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Impact of Capacity Shortage on The Feasibility of PV-Wind Hybrid Systems in Africa

A. Benallal, N. Cheggaga, and A. Ilinca

ABSTRACT

Reliable optimization of renewable energy system is the one that balances between electrical sizing of the system components in order to satisfy the load and the cost of that system. This techno-economic optimization can be assured by HOMER software through some sensitivity parameters such as capacity shortage. For Saharan villages in Africa, it is required to install off-grid power systems with low cost. To fulfill this requirement, is it necessary to avoid the over-sizing of system due to high and short peaks of load, so the optimization of PV-wind hybrid system on this article is done with sensitivity analysis of the system for different capacity shortage rates. The only rates that do not exceed the mean values of electrical outage of Algeria are 0 % and 0.5 %, and HOMER had favorited the optimal system with 0.5 % of capacity shortage due to the 18 % gain in total cost of system and the energy cost. The results achieved on this article encourage on techno-economical optimizing PV-wind hybrid systems with acceptable capacity shortage and electrical outage rates for a better economic feasibility in Saharan villages.

Keywords: Capacity shortage, HOMER, PV-Wind hybrid system optimization, techno-economic feasibility.

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I. Introduction

According to the World Bank 1.2 billion of the global population has no access to electricity, Sub Saharan African (SSA) hosts 55% of this population with no electrical access and most of it lives at a significant distance from the grid [1]. This access rate is very low to meet the economic development plans in Africa [2], and very far from the world plans to achieve 100% electrical supply by 2030 [3]. Especially when the energy demand is estimated to increase by 85% between 2010 and 2040 [4]. To bridge the energy gap, and achieve the African and universal objectives, SSA countries doesn't just need to intensify their energy generation, and supply through sustainable technologies, but also rationalize consumption [5].

For isolated sites that are far from a conventional power system as most of Saharan villages, technical solutions in favour of the usage of renewable energy sources (RES) in electricity production provide electricity access for such remote areas. In order to ensure power supply when considering the optimum solution, it is necessary to consider the acceptability of usage each RES hybrid systems. Wind and solar are clean energy sources with vast potential to reduce the dependence on conventional energy sources and are also seen as attractive and preferred alternative sources [6]. SSA possesses the highest potential in Africa with 3000-4000 TWh/yr for wind and 50,000-60,000 TWh/yr for solar energy [7], [8]. Combining both wind power and photovoltaic (PV) power would lead to minimize the storage requirements that are considered as the main techno-economic constraints in RES systems, and therefore the overall cost of the system [9]. What have been proved in the work of [10] by analyzing the performance of PV hybrid systems compared to a diesel generator (DG) stand-alone system, also in the work of [11] by techno-economic analyzing PV and wind stand-alone systems and PV-wind hybrid system.

The variability in the form of energy available for a PV-wind system requires precise sizing of the wind turbine, battery bank, and PV array so that the system meets load demand at any time of the year [12]. This sizing should be accompanied with an economic feasibility. So, any optimal sizing of RES hybrid systems is required to make the system technically as well as economically feasible and efficient [13]-[17]. In that purpose and due to the worldwide common issue of sizing and cost estimation of RES hybrid systems, many simulation programs are developed to obtain an optimal configuration by comparing the performance and cost of power generation of different system configurations. Some of widely reported packages in literature: HOMER, SAM, HYBRID2, and HOGA [18]. Among the most famous sizing programs for hybrid systems: HOMER software. This software includes several models of energy components and allows the evaluation of appropriate options considering the costs and availability of energy resources. Its database is very rich. Many authors have used this software to optimize hybrid systems for different locations worldwide which make HOMER one of the most widely used software for the optimization and sensitivity analysis of hybrid systems [19].

Fast improvement in renewable energy technologies especially PV and wind led to reduce net present costs (NPC) of RES systems investments and the cost of energy (COE) for renewables and make them very competitive to fossil fuels [20]. These falling costs encouraged countries to install bigger capacities of RES systems last few years. Unfortunately, that's not the case in Africa, where most electrical generation is based on fossil fuel energy sources and only 1.97% of the global RES installed capacity in 2018 [21]. According to [22] the faced barriers to exploit solar and wind energy in the SSA are:

- High start-up cost because RES energy is prepaid.
- Lack of access to information and technology.
- Limited financing by governments and private sector.
- Lack of qualified personnel.

Many studies on feasibility of RES systems in Africa concluded that main reason of slow electrical transition and electrification of new villages in micro-grids RES systems is the investment cost and the difficulty of attracting sufficient finance [23]. In literature of Collier & Venables, shortages of capital and skills prevent Africa from exploiting its RES [24]. In other literatures, financial weakness and dispersed demand constrict power generation by large RES systems installations [25], [26].

The installation of such off-grid PV-Wind hybrid system is quite expensive in Saharan villages, and the most expensive components are batteries, so any over-sizing of any components especially the storage bank increases the already high costs. Otherwise, the reduction in the size of the system and insufficient battery capacity can lead to an exploitation of the energy stored before it has started to be renewed and end up with a capacity shortage [27], [28]. This capacity shortage is related to electrical outage of the area, and it is different from a country to another, for example the best rate in Africa is around 12.42 days per year for Algeria where the site of this study is located, but its worst in other countries of SSA [29]. Hence, it is clear why a standalone system is a challenge. If the system components were technically designed to be as optimal as possible, high-cost performance of the system would necessitate a reduction in overcapacity cost [30].

In this article, HOMER software is used to optimize the standalone PV-Wind hybrid system and sensitivity analyses the system for different capacity shortage rates. The aim of sensitivity analysis is to study the influence of the capacity shortage on the optimal configuration of the off-grid PV system, also on the NPC and the COE. All that to prove that small capacity shortage is highly recommended for any optimization of PV-wind-battery hybrid system in SSA. Cause this shortage will allow the ignorance of the short high peaks of load that may cause an over sizing of the whole system. The paper is organized as follows: Section II presents the methodology starting with the description of the site then load profile and the configuration of the hybrid system. Finally, mathematical equations of capacity shortage fraction, NPC and COE. In section III, the main results were presented and finally in section IV the conclusions are given.

II. Optimization Methodology

A. Site Description

The chosen site for our study is

a new Saharan residential district located 7 kilometers north-west of the town of Bechar, Algeria, and 3 kilometers from Bechar airport "Boudghene Ben Ali Lotfi". Its geographic coordinates are as follows: Latitude: 31 ° 40'46 "North, Longitude: 2 ° 16'11" West. The location of the HOMER software study site is shown in Fig. 1.

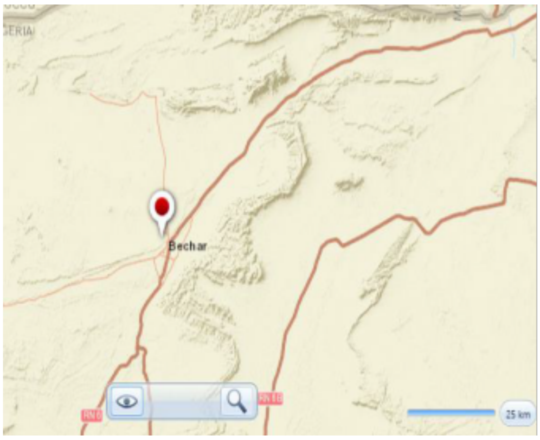

Fig. 1. Site localization.

B. Load Profile

The electrical load to be satisfied is a 12-class primary school located in the district previously announced; its average daily load profile of 126.75 kWh is displayed in Fig. 2.

Load characteristics are as follow:

- Minimum of 0.23 kW outside of working hours from 6:00 p.m. to 6:00 a.m.
- Consumption growth from 6:00 a.m. to 8:00 a.m.
- Maximum average of 14 kW during working hours from 8:00 a.m. to 4:00 p.m.
- Consumption decreases from 4:00 p.m. to 6:00 p.m.
- A peak of 24 kW rarely reached on certain days.

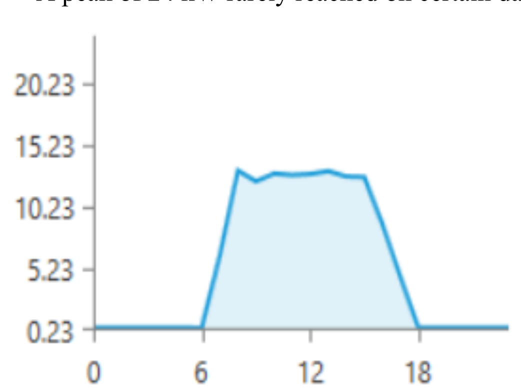

Fig. 2. Average daily load profile.

C. PV-Wind Hybrid System Configuration

The optimized system will be realized using the following components: the EO10 wind turbine, the photovoltaic field of the Jinko60 panels, the OPz battery bank and the Fron24 inverter / charger as shown in Fig. 3. These components will be sized by HOMER software.

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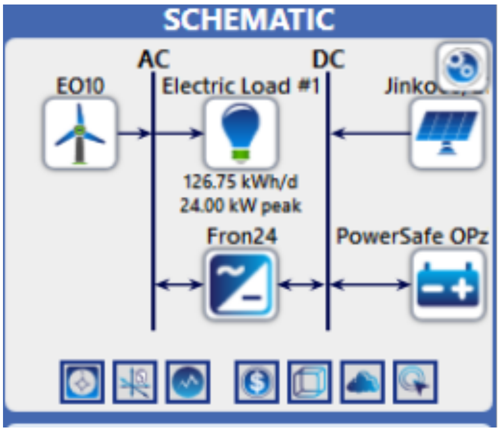

Fig. 3. Schematic configuration of the hybrid system.

In the purpose of assessing how easy would be the optimization of renewable energy hybrid systems on HOMER software to use in practice, we had to lay out a simplified flowchart of the process presented in Fig. 4.

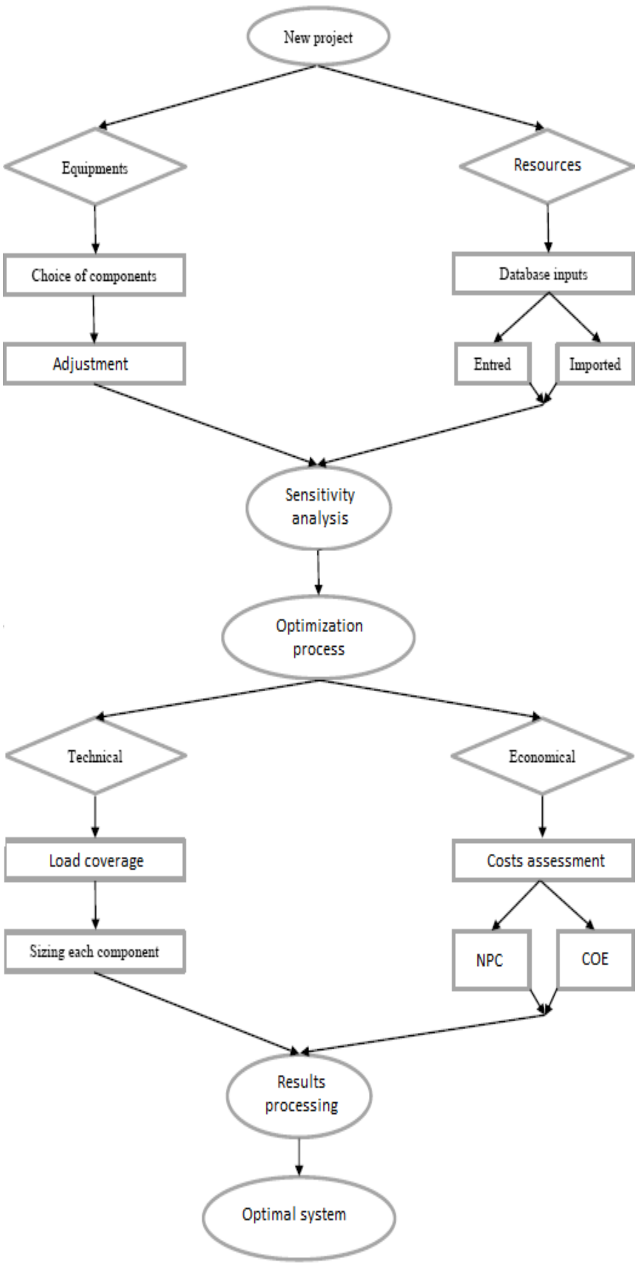

Fig. 4. Flowchart of the optimization process on HOMER.

This flowchart is, it shows that the process starts with the choice of components and their adjustment and the introduction of resources either by uploading them on file or importing them from HOMER database. Then, it is possible to fix some sensitivity parameters to be considered during the techno-economic optimization of the system. All results will be presented on results table from the favorable to the unfavorable configuration of the hybrid system.

The optimal system is obtained by processing the results of components sizing in order to satisfy the load needs and costs assessment especially the NPC and COE.

D. Mathematical Models

A capacity shortage is the gap between the required operating capacity and the amount of operating capacity the system can provide. Its fraction is calculated on HOMER by the following equation [31]:

$$f_{cs} = \frac{E_{cs}}{E_{demand}} \quad (1)$$

Where:

E_{cs}= total capacity shortage [kWh/yr]

E_{demand}= total electrical demand [kWh/yr]

Optimization of the schematized system on Fig. 3, will be done on HOMER for different capacity shortage rates as shown on Fig. 5.

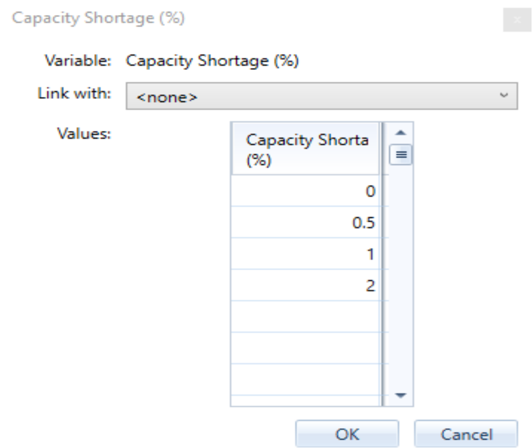

Fig. 5. Capacity shortage rates to be considered.

HOMER will optimize system for the four capacity shortage rates and then arrange them from the most favorable to the less favorable. Most significant results are the size of each component, in addition of the NPC and the COE. These costs are calculated on HOMER with following equations [31]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i,R_{proj})} \quad (2)$$

Where:

$C_{ann,tot}$= total annualized cost [$/yr]

CRF = function returning the capital recovery factor

R_{proj}= project lifetime [yr]

i = annual real discount rate [%]

$$COE = \frac{C_{ann,tot} - C_{boiler}H_{served}}{E_{served}} \quad (3)$$

Where:

$C_{ann,tot}$= total annualized cost [$/yr]

C_{boiler}= boiler marginal cost [$/kWh]

H_{served} = total thermal load served [kWh/yr]

E_{served} = total electrical load served [kWh/yr].

III. Results and Discussion

In this section, the results of sensitivity analysis and of techno-economic optimization will be displayed and discussed. The major techno-economic results will be presented and compared at the end of this section.

After configuration of the PV-Wind hybrid system on HOMER and uploading wind speed and solar radiation on it, an entering the different capacity shortage rates all technical and economical desired results will be displayed on results table as presented on Fig. 6.

Sensitivity	Architecture					
Capacity Shortage (%)	Jinko60/275 (kW)	EO10	PowerSafe OPzV 3000	Fron24 (kW)	NPC ($)	COE ($)
0.500	61.4	1	12	24.0	$45,349	$0.0763
0	54.4	1	24	24.0	$55,404	$0.0927
1.00	48.9	1	12	24.0	$40,816	$0.0690
2.00	40.2	1	12	24.0	$37,646	$0.0642

Fig. 6. Table of optimal systems for different capacity shortage rates.

Table VI of results displayed in figure presents the 4 optimal systems for the different proposed capacity shortage rates, and HOMER placed the system that consider 0.5% of capacity shortage in first place as most techno-economic optimal system. It is the system that balances the best between technical performances and economical returns.

The most performant system is the one with no capacity shortage, but it is the most expensive one at the same time. While the cheapest was the one that consider 2% of capacity shortage but it is ranked last because it is less performant than the others.

A. Sensitivity Analysis by Capacity Shortage

Fig. 7 below presents the sensitivity analysis results of NPC and COE estimated by HOMER for different capacity shortages:

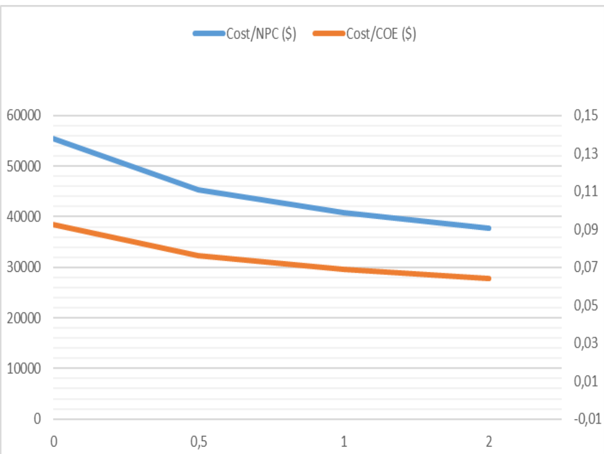

Fig. 7. Sensitivity analysis by max capacity shortage based on NPC and COE.

Capacity shortage has a considerable effect on the NPC and COE of the PV-wind-battery hybrid system. The biggest drop in both costs is between 0% to 0.5% capacity shortage, it was 10055 $ for the NPC and 0.0164 $ for COE. The gain on both costs registered in this interval is even bigger than the one registered from 0.5% to 2%.

At 2% of capacity shortage, the registered gain was 32% and 31% on NPC and COE respectively. It is estimated that the gain on costs will be amortized slowly for bigger capacity shortage rates.

Fig. 8 focuses on quantifying the electrical outage due to the sensitivity analysis of the system by max capacity shortage.

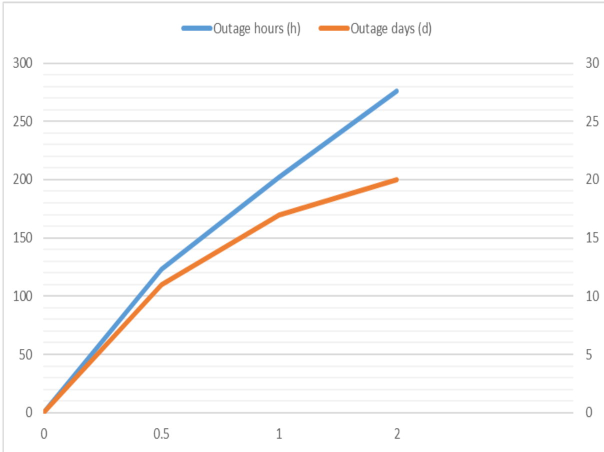

Fig. 8. Sensitivity analysis by max capacity shortage based on hours of outage and the number of days

As shown on Fig. 8, the hours of electrical outage were: 123, 202 and 276 hours dispatched on 11, 17 and 20 days for 0.5%, 1% and 2% of capacity shortage respectively.

For the rest of work only the optimization results of the system for 0% and 0.5% capacity shortage will be discussed. These results don't exceed the max yearly electrical outage 12.42 days and max monthly electrical outage estimated at 3.4 times [29]. There was no electrical outage for the system without capacity shortage, in contrast of the system with 0.5% of capacity shortage that experienced outage in 11 days per year but didn't exceed 3 days per month estimated for January, November and December.

B. Optimized System with 0% Capacity Shortage

The Most important technical results of the optimal system without capacity shortage are presented on Fig. 9.

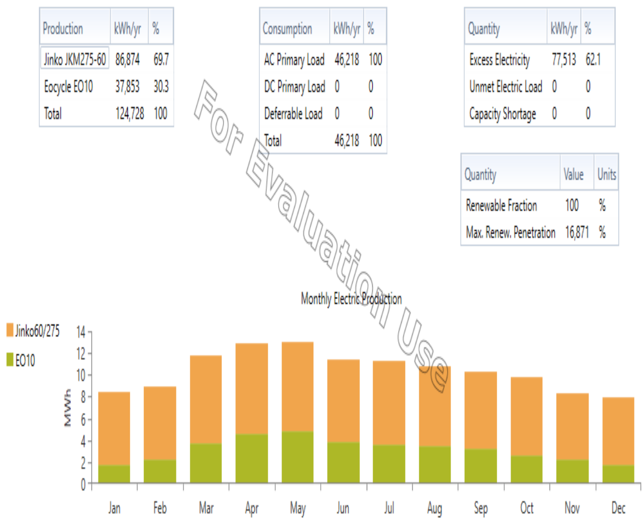

Fig. 9. Technical results of optimal system with 0 % capacity shortage.

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As shown on Fig. 9, the majority of PV-wind hybrid system total production rated at 124728 kW is 69.7% assured by PV generator and 30.3% by the wind turbine.

The excess of electricity rated at 77513 kW which present 62.1% of total production. And the max renewable penetration reached was 16.9%.

Fig. 10 presents the yearly profile of 0 % capacity shortage.

Fig. 11 displays the economical results of the same system.

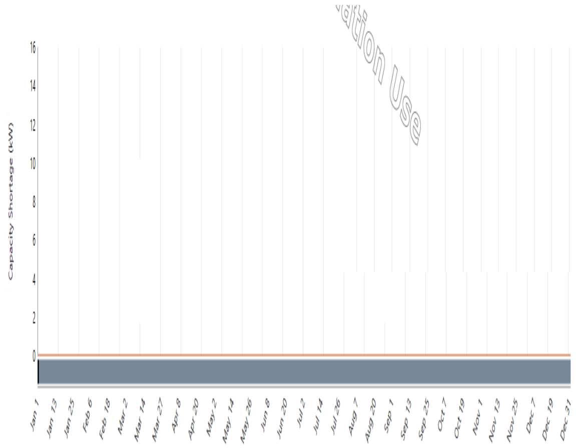
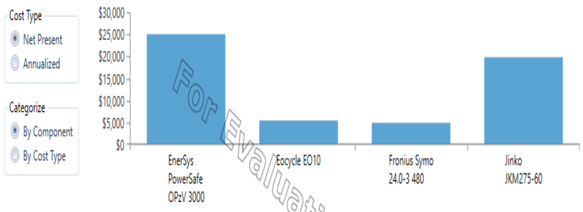


Fig. 10. Yearly profile of 0 % capacity shortage.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
EnerSys PowerSafe OPzV 3000	$18,000.00	$5,738.53	$4,653.91	$0.00	-$3,234.03	$25,158.41
Eocycle EO10	$5,000.00	$0.00	$646.38	$0.00	-$159.71	$5,486.67
Fronius Symo 24.0-3 480	$3,000.00	$2,208.59	$0.00	$0.00	-$299.45	$4,909.15
Jinko JKM275-60	$16,331.17	$0.00	$3,518.69	$0.00	$0.00	$19,849.86
System	$42,331.17	$7,947.13	$8,818.97	$0.00	-$3,693.18	$55,404.09

Fig. 11. Economical results of optimal system with 0% capacity shortage

The system total cost is estimated at 55 404 $ and it is divided between: battery bank, wind turbine, inverter/charger, and the PV generator with following rates: 45.5%, 9.9%, 8.9% and 35.8% respectively. While the cost of energy was estimated at 0.0927 $/kWh.

C. Optimized system with 0.5% capacity shortage

Fig. 12 resumes technical results of the optimal system with 0.5% capacity shortage.

As noticed; the majority of PV-wind hybrid system total production rated at 135773 kW is assured by PV generator with rate of 72.1% and 27.9% by the wind turbine.

The excess of electricity rated at 88832 kW which present 65.4% of total production. And the max renewable penetration reached was 18.6%.

The Fig. 13 presents yearly profile of 0.5 % capacity shortage.

The graph shows that this capacity shortage is recorded on 11 different days: 3 days in January, 2 days in February, 3 days in November and 3 other days in December.

Production	kWh/yr	%
Jinko JKM275-60	97,920	72.1
Eocycle EO10	37,853	27.9
Total	135,773	100

Consumption	kWh/yr	%
AC Primary Load	45,986	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	45,986	100

Quantity	kWh/yr	%
Excess Electricity	88,832	65.4
Unmet Electric Load	227	0.5
Capacity Shortage	227	0.5

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	18,612	%

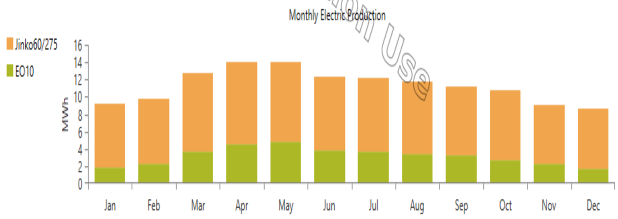


Fig. 12. Technical results of optimal system with 0.5 % capacity shortage.

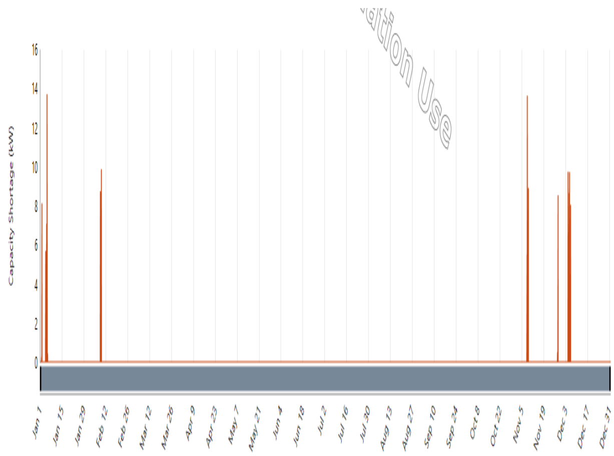


Fig. 13. Yearly profile of 0.5 % capacity shortage.

And the capacity shortage daily profile is presented on Fig. 14 below:

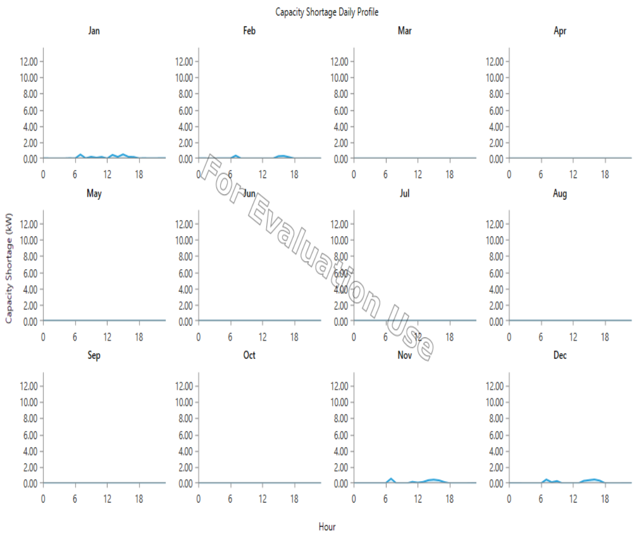
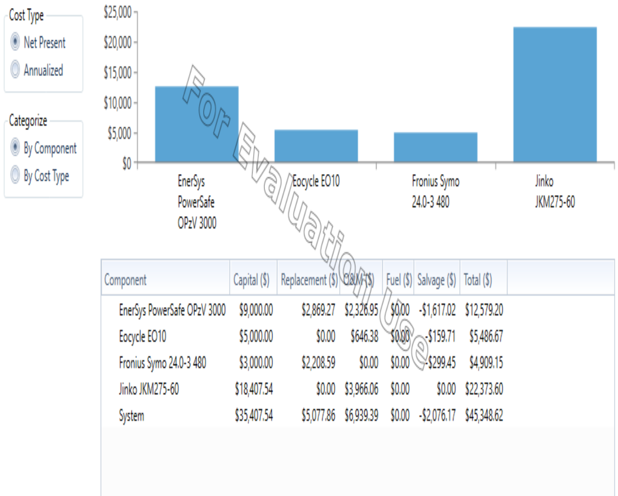


Fig. 14. Capacity shortage daily profile

It is clear from the daily profile graphs of capacity shortage that it is concentrated from 6am to 8am and from 3pm to 6pm during the following months: January, February, November, and December.

However, the system total cost is estimated at 45 349 $ and it is divided between: battery bank, wind turbine, inverter/charger, and the PV generator with following rates:

27.7%, 12.1%, 10.1% and 49.1% respectively. While the cost of energy was estimated at 0.0763 $/kWh, and these economical results are displayed on Fig. 15.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
EnerSys PowerSafe OPzV 3000	$9,000.00	$2,869.27	$2,326.95	$0.00	-$1,617.02	$12,579.20
Eocycle EO10	$5,000.00	$0.00	$646.38	$0.00	-$159.71	$5,486.67
Fronius Symo 24.0-3 480	$3,000.00	$2,208.59	$0.00	$0.00	-$299.45	$4,909.15
Jinko JKM275-60	$18,407.54	$0.00	$3,966.06	$0.00	$0.00	$22,373.60
System	$35,407.54	$5,077.86	$6,939.39	$0.00	-$2,076.17	$45,348.62

Fig. 15. Economical results of optimal system with 0.5% capacity shortage

D. Comparison of Optimized Systems

Table I compares the two configurations of optimal systems for the considered capacity shortage rate:

TABLE I: COMPARISON OF SYSTEMS CONFIGURATIONS WITH AND WITH NO CAPACITY SHORTAGE

Components	Optimization with no capacity shortage	Optimization with 0.5% capacity shortage
PV generator (kW)	54.4	61.4
Wind turbine	1	1
Battery bank	24	12
Inverter/ charger (kW)	24	24

Table I shows that the changes on RES hybrid system configuration didn't affect the number of wind turbines and the size of the inverter/ charger.

However, PV generator is expanded with 13% from 54.4 kW to 61.4 kW and the number of batteries is reduced 50% from 24 to 12 battery in the configuration of optimal system with 0.5% capacity shortage compared to the optimal system without it.

The difference in configuration of both systems leaded to different techno-economic results, these results obtained by HOMER were displayed on Fig. 9 to Fig. 15. Most significant results are resumed on Table II.

TABLE II: TECHNO-ECONOMICAL RESULTS COMPARISON FOR OPTIMIZED SYSTEMS WITH AND WITH NO CAPACITY SHORTAGE

Parameters	Optimization with no capacity shortage	Optimization with 0.5% capacity shortage
Total Production (kW)	124728	135773
Excess of energy (kW)	77513	88832
Max renewable penetration	16.87%	18.61%
Electrical outage hours (h)	0	123
Days of electrical outage (d)	0	11
System cost ($)	55404	45349
Energy cost ($/kWh)	0.0927	0.0763

From Table II, after considering 0.5% of capacity shortage during the optimization of system, noticeable increase of:

- 9% on total electrical production.
- 14% on excess of energy.
- 10 % on max renewable energy penetration

In addition of registration of 123 hours of electrical outage dispatched on 11 days per year.

However, a significant decrease of 18% was registered in system total cost and the energy cost.

The 13% expansion in the size of PV generator was chosen by HOMER to cover the load needs especially in the period 6-8am after reducing the number of batteries to the half. This operation increased the total production, the excess of energy and the max renewable energy penetration, it caused an electrical outage during 1.4 % of yearly total hours, and leaded to an 18% reduction in the NPC and COE.

IV. Conclusions

Economic feasibility is the key for the installation of renewable energy systems in SSA because of the lack of investment and financial resources although the high potential of renewable energies especially solar and wind. Therefore, many previous studies that focuses only on technical satisfaction alienated authorities of SSA countries of realizing such projects because their high estimated costs. For Saharan villages in this region, it is required to install small power systems with low cost. To achieve that, it is possible to consider an acceptable capacity shortage during the sizing of RES systems.

In this work, a techno-economic optimization of PV-wind hybrid system was done for different capacity shortage rates. After sensitivity analysis of the system by capacity shortage, it was noticed that very important gain on NPC and COE was registered between 0% and 0.5%, and it was even bigger than the gain between 0.5% and 2%. For the lowest mean electrical outage in SSA and north of Africa estimated at 12.42 days per year and max of 3.4 days month, only 0.5% of capacity shortage have been allowed in the optimization and compared to the case where no capacity shortage was allowed.

Due to consideration of 0.5% of capacity shortage in the optimization process, a 13% of expansion on the size of PV generator and reduce of the storage capacity to the half were registered in the new system's configuration as showed on Table I. Which leaded to an increase of 9%, 14% and 10% on total electrical production, excess of energy and max renewable energy penetration respectively, as resumed on Table II. HOMER did favorite the system with 0.5% of capacity shortage over the one without it as shown on Fig. 6. This choice was taken by HOMER although the electrical outage registered in few days, generally from 6 am-8 am and 3 pm-6 pm.

Hence, these outages especially between 3 pm and 6 pm can be easily avoided by electrical consumption regulation using smart management algorithms, which is the subject of the team further research, and the expansion in electrical excess can be used to satisfy deferrable load as the one for water pumping to the storage tank. Also, the increase on max renewable penetration is good index parameter for reliability of the new system.

In general, a 0.5 % of capacity shortage that caused 123 hours of electrical outage dispatched between 11 days per year, leaded to 18% of gain on NPC and COE. This seems to be good solution for the ignorance of short high peaks of consumption that cause over-sizing of system. Even the 32% and 31% of gain registered on NPC and COE, respectively, for 2% of capacity shortage can be so significant for installation of RES systems in other SSA countries, where the mean electrical outages are so higher that one considered in this work.

These results encourage on optimizing PV-wind hybrid systems with acceptable capacity shortage and electrical outage rates in rural villages in south-west of Algeria, and that is for a better economic feasibility of these systems in such areas, where the biggest constraint of RES systems realization are the high investment and energy costs.

Conflict of Interest

Authors declare that they do not have any conflict of interest.

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