

Research Article

Negasa Muleta* and Altaf Q H Badar

Techno-economic analysis and design of hybrid renewable energy microgrid for rural electrification

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Abstract: Electricity is the most sought after resource in this world and is crucial for the development of any community. The power system structure has been changing according to the evolving scientific technologies. A novel concept in this direction is a Microgrid (MG) which is a small power system having generation and distribution with negligible presence of transmission. A MG can operate in off-grid (standalone) or grid-connected mode. The objective of this study is to perform techno-economic analysis and to design a MG model for the purpose of rural electrification. The region being considered has different resources which are capable of providing reliable supply to the load. The proposed model is compared economically with the option of grid extension. The study considers power system reliability and economic feasibility as the primary objectives for MG modelling. The village of Jarre which is located in the eastern part of Ethiopian, Somali region, is selected for this study. Particle Swarm Optimization is implemented for obtaining the most economic and reliable MG having Hybrid Renewable Energy Sources (HRES). The simulation is performed using MATLAB and Homer.

Keywords: hybrid renewable sources; MG; optimization; particle swarm optimization; rural electrification; techno-economic analysis.

Introduction

Electricity has become a basic necessity all over the world. The most remote regions in underdeveloped countries still lack electric supply. There is a need to provide these regions with electricity. The electric supply can be extended to these regions either through the extension of grid or installation of standalone MG. A detailed analysis is required for selecting the optimal option.

MG is a small power system consisting of its own generation and load with negligible transmission. The MG can operate in off – grid (standalone) or grid – connected mode. Such power system modules improve the reliability, resilience and diversity of the power system. It also reduces carbon emissions and minimizes the cost of operation (Ghenai, Salameh, and Merabet 2020). Micro grids provide a promising solution towards the electrification of rural regions.

The extension of grid requires addition of infrastructure and its maintenance. This extension shall be constructed/installed from the nearest point to the remote region having electricity. The process of extension of grid will include installation of towers, transformers and other equipment as per the requirement. The distance for which this extension is to be implemented plays a very important role, as well.

On the other hand, installation of standalone MG, requires analysis of demand and availability of energy generation resources. The generation of electricity can be through renewable and non-renewable sources. Renewable Energy Sources (RES) like wind, solar, biomass, tidal, geothermal, etc. are continuously replenished through natural processes and should be utilised to the maximum limit. These sources are cheaper in operational cost (Russell 2020; Timilsina 2020) and do not pollute the environment (Le, Chang, and Park 2020) when compared to conventional sources. Benefits of being reliable and safe (Ali et al. 2020) can also be achieved.

A demerit related to the RES is its intermittent generation pattern which is not predictable. This behaviour of RES can create stability problems in the system. To overcome this demerit a hybrid system can be designed,

*Corresponding author: **Negasa Muleta**, Department of Electrical Engineering, National Institute of Technology Warangal, Telangana, India, E-mail: negasam@student.nitw.ac.in. <https://orcid.org/0000-0002-3386-2024>

Altaf Q H Badar, Department of Electrical Engineering, National Institute of Technology Warangal, Telangana, India, E-mail: altafbadar@nitw.ac.in. <https://orcid.org/0000-0002-1572-3717>

which combines different resources and Energy Storage Systems (ESS). HRES models have been found to be an attractive alternative to single source models.

The provision of electric supply to remote regions is dominated by factors like economics and reliability. These factors also help to determine the performance level of the system. Different Optimization techniques are used in MG proper design and operation of MG. Paper (Nagapurkar and Smith 2019; Ravanbakhshian and Amindoust 2020) deals with Genetic Algorithm (GA) application in MG for economic optimization. Particle Swarm Optimization (PSO) is also used in reliability improvement and cost minimization of renewable MG systems (Ding et al. 2019; Nekkache et al. 2018). GA, Fuzzy Logic Control (FLC), PSO and Artificial Bee Colony (ABC) are applied for energy cost optimization for hybrid resources such as PV, WT, FC, BS and diesel generator (Al-Sakkaf et al. 2019). In addition to above mentioned techniques such as Elephant Herd optimization (EHO) (Prasad, Subbaramaiah, and Sujatha 2019), Differential Evolution (OTCDE) (Kumar, Mandal, and Chakraborty 2019), Firefly Algorithm (FA) (Shayeteh and Moghaddam 2020), Lightning Search Algorithm (LSA) (Al-Nujaimi, Abido, and Al-Muhaini 2018) are some others used in optimization of MG with different objective function.

Sawle, Gupta, and Bohre (2018a) compare GA and PSO for optimization of reliability, cost and participation of renewables for a hybrid renewable system model. PSO is found to optimize the results better than GA. An analytical model using algebraic equations is proposed to determine PV array area and optimal battery storage capacity (Jakh-rani et al. 2012). The storage size is optimized for a stand-alone PV system, in terms of reliability and cost.

In Ethiopia, only 45% of the total population have access to electricity and 11% of its rural population gets electricity through decentralized systems (A and Ethiopia electricity, 2019). To supply power to the rest of the population, standalone (or isolated MG) power supply systems, can be implemented as grid extension is logistically challenging and too costly for the remote areas. The feasibility of establishing a standalone MG is dependent on utilization of resources, their planning, design and operation. The analysis of such a model is based on: costs, reliability and environmental effects. An analysis of cost-benefit and Green House Gas (GHG) emission of a hybrid system model for electrification of a remote rural village in Ethiopia is performed (Gebrehiwot et al. 2019). The comparison of different resources is performed using HOMER software.

In this research, an analyses is performed based on cost and reliability of supply for the rural region of Jarre, Ethiopia. The options considered for electrification of the concerned region are: grid extension and establishment of a MG. The optimal designing of MG is also performed. In

Sub-Saharan Africa, the average grid extension cost is estimated to be \$20,000/km for Medium Voltage (MV) line. Considering inflation rate and other factors, it escalates up to \$25,000/km (Longe et al. 2017). Grid extension feasibility analysis is conducted by comparing break-even point for grid extension and installation of stand alone or isolated MG costs. The cost of grid extension for this study is taken from Ethiopia's electric utility cost breakdown of MV line construction guideline (It was collected in person and hence no reference has been cited for the same). PSO is implemented using MATLAB to obtain the optimal combination of resources in the MG.

The contributions of this paper are: i) It considers a practical case of rural electrification and provides a feasible solution ii) It presents a justified comparison between the options of grid extension and standalone system based on economic and reliability factors, iii) The research gives more importance to reliability unlike previous research literature and provides a 100% reliable model as a solution for the standalone system and iv) It displays an application of optimization techniques for designing of standalone microgrid systems.

The sections in this paper are organized as: Section II deals with methods of power system integration. Section III discusses the performance evaluation parameters of the power system. Section IV deals with methodology and proposed algorithms. In Section V, the details of the case study are presented along with the analysis and discussion of the optimal model obtained. The final section presents the conclusion.

Rural electrification methods

In this section, we explore the options of availing electricity to remote regions through grid extension method and installation of standalone MG.

Grid extension deals with the installation of all equipments required to bring the grid power to the selected region of Jarre. The costs involved in this process are considered under grid extension. Grid extension may not be applicable everywhere in the rural areas due to limited budget and infrastructure, high cost per connection and the need for energy being supplied first at urban load centres due to economic factors (Iouis).

In the standalone MG system, different RES are studied which can be a part of this installation. According to the availability of resources, demand of the region and cost of renewable sources, the optimal design of MG can be found. The MG should be autonomous in nature and should be capable of controlling power within the network. A standalone MG system is favorable for remote areas where providing grid connection is not feasible. MG based

electrification is favorable than grid extension for the communities that are: far away from the grid, consume a small amount of energy, dispersed and not prioritized for grid extension.

This section is classified into two parts. In the first part, we explore the factors related to the installation of a grid connected systems like Break Even Distance (BED). In the second part, the details of a standalone system consisting of renewable sources and other related equipment's is presented.

Grid connected power system

The electrical grid is a complex system, designed to provide electricity to the customers in a secure, reliable and economic way. A grid is classified into generation, transmission, and distribution. Grid extension is used for connecting non electrified regions to the existing grid network and spread the electrical connectivity. It requires constructing the required and associated infrastructure between the grid and the region to be included in the grid. During grid extension, there is no compulsion for new generation or storage systems to be installed in the remote region.

BED is the distance at which the total Net Present Cost (NPC) of grid extension and installing a stand-alone system are equal (Walker; Azimoh et al. 2016) and calculated using Equation (1).

$$BED = \frac{C_{NPC} \times \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) - C_p \cdot E_t}{C_{capG} \times \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) + C_{omG}} \quad (1)$$

Where C_{NPC} : total net present cost power system (\$)

- E_t : total annual electrical demand, (kWh/yr)
- C_p : cost of power from the grid, (\$/kWh)
- C_{omG} : O & M cost of grid extension, (\$/yr/km)
- C_{capG} : capital cost of grid extension, (\$/km)
- i : interest rate per year, (%)
- n : project life time (yr).

Off-grid/standalone MG power supply system

The most common power supply sources for off-grid power system are the RES that are available in the vicinity of the proposed area. In Ethiopia, Solar and Wind power generations are the most commonly available RES for a stand-alone MG system. The RES also require certain specific

equipment's and energy storage systems to establish and install a complete standalone system.

Solar PV power

Solar power can be derived through solar panels. It can be utilized either for thermal loads or direct electricity generation.

The power output of the solar PV system (P_{pv}) is computed for every hour as given in Equation (2) (Sawle, Gupta, and Bohre 2018b).

$$P_{pv} = \begin{cases} nPr \left(\frac{R^2}{Rsr \times Rcr} \right) & 0 \leq R < Rcr \\ nPr \left(\frac{R}{Rsr} \right) & Rcr \leq R < Rsr \\ nPr & otherwise \end{cases} \quad (2)$$

Where Pr : PV panel rated power (W).

- R : radiation factor
- Rcr : certain radiation point, usually set as 150 W/m² (Maleki, Ameri, and Keynia 2015)
- Rsr : standard solar radiation at 1000 W/m²
- n : number of PV panels.

Harvesting of solar irradiation is optimized by using Mechanical and Electrical Maximum Power Point Tracking (Alharthi et al., 2018; Pakkiraiah and Sukumar 2016). Different techniques can be employed to implement the above methods.

Wind turbine

Wind energy is a clean and abundant form of energy available for rural electrification. The hourly output power of the wind turbine (P_{wt}) can be evaluated through Equation (3).

$$P_{wt} = \begin{cases} 0, & 0 \leq V \leq V_c \\ nPr \frac{(V - V_c)}{V_r - V_c}, & V_c \leq V \leq V_r \\ nPr, & V_r \leq V \leq V_f \\ 0, & V_f \leq V \end{cases} \quad (3)$$

Where n : number of turbines

- V : instantaneous speed, (m/s)
- V_c : cut-in speed, (m/s)
- V_r : rated speed, (m/s)
- V_f : cut-off wind speed, (m/s)
- Pr : rated electrical power, (w)

For this study, the values of 2, 9 and 30 m/s are used for V_c , V_r and V_f respectively (energy 2020).

The different atmospheric conditions and surface roughness of the site have influence on the vertical profile of winds. The wind speed at different altitude is estimated through different methods. The log law (logarithmic) and power law (exponent) are extrapolating techniques of wind speed to hub height ratio (Donnou et al. 2019).

To increase wind farm's electrical production performance in a given location, a deep analysis of wind characteristics is required. Wind energy potential in several regions of the world is evaluated through the use of Probability Density Functions (PDF). The Rayleigh, Weibull and Lognormal functions are commonly used to describe the measured wind speed probability distribution curves (Ucar and Balo 2009). To obtain the required energy or to control the wind turbine plants: pitch and stall control are commonly used (Samani et al. 2020).

Battery storage

Storage of electric power is a crucial factor especially for a standalone system. The energy storage system helps in improving the reliability of a system against the backdrop of intermittent renewable energy sources. For the case study being presented, Battery Storage (BS) is considered. It also improves the system stability and resource utilization rate (Zhu, Guo, and Zhao 2021). Battery State of Charge (SOC) is used to measure the level of charge present on an electric battery with respect to its capacity. It is calculated by using Equation (4).

$$\text{SOC}_{(t)} = (\text{SOC}_{(t-1)}(1 - \sigma)) + \left(E_{g(t)} - \frac{E_{l(t)}}{\eta_{inv}} \right) \eta_b \quad (4)$$

Where $\text{SOC}_{(t)}$: charge level of BS at a given time 't'

- $\text{SOC}_{(t-1)}$: charge level of BS at a given time 't-1'
- σ : self-discharge rate for 1 h (Maleki, Ameri, and Keynia 2015), 0.0002
- $E_{g(t)}$: generated energy, (kWh).

An accurate estimation of SOC helps to maintain the battery operation within specified limits. This avoids the chances of battery being fully discharged or overcharged.

Converters

Converters play an important role in integrating the renewable energy sources into the standalone MG. Power coming from the renewable source can be AC or DC. Also

the BS can be used for storing excess energy, when generation is more than demand. The power generated from these sources have to be converted such that the its parameters are suitable for consumption or storage. For this purpose the converters are used.

Converter rating (p_{con}) is selected depending on the peak load ($P_{peak}(t)$) and its efficiency (η_{con}), which is presented in Equation (5).

$$p_{con}(t) = \frac{P_{peak}(t)}{\eta_{con}} \quad (5)$$

Charge controller

The charge controller is used to regulate the excessive charging or discharging of BS by limiting the charging or discharging current. Charge controller capacity (I_{cc}) is obtained through the ratio of maximum generation capacity of the resource (P_{max}) and battery voltage (V_{batt}) as formulated in Equation (6).

$$I_{cc} = \frac{P_{max}}{V_{batt}} \quad (6)$$

There might be a situation in which there is excess generation and the batteries are charged to their maximum capacity. A dump load can be used in such situations, in addition to the charge controller (Salman, Al-Ismael, and Khalid 2020).

Problem formulation

Electrification of a remote rural region can be performed through the extension of the grid or by installation of a standalone MG system. This section presents the different factors associated with the evaluation of these options. For such a project involving planning and operation, the economic cost of the proposed solution is the most influential parameter. Reliability of the system is also one of the important factors that shall affect the power system performance. Another important factor that can be considered, is the pollution occurring due to the planned system. However, in this study, since all the resources are of renewable type, the emission of GHG is insignificant and hence can be neglected.

This section discusses the different factors considered while finding the optimal solution.

Reliability

Power system reliability refers to the ability of a power system to provide a stable and adequate supply. Electrical energy

sources such as solar and wind introduce unpredictability in the system due to their intermittent characteristics. The issue of reliability is a matter of great concern for the emerging power systems which employ intermittent sources.

To analyse the off-grid power system reliability: Unmet load and capacity shortage parameters are widely used. Unmet load is load demand that the power supply is unable to satisfy. This usually occurs when supply is quite less than the demand (kWh/year).

The Loss of Power Supply Probability (LPSP) is also widely implemented to assess the system reliability as discussed in (Ma and Javed 2019). LPSP is calculated for a time interval of 0 to T as seen in Equation (7).

$$LPSP = \frac{\sum_0^T (P_L - P_S)}{\sum_0^T P_L} \quad (7)$$

where P_L : total load demand, (W)

– P_S : total generated power, (W)

Lower value of LPSP indicates a highly reliable system. The objective of reliability analysis is to design a standalone MG with LPSP as zero, thus making system 100% reliable.

Economic cost

The economics involved in power generation employs different methods to determine the per-unit cost of electrical energy produced. In a power system network, Levelized Cost of Energy (LCOE) (\$/kWh/yr) is considered for analyzing the economic performance of various available resources and is formulated as in Equation (8).

$$COE = \frac{TAC}{E_L} \quad (8)$$

where E_L : annual energy produced, (kWh/yr),

– TAC: Total Annualized Cost of the system, calculated by using Equation (Nekkache et al. 2018).

$$TAC = N_{cop} \left(C_{cap} \times \frac{i(1+i)^n}{(1+i)^n - 1} + C_{OM} + C_{Rep} \times \frac{i(1+i)^{LF}}{(1+i)^{LF} - 1} \right) \quad (9)$$

- N_{cop} : number of components/units used
- C_{om} : O & M cost, (\$/yr/km)
- C_{cap} : total capital cost, (\$/km)
- C_{Rep} : total replacement cost, (\$/km)
- n : project lifetime, (yr)
- LF : components lifetime, (yr)
- i : interest rate per year, (%)

In the case study presented, the model formulation for the given site is a multi-objective function consisting of reliability and cost of energy. The optimal result should have minimized cost, but the reliability should be maximized or LPSP should be minimized. Thus the over all analysis is to minimize the objectives while satisfying the constraints as shown in Equations (10)–(14). The overall objective function is represented as:

$$\text{Minimize } F(LPSP, COE) \quad (10)$$

Subject to

$$0 \leq P_{PV} \leq P_{PVmax} \quad (11)$$

$$0 \leq P_{wt} \leq P_{wtmax} \quad (12)$$

$$SOC_{min} \leq SOC_{bat} \leq SOC_{max} \quad (13)$$

$$P_L \leq P_{PV} + P_{wt} \pm P_{bat} \quad (14)$$

where P_{PVmax} : maximum power that can be generated from solar PV

- P_{wtmax} : maximum power that can be generated from wind turbines
- P_{bat} : battery capacity at time ten
- SOC_{min} : minimum allowable state of charge for BS
- SOC_{max} : maximum allowable state of charge for BS
- P_L : Peak Load

The constraints are enlisted in Equations (11)–(14). The $\pm$ sign in Equation (14) is to imply that the battery may be charging or discharging. The individual resources should together supply the load at all times, thus their total capacity is required to be more than the peak load.

Proposed methodology

The methodology used in the study and the algorithms implemented for obtaining the output of the study are discussed in this section.

Methodology

The methodology applied for obtaining the optimal solution for the electrification of Jarre region in Ethiopia involves evaluation and comparison of costs related to grid extension and installation of standalone system. The optimized specification of standalone MG is obtained through the implementation of Particle Swarm Optimization (PSO). The methodology used to determine the size of power generating units to be installed in the MG is shown in Figure (1).

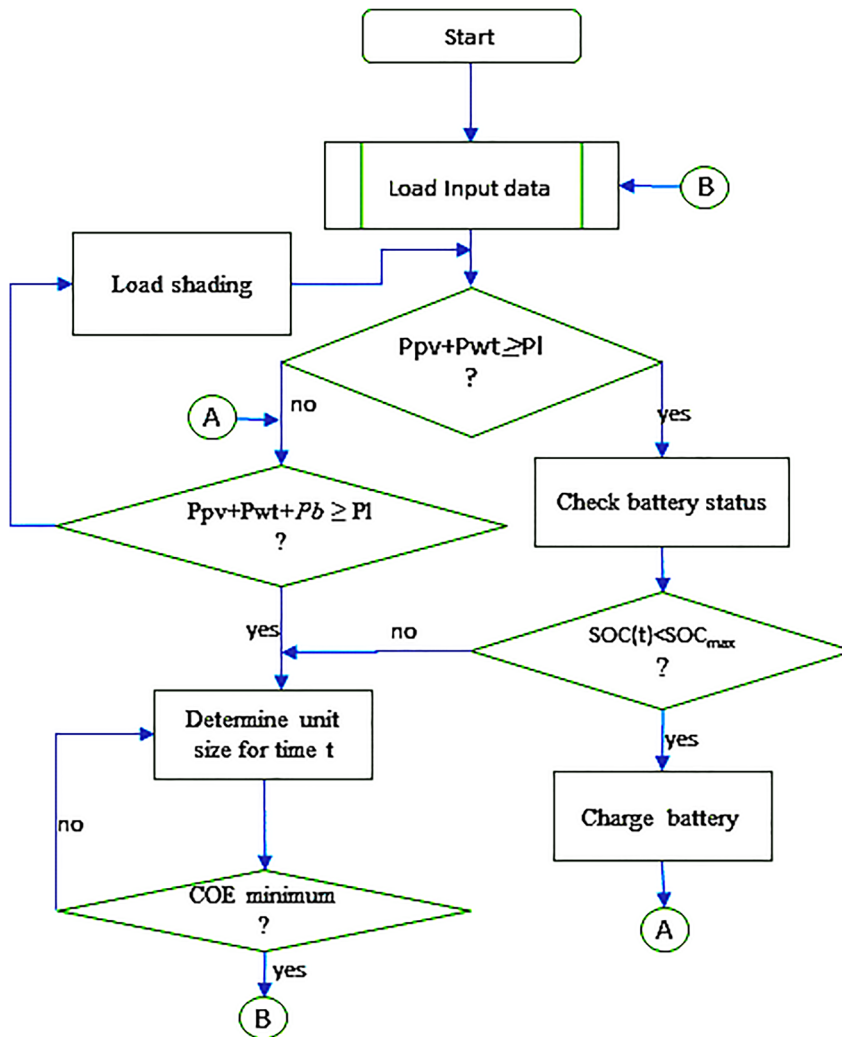


Figure 1: Flowchart of proposed methodology.

For a standalone MG system, the demand requirement at all times should be known. In case, there is excess generation, the demand is supplied and the batteries are charged, simultaneously. On the other hand, in case of generation being less than the demand will require the battery to discharge. The charging or discharging action of batteries shall depend on the state of charge and the generation of the standalone system in that hour. Load shedding can be resorted to as a final solution when renewable generation and battery storage fail to supply the loads. However, presence of load shedding would infer that the reliability of the system is not 100%.

In the analysis of providing electricity to the remote region of Jarre, two options are to be evaluated. In the first option, grid extension is considered. The costs of grid extension can be evaluated directly, based on the distance be the region being considered and the nearest electrified

point. In the second option, a standalone MG is proposed to be installed within the given region. The costs related to such a proposed standalone MG shall depend on the number of PV panels, wind turbines and batteries, that shall be a part of it. Optimization technique of Particle Swarm Optimization is employed to find the optimal combination of these components in case of standalone system.

Particle Swarm Optimization (PSO)

PSO is motivated with the movements of school of fishes or flock of birds. It was developed by Kennedy and Eberhart (1995). PSO is a global optimum search algorithm (Ding et al. 2019), that combines the process of exploitation and exploration. It is a robust method and has been

implemented for different variations, like (Badar, Umre, and Junghare 2012). During each iteration of the search problem, particle position is updated as:

- Particle velocity

Particle velocity gives the difference by which a particle moves from one position to the other in between two iterations. New particle velocity ($V(t+1)$) for i th particle is calculated by using Equation (15).

$$V_{i(t+1)} = wV_{i(t)} + c_1 \text{rand}(0, 1)[pbest - X_{i(t)}] + c_2 \text{rand}(0, 1)[gbest - X_{i(t)}] \quad (15)$$

- New particle position

The new particle position ($X(t+1)$) for i th particle is calculated by using Equation (16).

$$X_{i(t+1)} = V_{i(t+1)} + X_{i(t)} \quad (16)$$

where

- $V_{i(t)}$: current velocity of particle
- c_1 : personal influence coefficient
- c_2 : social influence coefficient
- w : inertia
- $pbest$: particle best position
- $gbest$: swarm best position
- $X_{i(t)}$: particle current position

The flowchart for designing the MG model at Jarre is presented in Figure (2). The initial data including constraints is read first and random particles are generated. The feasibility of the particles is checked in each iteration. Feasibility in this case relates to the combination of renewable sources and batteries being able to satisfy the load at the selected site at any given time. The particles are also checked for their constraint limits. The individual and global best positions are updated and the particles are moved to a new position. In case the stopping criteria is satisfied, the optimal results are printed.

The optimization problem being discussed in this research paper deals with finding the optimal combination of the number of PV panels, wind turbines and battery packs for the standalone microgrid system. The objectives of the optimization process is to find an economic and reliable solution. However, the value of LPSP is considered to be 0, to make system 100% reliable. This converts the problem from a multi objective problem to a feasibility problem, since there are very few solutions that can have LPSP as 0.

PSO method is employed due to ease in programming, gives high-quality solutions with stable convergence, adaptability and robustness. As discussed in (Nekkache et al. 2018;

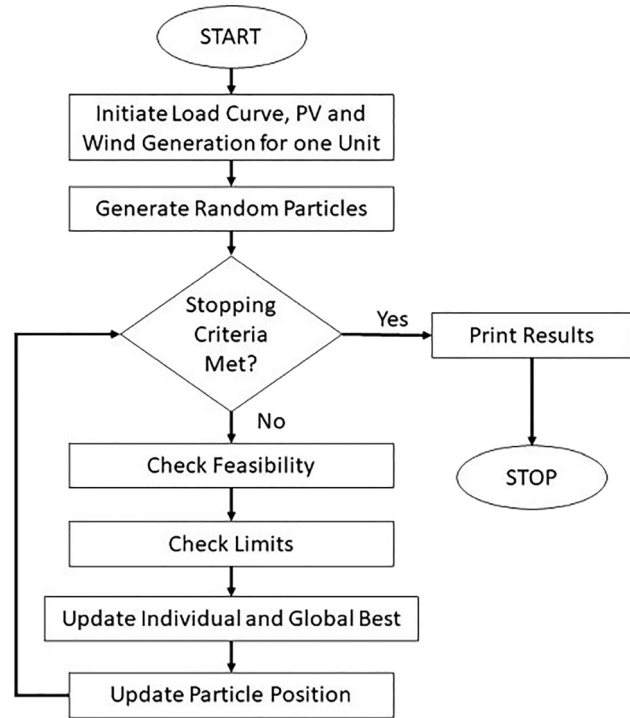


Figure 2: Flowchart for PSO.

Ghorbani et al. 2018), PSO provides credible results for optimization of reliability and operation cost.

Results and discussion

The proposed research work is carried out for obtaining optimal method to provide electricity to Jarre village situated in Somali region of Ethiopia located at 9.6908738 N, 42.7539328 E. The village consists of approximately 150 households. The nearest grid substations are located more than 50 km from the selected site. The renewable sources present in the region can be utilised to install a standalone MG. This MG system should be able to reliably supply the existing load. This study presents a methodology to justify the installation of a standalone system or a grid connected system. Some variations in input data can be expected with the change in the day being considered. The solar and wind data pattern is considered for days having leaner power generation capacity, which would mean that the power generation would be more for other days of the year.

This section presents and discusses the different aspects related to the design of isolated MG model or extension of grid for Jarre village. Pre-feasibility evaluation of the site is done based on weather data including load demand, solar irradiance and wind velocity.

Load profile

Electricity demand of connected households mainly relates to micro-economic theory; income, energy prices and preferences of the household (Louw et al. 2008). At the selected site, there are about 150 households having a daily average load of 3173 kWh/day with 285.5 kW of peak load and a minimum load of 8.25 kW as shown in Figure 3. The common loads used by different households are lighting lamps, TV and radio, mobile charger, refrigerator, ventilation, cooking stoves, etc. Primary school, health post, flour mills and water pumps for drinking and irrigation that operate at morning and afternoon are other loads present in the village.

Solar resource

In the power generation from solar PV, solar irradiation and temperature are the main factors that determine the output power of a PV cell. The hourly average solar irradiation of the site is taken from Global Solar Atlas

database. From the data base, the least solar irradiation is observed for the month of July and these values are considered during the design process to minimize the chances of energy shortage and is shown in Figure 4. Jarre has an average daily solar irradiation of 6.15 kWh/m². From the figure it can be observed that the peak occurs at 12 noon.

Wind resource

As a standard, there are classes of power potential that can be harvested from different wind speed and at different hub height. The classes are mainly influenced by site's wind speed as summarised in Table 1, taken from world wind speed standards (Wei Tong 2010). Accordingly, Jarre is categorized under class 4 (good) having average wind speed of 5.8 m/s and it is feasible to consider harvesting power from wind turbines.

The daily wind speed of the site is taken as shown in Figure (5). It represents the wind profile of 9th April, 2021 at the selected site.

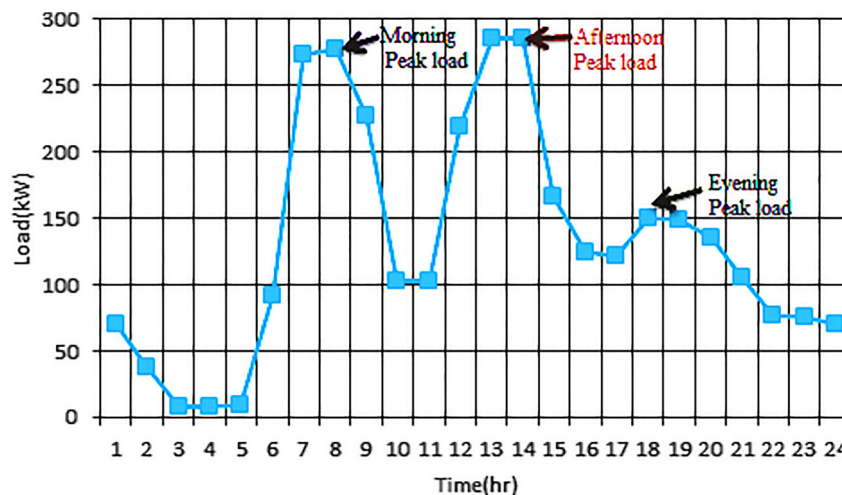


Figure 3: Hourly load variation for Jarre village.

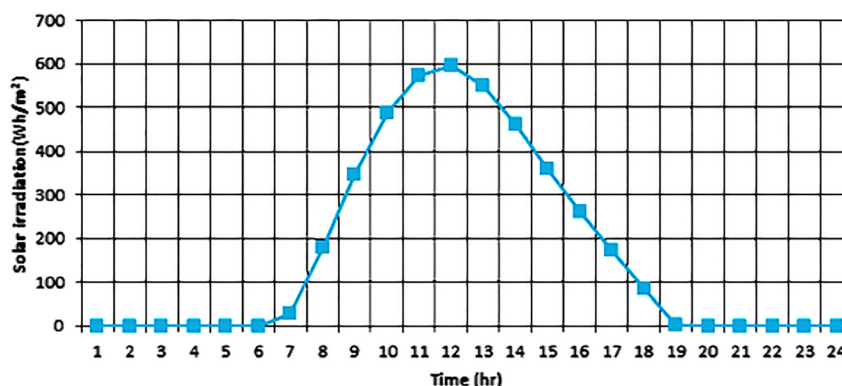


Figure 4: Hourly direct solar irradiation for Jarre village on Earth surface.

Table 1: Classes of wind power from (Wei Tong 2010).

Power class	Potential	P (W/m ²) @10m	V(m/s) @ 10m	P (W/m ²) @50m	V(m/s) @50m
1	Poor	<100	<4.4	<200	<5.6
2	Marginal	100–150	4.4–5.1	200–300	5.6–6.4
3	Moderate	150–200	5.1–5.6	300–400	6.4–7.0
4	Good	200–250	5.6–6.0	400–500	7.0–7.5
5	Excellent	250–300	6.0–6.4	500–600	7.5–8.0
6	Excellent	300–350	6.4–7.0	600–800	8.0–8.8
7	Excellent	>400	>7.0	>800	>8.8

Grid extension cost

In the extension of grid, the cost of MV transmission line is only considered along with its accessories. The costs related to Low Voltage (LV) line construction is neglected as it would be required for the grid extension as well as the standalone system. The total cost of constructing the MV transmission line for 1 km is summarized in Table 2. The data is presented in dollars converted from Ethiopian Birr.

The distance from the village to the nearest substation connected to the grid is approximately 50 km. Considering the costs from Table 2, the total costs involved in extension of the grid to Jarre is 1,148,264 and the COE is 0.362 /kWh.

Standalone system

The cost of standalone hybrid resource is taken from the present cost of components in the market and listed in Table 3. The load curve for the selected site is presented in Figure 3. It can be observed that there are multiple peaks in the curve. However, the peak at noon is the highest and is considered for setting the limits for the number of solar panels, wind turbines and batteries that can be installed in the standalone MG system.

The PSO is executed for obtaining the optimal combination for the number of PV panels, Wind turbines and

Table 2: Cost breakdown for grid extension per km.

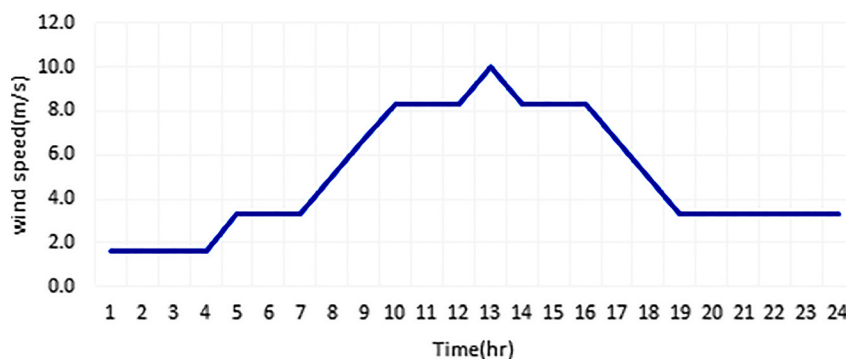
Activities list	Costs (\$)
Material cost	16,091.62
Labour cost	2237.14
Overhead cost	808.97
Total cost	19,137.74
Reserve cost (20% of total cost)	3827.55
Grand total	22,965.28

Table 3: Costs of components with accessories for off-grid supply.

Comp	Rating	Cap (\$/kW)	Rep (\$/kW)	O&M (\$/kW/yr)	Life span (yr)
Solar PV	1 kW	1000	0	5	20
Wind turbine	10 kW	4500	0	9	20
Battery	100 Ah (1.2 kWh)	150	150	2	5
Converter	300 kW	1000	1000	0	10

batteries with an objective of minimizing the cost. The output is also required to satisfy the constraint of LPSP = 0 i.e., the load should be satisfied at all times. PSO is executed 40 times for compilation of the results and in each execution it considers the performance of the system for 48 h. The first 24 h of the simulation is used to find the initial state of charge of the batteries at the beginning of the day. MATLAB is used to apply the PSO technique.

For analysis purpose two cases are assumed: 1) Ideal case – SOC_{min} is taken as zero while SOC_{max} is 100%. The efficiency of battery and converter is considered as 100% with zero self-discharge rate in Equation (4) and 2) Practical case – efficiency of battery and converter is taken as 90%, while self-discharge rate is considered as 10⁻⁴. As age of the batteries increase, their SOC capacity declines, resulting in a narrower range of SOC (Raj, Rodrigues, and Abraham 2020). Thus, in the second case, for the analysis of standalone system, SOC_{max} is taken as 90% and SOC_{min} as 20%.

**Figure 5:** Wind speed in Jarre village with hub height of 10 m from (World weather online (2021)).

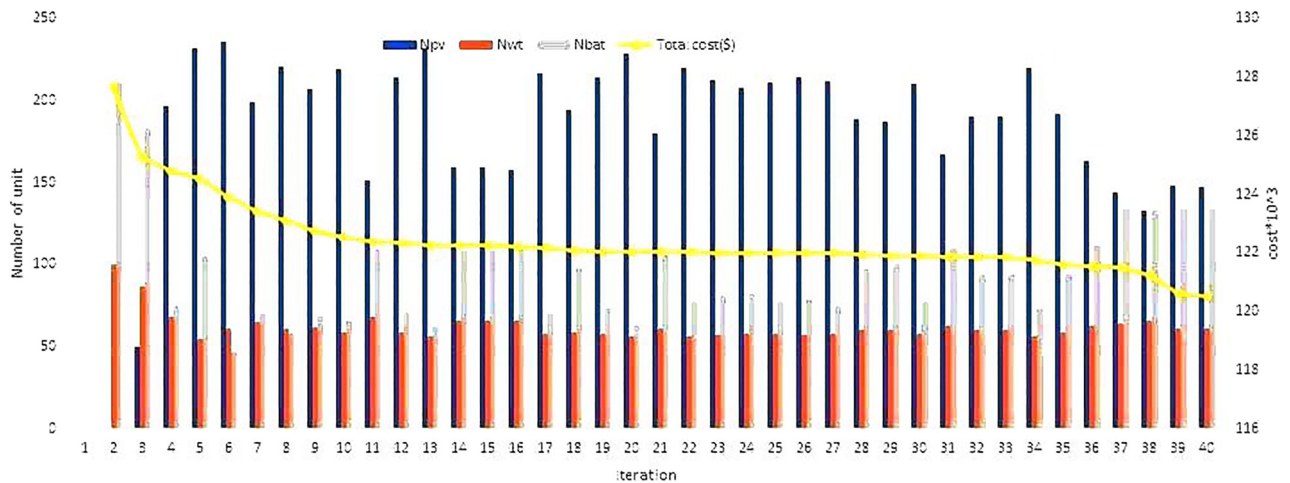


Figure 6: Variation of total costs for ideal case results.

Ideal system

Figure 6 shows the variation of cost with respect to variations in the number of panels, turbines and batteries for 40 executions in a sorted order. The minimum cost of stand-alone system is found to be 0.10368\$/kWh with 164 solar panels, 57 wind turbines and 128 battery packs, required to cover the given load, for the ideal case. The total energy balance during the day between the load, energy generated by RES and the charging and discharging of batteries is presented in Figure (8a). It can be observed that the battery is discharged thrice within the day corresponding to the peaks in the load curve.

and 182, respectively. The variation of costs with respect to number of PV panels, wind turbines and battery packs for 40 iterations of PSO is shown in Figure 7 in a sorted order. The optimal COE for the system is obtained as 0.11025 \$/kWh in this case. Similar to the Ideal case, the total energy available through renewable resources and batteries against the demand of the day is given in Figure 8b. In the practical case, the battery discharge is more for the first load peak and lesser for the second peak as compared to the ideal case.

The optimal results are summarized in Table 4, for both the cases. In the table, N_{PV} is the number of PV panels, N_{WT} is the number of wind turbines and N_{BAT} is the number of

Practical system

The number of PV panels, wind turbines and storage batteries obtained through PSO for the practical case are 215, 55

Table 4: Optimal results for different cases.

Cases	N_{PV}	N_{WT}	N_{BAT}	Converter	COE (\$/kWh)	LPSP
Ideal	164	57	128	1	0.10368	0
Practical	215	55	182	1	0.11025	0

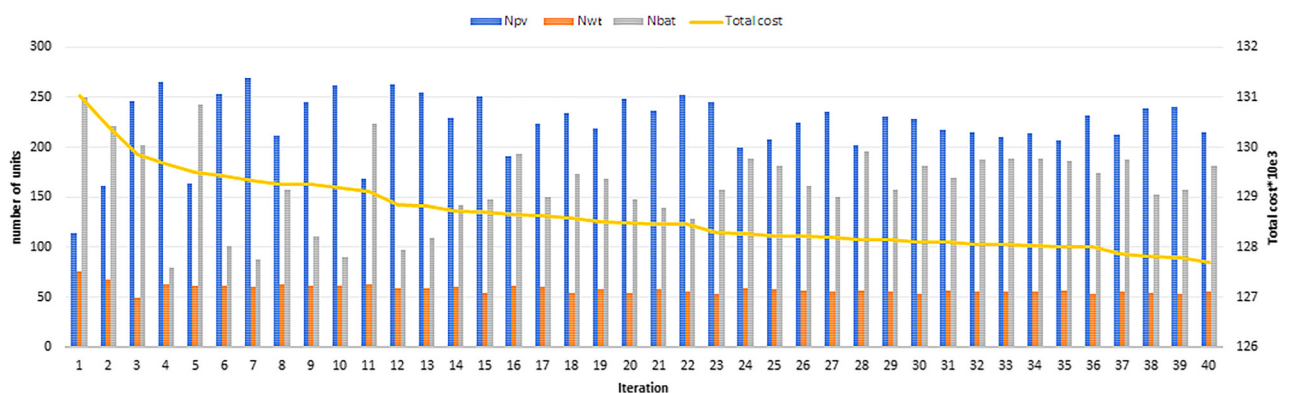


Figure 7: Variation of total costs for practical case results. (a) Power demand and supply characteristic for ideal case. (b) Power demand and supply characteristic for practical case.

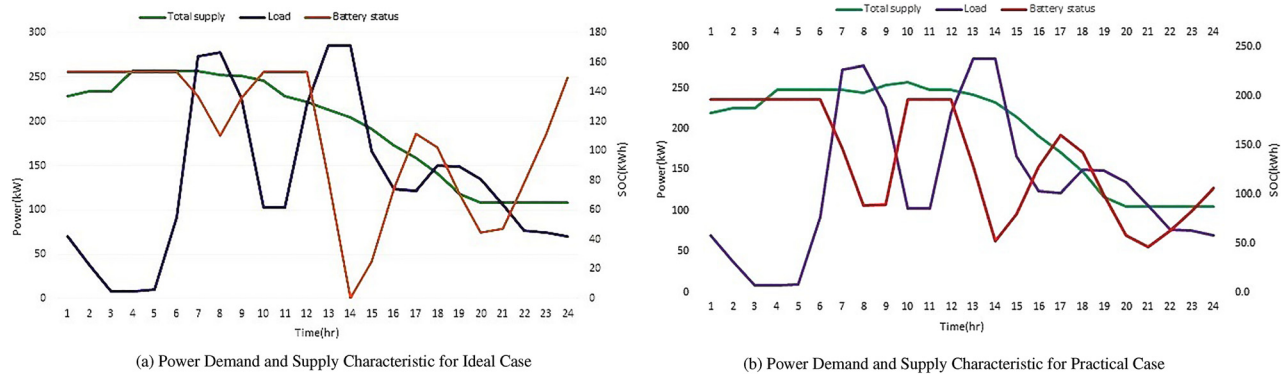


Figure 8: Comparison of energy and demand in different cases.

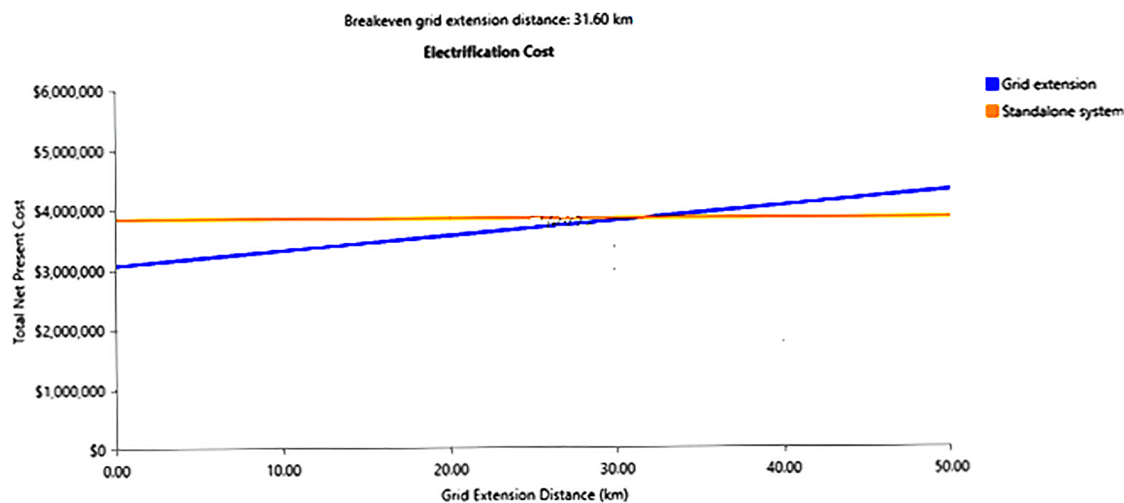


Figure 9: Grid extension cost for break even distance analysis.

battery packs. The objective function is minimized while considering all constraints. The combination of RES and battery packs is so formed that the value of LPSP is 0. Thus, the reliability of the system is also satisfied with no scarcity of supply.

The COE for grid extension at Jarre village is found to be 0.362 \$/kWh whereas the cost of installing a standalone system is 0.10368 \$/kWh for ideal battery operating conditions and 0.11025 \$/kWh for practical conditions.

Another method to compare the feasibility of the off-grid power supply system for the site, with respect to grid extension is through BED. BED is considered by taking present cost of stand alone system and grid extension costs as listed in Tables 2 and 3. As shown in Figure 9, BED is found to be 31.6 km. As the village is at a more distance from the grid, application of off-grid power supply system is more feasible for the selected site.

Conclusions

A feasibility study is performed for the electricity supply to a remote village of Jarre in Ethiopia. The village has a lower level of load but has a high availability of RES. A comparison of grid extension and standalone MG system is performed. Optimal combination of RES combined with battery packs is found to be more economical than extension of grid. It can be observed that standalone system installation costs is 69.5–71.3% lesser than grid extension costs. While considering the off grid system, reliability and economic cost are considered as the objectives. BED is also analysed for the village based on its distance from the nearest substation. Standalone system is found to be far more economical as compared to the option of grid extension. PSO has been implemented for obtaining the optimal combination of RES and battery units.

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