Techno-economic analysis of multiple paralleled diesel generators for micro isolated applications

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Abstract— This paper analyses the key benefits of a multiple paralleled diesel generator system over a "Single" diesel generator system for supplying small remote and isolated loads. Even though having several small diesel generators in parallel instead of one larger one will certainly induce higher capital cost of the generating unit, the resulting cost of kWh generated as well as the system is life cycle cost can be significantly decreased. In this study, HOMER Pro software is used to compare the technical, economic and environmental performance of the two configurations. For the selected case study, the simulation results reveal that multiple connected small diesel generators instead on a single large one can be considered for rural and isolated electricity generation.

***Index Terms*— Diesel generator, paralleled operation, rural electrification, cost effectiveness**

1 INTRODUCTION

In most of small, remote and isolated areas, the use of small diesel generators is still the most preferred option for electricity generation as opposed to other means such as renewable energy sources [1]. The main reason for this choice by users is the low specific capital cost per kW exhibited by the diesel generators when compared to other generators such as solar photovoltaic (PV), wind or even micro hydropower [2]. The other advantage of DGs is that the power produced is not dependent on variable and exogenous resources such as solar irradiance, water resource or wind speed; it is available on demand. Furthermore, DGs can be easily moved from one site to another, they are modular, and their power-to-weight ratio is high [3].

The main disadvantage of DGs is the fact that they are engines converting heat from the combustion of fuel into electricity. Therefore, the cost of fuel needed, the transportation and storage as well as the maintenance costs make the use of DGs very expensive in the long run [4].

Knowing the advantages, disadvantages and reasons why consumers select DGs over other supply options, it is therefore imperative to use means of decreasing the life cycle cost of DGs while supplying isolated demands. This can be done by forcing DGs to always operate close to their maximum ratings as this will result in an increase in the performance efficiency and a decrease in specific fuel consumption. Practical ways of realizing the condition above are:

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- Supplying the demand in parallel with a resistive load that can dissipate the excess power into heat while keeping the load factor high. However, this method is not energy efficient due to the energy wasted [5].
- Using DGs in conjunction with storage systems, such as batteries, in a charging-cycle dispatch strategy. However, the capital cost of the system is increased due to the addition of the battery bank to the system [6].

With the current availability of DGs rated up to several thousand kW, the current common practice is to install a single large generator that can be able to adequately supply the load even during peak time. However, in several standalone applications, there are benefits in sharing the total demand among different smaller DGs, connected in parallel to increase the supply reliability, availability, fuel efficiency and operational flexibility. This paper will explore the benefits of using small DGs in parallel in standalone and isolated applications. The Hybrid Optimization Model for Electric Renewable (HOMER Pro) software is used to compare the technical, economic and environmental performance of the following 3 cases while supplying the same demand:

- Single DG used,
- Battery-integrated DG,
- Multiple paralleled DGs.

2 METHODOLOGY

As stated in the introduction, the main objective of this paper is to minimize the life cycle cost of supplying isolated load by using multiple paralleled DGs while keeping the initial capital cost as low as possible.

To achieve the main goals of this research, the following methodological steps are followed:

2.1 Load description

The daily load profile of a single domestic household given on Fig. 1 is used as a case study. From this figure, it can be seen that the demand is minimal during the night and then increases during the day to reach a peak in the evenings

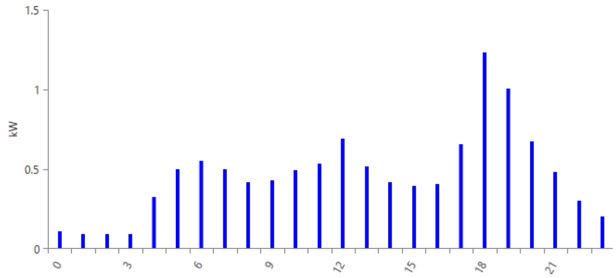

Fig. 1: Proposed domestic load profile

The load profile can be modelled with a day-to-day random variability of 10% and a timestep variability of 20%. This results in a load with an average energy requirement of 11.26 kWh/day, average power demand of 0.47 kW, a peak demand of 2.09 kW with a load factor of 0.22.

2.2 Supply options selection

DGs are selected based on their low initial capital cost as well as the fact that they are currently well deployed and used in isolated areas. The three selected architectures namely the single DG, the battery-integrated DG and the multiple paralleled DGs are presented in the subsections below.

2.2.1 Single DG

Fig. 2 illustrates the power flow in the single DG option. In this case, one DG is used to supply the load using the load following dispatch strategy where it is continuously adjusting its output to meet the demand. The major disadvantage of this architecture is that the specific fuel consumption is high when the useful demand is low.

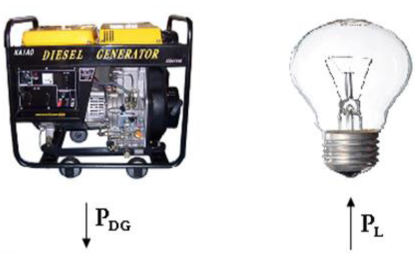

Fig. 2: Single DG

2.2.2 Battery-integrated DG

Fig. 3 illustrates the power flow in the battery-integrated option. In this case, whenever DGs operate, they are forced to produce more power than required to serve the load. This surplus electricity is stored in the battery bank for future use when the demand is low and the DG can be switched off to save fuel.

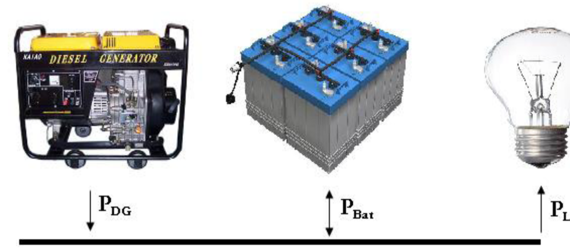

Fig. 3: Battery-integrated DG

2.2.3 Multiple paralleled DGs

Fig. 4 illustrates the power flow in the multiple paralleled DGs option where the total demand is shared among two smaller DGs. One of DGs is used as main supply while the second is used as complementary power source during peak demand periods only.

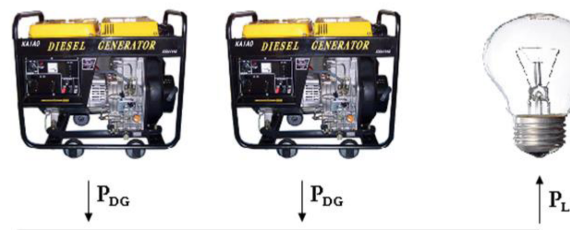

Fig. 4: Multiple paralleled DGs

2.3 System optimization

Several simulation tools that can help to achieve the goal of this research work are currently available on the market. Chandel S.S. gives an extensive list of software with their specific features [7]. HOMER Pro has been selected because of the following features:

- Simulation: With HOMER, it is possible to determine the technical feasibility, life-cycle cost and performance of a proposed design over the 8760 hours in a year.
- Optimization: HOMER can simulate several different system architectures with the aim of finding the one that meets the technical constraints at the lowest life-cycle cost.
- Sensitivity Analysis: HOMER can perform various optimizations under a range of input assumptions to determine the effects of uncertainty in the model inputs, such as fuel price fluctuations.

Information about the load demand, supply options, component sizes and costs are used as input in HOMER to simulate and find feasible solutions which can be examined and interpreted.

3 MAIN SIMULATION INPUT PARAMETERS

3.1 Single DG case

In this case, one single DG is used to supply the load. The DG's rating is 2.3 kW with a minimum load ratio of 25% and an operating lifetime of 15000 hrs. For this DG, the initial capital cost is taken as $500/kW with a replacement cost of $500/kW and an operation and maintenance cost of $0.03/hr. The fuel consumption as well as the efficiency curves in relation to the DG loading are given on Fig. 5 and Fig. 6 respectively.

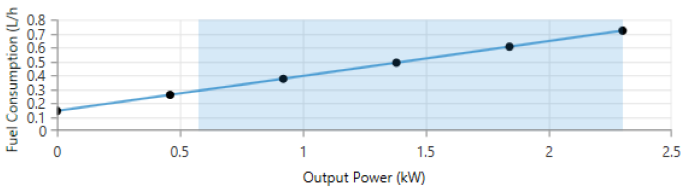

Fig. 5: DG fuel consumption versus output power

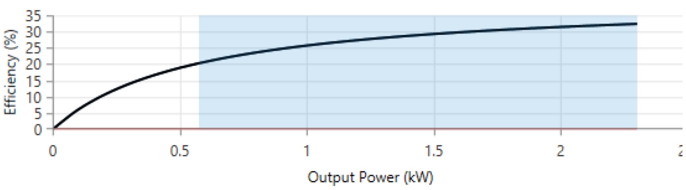

Fig. 6: DG fuel efficiency versus output power

3.2 Battery-integrated DG case

In this case, a DG with the same characteristics as the one used in the case above, has been used. A battery storage system and a bidirectional converter have been integrated in the supply system. The main parameters of the battery and for the converter are given in Table I.

Table I - Battery and converter parameters

Parameters	Battery	Converter
Initial capital cost	500 $/kW	300 $
Replacement cost	500 $/kW	300 $
Operation and maintenance cost	10 $/yr	-
Nominal voltage	12 V	-
Maximum capacity	83.4 Ah	100 %
Round Trip Efficiency	80 %	85 %
Life throughput	800 kWh	15 yr

3.3 Multiple paralleled DGs case

In this case, two small generators of the same rating are used in parallel to match the requirements of the load demand. Each DG is 1.2 kW with a minimum load ratio of 25% and an operating lifetime of 15000 hr. The capital cost of each DG is $750/kW with a replacement cost of $750/kW and an operation and maintenance cost of $0.03/hr. The fuel consumption as well as the efficiency curves in relation with the DG loading are given on Fig. 7 and Fig. 8 respectively.

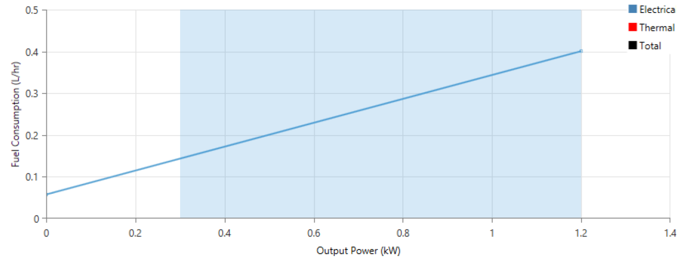

Fig. 7: DG fuel consumption versus output power

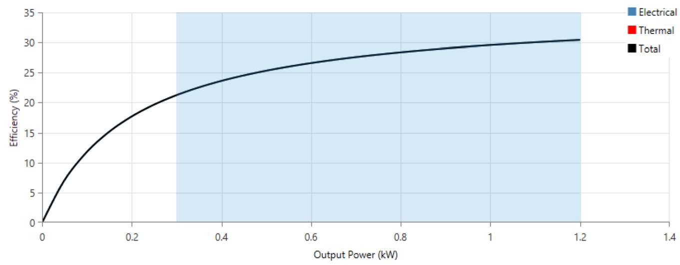

Fig. 8: DG fuel efficiency versus output power

4 RESULTS AND DISCUSSION

In this section, the single DG, battery integrated DG and multiple paralleled DGs options are simulated using HOMER Pro when supplying the same load demand. The simulation results of the three supply options performed for each of the 8,760 hours in a year are evaluated using techno-economic criteria such as the total Net Present Cost (NPC), the Cost of Energy produced ($/kWh) or the amount the amount of pollutant emission. For the three cases, the duration of the project is 25 years.

4.1 Result discussion

4.1.1 Single DG case

From Fig. 9, it can be seen that the DG operates a very low loading throughout the year, except in the evening when the peak power demand occurs between 18h00 and 20h00. The average output power from the DG is around 0.65kW, which is 28% of the DG's rated full load.

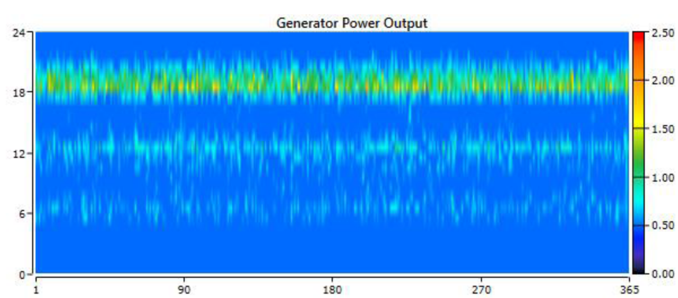

Fig. 9: Single DG yearly output power profile

The corresponding yearly fuel consumption profile is given in Fig. 10.

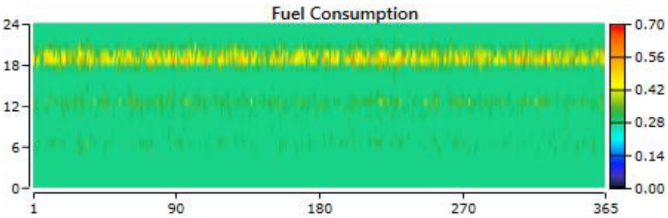

Fig. 10: DG yearly fuel consumption profile

4.1.2 *Battery-integrated DG*

The optimal configuration of the battery-integrated DG used to supply the selected load demand is composed of the 2.3 kW DG, 5 batteries of 1kWh each and a 2.3 kW converter.

From Fig. 11, we can see that the charging cycle dispatch strategy is used. When the generator is turned ON, three times a day on average during high load demand periods (morning, midday and evening) it is running at high load factor to supply the demand and recharge the battery at the same time. The DG is turned OFF for the rest of the day when the load is low.

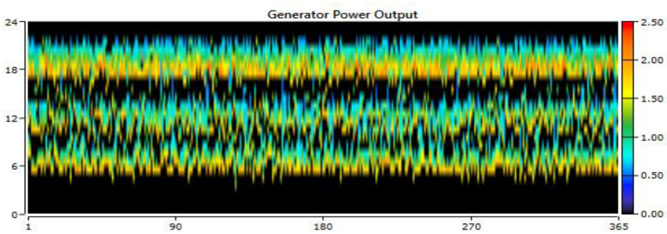

Fig. 11: DG (with battery integrated) yearly output power profile

The corresponding yearly fuel consumption profile is given in Fig. 12, which correspond to the time when the DG is operating.

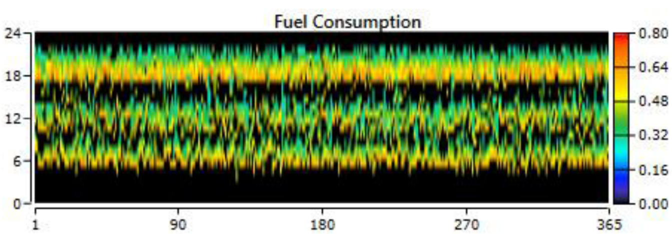

Fig. 12: DG (with battery integrated) yearly fuel consumption profile

Fig. 13 and Fig. 14 show the yearly power flow profile of the inverter and of the rectifier respectively. It can be seen from these two figures that the rectifier and inverter do not work at the same time. The rectifier output profile is following the same trend as the one from the DG on Fig. 12.

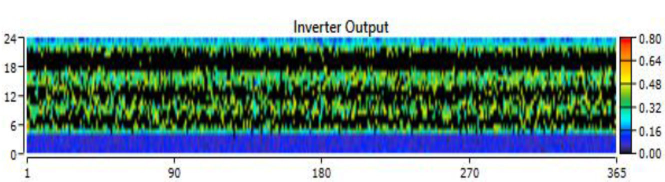

Fig. 13: Inverter yearly output power profile

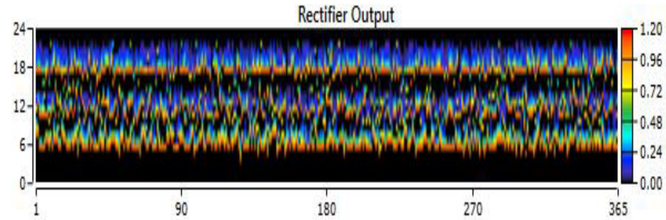

Fig. 14: Rectifier yearly output power profile

The battery bank state of charge is given in Fig. 15, where it can be seen that the battery is used to supply the load during off-peak time demand when the DG is OFF. When the minimum SOC of the battery (40%) is reached, the battery cannot be used anymore until the next recharge cycle.

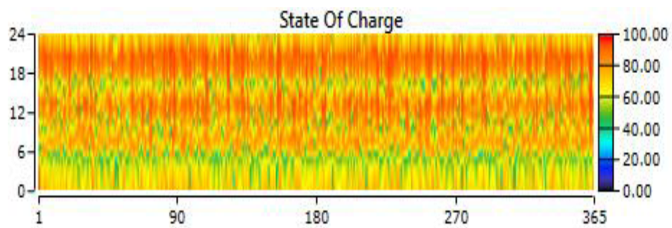

Fig. 15: Battery yearly state of charge profile

4.1.3 *Multiple paralleled DGs case*

Fig. 16 shows that one of the 1.2 kW DGs is used as the main supply, therefore it is running at a high load factor which results in better and more efficient fuel economy. However, when the peak demand occurs and the main DG is not able to supply the demand by itself, the second 1.2 kW DG is switched ON to balance the deficit of power needed as shown in Fig. 17.

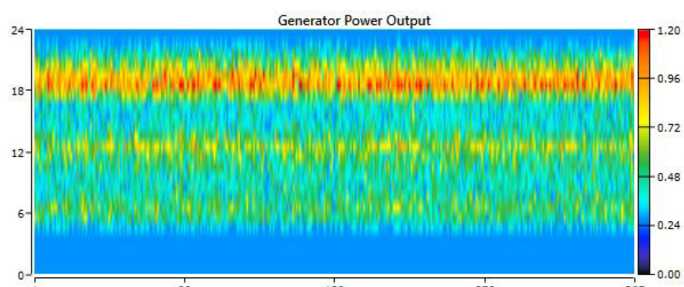

Fig. 16: Main DG (paralleled operation) yearly output power profile

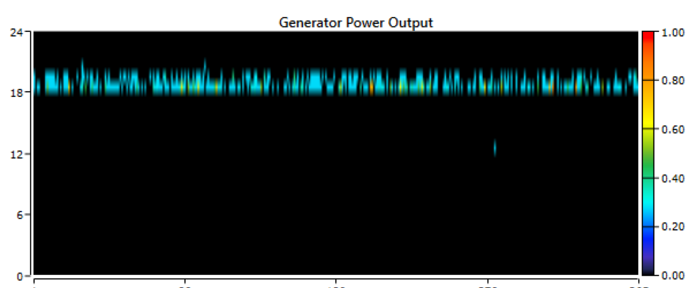

Fig. 17: Second DG (paralleled operation) yearly output power profile

4.2 Comparison of the three proposed supply options

A summary of economical, technical and environmental comparisons between the Single DG, battery-integrated DG and multiple paralleled DGs cases is presented in Table 4, 5 and 6 respectively.

4.2.1 *Economic comparison*

The economic comparison is done based on the Net Present Cost as well as the different costs involved in the life-cycle cost calculation (25 years). The breakdown of these costs is summarized in Table 2 below.

Table II: Costs comparison between the 3 options

Quantity (Unit)	DG	Battery-DG	DGs in //
Initial capital cost ($)	1,150	3,340	1,800
Replacement cost ($)	8,342.9	11,535	6,529
O & M cost ($)	7,813.9	4,057	4,250
Fuel ($)	34,557	23,344	23,306
Salvage ($)	-110.2	-231	-167.45
Total Net Present Cost ($)	51,753	42,044	35,719
Levelized Cost of Energy ($)	0.974	0.791	0.672

From the table above it can be seen that even though the investment cost of the two paralleled DGs is higher than that of the single DG, using multiple paralleled DGs is from far cost effective compared to the two other options in terms of Net Present Cost and Cost of Energy Produced.

4.2.2 *Technical comparison*

From Table III, it is noticeable that the two paralleled GDs are operating at very high capacity factor when only the main DG is switched ON. This makes the second DG to operate for a very short moment during the day resulting in a very high operation life of 40 years which is greater than the project lifetime (25 years). Therefore, there will be no need to replace the second DG; this will result in a salvage of replacement cost.

Table III. Technical comparison between the 3 options

Quantity (Unit)	DG	Battery-DG	DGs in //	
			DG1	DG2
Operation life (yr)	1.71	3.92	1.71	40.1
Electrical production (kW/yr)	5,641	5,006	4,340.6	123.44
Excess electricity (kW/yr)	1,530	0.4	341.1	-
Total fuel consumed (L)	2,673	1,805.7	1,802.85	56.85
Average fuel (L/day)	7.32	4.95	4.94	-
Specific fuel consumption (L/kWh)	0.47	0.36	0.4	-
Fuel energy input (kWh/yr)	26,303	17,769	17,180	559.36
Mean electrical efficiency (%)	21.45	28.17	25.27	22.07
Capacity factor (%)	28	24.8	41.3	-

4.2.3 *Environmental comparison*

Table IV shows that there is an important reduction of pollutant gas emitted into the atmosphere achieved when the Multiple paralleled DGs are used rather than the single DG.

Table IV: Emission comparison between the 3 options

Quantity (kg/yr)	DG	Battery-DG	DGs in //
Carbon dioxide	7,039.20	4,755.10	4,747.40
Carbon monoxide	17.38	11.74	11.72
Unburned hydrocarbons	1.92	1.30	1.30
Particulate matter	1.31	0.88	0.88
Sulphur dioxide	14.14	9.55	9.53
Nitrogen oxides	155.04	104.73	104.56

5 CONCLUSION

In this paper, the benefit of using small multiple paralleled diesel generators instead of a single large one is explored and discussed. A remote and isolated domestic load has been selected as case study to simulate the different supply options, namely single DG, battery-integrated DG and multiple paralleled DGs.

HOMER Pro has been used to compare the economical, technical and environmental characteristics of these three supply options while supplying the selected load. The results have shown that the use of multiple paralleled diesel generators has more benefits than the battery-integrated diesel generator or than a single large DG unit.

- Economically: Even if the capital cost of using multiple paralleled diesel generator is higher, the total Net Present Costs as well as the cost of energy produced are lower compared to the use of a single diesel generator.
- Technically: It has been shown that when using two diesel generators in parallel, one unit will be operating only during peak time. Therefore, its life in terms of operating hours will be extended. This will in turns decrease the life cycle cost because no replacement will be necessary for this particular unit.
- Environmentally: The emissions of pollutant gas are reduced.

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