BEHAVIOR ANALYSIS OF A HYBRID POWER SYSTEM UNDER TWO ENERGY MANAGEMENT STRATEGIES

BUNDA S.
*University of Oradea, Universităţii no.1, Oradea,
sbunda@uoradea.ro

Abstract - The paper aims to analyze the operational behavior of a solar-Diesel hybrid power system under two energy management strategies: load following and cycle charging. The economic effects of the two dispatch strategies were also studied. The possibility of optimizing HPS under the load following strategy was also analyzed, the results being presented both from a technical and economic point of view. Finally, the conclusions regarding the particular case of hybrid power system studied were drawn.

Keywords: hybrid power systems, energy management strategies, load following, cycle charging

1. INTRODUCTION

Electricity generation in hybrid power systems (HPS) is done through the connection of multiple sources of power based on renewable resources. For isolated consumers, far from the electricity grid, the most available renewable resources used to produce electricity are solar and wind. Due to variability and unpredictability of these resources the electricity generated by the conversion systems presents fluctuations in output power and in some conditions, it can happen to produce no power at all (day and night cycle, temporary calm of the atmosphere, sudden nebulosity etc.). In this case, so that there are no interruptions in the energy supply of the consumers, sources of accumulation of electricity are installed. The most common storage system used is battery banks and whatever the type, it have in common being with deep cycle of discharge.

It is very common for hybrid systems that power for isolated consumers to be provided with alternative/backup power sources, such as Diesel groups, Fig. 1.

Battery bank and Diesel generators play also an important role in improving system stability and smooth out fluctuations of power.

The interface with the load is given by the electrical connection nodes of the bus bar type, and all the switching, automation and protection equipments. HPS are designed in different bus bar configurations: dc bus, ac bus and a combination of dc-ac bus bars, in all cases electronic converters being necessary to deliver a quality power to the consumer.

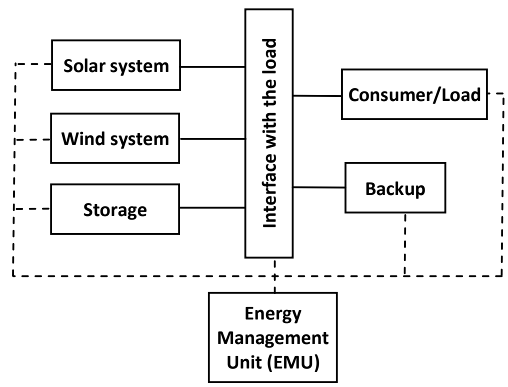


Fig. 1. Block diagram of HPS with EMU

In order to supervise the energy flows within the HPS and ensure a fully automatic system operation, the hybrid systems are equipped with an Energy Management Unit. This device includes a microcomputer with appropriate software to perform the following functions [1]:

- Monitoring and controlling the state of the entire system;
- Monitoring and controlling the battery state of charge;
- Starting and stopping Diesel group when appropriate;
- Establishing the priorities for generating and covering the load according to the preset priorities;

2. ENERGY MANAGEMENT STRATEGIES

The EMU plays a critical role in HPS, because it determines the system's behavior by controlling the energy flows and deciding the operating priorities of each subsystem [2].

In order for HPS to work properly, the EMU's energy strategy must be able to fulfill the following tasks [3]:

- Improving the power system stability;
- Ensuring the continuity of power supply;
- Minimizing the cost of energy (COE);
- Protecting components against damage due to overloads.

On the other hand, in HPS, photovoltaic and wind systems produce energy directly in line with the renewable resource available on site. The other two components, the battery and the Diesel group are switched on to compensate for intermittency of renewable systems, to achieve matching to the demand and finally to supply properly the load. Thus, the battery bank and the Diesel group often operate simultaneously within the HPS during a time interval.

At this point the question arises which is the optimal energy management strategy for HPS and that the EMU must be programmed to fulfill. There are two options to choose [4]:

a) **Load following** strategy (LF), in which the Diesel group produces power only to cover the load demand, the battery bank being charged only from the surplus of electric energy produced by the solar and/or wind systems;

b) **Cycle charging** strategy (CC), in which, the Diesel group works to the maximum rated capacity both for covering the load and for charging the battery bank by the excess power [4]. In this case, a set point state-of-charge (SOC) is specified for the battery so that the Diesel group does not stop from charging the battery until this point is reached.

This paper aims to examine the technical-economic performance of a hybrid solar-diesel system that supplies electricity to an isolated home under the two energy management strategies: load following and cycle charging.

3. THE PROPOSED CASE STUDY

3.1. The studied location

The data regarding the characteristics of the renewable resource in the site are obtained with the GPS coordinates of the consumer (Borod area, Roumania) and the NASA website, the HOMER simulation program providing global horizontal solar irradiation and scaled annual average for solar resource, Fig. 2.

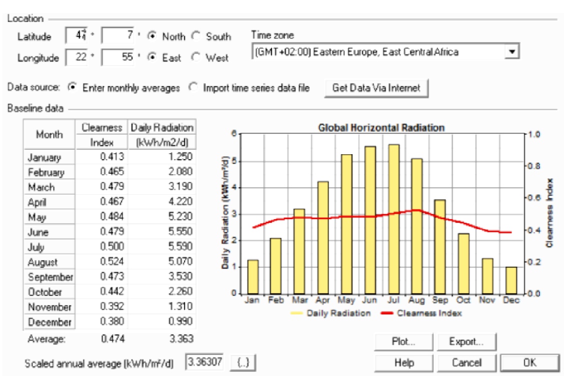


Fig. 2. Solar resource characteristic on site

3.2. The system load data

For the study purpose, we consider that the isolated consumer has the following home appliances with the main technical characteristics summarized in Table 1.

Table 1. Characteristics of the load

Load description	QTY		Load Current [A]		Load Voltage [V]		AC Load Power [W]
Lightning – LED 9W	5	**x**	0,041	**x**	220	**=**	45
Refrigerator	1	**x**	0,8	**x**	220	**=**	176
Hydrophore	1	**x**	3	**x**	220	**=**	660
Washing machine	1	**x**	6	**x**	220	**=**	1320
Tv	1	**x**	0,4	**x**	220	**=**	88
Radio	1	**x**	0,113	**x**	220	**=**	25
Total AC power (W)							2314

The possibility of establishing a pattern of the load (daily, weekly or monthly use cycle) allows the HOMER software to form a simulated load curve, covering the needs of the considered consumer, Fig. 3 showing the seasonal profile for the considered load [1].

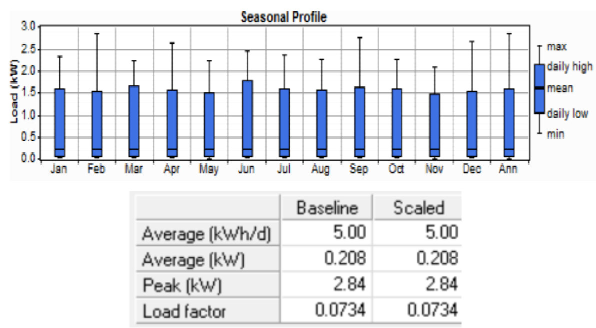


Fig. 3. The load profile of the remote consumer

3.3. The system configuration

For the electricity supply of the isolated consumer, a solar - Diesel hybrid power system (SDHPS) with accumulation in batteries was chosen, with dc-ac bus bars (48V-230V) and a pure wave bi-directional inverter, Fig.4.

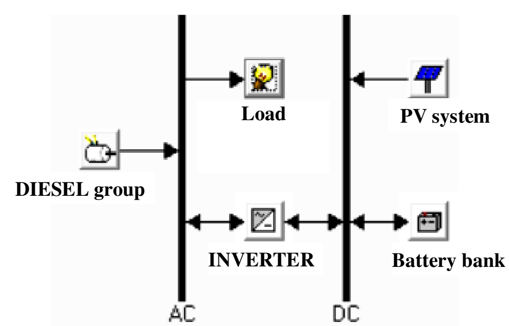


Fig. 4. Solar-Diesel HPS with battery bank

The proposed SDHPS components configuration consists in a photovoltaic system (PV), 6 PV panels grouped in two strings (of 3 per string), a battery bank (BA) with a total of 8 accumulators, also grouped in two strings of 4 per string, a 5.5 kW Diesel group (DG) on GPL and a 4.5 KW bidirectional inverter (INV), the main input parameter and costs of these components being summarized in Table 2.

Table 2. Characteristics of the main components of the SDHPS

PV system [5]	
Manufacturer	*Suntec*
Nominal power [W]	*270*
Nominal voltage [V]	*24*
Current nominal [Ahp]	*7,71*
Open circuit voltage [V]	*24,6*
Short-circuit current [A]	*8,2*
Derating factor [%]	*80*
Tracking	*fixed*
Capital cost [$]	*2982*
Cost of replacement [$]	*2982*
Lifetime [years]	*20*
Battery bank [6]	
Manufacturer	*Trojan*
Model	*T - 1275*
Type	*Deep cycle*
Capital cost [$]	*1600*
Cost of replacement [$]	*1600*
Nominal voltage [V]	*12*
Nominal capacity [Ah]	*150*
DIESEL group [7]	
Manufacturer	*Honda*
Electronic auto-start	*yes*
Fuel	*GPL*
Nominal power [kW]	*5,5*
Fuel consumption [l/h]	*4,27*
Capital cost [$]	*2250*
Cost of replacement [$]	*2250*
Operation &maintenance cost [$/h]	*7*
Lifetime [h]	*15000*
INVERTER [8]	
Manufacturer	*Xantrex*
Model	*Pure wave*
Nominal power [W]	*4500*
Nominal ac voltage [V]	*220*
Nomina dcl voltage [V]	*48*
Capital cost [$]	*2700*
Cost of replacement [$]	*2700*
Lifetime [years]	*15*
Operation &maintenance cost [$/h]	*0*

4. SIMULATION RESULTS

For the proposed case study, the hybrid system was simulated in HOMER optimization program under two different energy management strategies for EMU: load following and cycle charging.

4.1. Load following strategy

The LF strategy depicted in the Fig. 5 shows three modes of operation for the HPS, depending on the power produced by the PV system: first mode is when the PV output power is equal to the load power, second one is when the PV output power is higher than the load and the last mode when the PV output power is less than the load.

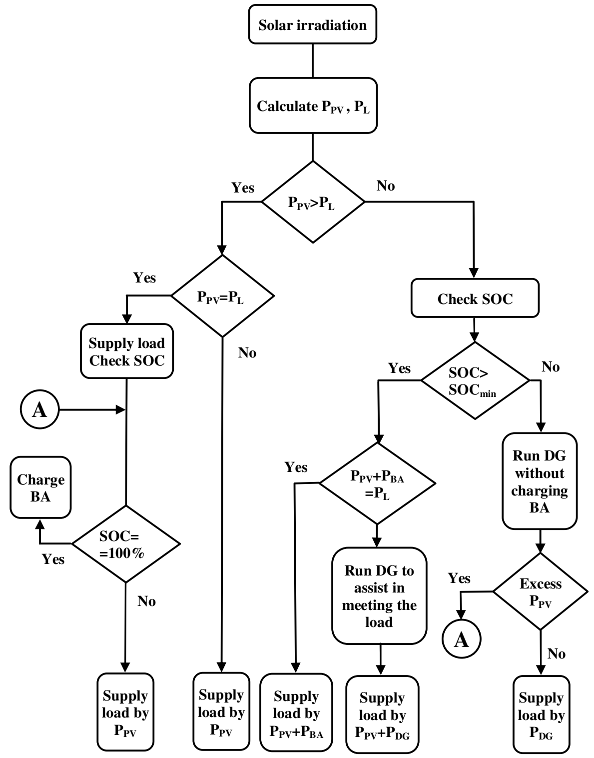


Fig. 5. LF strategy flowchart [4]

If the PV power is equal to the load power (P_L), it meets the load demands and the BA and DG stays off, no excess power is produced.

If the output PV power is higher than the demand power of the consumer, an excess power is produced so if the SOC is not 100%, this excess power is redirected to charge the BA. If BA is fully charged it is redirected to a dump load.

If the power produced by PV is less than the load demand, it is possible two scenarios [4]:

- If $SOC=SOC_{min}$, the DG starts and satisfy the net load without charging the battery. The BA will be charged only from excess power from PV;
- If $SOC>SOC_{min}$, DG starts in assist in meeting the load only if the combined power produced by PV and BA does not meet the demand. Otherwise, the EMU gives the command to discharge the BA and the load will be supplied by the PV and BA.

4.2. Cycle charging strategy

The CC strategy depicted in the Fig. 6 shows that if the PV output power is equal to the load power, EMU operating mode is identical to LF strategy.

The difference occurs when $SOC<SOC_{min}$, in which case DG starts at maximum rated capacity both for powering the consumer and for charging the BA with excess energy. When $SOC>SOC_{min}$, BA will be discharged for meeting the load.

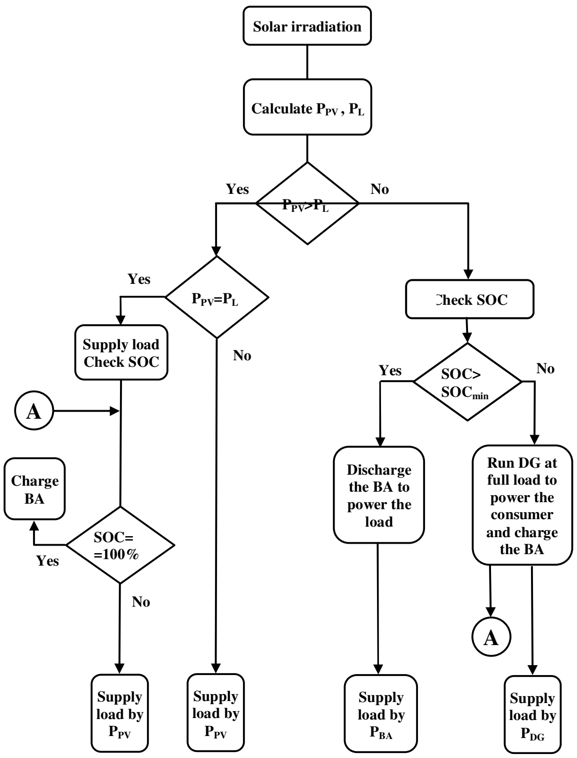


Fig. 6. CC strategy flowchart [4]

4.3. Technical results

By running the HOMER optimization program for both energy management strategies, the following results were obtained:

PV system annual electrical output is 1867 kWh/year at a capacity factor of 13,2% in both cases, due to the fact that the system array is the same size. In Fig. 7, it is noticed that the difference in the generated electricity is made by DG.

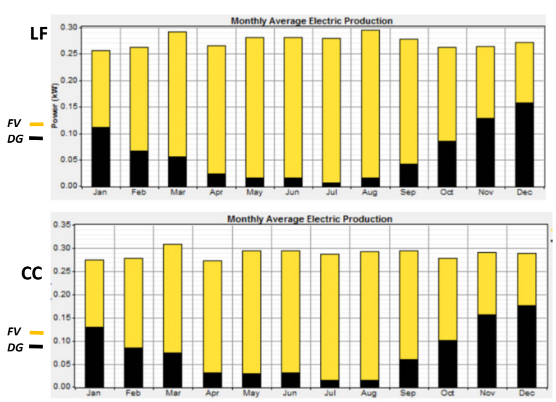


Fig. 7. Monthly average electric production

DG system performs differently under the two EMU dispatch strategies, the main results being depicted in Table 3.

Table 3. DG performance under the LF and CC strategy

Item	LF	CC	Unit
Hours of operation	319	124	hr/yr
Number of starts	315	60	starts/yr
Operational life	47	121	yr
Capacity factor	1.09	1.36	%
Electrical production	526	656	kWh/yr
Mean electrical output	1.65	5.29	kW
Min. electrical output	1.65	1.65	kW
Max. electrical output	1.77	5.5	kW
Fuel consumption	779	532	l/yr
Specific fuel consumption	1.479	0.812	l/kWh
Fuel energy input	5,120	3,499	kWh/yr
Mean electrical efficiency	10.3	18.7	%

From Table 3 it is observed that due to the lower number of operating hours and start-ups, the DG performs better under CC than under the LF strategy electrical efficiency in that last case being 18,7% against 10,3% in LF, Fig. 8.

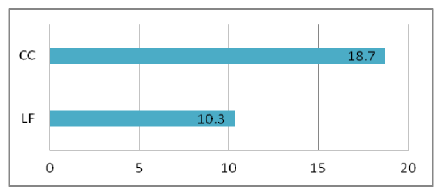


Fig. 8. Mean electrical efficiency of the DG under LF and CC strategy in [%]

It is to notice that DG works at full load under CC strategy (both for covering the load and for charging BA) and at partial load under LF strategy (only to meet the net load), so it would be expected that the consumption at CC strategy will be higher. However, the number of starts and hours of operation in CC mode is small enough to maintain consumption below that obtained in the LF mode.

On the other hand, the *BA system* under CC strategy has a higher amount of energy that cycle through per year (1393 kWh against 1250 kWh, Fig. 9), due to the fact that it is charged whenever DG is started, this fact affects the battery operational lifetime.

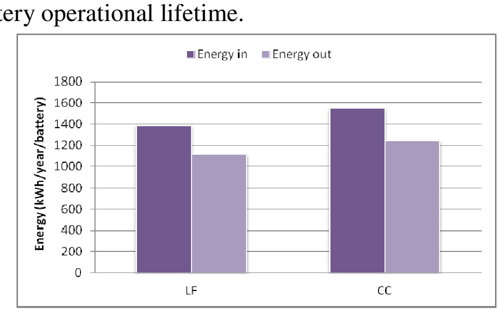


Fig. 9. Energy input / output of the BA

Although in the case of CC strategy BA throughput is higher than LF, the lower number of charging cycle make the number of years that battery bank last before it needs replacement to remain comparable (5 years).

The main results of the BA performance under the two EMU energy strategy are shown in Table 4.

Table 4. BA performance under the LF and CC

Item	LF	CC	Unit
Energy in	1,387	1,547	kWh
Energy out	1,118	1,246	kWh
Losses	260	293	kWh
Annual throughput	1,250	1,393	kWh/yr
Expected life	5.65	5.07	yr
Autonomy	41.5	41,5	hr
Lifetime throughput	7,067	7,067	kWh
Storage depletion	8	8	hr

The 41,5 hour BA autonomy is a result very close to the two-day assumption made in the sizing phase of the HPS components, an increased autonomy can be obtained by increasing BA size.

4.4. Economical results

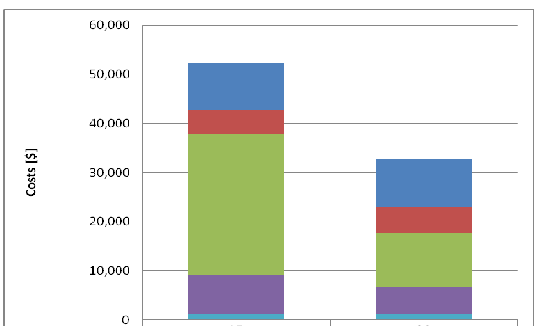
One of the main goals of the HOMER program is to reduce HPS operating costs and to optimally configure the system so that load demands can be met. The economic criterion based on which the optimal system is selected is that of the net present cost (NPC representing the sum of all the costs and benefits that occur throughout the life of the system).

Running the HOMER program for the two energy management strategies, it can be seen from Fig. 10 that the CC strategy is the most economically viable, with a NPC of 30182$ as against 49911$ of the LF. Also the average cost per kWh of producing electricity (COE) in CC is lower than in LF, as 1,294 $/kWh against 2,139 $/kWh.

				PV (kW)	GD (kW)	TRJ	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Propane (L)	GD (hrs)
				1.62	5.5	8	4.5	CC	$ 9,532	1,615	$ 30,182	1.294	0.74	532	124
				1.62	5.5	8	4.5	LF	$ 9,532	3,159	$ 49,911	2.139	0.78	779	319

Fig. 10. Simulated results in HOMER

The cost summary of the SDHPS, by components is shown in Fig. 11.



	LF	CC
Capital ($)	9,532	9,532
Replacement ($)	5,060	5,283
O&M ($)	28,545	11,096
Fuel ($)	7,965	5,444
Salvage ($)	1,191	1,173

Fig. 11. Cost summary for SDHPS under the two dispatch strategies (LF and CC)

From FIG. 11 it can be seen that the CC strategy has the lowest operating and maintenance costs (O&M), respectively fuel costs, due to the lower number of operating hours of the DG.

Also it can be noticed that replacement costs (these costs are originating from the remaining life of the system components [4]) and salvage are comparable.

4.5. Environmental assessment

Combustion of fuels in Diesel groups results in the emission of polluting gases into the atmosphere such as: nitrogen oxide (NOx), sulfur dioxide (SO2), particulate matter (PM), unburned hydrocarbon (UHC), carbon monoxide (CO), and carbon dioxide (CO2) [4].

Due to the smaller number of operating hours of the DG, the CC strategy is the most viable in terms of greenhouse gas emissions, as shown in Table 5.

Table 5. Pollutant emissions under the LF and CC strategy

Pollutant Emissions (kg/yr)	LF	CC
Carbon dioxide	1,185	810
Carbon monoxide	5.06	3.46
Unburned hydrocarbons	0.561	0.383
Particulate matter	0.382	0.261
Sulfur dioxide	2.56	1.75
Nitrogen oxides	45.2	30.9

5. OPTIMIZATION RESULTS

For the dimensioning of the SDHPS components, it was taken into account the fact that DG must be able to cover both the charging of BA and the required load [10]:

$$P_{DG} = P_{BAchg} + P_{ac} \qquad (1)$$

Where:

P_{DG} = Requested power for the HPS generator;
P_{BAchg} = Requested power to charge the BA;
P_{ac} = Total ac power requested at the consumer.

From the diagrams shown in Figures 5 and 6 it can be seen that only in the case of the CC strategy this mode of use of the DG is required, in the case of the LF strategy, DG being used only to cover the load, the task of BA charging being left to the PV system. Thus, the size of the DG can be chose based on total ac consumer load:

$$P_{DG} = P_{ac} \qquad (2)$$

On the other hand, from the previous simulations it is observed in Fig. 9 that at the same nominal power of the DG, the CC strategy is much viable in terms of costs: NPC, O&M and fuel cost decreases.

From the above it results that the size of DG can be optimized as follows: the total ac power requested by the consumers is P_{ac} = 2314 W, so a DG with a nominal power of 2,5 kW should be cover.

The DG size constitutes a sensitivity value in HOMER algorithm, thus a simulation was made for the values of 2,5 kW and 3,5 kW.

Running the simulation, it results that the unit of 2,5 kW not being economically justifiable, both NPC and fuel consumption increasing drastically even if the initial capital has decreased to 8782$ due to the lower price of the smaller size DG, as shown in Fig. 12.

PV (kW)	GD (kW)	TRJ	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Propane (L)	GD (hrs)
1.62	3.5	8	4.5	$ 9,082	2,172	$ 36,851	1.580	0.78	532	479
1.62	2.5	8	4.5	$ 8,782	2,978	$ 46,844	2.008	0.79	922	641

Fig. 12. Simulated results for SDHPS with the two different DG units

Therefore, the optimal value for DG under the LF strategy is 3,5 kW, all the cost components decreases compared to HPS with 5,5 kW group, Fig. 13.

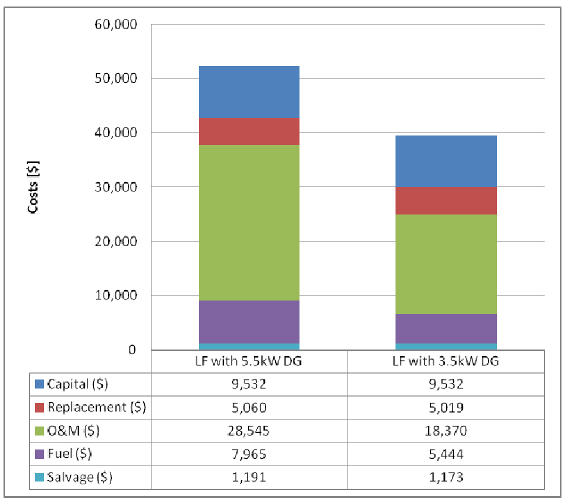


Fig. 13. Cost summary for SDHPS under LF strategy with DG of 4,5 kW and 3,5 kW

However, the reduction in costs under LF strategy through DG optimization is not sufficient, the CC strategy being optimal in this case, having the lowest NPC, Fig.14.

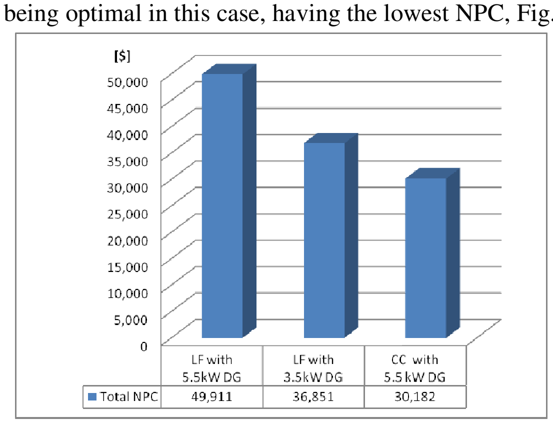


Fig. 14. Total NPC summary for SDHPS

5. CONCLUSIONS

The evaluation of an HPS project for supplying electricity to isolated consumers must include analysis of the energy strategy for EMU.

Each type of HPS has its own operating behavior, which is strongly dependent on the characteristics of the renewable resource in the site, its penetration degree, as well as the type of renewable subsystems chosen in the scheme. Therefore, for each HPS, a detailed analysis must be done to establish the best energy strategy.

In this paper, a hybrid solar-Diesel power system was chosen with accumulation in batteries, the operational behavior being modeled in HOMER optimization software under two different energy management strategies for EMU: load following and cycle charging.

The technical analysis shows that HPS performs better under the CC strategy due to the reduced number of operating hours of the DG. This is a key factor that influences the system due to the fact that normally, in LF Strategy DG consumption should be lower because the DG produces only enough power to cover the load. In the CC strategy, the DG must both cover the load and charge the BA, hence to operate at full load all the time.

The results show that, in this particular case, the reduced number of operating hours and start-ups compensate for the higher consumption of the DG at full load.

Regarding the operational behavior of BA, although the CC strategy has a higher amount of energy that cycle through per year, the small number of start-ups of the DG makes its lifetime comparable to that of the LF strategy.

The economic analysis shows that running the HPS under the CC strategy results in significant costs reductions for the same capital invested in main HPS components, the total economy obtained using CC strategy for EMU being of 19 ,729 $, Table 6.

Table 6: Total economy obtained under CC strategy

Economy	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
	17,449	2,521	18	19,729

The optimization analysis showed that, by lowering the size of the DG, the technical performances of the HPS can be improved under the LF strategy, obtaining a substantial reduction of the costs.

From Fig. 11 it can be seen that the O&M costs in the case studied decreased from $ 28,545 to $ 18,370, which represents a significant total savings of 10,175$. However, this economy is not sufficient in this case, the CC energy management strategy being preferred.

REFERENCES

[1]. Şerban Ioan Bunda, Sisteme hibride de producere a energiei electrice, Editura Universității din Oradea, 2015, ISBN 978-606-10-1534-4.

[2]. Li Han, et al., *Optimal energy management for industrial microgrids with high penetration renewables*, Protection and Control of Modern Power Systems 2017, [Online], available at

https://www.researchgate.net/publication/315966122/ 22.01.2020.

[3]. L. Olatomiwa, et al, *Techno-economic analysis of hybrid PV-diesel-battery and PV-wind-diesel-battery power systems for mobile BTS: The way forward for rural development* 2015, [Online], available at: https://researchgate.net/publication/ 274899123, 22.01.2020.

[4]. Aziz A.S. et al., *Energy Management and Optimization of a PV/Diesel/Battery Hybrid Energy System Using a Combined Dispatch Strategy*,[Online], available at: https://www.mdpi. com/2071-1050/11/3/683, 16.012020.

[5]. ***, http://pvcert.gr/assets/media/PDF/Publication /Informational%20Material/ Installing%20PV -Practical%20guide/68.pdf/ 21.01.2020.

[6]. ***, http://www.trojanbattery.com/Products/ T-127512V.aspx/21.01.2020.

[7]. *** - http://powerequipment.honda.com/generator /home-back-up-generators/21.01.2020.

[8]. *** - http://www.solar-electric.com/nexax wseinan.html/21.01.2020.

[9]. Fazelpour, F.; Soltani, N.; Rosen, M.A. *Economic analysis of standalone hybrid energy systems for applicationin Tehran*, Iran. Int. J. Hydrogen Energy 2016, ,[Online], available at: http://www researchgate.net/publication/303585824/23.01. 2020.

[10]. *** *Stand-Alone Photovoltai*c *Systems A handbook of recommended design practice* SAND87-7023 Distribution UNLIMITED RELEASE Category, Updated March 1995, [Online], available at: http://educypedia.info/ library/sand87_7023.pdf/24.01.2020.