***Original Research Article***

**Modelling and Optimizing Hybrids of Wind and Solar Renewable Energy Systems in the Case of Oda Robe New Residential Area by Iteration Method**

**Abstract**

This study focuses on optimizing the total annual cost of a hybrid renewable energy system combining wind and solar resources to ensure the energy demand of a community. By integrating both energy sources, the system leverages their complementary nature to provide a reliable and sustainable solution. An iterative optimization method was employed to determine the optimal configuration, balancing installation costs, operational efficiency, and energy reliability. The results demonstrate that the hybrid system significantly reduces dependence on conventional energy sources while meeting the community's energy requirements. The findings highlight the potential of renewable energy systems as a cost-effective and sustainable approach to addressing the energy challenges faced by society.

**Keywords**: Renewable Energy, Iteration Method, Bale Mountains National Park, Ethiopia etc.

1. **Introduction**

Energy is a cornerstone of modern civilisation, driving economic growth, technological advancement, and improved quality of life. It powers industries, fuels transportation, supports communication systems, and enhances access to education and healthcare. Without energy, progress in key developmental areas would stagnate. Reliable energy access is crucial in reducing poverty and fostering sustainable development, making it a vital component of global and national policies.

The disparity in energy access between urban and rural areas is a significant challenge worldwide, particularly in developing nations. Urban regions often enjoy higher electrification rates due to concentrated populations, developed infrastructure, and substantial investments. For instance, urban electrification rates in many countries exceed 90%, enabling robust economic activities and improved living standards [1].

In contrast, rural areas lag far behind. Factors like dispersed populations, insufficient infrastructure, and limited financial resources hinder rural electrification. In Sub-Saharan Africa, including Ethiopia, rural energy access is particularly low, with millions relying on traditional biomass for cooking and lighting. This urban-rural divide perpetuates inequalities, constraining rural communities' ability to thrive.

Improving universal access in the world to a successful percentage remains a significant challenge, especially in remote areas. Current data indicate that about 57% of Sub-Saharan African Countries' population were living without access to electricity. In the past two decades, Ethiopia has made maximum effort in expanding its electricity expansion, but the imbalance issue about 97% of urban households have electricity, compared to just 33% meaning about 40 million people in rural areas [2]. Basic human activities like lighting, cooking foods, economic activities, capacity building works, health care and environmental sustainability through technology were not imaged without electricity.

In Ethiopia, the energy demand is escalating rapidly due to economic growth and demographic trends. Meeting this demand is crucial for maintaining the country’s development momentum. However, traditional energy sources such as wood, biomass, and animal products which dominate rural households, are unsustainable and environmentally harmful. Fossil fuels, while a major contributor to the global energy supply, present challenges such as environmental degradation, greenhouse gas emissions, and vulnerability to market volatility. Therefore, transitioning to sustainable energy sources is imperative to meet growing demands without compromising environmental integrity or future generations' needs.

Renewable energy, derived from naturally replenishing sources like sunlight, wind, water, and geothermal heat, offers a sustainable solution to the energy crisis. It has the potential to bridge the urban-rural energy gap, promote environmental sustainability, and provide a reliable energy supply in regions lacking traditional grid infrastructure.

In Ethiopia, renewable energy is essential due to the country's abundant resources and its urgent need to expand electricity access to rural areas, where over 60% of the population lacks reliable power. By transitioning to renewables, Ethiopia can enhance energy security, support economic development, and improve living standards while contributing to global sustainability goals [3].

Hybrid energy systems, which combine solar and wind power, are particularly valuable for Ethiopia. The country’s geographical diversity ensures high potential for both energy sources solar energy is abundant in most regions, while wind resources are significant in areas like the Rift Valley. Hybrid systems are highly efficient as they leverage complementary generation patterns; solar energy is abundant during the day, while wind often peaks at night. This integration ensures a continuous and reliable energy supply, reducing reliance on hydropower, which is vulnerable to droughts and climate variability.

For Ethiopia, hybrid systems are not only environmentally friendly but also economically viable. They can be deployed in decentralized setups to electrify remote communities, reducing the costs of extending the national grid. Additionally, investments in hybrid systems align with Ethiopia’s ambitious climate and energy policies, such as its commitment to achieving a carbon-neutral economy by 2050. By focusing on hybrid renewable energy systems, Ethiopia can achieve inclusive development while positioning itself as a leader in sustainable energy in the region.

The Bale Zone is one of the administrative zones in the Oromia Region of southeastern Ethiopia. Known for its rich history, diverse culture, and breathtaking landscapes, it has played a significant role in Ethiopia’s history. The geographical location of Bale Zone is between about 9. 05º to 7.5° North latitude and 39 .5° to 40.5o East longitude with elevation ranges from less than 300 meters to over 4,377 meters above sea level.

Bale is famous for the Bale Mountains National Park, which is home to unique wildlife, including the Ethiopian wolf and mountain nyala. The region is also known for its agricultural activity crops such as barley, wheat, and maize, livestock rearing and honey production. Tourism is growing due to the natural beauty of the Bale Mountains and cultural heritage sites. As a result, the zone remains a vital region in Ethiopia, blending rich history, diverse culture, and significant ecological importance. It continues to be a focal point for sustainable development and conservation.

The Bale Zone has experienced gradual progress in electricity coverage, with many urban centres and rural areas beginning to access power infrastructure. Robe City, as the capital of the Bale Zone, enjoys a relatively better electricity supply compared to surrounding rural towns. However, the grid connection often faces interruptions, limiting consistent access to energy for residents and businesses. The city's growing population and expansion of residential areas have further strained the existing infrastructure, highlighting the need for alternative energy solutions to meet rising demands.

The electricity supply in Robe City faces significant challenges due to the limitations of the local power station. The power infrastructure, designed to support a smaller population, now struggles to accommodate the expanding urbanization and increasing energy consumption. Newly established neighbourhoods, such as the commonly known teachers' residential area, of Oda Robe kebele which currently hosts 47 households of similar category face acute energy shortages. This area often experiences frequent power outages, leaving residents without adequate lighting, heating, and access to essential appliances. This challenge disrupts daily life and hinders the area's socio-economic activity.

To address these challenges, hybrid wind and solar renewable energy systems present a viable solution for ensuring consistent and sustainable power supply. Wind and solar energy complement each other, with wind energy often being more available at night and solar energy during the day. Implementing these systems in Robe City, particularly in areas like the teachers' residential village of Oda Robe kebele, can significantly reduce dependence on the strained grid, provide reliable power, and improve the quality of life. Additionally, these renewable energy sources are environmentally friendly and economically advantageous, offering a sustainable path to overcoming the energy challenges of the village.

1. **Literature Review**

Recently new ideas have been immersed on comprehensive model for optimizing wind-solar hybrid systems in rural electrification projects using Genetic Algorithms (GA) to balance the load demand and optimal sizing of the involved components (see [4] and [5]). The proposed methodology named Genetic Algorithm run with the developed model of the components to minimises energy costs while ensuring system reliability, by considering all the predetermined environmental and economic constraints. Real-world case studies in rural regions highlight the effectiveness of this approach in improving energy access. New results have been developed on optimal sizing of different hybrids of renewable energy systems to satisfy the energy demand of rural areas of Ethiopia (see [6], [7] and [8]), checking levelized energy costs, maintaining reliability, component sizing, total cost reduction and controlling energy loss are some of the concerns of the papers. The simulation results of such algorithms with different nature-inspired algorithms to check an efficient and cost-competitive system are promising to electrify the rural areas of Ethiopia.

Two groups of researchers worked on the optimal sizing of hybrid wind-solar renewable energy systems in off-grid rural areas with a Particle Swarm Optimization (PSO) framework, their objective was minimizing both energy loss and system cost which satisfies the desired load through energy balancing and retaining the reliability of the system. The simulation result shows that the PSO algorithm enables more sustainable and cost-effective solutions for energy supply in remote locations (see [9] and [10]). In [11], a technique is employed as the methodology, Harmony Search Algorithm (HSA) to design and optimise hybrid renewable energy systems in rural areas. The objective of the paper is to reduce the levelized cost of electricity (LCOE) while ensuring system reliability and minimizing the total annual cost of electricity. Case studies from rural villages demonstrate the potential of HSA to outperform conventional techniques in balancing costs and power quality. Several other scholars of the field (see [12]-[18]), have employed their own different nature inspired algorithms to optimise the integration of different hybrid energy resources in for the rural areas. Some approaches emphasise minimising both the levelized cost of energy and emissions while ensuring the stability of the desired power supply while others focus on the economic feasibility and reliability of the system. From their simulation results even though hybrid nature-inspired algorithms have superiority over the others, all the applied optimise algorithms have the promising character in handling complex multi-objective scenarios compared to traditional algorithms.

1. **Modelling of Hybrid Renewable Energy System**

The first basic procedure in Optimizing Hybrids of Energy Systems is modelling all the involved components which can make the system suitable for effective and efficient of it to get the maximum energy output. Here the model of the system as well as the individual components which constitute the system is reviewed. A hybrid wind and solar renewable energy system combines two renewable energy sources wind and solar power and energy storage (typically a battery system) to provide continuous power. The bi-directional converters and controllers also participate in the system to convert and control the energy output. Such systems are typically used in both grid-connected and off-grid scenarios to ensure a more reliable and consistent power supply. Various modelling techniques have been developed to model Hybrids of Wind and Solar Renewable Energy System components in previous studies. This paper presents a detailed model of a hybrid system, including the unit models of each component: wind turbine, solar photovoltaic (PV) array, battery energy storage system, and power electronics like converters and inverters.

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Battery

DC/AC Inverter

Wind

Turbine

AC/DC

Converter

PV

Module

DC/DC

Converter

AC/Dc Bus

**Picture 1**. Schematic diagram of hybrids of wind and solar energy system with storage battery.

Due to the supportive nature of these renewable sources, the generated power at a certain duration of time is assumed to be constant. To analyze the performance of the system and control the balance between desired and generated power, the mathematical modelling of different components of the proposed hybrid wind and solar energy with battery system is discussed in this section. Here under the model of each unit is discussed.

* 1. **Modelling Wind Generator**

Wind energy is one of the promising renewable energy sources and the main source of power generated from wind and solar hybrid energy systems. A wind generator, commonly referred to as a wind turbine generator, is designed to convert the kinetic energy of wind into electrical energy. Modelling a wind generator involves capturing the physics of wind energy conversion, the electromechanical systems involved in generating electricity, and control mechanisms to optimize the energy production.

The wind turbine captures energy from the wind by converting the wind's kinetic energy into mechanical energy through the rotation of blades. The mechanical energy is then converted into electrical energy by a generator, the key equation governing wind energy conversion in [4] is given as:

(1)

Where: wind power is the power coefficient of the turbine defined due to its limitations and its theoretical value is taken as 0.593, is Air density which is typically at sea level, is the swept area of the turbine blades and , where is the radius of the blade and is wind speed .

**3.2 Modelling Solar Generator**

1. Top of Formofof

Bottom of Form

A solar generator, commonly known as a solar photovoltaic (PV) system, is designed to convert sunlight into electrical energy using photovoltaic cells. This type of power generator is the most common and cheap power generating scheme throughout the world. Modelling a solar generator involves designing the physical and electrical behaviour of PV cells, arrays, and power conversion units to optimize energy generation under varying solar irradiance and temperature conditions. Here, the comprehensive mathematical overview of PV power generators is given as follows.

Where: Efficiency of the PV panel dependant on temperature, is the total surface area of the panel (), Solar irradiance on the panel's surface efficiency (W/m2) at time t and is angle of incidence between sunlight and the panel's surface normal.

**3.3 Modelling Storage Battery**

Even though the defined system generates constant power due to the subordinate nature of the components, to control the balance between power demand and supply, defining the proper model of the battery is crucial. A storage battery is a basic component of renewable energy systems, providing energy storage to balance supply and demand, improve grid stability, and enable the efficient use of intermittent energy sources like solar and wind. At any time, the state of charge of the battery is dependent of the previous state of charge, the energy production and load demand at the time . The state of charge of the battery is used as a decision variable for the control of the overcharge and discharge. The process of charging and discharging plays between maximum charge and energy demand. The state of the battery reaches its maximum value C(batt, max), when the system generates above demand and reaches its minimum level C(batt, min) when discharging becomes high [15]. In a hybrid system, the battery charging and discharging are controlled based on the power balance between the generation sources (solar, wind) and the load demand. If the energy produced by the solar PV and wind turbine exceeds the load demand, the excess energy is stored as charging the battery and given by the following formula [4];

Where: is power flowing into the batter, is total generated power from the system and is the total demand load.

Under the condition load demand is higher than the energy generated by the renewable sources, the battery must supply the required energy.

The State of Charge (SoC) is the most critical variable in battery management situations. It indicates the current energy level of the battery relative to its full capacity. In [4], the SoC can be modelled as

(5)

Where: is battery current (positive for charging and negative for discharging), is maximum battery capacity (Ah) and is the initial state of charge at

SoC must be constrained between 0% and 100% to avoid overcharging or deep discharging, which can damage the battery.

1. **Problem Formulation**

**4.1 Objective Function Formulation**

In the process of problem formulating, optimizing a hybrid of wind and solar renewable energy systems involves defining the objective function and constraints to maximize energy production, minimize costs, or balance multiple performance factors, considering both the wind and solar energy resources. One of the major objectives in the modelling and optimal sizing optimization problem is to minimize the total annual cost of the system. In [10], the total annual cost is taken as the sum of the initial capital cost, operation cost and annual maintenance cost. Thus, the problem to be minimized will be stated as follows.

Minimize (6)

Where initial capital cost needed to establish the project and is operation and maintenance cost of the system occurs during the project lifetime. To compare the cost needed at the initial of the project with the costs throughout the project’s life span, the capital recovery factor (CRF) cost is defined as:

(7)

Where the interest rate and denotes the lifespan of the system.

The initial capital cost of the system is constituted of costs of solar panels, wind turbines, batteries, controllers, inverters, and backup generators redefined by capital recovery cost which is outlined as follows:

(8)

Where *NPV &* are numbers and cost of PV panels, *NWT &* C*WT*  are numbers and cost of wind turbines, are numbers and cost of batteries,are numbers and cost of converters, are numbers and cost of inverters and *CBackup* is the cost of battery through the life span of the project. Each cost of the components, solar panel and wind turbine includes the cost of the material and its installation fee.

(9)

Where are unit material cost and maintenance cost respectively.

The number of batteries, controllers and inverters needed for the system is dependent of the number of solar panels and wind turbines and on its efficiency and storage capacity. The expression gives the roundup value for the number of batteries is given as follows:

Where: is efficiency, is rated capacity and is the storage capacity of the battery.

The annual operation and maintenance cost of the hybrid system was calculated by the following equation.

(11)

Where are unit operation and maintenance costs of solar panels and wind turbines respectively, and are the power generated from both components at a given time and are operation and maintenance costs of solar panels, wind turbines and batteries respectively.

**4.2 Constraints**

In a hybrid wind and solar renewable energy system, several constraints must be considered to ensure the system operates efficiently, reliably, and within practical limits. These constraints are usually related to energy generation, demand fulfilment, storage, system components, and cost limitations. Here is a detailed breakdown of all possible constraints [10];

**[I].** Decision variables constraint

 (12)

### ****[II].** Reliability constraint**

Reliability in hybrid renewable energy systems can be expressed as a constraint to ensure that the combined energy output meets the demand consistently, even under varying environmental conditions. Mathematically:

Where is power generated from solar panel at time t, is power generated from wind turbine at time t, is battery discharge power at time t, is demand at a given time and is reliability margin to account for uncertainties in energy production.

### ****[III].** Generation constraints**

The power generated by solar and wind components depends on their installed capacity and the availability of resources (e.g., sunlight and wind speed).

(14)

Where , are power generated from from panel and turbine at time t, , are components power generating capacity and , are availability factor.

**[IV]. Battery constraints**

Battery storage is often used to balance the intermittent nature of solar and wind energy. The state of charge of the battery is updated over time based on charging and discharging activities:

Where is energy stored in the battery at time t, is the charging efficiency of the battery, is power used to charge the battery at times t and is the power discharged from the battery.

1. **Iteration method**

Iterative method was attempted to find the optimal size of hybrid system of wind and solar renewable energy based on minimization of total annual cost under set of constraints to satisfy the desired load. The main concern here was to determine the size of each component, numbers of wind turbines, solar panels, batteries, and controllers participating in the system [10].

The iterative method for solving hybrid wind and solar renewable energy systems involves optimizing energy production and distribution while meeting specific constraints such as demand, weather variability, and cost-effectiveness. This method iteratively refines the energy mix by modelling wind and solar resources, simulating energy generation, and balancing it against load demands. It ensures that the hybrid system is cost-effective, reliable, and sustainable, making it a practical solution for areas like Robe city’s teachers' residential zone.

A typical approach incorporates swarm based and evolutionary optimization techniques like Particle Swarm Optimization (PSO) or Genetic Algorithms (GA), which are well-suited to handle non-linear and multi-objective problems inherent in hybrid systems. The method leverages data inputs such as wind speed, solar irradiance, system efficiency, and storage capacity to adjust system parameters and converge toward an optimal solution.

Main steps in iteration Algorithm are:

1. Select suitable and commercially available unit sizes for wind turbine, PV panel, and storage battery based on the given data.
2. Since the unit cost for the wind turbine far exceeded that of a single solar panel, kept the number of wind turbines (NWT) constant and increased the number of PV panels (NPV) until the system is balanced.
3. Record number solar panel, and number of wind turbines at which the desired load was satisfied.

Flow chart of optimization of hybrid wind and solar energy system by iteration method

Calculate the Optimal Value

Set Iteration t = t+1

Is Termination

Satisfied?

Calculate the Total Annual Cost of the System

Iterate NPV

Battery Storage

Load Profile

Wind Turbine Cost

Solar Panel Cost

Battery Cost

Initialize NWT, NPV, NBatt, NCont

Check all the Inequality Constraints

Fixed NWT

Calculate for NPV =0

Daily Data of Load Demand, Wind Power and Solar Power Profiles

Check for all Inequality Constraints

Controller Cost

**Figure 1.** Flow chart of optimization of hybrid wind and solar energy system by iteration method.

1. **Numerical Data for Analysis**

**6.1 Electric Demand of the Area**

The teacher's residential area in Oda Robe Kebele, which accommodates 47 households, exhibits a standard of living that aligns closely with the typical usage of household appliances outlined above. The residents commonly rely on essential kitchen appliances such as refrigerators, electric kettles, and mixers for food preparation and preservation. Washing machines, irons, and water heaters play a pivotal role in maintaining cleanliness and comfort in daily life. Entertainment needs are met with televisions and Wi-Fi routers, ensuring access to information and connectivity. Lighting is provided by energy-efficient LED bulbs, while smartphones, laptops, and occasional use of small grooming devices like electric shavers’ full fill personal and work-related requirements. These households reflect a balanced lifestyle, emphasizing convenience and functionality within an energy consumption framework of approximately 12.6 kWh per day per household. Energy-saving practices are often employed to manage costs effectively while ensuring essential needs are met.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Table 1**. Daily Electric Consumption of the Village | | | | |
| **Category** | **Appliance** | **Power (W)** | **Usage Time (hrs)** | **Energy Consumption (kWh)** |
| **Kitchen Appliances** | Refrigerator | 30 | 24 | 0.72 |
| Mixer/Blender/Grinder | 750 | 0.25 | 0.1875 |
| Toaster | 800 | 0.2 | 0.16 |
| Water Purifier | 50 | 4 | 0.2 |
| **Cleaning & Maintenance** | Washing Machine | 500 | 1.5 | 0.75 |
| Iron | 450 | 0.2 | 0.09 |
| Water Heater (Geyser) | 700 | 1 | 0.7 |
| **Entertainment** | Television | 45 | 5 | 0.225 |
| Wi-Fi Router | 10 | 24 | 0.24 |
| **Lighting** | LED Lights (x10) | 10 | 5 | 0.05 |
| **Personal Gadgets** | Smartphone Charger (x2) | 5 | 3 | 0.015 |
| Laptop/Tablet (x2) | 50 | 6 | 0.3 |
| Electric Shaver/Trimmer | 10 | 0.5 | 0.005 |
|  |  | Total (kWh) | | 3.6425 |

**Figure 2**. Apparatus versus power Consumption

The residential area consumes approximately 592.2 kWh of electricity daily to meet the needs of all 47 households. This reflects a substantial demand that emphasizes the need for efficient energy use and potentially renewable energy solutions to manage consumption sustainably.

**6.2 Energy Demand and Supply of the Village**

The daily energy demand of the teacher's residential area in Oda Robe Kebele, comprising 47 households, is approximately 592.2 kWh, reflecting the collective consumption of common household appliances over a 24-hour period. This demand and the supply from wind turbine and solar panel was given in the following table.

**Table 2**. Daily energy demand and supply of the village

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Time (t)** | | PDem(KW) | PWT (KW) | PPV (W) | PPv (KW) | **PGen(KW)** | ΔP (KW) |
| 1 | 20.25 | | 3.58 | 110 | 0.11 | 3.69 | -16.56 |
| 2 | 20.04 | | 3.49 | 110 | 0.11 | 3.6 | -16.44 |
| 3 | 17.86 | | 3.48 | 110 | 0.11 | 3.59 | -14.27 |
| 4 | 17.82 | | 3.53 | 110 | 0.11 | 3.64 | -14.18 |
| 5 | 19.42 | | 3.47 | 110 | 0.11 | 3.58 | -15.84 |
| 6 | 24.62 | | 3.51 | 110 | 0.11 | 3.62 | -21 |
| 7 | 34.46 | | 3.46 | 111.6 | 0.1116 | 3.5716 | -30.8884 |
| 8 | 38.45 | | 3.46 | 113.4 | 0.1134 | 3.5734 | -34.8766 |
| 9 | 31.54 | | 3.61 | 120.3 | 0.1203 | 3.7303 | -27.8097 |
| 10 | 18.56 | | 3.76 | 134.6 | 0.1346 | 3.8946 | -14.6654 |
| 11 | 15.25 | | 4.1 | 141.7 | 0.1417 | 4.2417 | -11.0083 |
| 12 | 36.68 | | 4.53 | 145.3 | 0.1453 | 4.6753 | -32.0047 |
| 13 | 34.45 | | 4.67 | 846.6 | 0.8466 | 5.5166 | -28.9334 |
| 14 | 29.42 | | 5.89 | 747.6 | 0.7476 | 6.6376 | -22.7824 |
| 15 | 19.69 | | 5.43 | 746.8 | 0.7468 | 6.1768 | -13.5132 |
| 16 | 20.74 | | 5.45 | 543.5 | 0.5435 | 5.9935 | -14.7465 |
| 17 | 28.96 | | 4.91 | 134.2 | 0.1342 | 5.0442 | -23.9158 |
| 18 | 33.06 | | 4.76 | 123.4 | 0.1234 | 4.8834 | -28.1766 |
| 19 | 21.05 | | 4.57 | 115.6 | 0.1156 | 4.6856 | -16.3644 |
| 20 | 19.25 | | 4.16 | 111.6 | 0.1116 | 4.2716 | -14.9784 |
| 21 | 19.94 | | 3.87 | 110 | 0.11 | 3.98 | -15.96 |
| 22 | 22.06 | | 3.76 | 110 | 0.11 | 3.87 | -18.19 |
| 23 | 24.98 | | 3.74 | 110 | 0.11 | 3.85 | -21.13 |
| 24 | 23.67 | | 3.7 | 110 | 0.11 | 3.81 | -19.86 |
|  | 592.22 | | 98.89 |  | 5.2362 | 104.1262 |  |

**Figure 3**. Energy demand and supply of the village

**6.3** **Apparatuses used for Analysis**

As per above Table 3, we can draw following input variables and their corresponding values:

|  |  |
| --- | --- |
| Variables/ Apparatuses | Values |
| Annual interest (*i*) | 6% |
| Life span of the system (n) | 20 years |
| Solar panel price | $167/panel |
| Solar panel installation fee | 50% of the price |
| Wind turbine price | $458.3/Turbine |
| Wind turbine installation fee | 25% of the price |
| Unit cost of the battery | $85 |
| Cost of controller | $16.7 |
| Usage % of battery rated capacity (η) | 90% |
| Battery rated capacity | 2.1kWh |
| Batteries life span | 4 years |
| Unit time (Δt) | 1hr |
| Maintenance cost of PV array | 1% of installation cost per year |
| Maintenance cost of wind turbine | 2% of installation cost per year |

1. **Results and Discussions**

When iteration method was applied to find the number of components (numbers of panel, turbine, batteries, and controllers), which satisfy the total demand, it gives three different combinations as shown below.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 4.** Possible numbers of wind turbines and solar panels | | | | | | | |  |
| **No. of Iterations** | **N(PV)** | **P(PV)** | **N(WT)** | **P(WT)** | **Total PGen** | **Total PDem** | **ΔP (KW)** |  |
| 1 | 1 | 11.88 | 1 | 25 | 36.88 | 592.2 | -555.32 |  |
| 2 | 2 | 11.88 | 2 | 25 | 73.76 | 592.2 | -518.44 |  |
| 3 | 3 | 11.88 | 3 | 25 | 110.64 | 592.2 | -481.56 |  |
| 4 | 4 | 11.88 | 4 | 25 | 147.52 | 592.2 | -444.68 |  |
| 5 | 5 | 11.88 | 5 | 25 | 184.4 | 592.2 | -407.8 |  |
| 15 | 15 | 11.88 | 15 | 25 | 553.2 | 592.2 | -39 |  |
| 16 | 16 | 11.88 | 16 | 25 | 590.08 | 592.2 | -2.12 |  |
| 17 | 17 | 11.88 | 17 | 25 | 626.96 | 592.2 | 34.76 | \*\* |
| 18 | 18 | 11.88 | 18 | 25 | 663.84 | 592.2 | 71.64 |  |
| 19 | 19 | 11.88 | 19 | 25 | 700.72 | 592.2 | 108.52 |  |
| 20 | 20 | 11.88 | 20 | 25 | 737.6 | 592.2 | 145.4 |  |
| **Table 5.** Possible numbers of wind turbines and solar panels for constant turbine | | | | | | | |  |
| **No. of Iterations** | **N(PV)** | **P(PV)** | **N(WT)** | **P(WT)** | **Total PGen** | **Total PDem** | **ΔP (KW)** |  |
| 1 | 1 | 11.88 | 5 | 25 | 136.88 | 592.2 | -455.32 |  |
| 2 | 2 | 11.88 | 5 | 25 | 148.76 | 592.2 | -443.44 |  |
| 3 | 3 | 11.88 | 5 | 25 | 160.64 | 592.2 | -431.56 |  |
| 4 | 4 | 11.88 | 5 | 25 | 172.52 | 592.2 | -419.68 |  |
| 5 | 5 | 11.88 | 5 | 25 | 184.4 | 592.2 | -407.8 |  |
| 35 | 35 | 11.88 | 5 | 25 | 540.8 | 592.2 | -51.4 |  |
| 36 | 36 | 11.88 | 5 | 25 | 552.68 | 592.2 | -39.52 |  |
| 37 | 37 | 11.88 | 5 | 25 | 564.56 | 592.2 | -27.64 |  |
| 38 | 38 | 11.88 | 5 | 25 | 576.44 | 592.2 | -15.76 |  |
| 39 | 39 | 11.88 | 5 | 25 | 588.32 | 592.2 | -3.88 |  |
| 40 | 40 | 11.88 | 5 | 25 | 600.2 | 592.2 | 8 | \*\* |
| 41 | 41 | 11.88 | 5 | 25 | 612.08 | 592.2 | 19.88 |  |
| 42 | 42 | 11.88 | 5 | 25 | 623.96 | 592.2 | 31.76 |  |
| 43 | 43 | 11.88 | 5 | 25 | 635.84 | 592.2 | 43.64 |  |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 6**. Possible numbers of wind turbines and solar panels for constant panel | | | | | | | |  |
| **No. of Iterations** | **N(PV)** | **P(PV)** | **N(WT)** | **P(WT)** | **Total PGen** | **Total PDem** | **ΔP (KW)** |  |
| 1 | 10 | 11.88 | 1 | 25 | 143.8 | 592.2 | -446.47 |  |
| 2 | 10 | 11.88 | 2 | 25 | 168.8 | 592.2 | -421.47 |  |
| 3 | 10 | 11.88 | 3 | 25 | 193.8 | 592.2 | -396.47 |  |
| 4 | 10 | 11.88 | 4 | 25 | 218.8 | 592.2 | -371.47 |  |
| 5 | 10 | 11.88 | 5 | 25 | 243.8 | 592.2 | -346.47 |  |
| 10 | 10 | 11.88 | 10 | 25 | 368.8 | 592.2 | -221.47 |  |
| 18 | 10 | 11.88 | 18 | 25 | 568.8 | 592.2 | -21.47 |  |
| 19 | 10 | 11.88 | 19 | 25 | 593.8 | 592.2 | 3.53 | \*\* |
| 20 | 10 | 11.88 | 20 | 25 | 618.8 | 592.2 | 28.53 |  |
| 21 | 10 | 11.88 | 21 | 25 | 643.8 | 592.2 | 53.53 |  |
| 22 | 10 | 11.88 | 22 | 25 | 668.8 | 592.2 | 78.53 |  |
| 23 | 10 | 11.88 | 23 | 25 | 693.8 | 592.2 | 103.53 |  |

As shown in Table 4, the total energy demand and supply was balanced on the 17th iteration with 34.76KWh extra power which used to charge the battery. Due to high price of wind turbine and potential of sun light, the researcher fixed number of wind turbine to 5 and get the balanced power on 40th iteration with extra 8KWh as shown Table 5.

For the developed model, equations (1)-(10) was simulated for the data shown on Table 3, and different alternatives of numbers of components on Table 4-6, optimal result was shown as follows.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 7**. Optimal value for different iteration of number of panels | | | | | | | | |  |  |  |  |  |
| **CRF** | **NPV** | **Cpv** | **NWT** | **CWT** | **n⁄LSBatt** | **Nbatt** | **Cbatt** | **N-con** | **C-Con** | **Days** | **TAC** | **TAC** |  |
| 0.0872 | 1 | 167 | 1 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 55326.61 | 55326.61 |  |
| 0.0872 | 2 | 167 | 2 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 75228.66 | 75228.66 |  |
| 0.0872 | 3 | 167 | 3 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 95130.71 | 95130.71 |  |
| 0.0872 | 4 | 167 | 4 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 115032.8 | 115032.8 |  |
| 0.0872 | 5 | 167 | 5 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 134934.8 | 134934.8 |  |
| 0.0872 | 6 | 167 | 6 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 154836.9 | 154836.9 |  |
| 0.0872 | 7 | 167 | 7 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 174738.9 | 174738.9 |  |
| 0.0872 | 8 | 167 | 8 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 194641 | 194641 |  |
| 0.0872 | 9 | 167 | 9 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 214543 | 214543 |  |
| 0.0872 | 10 | 167 | 10 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 234445 | 234445.1 |  |
| 0.0872 | 11 | 167 | 11 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 254347.1 | 254347.1 |  |
| 0.0872 | 12 | 167 | 12 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 274249.1 | 274249.1 |  |
| 0.0872 | 13 | 167 | 13 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 294151.2 | 294151.2 |  |
| 0.0872 | 14 | 167 | 14 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 314053.2 | 314053.2 |  |
| 0.0872 | 15 | 167 | 15 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 333955.3 | 333955.3 |  |
| 0.0872 | 16 | 167 | 16 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 353857.3 | 353857.3 |  |
| 0.0872 | 17 | 167 | 17 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 373759.4 | 373759.4 | \*\* |
| 0.0872 | 18 | 167 | 18 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 393661.4 | 393661.4 |  |
| 0.0872 | 19 | 167 | 19 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 413563.5 | 413563.5 |  |
| 0.0872 | 20 | 167 | 20 | 458.3 | 2 | 6 | 85 | 6 | 15.5 | 365 | 433465.5 | 433465.5 |  |

Analysis of the data with the developed hybrid renewable energy system was made. All the objective function and constraints were satisfied and annual optimal solution was obtained as follows.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Table 8**. Optimal result of hybrids of solar and wind renewable energy system | | | | | |
| Sl.  No. | No of Panels | No of Turbines | No Batteries | No of Controlers | Total Annual Cost in USD |
| 1. | 17 | 17 | 17 | 17 | 373,759.40 |
| 2. | 40 | 5 | 17 | 17 | 326,380.20 |
| 3. | 10 | 19 | 17 | 17 | 365,726.00 |

Among the analysed configurations results shown on Table 8, the second row with 40 solar panels, 5 wind turbines, 17 batteries, and 17 controllers stands out as the most cost-effective solution, achieving a total annual cost of $326,380.20. This result shows the best trade-off between cost, reliability, and resource utilization. By prioritizing solar panels, which are more cost-effective, and minimizing the number of wind turbines, this configuration demonstrates how an optimal hybrid system can be designed to meet energy demands sustainably and economically.

1. **Conclusion**

The iterative optimization method applied in this study demonstrates the feasibility and cost-effectiveness of hybrid wind and solar renewable energy systems for meeting the energy demands of rural areas like Oda Robe in Ethiopia. The analysis revealed that optimal configurations could balance energy supply and demand while minimizing total annual costs. For instance, fixing the number of wind turbines at five resulted in a balanced system at the 40th iteration, with a surplus of 8 KWh, reflecting the complementarity of wind and solar resources.

The optimal configuration varied depending on constraints and objectives. The configuration with 40 solar panels and 5 wind turbines provided the most economical solution, with a total annual cost of $326,380.20. This hybrid system not only meets the energy demand of the residential area but also integrates battery storage to address energy variability, ensuring reliability.

The results emphasize that combining wind and solar energy, with appropriate optimization techniques like the iteration method, can offer scalable, sustainable solutions for rural electrification. This approach reduces dependency on the national grid, mitigates power outages, and promotes environmental sustainability, aligning with Ethiopia's renewable energy targets. Further research and real-world implementation can refine these models, contributing to broader energy access and sustainability goals.

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