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Design of optimal hybrid power system to provide reliable supply to rural areas of Ethiopia using MATLAB and Homer

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Abstract

Integrating different energy resources, like solar PV, wind, and hydro is used to ensure reliable power to the rural community loads. Hybrid power system offers sufficient power supply for the rural villages by providing alternative supply for intermittent nature of renewable energy resource. Hence, intermittency of renewable energy resources is a challenge to electrify the rural community in a sustainable manner with the above sources. Thus, efficient resources management is a reasonable choice for intermittent renewable energy resources. The majority of rural villages in Ethiopia are suffering from lack of electricity. This causes deforestation, travel for long distance to fetch water, and no good social services, like clinic and schools, sufficiently. Therefore, the objective of this study was to maximize reliability of power supply by renewable energy sources. Data on wind speed and solar radiation are obtained from the NASA surface meteorological agency. While hydro data are obtained from physical measurements. Different configuration options are considered by Homer software to find the optimal configuration of hybrid system. The optimal configuration system is selected and hybrid components are sized. The optimal hybrid system consists of solar PV, wind, and hydro to supply a community load with a share of 13%, 52%, and 35% respectively. The fuzzy logic controller is designed to manage the intermittent nature of energies. Hence, the demand and energy sources are unpredictable; intelligent control system is important to manage the system accordingly. The control system is designed in MATALAB software. The result obtained from resource combination shows demand and supply are balanced. From the Twelve probabilistic combinations of demand and energy sources, one of the combinations shows that when 7.5 kW is demanded, the power generated/output from hybrid system is 10 kW which is greater than demand. To satisfy 7.5 kW demand control system takes 4.25 kW, 2.75 kW, and 1.08 kW share from wind, hydro, and solar sources respectively. The fuzzy logic control system is designed, to monitor the resource availability and load demand. This controller was managing the demand and the available resources according to the rule.

Keywords: PV–wind–hydro, Hybrid power system, Load profile, Fuzzy logic controller and MATLAB/SIMULINK

Introduction

The substantially to rapid economic growth and industrialization depends upon the electrical energy. To ensure the sustainable development, having reliable, secure and affordable energy service to the community is important (Ozcan and Ozturk 2019; Sultan and Alkhateeb 2019).

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In Ethiopia, rural community uses fossil fuel and wood for their domestic power demand. Using these energy sources leads to climate changes, environmental changes, and health-related problems. Thus, the renewable energy resources interest is increased due to environmental friendliness, availability, and low running cost (Østergaard et al. 2020; Gürel et al. 2020). Integrating different energy resources, like solar PV, wind, and hydro is used to ensure reliable power to the rural community loads. Hybrid power system offers sufficient power supply for the rural villages by providing alternative supply for intermittent nature of renewable energy resource. Hence, intermittency of renewable energy resources is a challenge to electrify the rural community in sustainable manner with the different renewable energy resources (Kharchenko et al. 2019; Koneru et al. 2019; Assaf and Shabani 2019). Thus, efficient resource management is important for intermittent renewable energy resources. The majority of rural villages in Ethiopia are suffering from lack of electricity energy (Bersisa 2019; Gebrehiwot et al. 2019). This causes deforestation, travel for long distance to fetch water, and no good social services, like clinic and schools sufficiently.

Data on wind speed and solar radiation are obtained from the NASA surface meteorological agency. However, hydro data are obtained from physical measurements. Homer software is used to find the optimal configuration of hybrid system. Based on the optimal configuration of Homer, the hybrid system is modeled.

Fuzzy approach is proposed to find the optimal power output to the varying community load in 24 h of a day. It is designed to manage the power demand and supply conditionally to reduce power interruption due to intermittent nature of the renewable energies (Marzougui et al. 2019; Hailemariam et al. 2015). Hence, the demand and sources are unpredictable; intelligent control system is important to manage the system accordingly. This control system is designed using MATALAB software to increase power system reliability. Therefore, the objective of this study was to maximize reliability of power supply by renewable energy sources.

Literature review

There is a different hybrid power system-related studies in which fuzzy logical controller has been used for energy source and demand management. Varying load demand and intermittent nature of renewable energies are conditioned to write logical rules.

Most researchers (Zhang et al. 2020; Khan and Mathew 2019) agreed that fuzzy logic approaches are suited to manage the integrated power system. Fuzzy control methods offer a systemic way to control the randomly varying loads and energy sources to increase the reliability of the integrated power system. Homer software is used to determine the optimal hybrid system configuration.

Althubaiti et al. (2017) worked on fuzzy logic-based hybrid power system provided fuzzy logic control application of fuzzy with MATALB to manage the load and available energy source according to rules. This study addresses the energy management, without considering the optimal hybrid power system configuration in Homer.

Rekioua et al. (2019) recommended the fuzzy logic controller method to control hybrid power system intelligently. However, the load sharing from each energy source did not include in this study.

Li et al. (2019) proposed the fuzzy logic controller to manage hybrid power systems efficiently. There was no more probabilistic combination of sources to sever the demand in a reliable manner.

Rehman et al. (2020) proposed the Homer to study the economic feasibility of hybrid power system. The optimal load share did not include in this work.

Oladigbolu et al. (2019) recommended the Homer software to model hybrid power system. However, the optimal load sharing from each energy source was not considered in this study.

This study contributes to the existing literature by proposing the integration of fuzzy logic controller with Homer approach for hybrid control and optimal configuration of hybrid system. The Homer is used to identify optimal hybrid power system, whereas the fuzzy system is used to control the demand and sources with conditional rules.

Materials and methods

Study area

This study was conducted in Keltafa village in Amhara regional state. Keltafa is a village in the South Achefer district in Amhara regional state. It is located at 11.6° latitude 36.91° longitude. The village has about 300 households. The village has one health post and one elementary school. There was no electricity access to the village and the surrounding community. However, there are abundant renewable energy resources, like wind/solar/hydro power.

Data collection

Data were obtained from the total electric appliance of households and elementary school. The daily duration hour of use was obtained from interview of nearby community those using electricity.

The head of micro-hydro system was taken by physical measurement (10 m). The wind speed and solar irradiation data were taken from NASA (6.832 m/s at 36 m height) and (6.197 kWh/m^2), respectively. These data were prepared in suitable format for input to HOMER to find an optimal load share of the resources.

Demand prediction of the village

The first phase in designing power system is determining the total power consumption of the study area. Electric consumption depends on weather, economic level, and time of the day and seasons. Estimating the demand is vital in the hybrid power system design (Table 1). Hence, the size and cost of power system components are highly influenced by the size of electrical loads.

Table 1 Village load estimation

Service type	Load type	Rated power (w)	Quantity	Duration (h)	Energy (Wh/day)	(kW/day) of village
Typical home	Light	11	4	5	220	0.22
	Radio	10	1	11	110	0.11
	TV	70	1	10	700	0.7
	Other	50	1	3	150	0.15
Subtotal (300)						354
Elementary school	Light	11	60	2	1320	1.32
	Office load	200	1	10	2000	2
	Radio	11	10	8	176	0.88
	Other	50	1	6	300	0.3
Sub total						4.5
Total						358.5 or 15 kW

Modeling of hybrid system with HOMER

Hybrid energy system is an excellent solution for rural electrification where the grid extension is difficult and not economical. The hybrid system integrates more renewable energy sources. Combination energy resources provide a constant flow of uninterrupted power.

HOMER is a user-friendly micro-power design tool that was developed by NREL in the U.S.A to assist the design of power systems and facilitate the comparison of power generation technologies across a wide range of applications (Oladigbolu et al. 2019). HOMER is used to model a power system physical behavior. In the optimization process, HOMER simulates every possible system configuration. Optimal possible matching of demand and supply sorts the viable combinations based on the total net present cost.

Hybrid system component Power sizing

Power generated from wind

The average electric power production share of solar is 52%. Therefore, it is calculated as follows:

$$\text{Power generated from power} = \text{PD} \times \frac{52}{100} = 15 \times 0.52 = 7.8, \tag{1}$$

$$\text{Installed capacity} = \text{Power generated} + \text{Power generated} \times 0.1 = 8.58, \tag{2}$$

where PD indicates power demand; 10% loss is considered in all three cases.

Power generated from solar

The average electric power production share of hydro is 13%. Therefore, it is calculated as follows:

$$\text{Power generated from power} = \text{PD} \times \frac{13}{100} = 1.95, \tag{3}$$

$$\text{Installed capacity} = \text{Power generated} + \text{Power generated} \times 0.1 = 2.15, \tag{4}$$

where PD indicates power demand.

Power generated from hydro

The average electric power production share of wind is 35%. Therefore, it is calculated as follows:

$$\text{Power generated from power} = \text{PD} \times \frac{35}{100} = 5.25, \tag{5}$$

where PD represents power demand.

$$\text{Installed capacity} = \text{Power generated} + \text{Power generated} \times 0.1 = 5.775. \tag{6}$$

Table 2 If–then rules

If (PD is low) or (Wp is low) or (Hp is low) or (Sp is low) then (Po is Wp)
If (PD is low) or (Wp is low) or (Hp is low) or (Sp is low) then (Po is Hp)
If (PD is low) or (Wp is low) or (Hp is low) or (Sp is medium) then (Po is Wp)
If (PD is low) or (Wp is low) or (Hp is low) or (Sp is medium) then (Po is Hp)
If (PD is low) or (Wp is low) or (Hp is low) or (Sp is large) then (Po is Wp)
If (PD is low) or (Wp is low) or (Hp is low) or (Sp is large) then (Po is Hp)
If (PD is medium) or (Wp is medium) or (Hp is low) or (Sp is low) then (Po is Wp + Hp)
If (PD is medium) or (Wp is large) or (Hp is low) or (Sp is large) then (Po is Wp + Sp)
If (PD is medium) or (Wp is large) or (Hp is low) or (Sp is large) then (Po is Wp + Sp)
If (PD is medium) or (Wp is medium) or (Hp is low) or (Sp is low) then (Po is Wp + Hp)
If (PD is medium) or (Wp is medium) or (Hp is low) or (Sp is low) then (Po is Wp + Hp)
If (PD is large) or (Wp is large) or (Hp is large) or (Sp is large) then (Po is Wp + Hp + Sp)

Controller system

In this study the hybrid system has three sources: solar, micro-hydro, and wind. The electric power generated from hybrid system should be equal or greater the demand. This is the most important constraint to write if–then rules to control the hybrid system (Table 2). Controller system was designed to manage demand and available energy resources to reduce the power interruption due to the intermittent nature of energy sources. Fuzzy controller switches the load to available energy sources to satisfy the demand in 24 h. Thus, there is no need of battery and charge controller (Lü 2020; Chen et al. 2020; Nebey 2020; Hailemariam et al. 2015). Controller is important to efficiently manage the energy balance between the total generation and the total demand.

Controller algorithms

The Fuzzy logic controller is used to make decisions based on if–then rules (Boloș et al. 2019). This control system is an intelligent tool to manage the energy source, so as to stratify the load demand. The proposed control system inputs and output are defined as follows:

PD represents the varying load demand of community in 24 h.

Wp represents the power generated from wind power plant.

Hp represents the power generated from mini-hydropower plant.

Sp represents the power generated from solar PV.

Po represents the power output of hybrid power system.

To write the rules for control system, the input and output variables are used. Inputs of the control system are Sp, Hp, Wp, and PD, whereas the output is the power generated from three energy sources. The inputs and output values are assigned as low, medium, and large.

Membership function

Fuzzy logic is a multivalued logic control system in between "Yes" case and "No" case. Membership function specifies the degree to which a given input belongs to a set. This partial case in between is membership values, loading and energy source availability conditions are monotonically increasing and monotonically decreasing. Therefore, the triangular membership function was selected in this study. The input and output membership functions are scaled in a specific range (Hailemariam et al. 2015; Xu 2019; Rajan and Fernandez 2019; Yin et al. 2019). Inputs and output values are converted from classical values (Yes, No) into two of fuzzy values (Fuzzification) vice versa.

Membership of demand (*PD*) was input linguistic variable having three linguistic values low (0 2 5), medium (5 7 10), and large (10 12 15).

The membership function of wind power (*Wp*) was input linguistic variable having values low (0 2 3), medium (2 5 7), and large (5 6.8 8.5).

The membership function of hydro (*Hp*) was one of the input linguistic variables with values low (0, 1.5, 3), medium (2 3 4.5), and large (3 5 5.5).

The membership function of solar (*Sp*) *was input linguistic variable and values* were low (0 0.5 1), medium (0.5, 1, 1.5), and large (1.5, 1.8, 2.15).

The membership function of output power (*Po*) was linguistic variable having values Wp − only (0 5 8.5), (0 3 5.75), Wp + Sp (5 7 10.73), Wp + Hp (7 10 13), and Hp + Sp + Wp (10 12 15.5).

Switching system

In this study the integration of renewable energy resources is represented in Fig. 1. Wind, solar, and hydro sources are combined to satisfy the load demand. The integrated power system is monitored by the intelligent switching system. The rules are written with restrictions

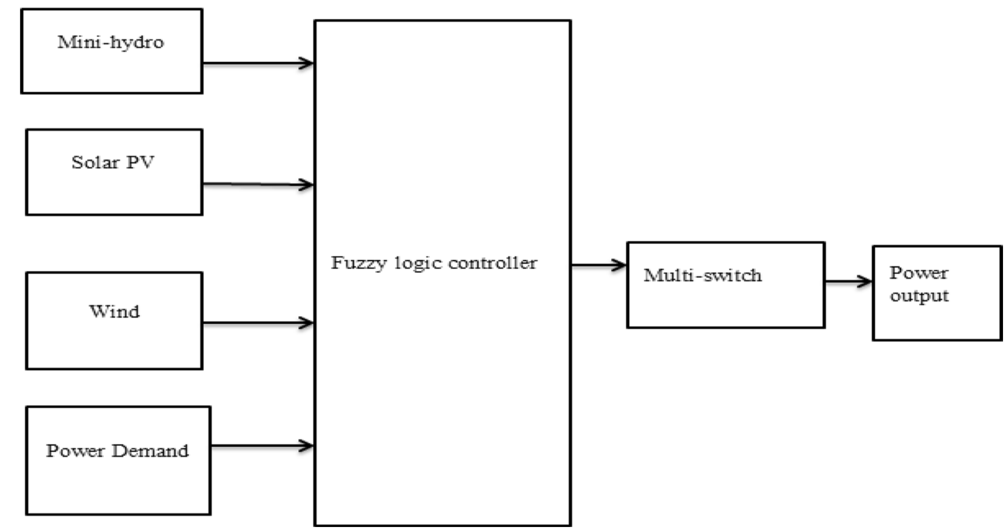

Fig. 1 Fuzzy controller system

in MATLAB toolbox. These rules are loaded on the fuzzy logic controller for controlling the hybrid power system. Varying load demand of the community is switched to the available source according to written Hailemariam et al. (2015).

Data analysis interpretation

The data were taken from a direct interview, measurement, and meteorological agencies. The data were entered into Homer for optimal hybrid system configuration and MATLAB software for source and power demand management. The load was estimated as 15 kW, and the installed capacity was 16.5 kW (10% loss). Hybrid power system sizing was used to design the system with the desired capacity as load estimated. The power sharing was wind followed by hydro then solar (52%, 35%, and 13%), respectively. The inputs of the fuzzy controller system are solar, micro-hydro, wind, and power demand. And the output of controller system is the generated power from three energy sources. Input values are levelled as low, medium, and large. For balancing demand and resources the power generated from each resource (8.58 kW wind, 2.15 kW solar, and 5.775 kW hydro) should not be less than the maximum load (15 kW).

Results and discussions

Optimal results from Homer

All possible hybrid system configurations are listed in ascending order of their total net present cost with Homer software. Powers generated from three sources are 52% wind, 35% hydro, and 13% solar. Three hundred households were considered in this study, which made the estimated load 15 kW. Figure 2 shows average electric production from three energy sources. Most of the electric power is produced by the wind turbine followed by the hydro turbine and then solar.

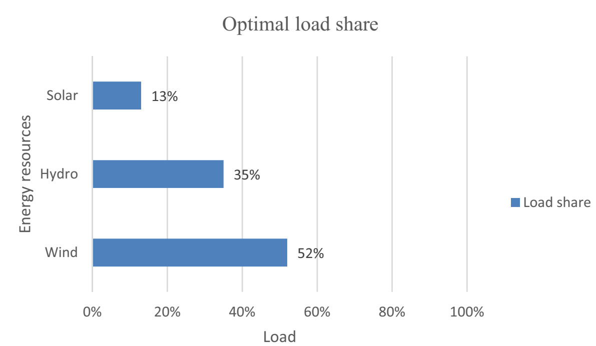

Fig. 2 Optimal load share of hybrid system

Hybrid performance evaluation

The controller looks the load and switches the appropriate sources to meet the demand from the customer side. Thus, there is no need of battery and charge controller. The result obtained from resource combination shows demand and supply are balanced (Fig. 3). For balancing demand and resources the power generated from each resource (8.58 kW wind, 2.15 kW solar, and 5.775 kW hydro) should not be less than the maximum load (15 kW). From the twelve probabilistic

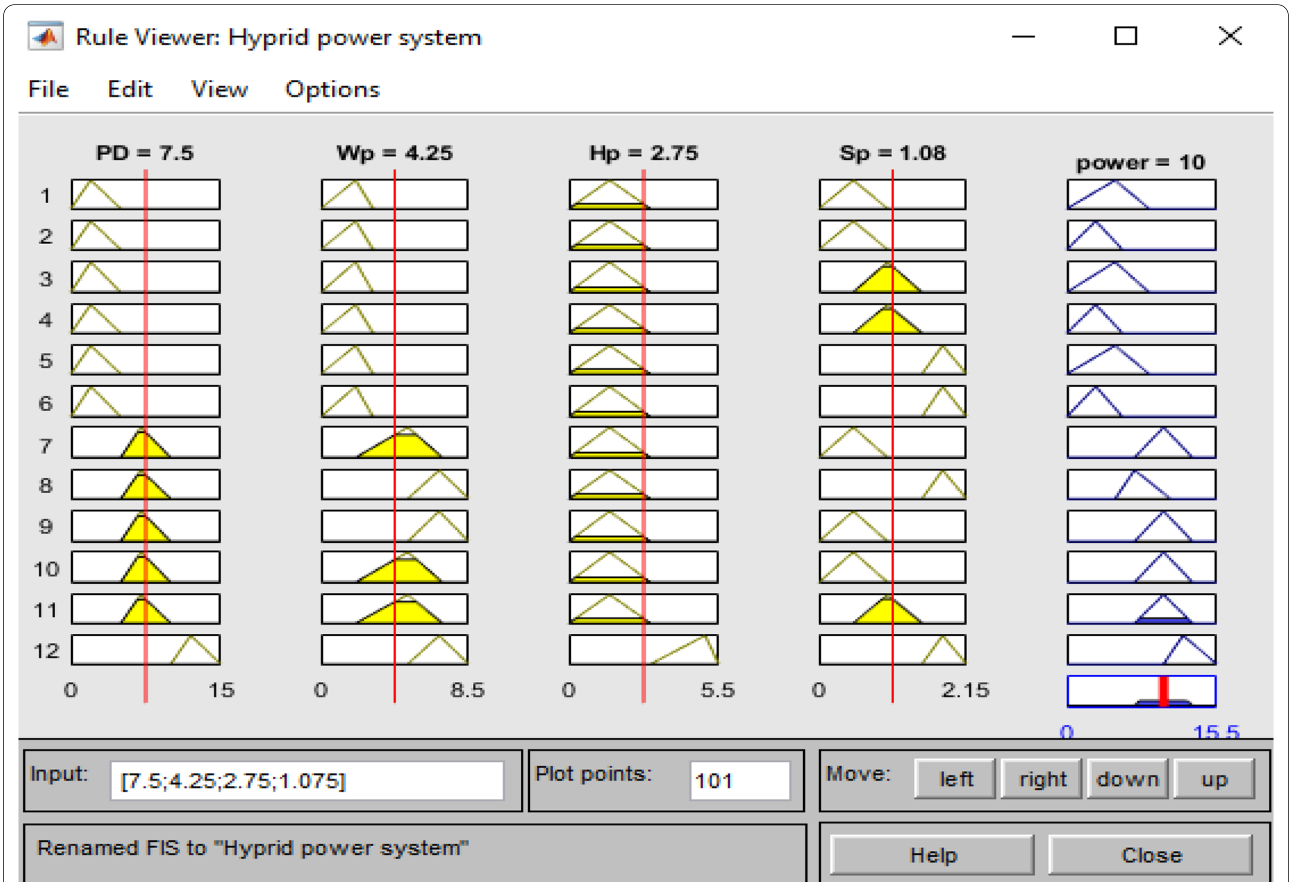

Fig. 3 Rule viewer

combinations of demand and sources, one of the combinations shows that as 7.5 kW is demanded, the power generated/output from hybrid system is 10 kW which is greater than demand. To satisfy 7.5 kW demand control system takes 4.25 kW, 2.75 kW, and 1.08 kW share from wind, hydro, and solar sources, respectively. The controller was managing the demand and the available resources according to the rule.

Conclusions

Homer software provides optimal hybrid power system configuration. The optimal configuration of the hybrid system is determined by Homer software. A Large portion of the load is supplied by wind.

The fuzzy logic control system is designed to monitor the resource availability and load demand. The demand is switched to the available resource at a time. Intelligent controller is used to make intelligent decisions by sensing the amount of load and energy source available in 24 h. This energy source and demand management contribute to reduce power system interruption due to the intermittent nature of energy sources. It has also reduced the cost of the battery; hence, there is no battery in this hybrid system.

Power demand, solar power, mini-hydro power, wind power, and power balance are factors in writing the rule in the control system. From the logical combination of the energy resources and demand, power generated for any specific time is a greater demand to balance the system. Wind has the highest contribution to supply the community load.

It is concluded that integrating different energy sources for rural electrification with an intelligent control system is a rational choice to reduce power interruption due to intermittent nature of energy resource. Therefore, using a hybrid power system for reliable power supply is important to overcome the energy poverty in Ethiopia.

Abbreviations

DC: Direct current that does not depend on time; DES: Distributed energy systems; DG: Distributed generation; kWh: Kilo Watt hour; PV: Photovoltaic; Pw: Power in the wind.

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Authors' contributions
AH contributed to the design of this study; conceived the study, collected, modeled, analyzed, and interpreted data; drafted the manuscript for important intellectual content; and read and approved the final document.

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Availability of data and materials
The data of this study will be shared upon author request.

Competing interests
The author declare that there is no conflict of interest in regarding the publication of this paper.

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