cell consuming the hydrogen previously stored.

A. Wind turbine model

The ENERCON E33 wind turbine is used, its diameter is 33.4 m. it produces a power of 330 KW at a wind speed of 12.5 m/s. the wind turbine power curve obtained from the manufacturer is shown in fig. 3.

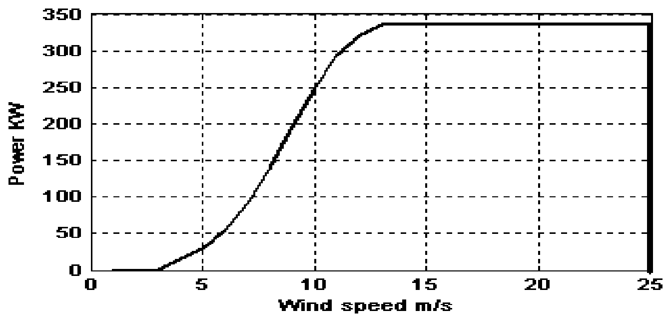

Fig.3: ENERCON E33 wind turbine power curve.

A wind turbine model is developed using simulink, it is shown in fig 4

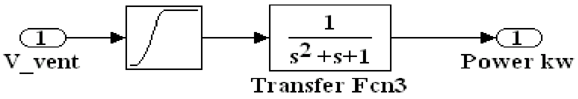

Fig.4: wind turbine model.

B. Electrolyzer Model

According to Faraday law, the production rate of hydrogen in an electrolyzer is given as **[5]:**

$$n_{H2} = \frac{\eta_F . n_C . i_e}{2.F} \qquad (1)$$

Where i_e is the electrolyzer current, n_c is the number of electrolyzer cells in series and η_F is the Faraday efficiency which is the ratio between the actual and theorical amount of hydrogen produced in the electrolyzer, it can be given as **[3]:**

$$\eta_F = 96.5 * exp\left(\frac{0.09}{i_e} - \frac{75.5}{i_e^2}\right) \qquad (2)$$

According to the Eqs (1) and (2), a simple electrolyzer model is developed using simulink, which is illustrated in fig 5.

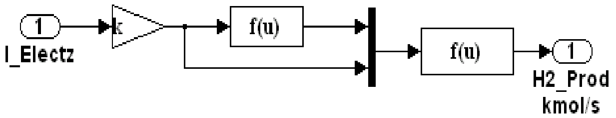

Fig.5: Electrolyzer model

C. Fuel Cell Model **[15]**

The Proton Exchange Membrane Fuel Cell (PEMFC) system parameters are given in table2.

TABLE 2: FC SYSTEM MODEL PARAMETERS

FC model parameters	
Activation voltage constant (B)	0.04777 A^{-1}
Activation voltage constant (C)	0.0136 V
Faraday's constant (F)	96484600 $ckmol^{-1}$
Hydrogen time constant (τ_{H2})	3.37 s
Hydrogen valve constant (K_{H2})	4.22 10^{-6}
Kr constant	1.8449 10^{-6}
N_O load voltage (E0)	0.6 V
Number of cells (N0)	712
Oxygen time constant (τ_{O2})	6.74 s
Oxygen valve constant (K_{H2})	2.11 10^{-5} kmol/s atm
FC internal resistance (R_{int})	0.00303 Ω
FC absolute temperature (T)	343 K
Universal gas constant (R)	8314.47 J/kmol k
Utilization factor (U)	0.8
Water time constant (τ_{H2O})	18.418 s
Water valve constant (K_{H2O})	7.716 10^{-6} K MOL/s atm

The amount of hydrogen and oxygen consumed in the fuel cell depends upon the input and output flow rates and the current drawn out of the fuel cell; it also depends upon the volume of electrodes.
The different partials pressures can be given as **[16]**:

$$P_{H2} = \frac{\frac{1}{K_{H2}}}{\tau_{H2}.S + 1}\left(\dot{m}_{H2}^{in} - 2.K_r.I\right) \qquad (3)$$

$$P_{O2} = \frac{\frac{1}{K_{O2}}}{\tau_{O2}.S + 1}\left(\dot{m}_{O2}^{in} - K_r.I\right) \qquad (4)$$

$$P_{H2O} = \frac{\frac{1}{K_{H2O}}}{\tau_{H2O}.S + 1}(2.K_r.I) \qquad (5)$$

The thermodynamic potential E is given by **[2]:**

$$E = \left[E_0 + \frac{R.T}{2.F} * \log\left(\frac{P_{H2}.P_{O2}^{\frac{1}{2}}}{P_{H2O}}\right)\right] \qquad (6)$$

The ohmic voltage loss in the fuel cell is given by:

$$\eta_{ohmic} = I.R_{int} \qquad (7)$$

The parametric equation for the over-voltage due to activation resistance is given as**[5]**:

$$\eta_{act} = B * \log(C * I) \qquad (8)$$

The output voltage of the cell can be determinated from the combined effect of thermodynamics, mass transport, kinetics, and ohmic resistance, it is defined as:

$$V = E - \eta_{act} - \eta_{ohmic} \qquad (9)$$

The fuel cell power is a function of the current and voltage; it is given as follows **[16]**:

$$P = V_{Stack} . I \qquad (10)$$

From the various equations (partial pressures, thermodynamics potential, voltage ohmic…) and the characteristics given in table 1, we carried out a model of a fuel cell using Matlab simulink, as it is shown below:

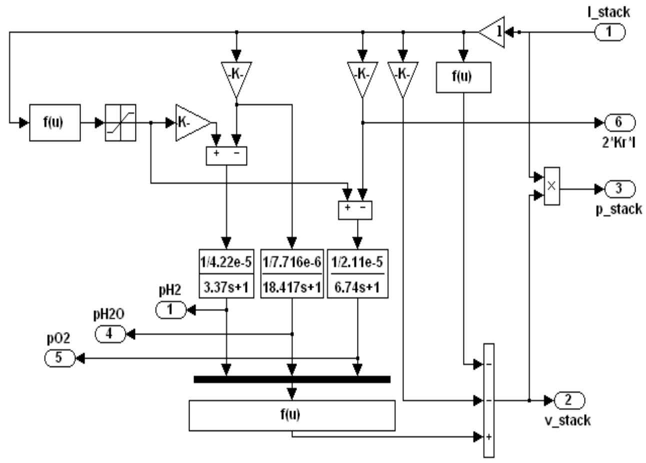

Fig.6: Fuel cell model

VI. Wind speed data

The wind speed data were taken over a period of one year at a height of 10 m above ground level. These data were calculated at 70 m hub height using power law (Justus 1978), at this height the average wind speed became 9 m/s while at 10 m it was only 6.3 m/s, the wind speed evolution at 70 m is shown in fig 7.

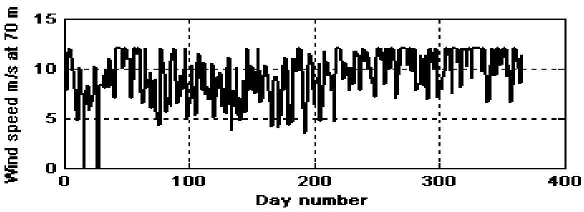

Fig.7: wind speed

VII. User electric request

The energy demand of user in the site of Adrar is shown in fig.8. The annual peak load of 150 Kw was observed on January and minimum of 55 KW on June, July, August. So the higher demand exists between January and March, and December, while relatively average load requirements are found during rest of the period of the year.

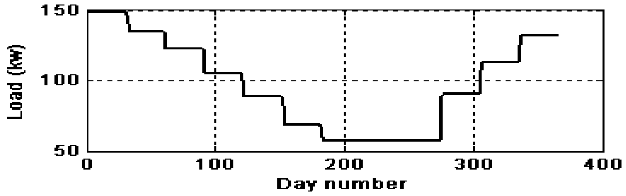

Fig.9: wind power.

The wind power available at a height of 70 m above ground level is in continuous variation over the year, the average power of the wind is about 500 KW, this power reaches its maximum spade of approximately 3000 KW. The power of the weakest wind which characterizes the site of Adrar is about 90 KW.

The capacity operating by the wind turbine is 200 kw, with sometimes significant powers reaching up to 350 kw lasting the season of winter, as it is shown in fig.10

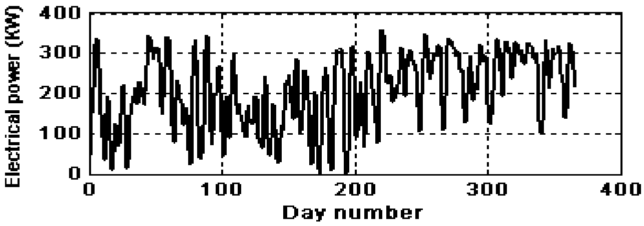

Fig.10: Electrical power.

The power provides to the electrolyzer represents the excess of energy produced by the wind turbine and not consumed by the user. It is seen that the current is of as much significant, and of this fact as deferred in fig.11.

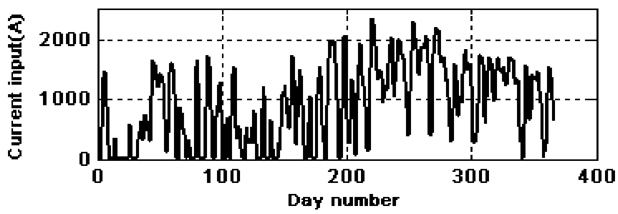

Fig.11: Electrolyzer current input.

The fig.12 shows that, the hydrogen production depends on electrolyzer current input, the quantity of hydrogen produced increases with the packing of current, the production of hydrogen is significant that the needs for the load are less weak. The average quantity of hydrogen produced is about 0.025 kmol/s

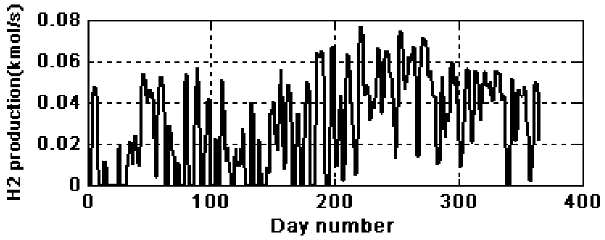

Fig.12: hydrogen production.

The fuel cell consumes only the quantity of hydrogen necessary to the supply of the current required by the load.
The hydrogen consumption is maximum during February and January about $1.2*10^{-4}$ kmol/s.
The quantities of oxygen and hydrogen are null during the periods or the turbine satisfies the energy needs for the fed site, such as it is the case for February, March, April, May, June and October. As it is illustrated in fig.13 and 14.

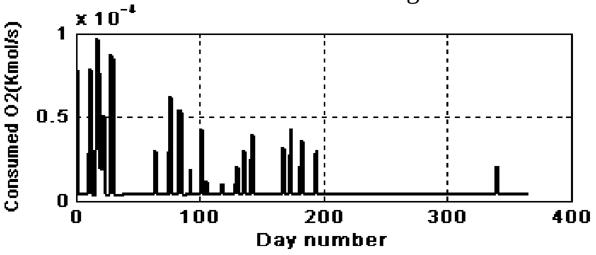

Fig.13: oxygen consumption.

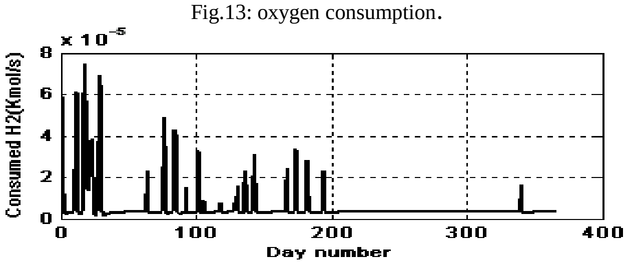

Fig.13: hydrogen consumption.

The maximum voltage of the FC is 420 V, it follows the variations of the current. As it is shown in fig.14

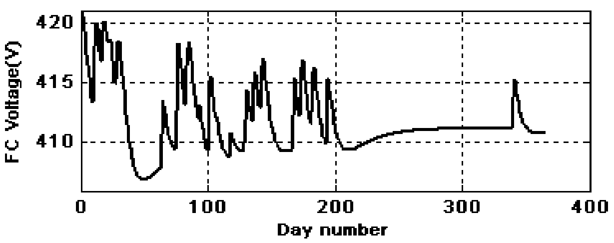

Fig.14: fuel cell voltage.

The fuel cell power follows the variations of the output current, quantity of required energy. For the climatic periods or favorable conditions and when the wind turbine satisfies the load, the production of the FC ceases, just as it is the case for the periods (40^{th} -60^{th} day, 200^{th} to 340^{th} day of the year (There is no electricity production).

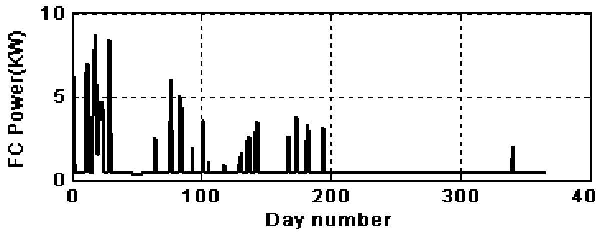

Fig.15: fuel cell power.

VIII. SYSTEM DIAGRAM

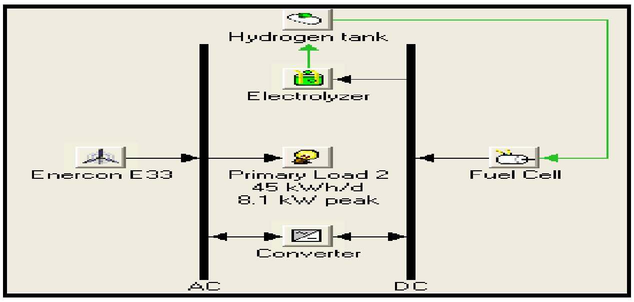

Fig.16: System diagram.

IX. SIMULATION AND RESULTS

The possible configurations of WG-FC hybrid system are shown in fig.17

E33	FC (kW)	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	FC (hrs)
1	8	6	4	8	$ 902,720	4,207	$ 1,007,898	2.456	1.00	22
1	8	8	4	8	$ 902,853	4,212	$ 1,008,148	2.457	1.00	22
1	8	6	5	8	$ 902,970	4,212	$ 1,008,273	2.457	1.00	22
1	8	10	4	8	$ 902,987	4,216	$ 1,008,398	2.457	1.00	22
1	8	8	5	8	$ 903,103	4,217	$ 1,008,523	2.457	1.00	22
1	8	6	6	8	$ 903,220	4,217	$ 1,008,648	2.458	1.00	22
1	8	10	5	8	$ 903,237	4,221	$ 1,008,773	2.458	1.00	22
1	8	8	6	8	$ 903,353	4,222	$ 1,008,898	2.458	1.00	22
1	8	10	6	8	$ 903,487	4,226	$ 1,009,148	2.459	1.00	22
1	8	6	8	8	$ 903,720	4,227	$ 1,009,398	2.460	1.00	22
1	8	8	8	8	$ 903,853	4,232	$ 1,009,648	2.460	1.00	22
1	8	10	8	8	$ 903,987	4,236	$ 1,009,898	2.461	1.00	22
1	8	6	10	8	$ 904,220	4,237	$ 1,010,148	2.461	1.00	22
1	8	8	10	8	$ 904,353	4,242	$ 1,010,398	2.462	1.00	22
1	8	10	10	8	$ 904,487	4,246	$ 1,010,648	2.463	1.00	22
1	10	6	4	8	$ 902,920	4,515	$ 1,015,807	2.476	1.00	19
1	10	8	4	8	$ 903,053	4,520	$ 1,016,057	2.476	1.00	19
1	10	6	5	8	$ 903,170	4,520	$ 1,016,182	2.476	1.00	19
1	10	10	4	8	$ 903,187	4,525	$ 1,016,307	2.477	1.00	19
1	10	8	5	8	$ 903,303	4,525	$ 1,016,432	2.477	1.00	19
1	10	6	6	8	$ 903,420	4,525	$ 1,016,557	2.477	1.00	19
1	10	10	5	8	$ 903,437	4,530	$ 1,016,682	2.478	1.00	19
1	10	8	6	8	$ 903,553	4,530	$ 1,016,807	2.478	1.00	19
1	10	10	6	8	$ 903,687	4,535	$ 1,017,057	2.479	1.00	19
1	10	6	8	8	$ 903,920	4,535	$ 1,017,307	2.479	1.00	19

Fig.17: System configurations

The optimal system is composed of a wind generator, an electrolyzer, a fuel cell (FC), the size and the capacity of the elements of this system suggested by HOMER are illustrated in table 3.

TABLE 3: OPTIMAL SYSTEM CHARACTERISTICS

Components characteristics	
Number of aerogenerators	1
Converter nominal power (kw)	8
Electrolyzer nominal power (kw)	6
Tank capacity (kw)	4
FC nominal power (kw)	8

The wind generator energy production is showen in fig18.

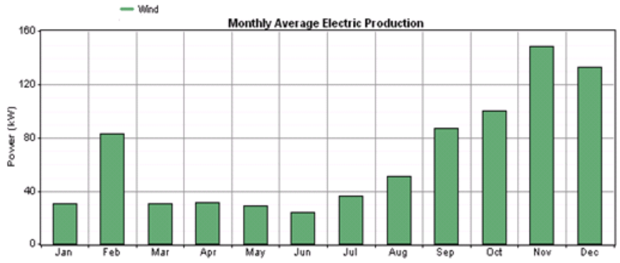

Fig.18: Monthly wind generator energy production.

The excess electrical production monthly average is shown in fig.19.

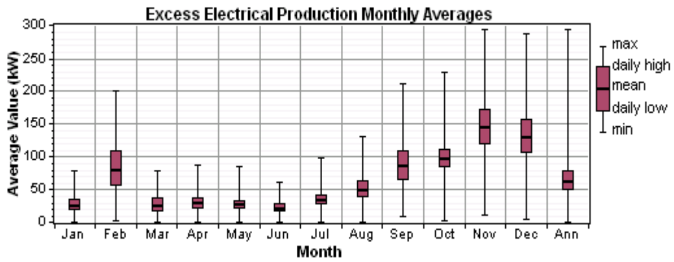

Fig.19: Excess electrical production monthly average

Table 4 shows the hydrogen consumption and production.

TABLE 4: HYDROGEN

Element	**Quantity kg/y**	**%**
Production	26.5	100
Consumption	26.2	100
Excess	0	0

A WG-FC system seems to be most feasible economically with a minimum total net present cost (NPC) of 1,007,150 $ and minimum cost of energy (COE) of 2.456 $/KWh. Although, the system represent a higher initial capital.

TABLE 5: ECONOMICAL ASPECT OF SYSTEM.

Component	**costs**	**Elementary cost**
WG	905,625	0.0334 $/kwh
Converter	1,000	----
Hydrogen	-----	706,661 $/kg
FC	166,633	180 $/kg
system	1,077,150	2.624 $/kwh

The concentrations of various constituents of pollution like CO2, CO, nitrogen, for the hybrid system are summarized in table 6.

TABLE 6: GREEN HOUSE GASES EMISSIONS.

Elements	**Emission kg/year**
CO2	0
CO	0
SO2	0
NO	1.52

X. CONCLUSION

The work presented in this document relates to devices power of autonomous systems. These devices are set to under go major developments related mainly to a desire to display more diversification of means of production and improved environmental friendliness. The processing of wind data available, enabled us to note that Algeria has appreciable wind resources with mean velocities annual higher than 4 m/s, and that the season of spring is been windy with speeds of about 5m/s.

The comparative study between the sites object of our study, reveals that the site of Adrar is favorable for the implementation of our autonomous hybrid system, our choice is based partly on the significant wind potential available in this site, and to the presence of water sources, the thing which facilitates the supply water to ensure the quantity of water necessary to supply the electrolyzer.

To study the dynamic behavior of the entire system, a simulation program using MATLAB SIMULINK was developed, and an example of simulation was applied to an isolated site (Adrar) in southern Algeria where the meteorological data are available.

For the optimization and the simulation of our hybrid autonomous system WG-FC, we chose software HOMER (**Hybrid Optimization Model** for **Electric Renewables**) which is a tool of simulation and optimization of the simple and hybrid installations, stand-alone or connected to the network, and integrating renewable energies.

The environmental study, allowed us to better justify the interest of hybrid plants using renewable energies, with reductions of the greenhouse gases emissions. The recourse to a hybrid installation thus presents a strategic choice, which is justified by a positive incidence that is from the economic point of view or the environmental level. This choice becomes very significant if the environmental criterion passes initially, in order to cure the problem of the air pollution and consequently the climatic reheating.

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