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Optimal Design and Techno-Economic Analysis of Grid-connected PV power System for Industry Park under grid outages

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Abstract- The existing distribution system of Ethiopia has encountered frequent power outages. During this outage, the critical load of most firms in the country is supplied by diesel fuel. This study examines the feasibility of integrating solar PV system into an existing unreliable grid/diesel generator system for supplying the critical load of Kombolcha Industry Park (11°5′0″ N, 39° 44′ 0″ E), Ethiopia. The work was begun by collecting the load data, grid outage and meteorological data of the study site. Then, optimal design, modeling and techno-economic analysis of grid connected PV/diesel system has been carried out using HOMER Pro optimization software by exploring three different scenarios. Results showed that grid/PV/diesel systems are technically, economically and environmentally feasible for the selected location with the cost of energy 0.048 $/kWh. It is also found that the emissions in the optimized grid/PV/diesel systems for the locations decreased by 46%, compared to the existing grid/diesel system. This study will provide a helpful awareness to the concerned stakeholders and policy makers to implement grid-connected PV systems in the north central part of Ethiopia.

Key words: Solar PV; Grid-connected; Unreliable grid; Techno-economic analysis; Emission

1. NTRODUCTION

Everywhere within the world, reliable electric power supply is key for economic development. However, in many developing and less developed countries, access to stable and uninterrupted supply of electricity is considered as a luxury. Ethiopia is one of a developing country, which has an area of 1,127,127 square km with a population of 105 million [1]. The existing electricity supply system of the country is characterized by frequent and prolonged outages. According to [2] report, in Ethiopia, 8.2 power interruptions in a typical month with an average outage duration lasting 5.8 hours are estimated. In order to with stand this outage and to get a reliable power, most industry in the country uses diesel generators as aback up [3]. However, due to the commercial maturation of renewable energy-based technologies like solar PV as well as the constant rise in fuel prices makes the renewable distributed generation system as a viable option for grid backup and off-grid electrification. To realize a zero net carbon emission, Ethiopia has also a target to reach a share of 15-20 % of its energy supply from non-hydropower-based resources (solar, geothermal and wind) [4].

In order to develop feed in tariff technology and to attain the placed goal of the country, optimal design and analysis of grid-connected PV system is very important. Varies studies have also analyzed the techno economic feasibility of grid-integrated renewable distributed generation systems and off-grid hybrid systems using different optimization techniques.

Gonzalez et al.[5] Presented the economic and environmental impact of grid-integrated hybrid PV/wind /biomass system in central Catalonia using Genetic algorithm optimization technique. The results show that, the grid-integrated hybrid renewable systems is less cost effective than the grid- only systems for the case under consideration , but it has lower environmental impacts compared to grid only systems. Rehman et al. [6] examined grid-connected PV system for household in Pakistan under unreliable grid consideration using HOMER Pro simulation software. The authors in [7] used the modified version of simulated annealing algorithm for optimal sizing of PV/Wind hybrid systems with battery and hydrogen storage for a remote area of Iran. Tawfik et al.[8] designed standalone hybrid PV/wind diesel/battery system for desalination purpose in Noubarya, Egypt. iHOGA software that is based on genetic algorithm has been used as a tool to perform the optimization.

As it is observed in different literature, the techno-economic analysis study of grid-tied PV system by considering outage in developing country is not explored thoroughly enough. Therefore, this study presents the optimal design and techno-economic analysis of grid-tied PV system under unreliable grid consideration to supply the critical load of Kombolcha Industry Park (IP) in Ethiopia. Previously diesel fuel was used as a backup in the industry park. In this case, this research is also studied for the reduction of diesel fuel consumption in the location.

2. METHODOLOGY

With the collected load, grid outage and climate data, the techno-economic, optimization and sensitivity analysis of the grid-tied PV system for the selected location is carried out using HOMER Pro as shown in Fig.1 below.

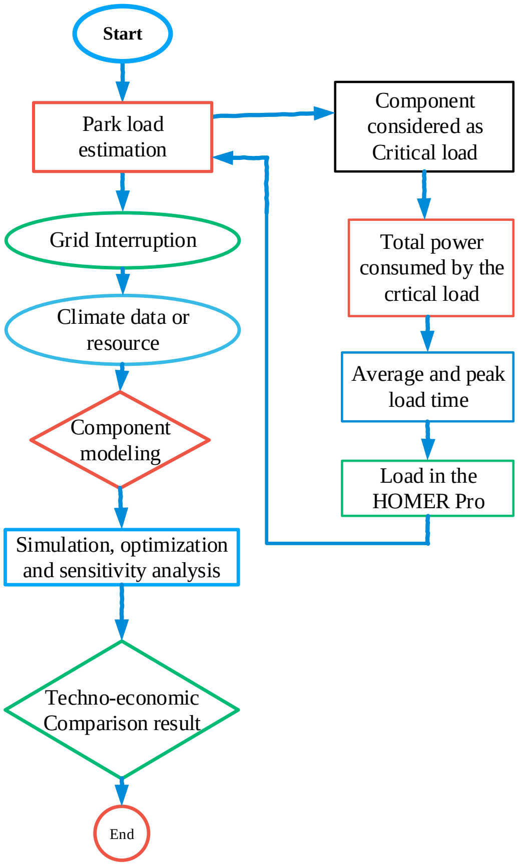

Fig. 1. Methodology of the study.

2.1.Electrical load estimation

The industry park under the study is situated in the north central part of Ethiopia. It covers 700 hectares [9]. The average daily electricity consumption of the park was 43MWh. From this total load, an average of 324 kWh/day consumptions are considered as a critical load as shown in Fig.2. The monthly average load profiles are also shown in Fig.3.The load profile of the location was obtained from the respective region of Ethiopian electric utility.

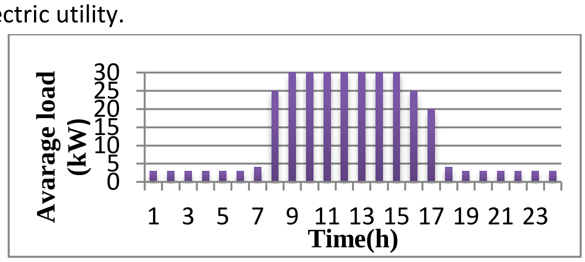

Fig.2. The average daily load profile of the Park.

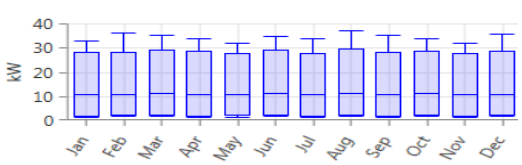

Fig.3. Monthly Average load profile of Kombolcha IP.

2.2. Grid outage

The interruption duration and the interruption frequency of the site that has been collected from Ethiopian electric Utility (EEU) of the region are shown in Table 1.

Table 2: line interruption data of the industry Park.

Name of feeder	Year	Average interruption frequency (Int/year)	Average interruption duration (Hr/year)
Kombolcha IP	2018	99	240

2.3. Solar resource analysis of the Site.

In most developing countries including the investigated location, there is no properly recorded solar radiation data. What usually available is sunshine duration data. However, it is possible to compute the solar radiation data using empirical Eq. (1) [10].

$$H = H_O\left(a + b\left(\frac{S}{S_O}\right)\right) \qquad (1)$$

Where H is the monthly average daily radiation on a horizontal surface (MJ/m^2); H_O the monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m^2); S the monthly average daily number of hours bright sunshine and S_O is the maximum possible daily hours of bright sunshine. a and b are regression coefficients based on the co-ordinates of a site. In this investigation, the regression coefficients having average value of a = 0.33 and b = 0.43 were used [11].

The Monthly average extraterrestrial radiation is analyzed using Eq. (2).

$$H_O = \frac{24 * 3600 * G_{SC}}{\pi}\left(1 + 0.033 * \cos\left(\frac{360 n_d}{365}\right)\right) * \left(\cos\phi \cos\delta \sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \qquad (2)$$

Where n_d is the day number starting from January 1st as 1; G_{SC} is the solar constant (1367 W/m^2); ϕ is the latitude of the location (11°5'0" N); δ is the declination angle (^{o}), given by Eq. (3) and ω_s is the sunset hour angle (^{o}), which is given by Eq (4) below.

$$\delta = 23.45\sin\left(360\frac{284+n_d}{365}\right) \qquad (3)$$

$$\omega_s = \cos^{-1}(-\tan\phi \tan\delta) \qquad (4)$$

The maximum possible sunshine duration S_O is given by;

$$S_O = \cos^{-1}(-\tan\phi \tan\delta) \qquad (5)$$

Based on the above equations, the computed solar radiations of the site are shown in Fig. 4. The calculated annual average data is 5.95 kWh/m^2/day.

To validate the calculated result, the data taken from NASA database was also compared. The radiation data taken from NASA is shown in fig .5. The annual average data is 5.87 kWh/m^2/day. In this study the calculated radiation data was used.

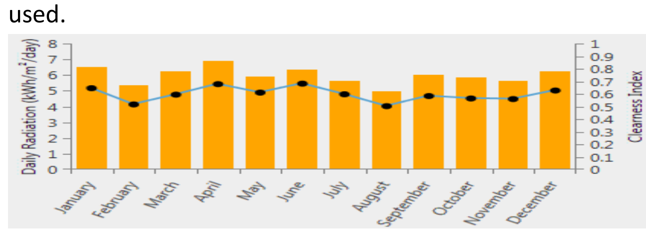

Fig. 4. Monthly average calculated solar radiation.

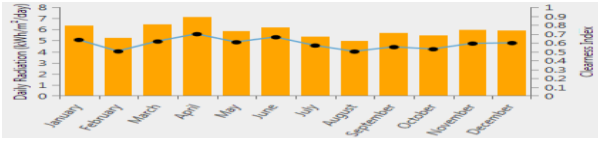

Fig. 5. Monthly average solar radiation taken from NASA.

3. PROPOSED SYSTEM ARCHITECTURE

The proposed system shown in Fig. 6 foresees the addition of solar PV, battery bank and convertors with the target of reducing the operation hours of diesel generator by increasing the share of the solar PV system during grid outage.

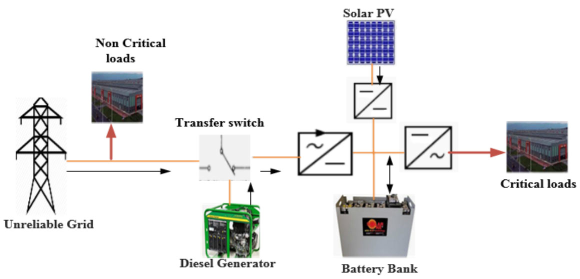

Fig. 6. The proposed grid-tied PV systems.

4. COMPONENET MODELING

4.1. Grid Modeling

By specifying the mean failure frequency, mean repair time and variability in repair time, Unreliable grid was modeled by HOMER Pro. Unscheduled grid outages imported from the simulations software are shown in Fig.7. From the figures, the black spot indicates the random outage throughout the year and the regular grid operation appears in a green.

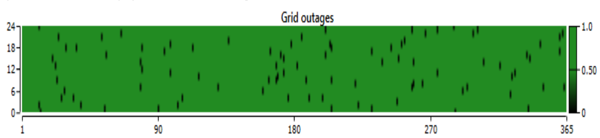

Fig. 7. Random grid outages in HOMER for Kombolcha IP.

4.2. Solar photovoltaic

The electric power output of the PV module is given by the following equation [12].

$$P_{pv} = Y_{pv} f_{pv} \left(\frac{G_T}{G_{T.STC}}\right)\left[1 + \alpha_p (T_C - T_{c.STC})\right] \qquad (6)$$

Where: Y_{pv} is the rated capacity PV array [kW], f_{pv} is the PV derating factor (it is a scaling factor that shows the actual performance of the module due to effects of dust on the panel, wiring losses and etc.), G_T is the solar radiation incident on the PV array in the current time step [kW/m^2], $G_{T.STC}$ is the incident radiation at standard test conditions [1 kW/m^2], α_p is the temperature coefficient of power [%/°C], T_C is the PV cell temperature in the current time step [°C] and $T_{c.STC}$ is the PV cell temperature under standard test conditions [25 °C].

4.3. Battery

Surrette 6CS25P battery model that are appropriate for renewable energy system as storage were chosen for this research. The discharging and charging equation of the battery is given by Eq. (7) and Eq. (8) respectively [13].

$$E_{bt}(t) = E_b(t-1) *(1-\sigma) - [E_{bh}(t) / n_{bi} - E_{bl}(t)] \qquad (7)$$

$$E(t) = E_b(t-1) *(1-\sigma) + [E_{bh}(t) - E_{bl}(t)/ n_{bi}) * n_{bb}] \qquad (8)$$

Where; Eb is the battery energy in time interval; E_{bh} is the total energy generated by PV array; E_{bl} is the load demand in time interval; n_{bi} is the inverter efficiency; n_{bb} is the battery charging efficiency and σ is the self-discharging factor.

4.4. Diesel Generator

The fuel consumed by diesel generator as a function of its electrical power output is given by the following equation [14]

$$F = F_0 Y_{gen} + F_1 p_{gen} \qquad (9)$$

Where: F_0 is generator fuel curve intercept coefficient, F_1 is the fuel curve slope, *Ygen* is the rated capacity of the generator in kW and P_{gen} is the electrical output of the generator in kW.

4.5. Economic and technical data of the component

The overall component technical specification and economic input data given to the optimization software are shown in the following table 2.

Table; 2 Economic and technical data of the component.

PV Parameter	**Specification**	**Battery parameter**	**Specification**
Capital cost	800$/kW	Size	1156Ah
		Capital cost	900$
Operation cost	8$/kW/yr.	Replacement cost	700$
Panel Type	Flat plate	Operation cost	9$/year
Derating factor	0.85	Round trip Efficiency	80%
Lifetime	25 years	Lifetime	9645kWh
Diesel generator Parameter	**Specification**	**Convertor parameter**	**Specification**
Capital cost	0	Capital cost	750$/kW
Operation cost	0.5$/hour	Replacement cost	700$/kW
Diesel price in the country	0.64$/liter	Operation cost	7.5$/year
Generator Type	Synchronous	Efficiency	95%
Rated power	50kW	lifetime	15 years
lifetime	25000 hour		
Current grid tariff in the country	0.04 $/KWh		

5. OPTIMIZATION RESULTS

Scenario 1; Grid/Diesel Generator systems

The Economic and environmental related output in this scenario for the investigated locations are shown in table 3. Since the main source of the grid in the country is hydro, and the emission expected in this system is only come from diesel generator.

Table 3; Economic and emission characteristics of optimized Grid/Diesel system.

Quantity	value
Grid	80kW
Diesel	50kW
Net present cost (NPC) in $	112,905
Cost of energy (COE) in $/kWh	0.047
Annual emissions (kg/yr) from diesel generator	3704

Scenario 2; Grid/Diesel/PV/battery systems

The economic and environmental output of this optimized system is shown in table 4.

Table 3; Economic and emission characteristics of optimized Grid/Diesel/PV/Battery system.

Quantity	value	Quantity	Value
Grid	80kW	Converter	8kW
Diesel	50kW	Net present cost in $	115,825
PV	14kW	Cost of energy in $/kWh	0.048
Battery	5	Renewable fraction	18.1%
Total annual emissions (kg/yr) from diesel generator in the form of CO_2, NO_2, CO, SO_2			2015

Scenario 3; Grid/PV/battery systems

As it is indicated in table 4 below, from the considered scenario, the net present cost and the cost of energy of grid/PV/battery system were the highest. However, the system is fully free from emission

Table 3; Economic and emission characteristics of optimized Grid/PV/Battery system.

Quantity	value	Quantity	Value
Grid	80kW	Converter	25kW
PV	35kW	Net present cost in $	135,260
Battery	20	Cost of energy	0.056
		Renewable fraction	41%
Total Annual emissions (kg/yr) from diesel generator in the form of CO_2, NO_2, CO, SO_2			0

6. CONCLUSION

In this paper, the techno-economic feasibility analysis of grid integrated solar PV system under grid interruption consideration for industry park load in the north central part of Ethiopia was investigated. The study is an input to the regime of Ethiopia to fulfill the country target of raising the non- hydropower based renewable share to 15-20 % by 2020. The investigation has demonstrated that the integration of solar PV helped the existing system by reducing the consumption of diesel fuel from the diesel generator operating as backup with unreliable grid. It was shown that the COE of solar PV system operating in hybrid mode with Grid/Diesel generator is 0.048$/KWh, which is a little bit higher than Grid/diesel system with the COE 0.047$/KWh. The emissions from Grid/Diesel/PV systems were lower than grid/diesel systems. Without out any emission, the COE of Grid/PV/battery is 0.056$/KWh. By considering the economics and emission as a constraint, the optimized grid/diesel/PV system with battery storage was a better option for the location than the other considered scenarios. Finally, to make the proposed optimized system more attractive, implementing the feed in tariff regulation is very beneficial.

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