Technical, Economical and Environmental Comparative Analysis of a Microgrid Using Battery and Pumped Hydro Storage for Remote Area Electrification in Southern Algeria

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***Abstract*—Aim of this research is to analyze the techno-economic and environmental performance of the hybrid energy system (HES) to meet the electricity demand of an off-grid community and the dump load in the Indalek village located in the southern of Algeria. Different combinations of HES, such as PV/FC/DG/battery (BESS) and PV/FC/DG/Pumped hydro storage (PHS), are modeled, analyzed and compared using HOMER software. The techno-economic environmental performance analysis has evaluated the net present cost (NPC), cost of energy (COE), excess electricity (EE), fraction of renewable energy (RF) and CO2 emissions of the different combinations of HES. The simulation results shows that the hybrid energy system with BESS is the best feasibility techno-economic performance with the least NPC, COE and the higher EE of $438335.21, $0.1423/KWh, 36222 KW/year, respectively. On the contrary, the HES with PHS has the highest fraction of renewable energy of 87.4% and the most environmentally friendly with 96.43% reduction in CO2 emissions compared to the HES with BESS. Finally, the sensitivity analysis is performed on the hybrid energy system with BESS shows that the improvement of the derating factor with the increase load leads to a lower the COE.**

Keywords—Microgrid, hybrid storage, remote area, economical study, technico-economical analysis, environmental analysis.

I. Introduction

The growth for electrical energy demand is expected to blow up by 30% in 2030, mainly because of the world's industrial development needs [1]. Despite some progress in renewable energies in some countries, more than 70% of the global electricity demand is provided by fossil fuels resources (oil, natural gas and coal) [2]. In remote areas, the need for electricity is also increasing for best quality of population live. These regions are usually supplied by diesel-based generation systems. Diesel generators have environmental and economic issues, which can be mitigated by the inclusion of renewable energy sources in the energy mix [4]. From the beginning of 2000, there has been an increasing interest for the use of various renewable energy sources such as solar energy, wind energy, wave energy, geothermal energy and biomass energy [3]. The production of electrical energy by the renewable energies faces the problem of intermittency, particularly in the case of the use of solar and wind energy. The use of hybrid energy generation systems that can combine several alternative (PV and wind, etc.) and conventional (oil, gas and coal) energy sources with the energy storage systems (BESS, PHS and fuel cell (FC)) represents an interesting deal in generating continious electricity and meeting various levels of demand in remote areas. There are several research studies on the hybrid energy systems (HESs) with different storage systems. Moreover, there are several research literatures focus on the techno-economic analysis environment of the HESs with the different storage systems. For example, PV solar, generator diesel (GD), fuel cell (FC), BESS; PV solar, wind turbine (WT), GD, PHS; PV, GD, PHS; PV, GD, BESS in [3,5,7]. However, there is a brief review of the literature related to the HESs in remote areas in the south of Algeria. It is obvious that the HESs based on PV, GD, fuel cell, BESS, PHS for remote areas of Algeria where it has not been studied yet. Thus, the main objective of this paper is as follows: The technical, economical and environmental comparative analysis between the two HESs, such as PV/ GD/ FC/ BESS and PV/ GD/ FC/PHS for supply the electricity in the Indalek village in the south of Algeria.

This work is organized as follow: in section II, we have described the area of the Indalek village for highlighting the opportunity of implanting a Microgrid there. In the section III, we have resumed the existing configuration, and material data information. In the section IV, a simulation allowed us to fixe energy cost parameters for various storage configuration, and in the last section, we have performed a sensitivity analysis.

II. Site description

The model of the HES in this study was proposed for the Indalek village. The location of this village is 22.59°N, 5.80°E, 1377 m for latitude, longitude and altitude respectively. The study under site has a good level of solar radiation. It receives an annual average solar radiation of 7.26 kWh/m2 per day [6]. The solar radiation data for the study site is extracted from the NASA database [8]. The maximum and minimum solar radiation levels in this village are 7.180 KW/m2/day ,4.10 KW/m2/day in July and December respectively, as shown in the figure 1. The average total solar radiation per year is 5.90 kWh/m2/day. The Indalek village is known by the activity of agriculture, live stockbreeding; its population is estimated at around 500 inhabitants which are not completely connected to a grid utility. the estimates of the load of the unconnected village to a grid utility include the future energy demand calculated as a daily primary demand of 640.98 kwh/day for 11 houses and the dump load of 11.89 kwh/day. The figure 2. shows the daily average energy consumption for different seasons in the Indalek village.

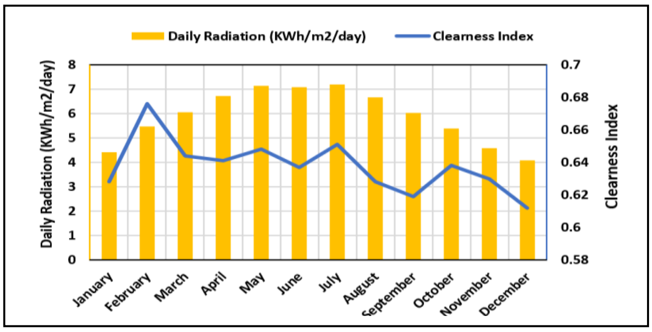

Fig.1. Monthly average solar radiation and clearness index of the Indalek village.

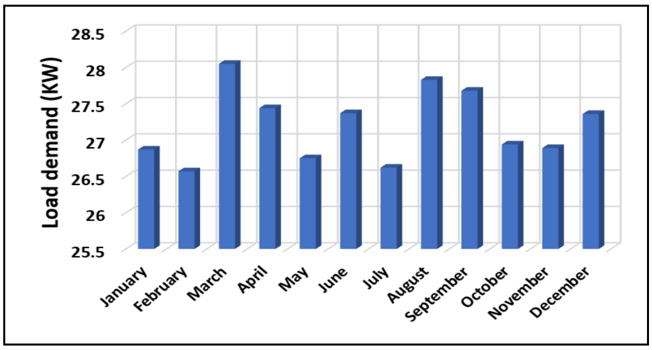

Fig.2. The daily average energy consumption patterns for different seasons in the Indalek village.

III. HYBRID ENERGY SYSTEM MODELING AND SIZING

Figure 3. is a schematic for an hybrid model of the HES using BESS and PHS. The detailed mathematical modelling of the system components and their technical, economic and environmental criteria are performed by HOMER, which are an important step before the sizing and optimization of the system. Table I presents a description of the different components of the hybrid energy system.

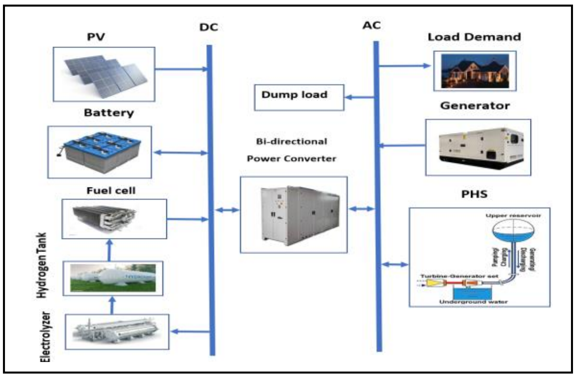

Fig.3. Schematic diagram of the studied HES using BESS and PHS storage.

A. photovoltaic array modelling

The power generated by the PV system is estimated by the Eq. (1) [2].

$$P_{PV} = C_{PV} D_{PV} = \frac{G_T}{G_{T,STC}} \left[1 + \alpha_P (T_C - T_{CS,STC})\right] \quad (1)$$

where, C_{PV} (kW) is the rated capacity of the PV array under standard test conditions, D_{PV}(%)is the degrading factor, G_T (kW/m^2) is the solar radiation incident on the PV array, $G_{T,STC}$is the incident radiation under standard test conditions (1 kW/m^2), α_P(%/°C)is the temperature coefficient of power, T_C and $T_{CS,STC}$are the temperature of the PV cell (°C) and the temperature of the PV cell under standard test conditions (25 °C), respectively.

B. Fuel

The fuel cell is used to convert the chemical fuel (hydrogen) to electricity. The electric power output from the fuel cell P_{Fc} is given by the Eq. (2) [10].

$$P_{Fc} = U_{stack} I = U_{sc} N I \quad (2)$$

Where U_{stack} is the stack voltage, I represent the current, U_{sc} is the single cell voltage, and N is the number of cells. The PEM fuel cell electrical efficiency is given by the Eq. (3).

$$n_{Fc} = \frac{P_{Fc}}{m H_2 HHV_{H2}} \quad (3)$$

Where HHV_{H2} is the hydrogen higher heating value (120–140 MJ/kg) and m˙ m_{H2} (kg/s) is the H_2mass flow rate.

C. Electrolyzer for hydrogen production

The hydrogen is produced in the Electrolyzer by splitting water, in hydrogen and oxygen. Power input is needed for the Electrolyzer to split the water for hydrogen production. The electrical power consumed by the Electrolyzer is given by Eq. (4).

$$P_{EZ} = \frac{m H_2 HHV_{H2}}{n_{EZ}} \quad (4)$$

where, $P_{EZ}$is the power consumption of the Electrolyzer, m_{H2} is the produced hydrogenmass flow rate (kg/s), and $HHV_{H2}$is the gross calorific value (MJ/kg) and n_{EZ} is the Electrolyzer efficiency.

D. Diesel generator

The power generated from the Diesel backup generator depends on the fuel consumption. A linear equation is used to model the generator fuel consumption:

$$F_D = \alpha T_G + b P_G \quad (5)$$

where, $F_D$is fuel consumption in (l/h), $\alpha$is the fuel curve intercept coefficient (0.0165 l/h/kW), b is the fuel curve slope (0.267 l/h/kW), T_G is the rated capacity of diesel generator and $P_G$is diesel power generation.

E. Pumped Hydro Storage

A Pumped Hydro storage System builds potential energy by storing water in a reservoir at a certain height when there is excess energy. the energy storage capacity of a pumped hydro storage system is given by Eq. (6).

$$E[J] = 9.8 P_{water} V_{res} h_{head} \eta \quad (6)$$

Table I. CHARACTERISTICS OF THE HYBRID ENERGY SYSTEM COMPONENTS.

Components	Type	Size (KW)	Effeciency (%)	Capital cost ($)	Replacement cost ($)	Cost of O & M($/year)	Lifetime
Solar PV [2]	Generic flat plate PV	120-160	-	1,176.00	1,176.00	0	25(year)
GD [2]	Generic Medium Genset	50	-	342.00	342.00	0.050	15000 (Hours)
Fuel cell [9]	Generic Fuel Cell	5-20	-	3,000.00	2,500.00	0.080	40000 (Hours)
Electrolyzer [9]	Generic Electrolyzer	0-15	85	1,500.00	1,000.00	20.00	15(year)
Hydrogen tank [9]	Generic Hydrogen tank	0-20	-	1,200.00	800.00	15.00	25
BESS [2]	HoppeckeOPz 2000	-	86	276.00	276.00	20.00	10 (year)
PHS [16]	Generic 245kWh Pumped Hydro	-	90	22,000.00	500.00	22,000.00	7 (year)
Converter [2]	Generic large, free converter	95-110	90	341.00	341.00	3.00	15 (year)

Where,E is the energy stored in joules. Divide by 3.6 x 106 to convert to kWh;$P_{water}$is the density of water, usually about 1000kg/m^3;V_{res} is the volume of the reservoir in cubic meters;$h_{head}$is the head height in meters;$\eta$is the efficiency of the energy conversion, and must consider losses like turbine efficiency, generator efficiency, and hydrodynamic losses.

F. Battery

The battery energy storage system is the most important part of the hybrid generation system out of all the components. The battery SOC varies between any two instants t and t − 1 based on whether the battery in the charge or discharge mode [11]. The following formula is used to calculate the SOC of the battery:

$$SOC(t) = SOC(t-1) \times \int_{t-1}^{t} \frac{n_{batL_b(t)}}{V_{bus}} dt \qquad (7)$$

Where n_{bat} : battery efficiency [%];$P_b(t)$: load power of the battery [Kw];V_{bus}: bus voltage [Volt].

G. Inverter/converter modeling

AC and DC buses are linked through an inverter, and the output power of which is determined using Eq. (8), where Pin is the input power to the inverter and η_{inv} is the inverter's efficiency (95%) [11]. The HOMER calculates the required capacity of the inverter based on the energy flow from the DC to AC.

$$P_{out} = P_{in}\eta_{in} \qquad (8)$$

H. Net present cost

The NPC of a system is the present sum value of all costs experienced over the system lifetime, excepting the present value of all revenue the system receives. The NPC is determined by Eq. (9) [12] where InC, OpC, FuC, ReC, SaC, and Nc is the initial capital cost, operating cost, fuel cost, replacement cost, salvage cost, number of elements, respectively. The discount factor (DF) is a ratio utilized to define the present value of an income (a series of equal yearly cash flows) which is a function of the real interest rate (i_r%) and the number of years (n).

$$NPC = \sum_{j=1}^{Nc} \sum_{n=1}^{Ny} Nj\, [InCj + DF(\, OpCj + FuCj + ReCj - SaCj)] \qquad (9)$$

$$F = \frac{1}{(1+i_r)^n} \qquad (10)$$

I. Cost of energy

The cost of energy is the average cost/kWh, which reflects the average cost/kWh of the useful energy produced (E_g) by the system over its lifespan (Ny). The COE is evaluated using Eq. (11), where CRF is the capital recovery factor [13].

$$COE = \frac{NPC.CRF\,(\,i_r\,,n\,)}{\sum_{j=1}^{Nc}\sum_{n=1}^{8760} Eg,j(t)} \qquad (11)$$

$$CRF(i_r, N_y) = \frac{(1+i_r)^{Ny}}{(1+i_r)^{Ny}-1} \qquad (12)$$

J. Carbon emession impact

The CEI calculates the carbon dioxide emissions emitted from the energy system to the environment in a specific time. The CEI can be determined using Eq. (13) based on the annual generated energy [14] where Vol (CO2) is the aggregated quantity of CO2 emission in (tCO2/kWh) and $E_{g,non-ren}$ is the energy generated using non-renewable sources (kWh).

$$EI = \sum_{t\in T} Vol(CO2) \cdot E_{g,non-ren} \qquad (13)$$

K. Renewable energy fraction

Renewable energy fraction (RF) is the percentage of energy that originated from renewables ($E_{g,ren}$) to the total load (E_l). Typically, it is desired to have a high RF toward zero-emission cities considering their impact on system costs. The RF is expressed using the formula in Eq. (14) [15].

$$RF = \frac{E_{g,ren}}{E_l} \qquad (14)$$

IV. SYSTEM SIMULATION

In this study, we have performed the comparison between two combinations of HESs such as PV/FC/DG/BESS and PV/FC/DG/PHS are designed to meet the load demand of the

Indalek village. The objective of this study is to compare the influence of PHS and BESS on the HES on the basis of economic indicators (COE, NPC), technical parameters (EE, RF) and environmental indicators (CO2 emissions). This study takes into account the constraints listed in the table II.

TABLE II. MODEL CONSTRAINTS.

Constraints	Value	Description
Maximum annual capacity shortage (%)	1	The maximum allowable value of the capacity shortage fraction.
Load in current time step (%)	10	The system must keep enough spare capacity operating to serve a sudden 10% increase in the load
Annual peak load (%)	10	The percentage of the peak primary load (AC) to the required operating reserve in each time step.
Solar power output (%)	25	The percentage of the peak primary load (AC) to the required operating reserve in each time step.

A. Result and discution

The optimized results of the two HESs such as System I: PV/FC/DG/BESS and System II: PV/FC/ DG/PHS are presented in the table III.

TABLE III. SUMMARY OF OPTIMIZATION RESULTS FOR DIFFERENT HESS CONFIGURATIONS.

Characteristics	**System I : PV/FC/DG/BESS**	**System II : PV/FC/DG/PHS**
COE ($/KWh)	0.1423	0.1681
NPC ($)	438335.21	517922.65
Fuel cell (KW)	5	5
PV panels (KW)	160	160
Diesel genset (kW)	50	50
Electrolyzer (KW)	5	5
Hydrogen tank (Kg)	10	10
PHS (KWh)		1017
Battery (KWh)	686	
Converter (KW)	25.3	25.5
Production (KWh/yer)	324242	322750
Excess electricity (KWh/yr)	36222 (11.2%)	29357 (9.1%)
f_{ren} (%)	86.8	87.4
CO2 (Kg/yr)	23297	22467

1) Energy production

Fig 4. shows the power generated by PV, FC and GD for the system I and system II throughout the year to meet the 652.87kWh per day demand of the Indalek village. The energy production by PV, FC and GD of system I is high at system II, which estimated 324242 (kWh/year) and 322750 (kWh/year) respectively. This explains the effect of BESS on system performance where the annual productivity of the BESS is higher than PHS because the response of BESS is very high in a very short time (power density), which makes its performance better than PHS, which has a high energy density.

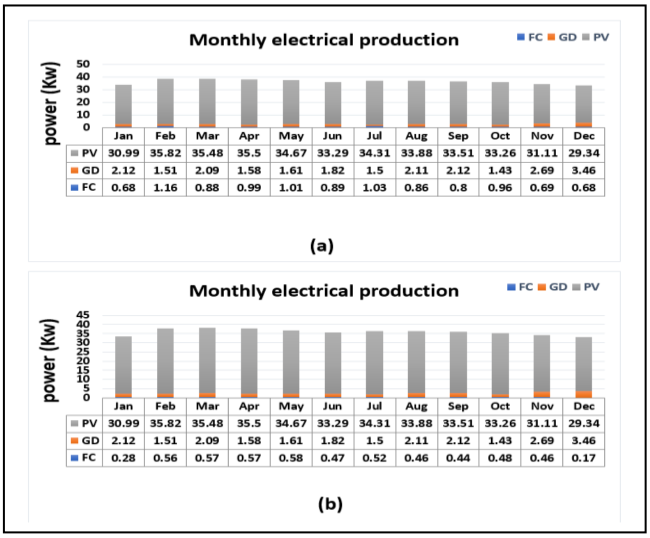

Fig.4. Monthly average electric production of HES for both systems: (a) PV/FC/DG/BESS, (b) PV/FC/DG/ PHS.

2) Economic analysis

The net present costs of all components of the two HESs are shown in the table IV. The net present cost of solar PV system, inverter, Electrolyzer and hydrogen tank is the same for System I and System II, while the net present cost of diesel generator and fuel cell of System II is lower than System I. System II has the highest net present cost ($517922.65), while System I have the lowest net present cost ($438335.21). The costs of energy are $0.1423, $0.1681 for the system I and system II respectively. The cost of energy of System II is higher than the cost of energy of System I because of the capital cost and the replacement cost of PHS is higher than BESS, therefore the net present cost and the cost of energy of System II are higher than System I. The figure 5. shows that System I is better than System II in economic terms after the comparative analysis of the NPC and the COE for both systems.

TABLE IV. THE NET COSTS OF ALL COMPONENTS OF THE TWO HESS.

Components	**System I** ***NPC ($)***	**System II** ***NPC ($)***
PV	188160	188160
Fuel cell	2549	2487.02
GD	56438.19	59042.68
Battery	117011	/
PHS	/	194056
Electrolyzer	10514.86	10514.86
Hydrogen	13939.13	13939.13
converter	49723.02	49723.02
System	438335.21	517922.65

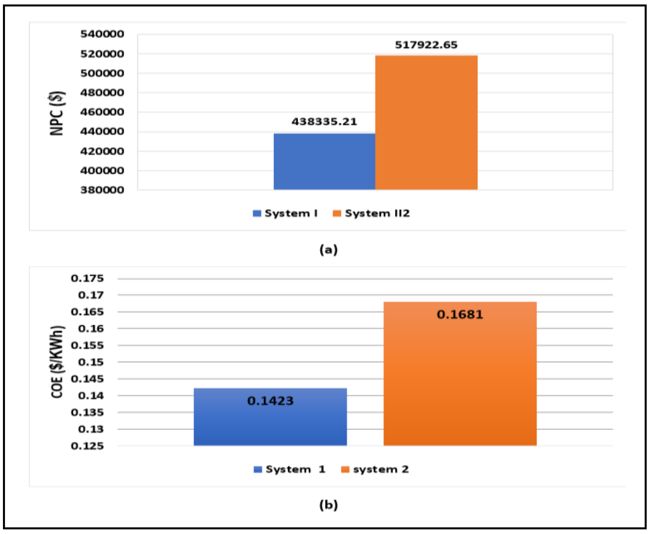

Fig.5. Economic comparison of the two HESs: (a) NPC ($), (b) COE ($/kWh).

3) *Technical analysis*

In this study, the technical performance of the two HESs is based on two parameters: the RF and the EE. figure 6. clarifies the technical performance of the two HESs. System I have the RF value up to 86.8% and the EE of 36222kWh/year (11.2%), on the other hand system II has the RF of 87.4% and the EE of 29357 kWh/year (9.1%). The RF of system II is higher than the RF of system I due to the high nominal capacity of the PHS which allows to integrate a lot of renewable energy compared with the BESS in system I. The EE of system I is higher compared to system II because the throughput of BESS is higher than the PHS, this explains the lower COE in system I. It is noticed in the figure 6, both systems can easily cope with sudden load variations and future increase in load demand.

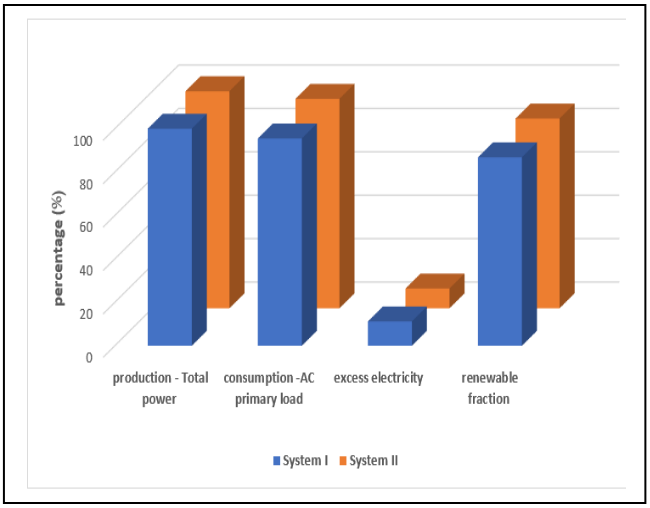

Fig.6. Electrical system performance for the two HESs.

4) *Environmental analysis*

The main environmental risk factors are due to the conventional generator through its greenhouse gas (GHG) emissions during the combustion of fuel in the generator. The HES produces the lowest percentage of GHG. The amounts of CO2, carbon monoxide (CO), sulfur dioxide (SO2), nitrogen oxide (NOx), unburned hydrocarbons (UHC), and particulate matter (PM) determine the carbon footprint of each system. The figure 7. shows the GHG emissions emitted by the two HESs. System II has less environmental impact than system I in terms of carbon footprint. The CO2 amounts of system II and system I are 22467 kg/year, 23297 kg/year respectively. The reduction of CO2 in system II due to the renewable fraction is high in this system compared with system I, which reduces fuel consumption and improves the environment in the Indalek village. Moreover, the CO, UHC, SO2 and Nox from system II are lower than system I.

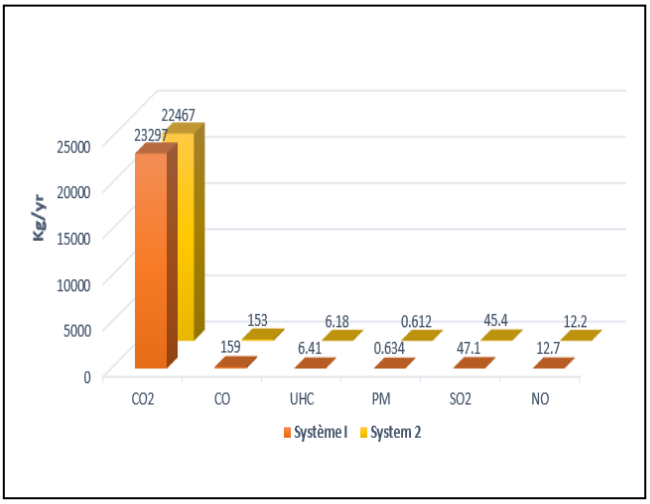

Fig.7. Greenhouse gas (GHG) emissions released from of two HES.

V. SENSITIVITY ANALYSIS

The technical-economical performance of system I is better than system II and his environmental impact is a little higher than system II, but it is acceptable. System I is better to supply electricity in the Indalek village. The sensitivity analysis is necessary to investigate the performance of the system I, because the Indalek village is exposed the sandstorms in the summer. The objective of this analysis is to know the influence of the derating factor and the load increase on the cost of energy in the system I. The sensitivity analysis parameters in the table V.

TABLE V. The Sensitivity analysis paramètres of system I.

sensitivity	
The derating factor (%)	**Electrical load (kWh/d)**
75	641
88	641
75	833.247
88	833.247

The figure 8. shows the influence of the derating factor with the increasing load on the cost of energy in system I. the cost of energy is reduced from 0.141$/KWh to 0.135$/KWh respectively in the case the load is fixed at 641 kWh/d and vary the derating factor from 75% to 88%. In addition, in the case the load is varied from 641 KWh/d to 833.27 kWh/d and the derating factor is varied from 75% to 88% respectively, the cost of energy is reduced from 0.131$/KWh to 0.129$/KWh. The improvement of the derating factor increases the energy production of the solar panels, consequently reducing the cost of energy.

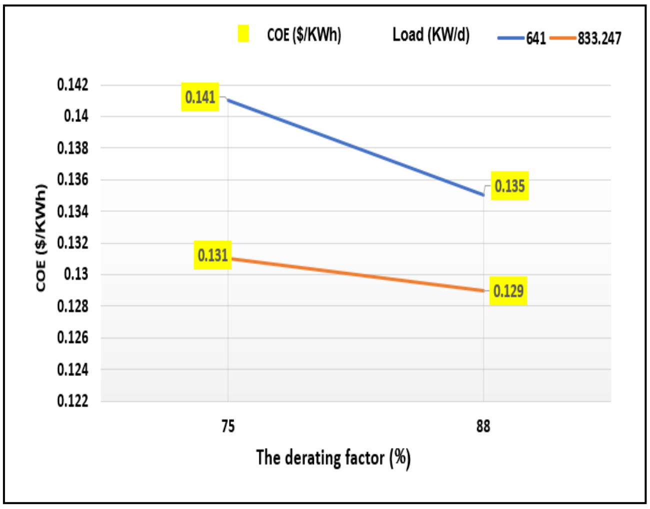

Fig.8. Influence of improving the derating factor and the increasing load in the cost of energy in system I.

VI. CONCLUTION

This study presents the techno-economic environmental analysis between the two HESs, such as PV/FC/DG/BESS and PV/FC/DG/PHS to supply the electricity demand of an off-grid community and the dump load in Indalek village in southern Algeria. This analysis evaluates the NPC, COE, RF, EE and CO2 of the two HESs using HOMER software. The sensitivity analysis is also performed to know the performance of HES selected. The simulation results show that the NPC, COE and RF for PV/FC/DG/BESS (NPC=$438371, COE= 0.1423/KWh and RF=86.8%) are lower than those of PV/FC/DG/PHS (NPC=$517922.65, COE= $0.1681/KWh and RF=87.4%). The PV/FC/DG/BESS has the highest EE (36222kWh/year) and the PV/FC/DG/PHS has the lowest EE (29357 kWh/year). The PV/FC/DG/PHS is the more environmentally friendly with CO2 emissions of 22467 Kg/year compared with the PV/FC/DG/BESS with CO2 emissions of 23297 Kg/year. The sensitivity analysis is performed on the PV/FC/DG/BESS shows a lower the COE when increase the electrical load and the improvement of the derating factor.

In continuation of this work, we will explore other storage means such as fuel cells, flywheels for reducing cost investments, and to gain a total autonomy of the Microgrid, and obviously we will develop a management method for optimizing the use of the less cost storage.

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