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A comparative study of the size and management of standalone hybrid renewable energy systems for remote locations in India

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Abstract
Electrification of rural areas is a challenging task, as it is more expensive than in urban areas. This study aims to identify the most efficient and sustainable combination of hybrid renewable energy systems (HRES) to meet the energy demands of rural areas cost-effectively. The research focused on the size optimisation of standalone hybrid photovoltaic–wind turbine–biogas–battery systems using HOMER software based on the availability of the sources at the study location. Different HRES combinations are compared based on technical performance, costs, and electricity production. The findings of the study for the most economical HRES configuration are compared with each other to provide a reliable and cost-effective solution. In this work, the COE per unit for the various combinations has been calculated following the analysis of the resources. Combining PV, a WT generator, and biogas is the least expensive and most practical alternative, with a battery storage system having a COE of around ₹17.24/kWh.

Keywords: Hybrid renewable energy systems, solar photovoltaic, wind turbine, optimization, cost of energy,

1. Introduction

Renewable energy sources such as solar PV, wind, biogas, and biomass are gaining immense popularity because of their sustainable nature and environmentally friendly characteristics. Their impact as a driving force for building a robust economy is becoming increasingly clear. It is important to note that renewable energy sources when used solely, have their limitations. Power generated from wind turbines and solar PV panels heavily relies on environmental conditions. Combining solar and wind energy with other sources overcomes their limitation. This creates hybrid renewable energy systems (HRES) that combine multiple renewable sources to increase efficiency and overcome source limitations(Vendoti, Muralidhar and Kiranmayi, 2020). HRES is a superior long-term energy solution compared to standalone alternatives. The global focus on reducing negative environmental effects, such as greenhouse gas emissions, climate change, and global warming, has increased interest in alternative energy sources like solar, wind, hydro, tidal, and biogas. The goal is to provide cost-effective electricity access to remote areas, enhancing their quality of life and countering the urban migration trend(Prakash and Dhal, 2022). The research objective revolves around designing and optimizing hybrid renewable energy systems to fulfil the electricity needs of remote rural areas. These systems combine various renewable sources along with energy storage solutions, such as batteries. Optimization techniques, using tools like HOMER software, are employed to determine the optimal sizing and economic feasibility of these hybrid systems. Different HRES combinations are compared and the best combination is solar PV, wind, and biogas systems with the battery storage system. The hybrid renewable energy system model combines solar, wind, biogas, and energy storage to reduce costs and evaluate performance in various configurations. In conclusion, hybrid renewable energy systems offer a promising solution for rural electrification in remote areas. Integrating renewable energy and storage tech can improve access to affordable and sustainable electricity, enhancing the quality of life(Thirunavukkarasu and Sawle, 2021). A model for optimizing the cost of off-grid renewable energy systems is developed for electrification in Achattipura, a village in the Chamarajanagar district of Karnataka, India. System performance is investigated and compared for a minimum value of NPC and COE, ideal configurations, and various combinations of HRES (Chen, Li and Yin, 2021).

1.1 Main contributions of the work

The primary contributions are listed below:

1. For size optimization, a unique HRES is designed.
2. Analysis of a system that combines solar, wind, biogas, and batteries in various combinations that can reliably, constantly, and sustainably meet the village load need has been carried out.
3. Minimization of COE and NPC is done for the proposed model.

2. Problem formulation

The objective function for the problem formulation is provided:

2.1 Objective function

To achieve optimum cost in a hybrid renewable energy system, it is crucial to consider all the expenses involved. These expenses include capital costs, maintenance and operation costs, replacement costs, fuel costs, and more. The goal is to minimize the total net present cost of the system. It is given as:

$$Min(\text{NPC}) = \frac{T_{Ac}}{CRF} \tag{1}$$

The equation provided represents the relationship between the total annualized cost of the system T_{AC} and the capital recovery factor (CRF). The determination of the CRF for a given system or component is contingent upon the specific discount rate 'i' utilized to convert one-time costs into annualized costs, as well as the useful lifespan 'n' of said system or component. This relationship can be mathematically expressed (Jamshidi and Askarzadeh, 2019).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

The annualized capital cost (A_{CC}), annualized operation and maintenance cost (A_{OMC}), and annualized fuel cost (A_{FC}) are added to determine the system's overall annualized cost. A system's T_{AC}, or total annualized cost, can be computed as follows:

$$T_{AC} = A_{CC} + A_{OMC} + A_{FC} \tag{3}$$

The annualized capital cost of HRES is determined by aggregating the capital costs associated with each component comprising the system. This calculation can be expressed as(Jamshidi and Askarzadeh, 2019):

$$A_{CC} = A_{CC-PV} + A_{CC-WT} + A_{CC-BG} + A_{CC-BSS} + A_{CC-INV} \tag{4}$$

Here the annualized capital cost of the solar photovoltaic system (A_{CC-PV}), the annualized capital cost of the wind energy conversion system (A_{CC-WT}), the annualized capital cost of the biogas generation system (A_{CC-BG}), and the annualized capital cost of the battery bank storage system (A_{CC-BSS}) are all shown. The annualized capital cost of the converter is denoted by Acc-conv. The annual cost of the solar PV system can be estimated by using the following formula:

$$A_{CC-PV} = CRF_{PV} \times N_{PV} \times (\mathrm{C}_{CPV} + C_{INS-PV}) \quad (5)$$

where N_{PV} displays the number of PV modules and CRF_{PV} the PV module's capital recovery factor. The initial capital cost of a PV module is denoted by the letters C_{CPV}, while the installation cost is denoted by $C_{INS\text{-}PV}$. A wind energy conversion system's annual capital cost may be calculated as follows:

$$A_{CC-WT} = CRF_{WT} \times N_{WT} \times (\mathrm{C}_{CWT} + C_{INS-WT}) \quad (6)$$

where C_{CWT} stands for a wind turbine's initial capital cost, $C_{INS\text{-}WT}$ for its installation cost, and CRF_{WT} stands for the capital recovery factor of a wind turbine. The initial capital costs of the engine-generator set and civil works (CW_{BG}) are included in the annual capital cost of the biogas system ($C_{EG\text{-}BG}$). It can be calculated as:

$$A_{CC-BG} = CRF_{CW-BG} \times (\mathrm{CW}_{BG}) + (\mathrm{CRF}_{EG-BG} \times C_{EG-BG}) \quad (7)$$

where $CRF_{EG\text{-}BG}$ stands for the engine-generator set of the biogas system and $CRF_{CW\text{-}BG}$ stands for the capital recovery factor for the civil works of the biogas system. The battery storage system's annual capital cost may be calculated as follows:

$$A_{CC-BSS} = CRF_{BSS} \times N_{BSS} \times \mathrm{C}_{BSS} \quad (8)$$

where C_{BSS} is the initial capital cost of a battery and CRF_{BSS} is its capital recovery factor. Additionally, the hybrid standalone renewable energy system's annualised operating and maintenance costs may be calculated as follows(Jamshidi and Askarzadeh, 2019):

$$A_{OMC} = \sum_{d=1}^{365} \sum_{h=1}^{24} \sum_{k=1}^{4} \left[C_{O\&M}^{k} \times E_{di}(\mathrm{h}) \right] \quad (9)$$

Where k stands for the number of renewable energy sources, $C_{O\&M}^{k}$ is the operating and maintenance cost of the k_{th} renewable energy source (₹/kWh), and displays the amount of energy produced by the i^{th} renewable energy source at hour 'h' of the day 'd' of the year. The main fuel used to operate the biogas system is cow dung. For HSRES, the annualised fuel cost may be computed as (Purohit and Kandpal, 2007):

$$A_{FC} = 8760 \times CUF_{BG} \times C_{D} \times Q_{D} \times S_{BIO} \times P_{BG} \quad (10)$$

where CUF_{BG} stands for the biogas-based generator system's capacity utilisation factor, C_D for the cost of dung (in rupees per kilogramme), Q_D for the amount of dung needed to create one m^3 of biogas (in kg per m^3), and S_{BIO} for the amount of biogas specifically used (in m^3/kWh).

3. Case study

The case study is based on three newly formed non-electric village hamlets in India’s Achattipura village of the district Chamarajanagar Karnataka. 341 houses and 1,532 individuals are included in the study(DDUGJY, 2020). For the chosen study area, the coordinates are 11.92′ N latitude and 76.94′ E longitude. The load profile in the selected area is shown in **Figure 1**. There are many renewable energy sources available at the study location, including solar PV, wind, biomass, and biogas. The energy requirements at the study location, data are collected from NREL, with most of the energy demands coming from homes, farms, communities, businesses, hospitals, schools, and retail outlets(Chauhan and Saini, 2016). The HOMER Pro software accurately calculates the global horizontal solar radiation, average wind speed, and optimal system size based on the longitude and latitude of a specific geographic region. The research location's expected daily load is 600.00 kWh. Using HOMER Pro software, the annual energy usage was calculated and found to be 219000 kWh/year.

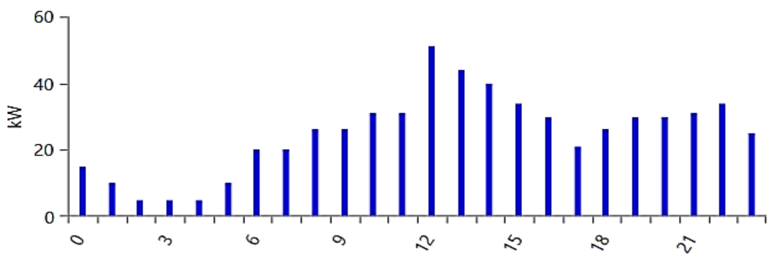

Figure 1: The hourly load profile of the proposed area

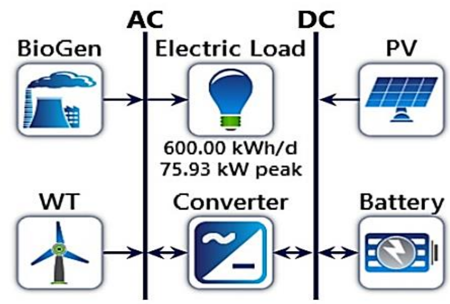

Figure 2: Schematic diagram of the proposed system

4. Results and discussion

The HOMER modelling technique employs a list of system configurations and their capacities that are ordered by the lowest COE and NPC to calculate the cost and long-term feasibility of hybridised energy systems. An optimized schematic diagram of the different sources is shown in **Figure 2**.

Combination 1: PV-WT-BioGen-Battery: The lowest NPC and COE of the system are found to be 66.8M₹ and 17.24 ₹/kWh at 0% capacity shortage. Compared to the annual energy requirement of 219000 kWh, the size of the systems taken into consideration by PV, WT generators, and biogas with batteries is 546 kW, 45 kW, 84 kW, and 1004 respectively.

Combination 2: PV-BioGen-Battery: The system sizes for PV, biogas, and the number of batteries are 698 kW, 840 kW, and 1050 no., respectively. NPC and COE of the system are found to be 68.4M₹, and 17.66 ₹/kWh respectively.

Combination 3: WT-BioGen-Battery: In this combination, the battery, WT generator, and Biogen systems are considered. The size of the systems considered as WT generator, BioGen, and the number of batteries are 603 kW, 840 kW, and 3894, respectively.

It has been found in the research that combination 1 is more effective in terms of both economy and environment.

Table 1. Comparison of cost and components of three combinations

Configuration	Energy Sources	NPC (M₹)	COE (₹/kWh)	PV Size (kW)	WT Generator Size (kW)	Biogas Size (kW)
1	PV-WT-BioGen-Battery	66.8	17.24	546	45	840
2	PV-BioGen-Battery	68.4	17.66	698	N/A	840
3	WT-BioGen-Battery	749	193.34	N/A	603	840

5. Conclusion

Three alternative HRES combinations have been created by the HOMER Pro programme and analysed. Combination 1 was determined to have the lowest NPC and COE, with values of 66.8M and 17.24 Rs/kW, respectively, when all potential configurations were compared. With this setup, the research area's necessary energy requirements are met at the lowest possible cost. In conclusion, the PV/wind/biogas/battery system configurations are completely capable of satisfying the load needs of the examined region and have the lowest COE and NPC among system configurations. The suggested systems have the following capacities: 840 kW biogas, 45 kW wind turbine, 546 kW solar, and 1004 batteries. Therefore, our analysis has suggested the resource combination-1 (PV-WT-BioGen-Battery) as the optimal configuration that might be used.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial conflict of interest.

Author Contributions

The proposal was created by Dr Naqui Anwer and Ameer Faisal. The calculations and theory were created by Ameer Faisal. The findings were examined, and both writers participated by offering constructive criticism that shaped the study the analysis, and the report.

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