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RESEARCH ARTICLE

A TLBO algorithm-based optimal sizing in a standalone hybrid renewable energy system

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Abstract
Depletion of fossil fuels, increase in fuel prices, and global warming have motivated the utilization of renewable energy resources like solar and wind, as they are eco-friendly. Due to the stochastic nature of PV and wind, using a single energy source is not reliable and uneconomical as it results in system over-sizing. Integration of renewable sources such as PV and wind can significantly increase energy reliability compared to single-source systems. PV and wind hybrid systems are economically advantageous in isolated areas for providing continuous and quality power due to their inherent complementary characteristics and availability in most areas. Utilizing grid-tied renewable energy resources is also economical and reliable to overcome power outages in remote areas. This study proposes a TLBO algorithm for optimal design and sizing of HRES in both standalone and grid-connected modes due to its simplicity and fewer parameters to adjust. The objective of the optimization problem in standalone, as well as the grid-connected mode, is to minimize the LCE and maximize the system reliability and renewable energy integration while satisfying the system constraints and load demand. The number of PV panels, wind turbines, and batteries is taken as decision variables optimally determined by the proposed optimization algorithm. The simulations are carried out in MATLAB software. The effectiveness of TLBO in designing and sizing the hybrid system is investigated, and its performance is compared with other well-known optimization algorithms PSO; the TLBO provides the best optimal solution, better performance, and faster convergence speed compared to different algorithms.
Keywords: Renewable energy system, Hybrid system, TLBO algorithm, Standalone RES, PV system.

Introduction
The rapid growth in the economy of world directly indicates a massive requirement for power generation. On the other hand, power generation from conventional energy sources alarms severe global warming and also depletes fossil fuels.

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Renewable energy is a promising solution to tackle this issue and meet the increased demand. In the last two decades, there has been a rapid increase in the utilization of RES and storage units in the electric sector to reduce greenhouse gas emissions and air pollution, deregulation of the energy market, and privileged prices of green energy (Al-falahi *et al.,* 2017). Renewable energy sources such as solar and winds are the best alternative to conventional power generation and have great potential worldwide. Earth receives 174 trillion kWh of energy per hour from the sun. This solar energy can be used directly to generate electricity using photovoltaic panels. These cells produce electric current directly from sunlight. Power from solar has the highest potential compared to other renewable sources (Azaza & Wallin, 2017). As of 31 May 2021, India has an installed power capacity of 383.37 GW, out of which 95 GW is from renewable energy sources (Solar is 40.5 GW and Wind is 39 GW). These are inexhaustible and available everywhere, irrespective of location. Renewable energy resources can be utilized in areas where the construction of new transmission lines is expensive, but they are uneconomical and unreliable when used independently due to their intermittent nature as they are affected by weather conditions and diurnal variations. Therefore, the integration of solar and wind can be a suitable alternative for a reliable and economic system

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as they complement each other (Sandhu and Mahesh, 2018). The use of HRES improves reliability and reduces power fluctuations, investment costs, and the size of storage systems (Anoune *et al.,* 2018). The storage capacity of the battery must be sufficient to compensate for the fluctuations of renewable sources, especially in a standalone system as there are no other means to compensate otherwise, the system will not be reliable (Akram *et al.,* 2018). The power balance between renewable power generation and load demand is required, which is maintained by the energy management system (Abdelkader *et al.,* 2018). Hybrid renewable can be connected in standalone mode or grid-connected mode, but standalone faces more challenges in terms of reliability as there is no alternative to supply deficit power (Aziz *et al.,* 2018). The combination of the distributed generators and energy storage varies with location; hence, techno-economical feasibility study is required to supply the load reliably (Sawle *et al.,* 2018). Generally, the task of optimal planning of RDG is to determine its optimal location and size to minimize or maximize the desired objective function, considering different technical, economic, and environmental constraints (Sanajaoba & Fernandez, 2018). The main purpose of optimal sizing was to balance the generated power and load demand and minimize the size of system components and their relevant costs. Optimal sizing of each system component is necessary to obtain an economical solution. Hence PV/WT/DG/Battery based HRE system with HOMER software has been proposed (Sun *et al.,* 2019).

The HRES design and optimization problem has been discussed in numerous papers. Size optimization of HRES using conventional methods has limited studies in recent literature. Most of the studies adopted iterative methods. These traditional methods give a guaranteed solution but are unsuitable for solving complex problems. (Nurunnabi *et al.,* 2019; Hu *et al.,* 2019; Mellouk *et al.,* 2019). Besides these traditional methods, the simulation software tools used frequently in hybrid systems design applications are HOMER, INSEL, HYBRID2, ORIENTE, RET Screen, RAPSIM, and PVSYST. The techno-economic optimization of PV/WT-based systems with HOMER and GAMS software was proposed in 2019 (Kaabeche & Bakelli, 2019; Gan *et al.,* 2019). Metaheuristic techniques like a genetic algorithm (GA), simulated annealing (SA), differential evolution (DE), etc., are very popular in solving complex problems. Several methods for sizing hybrid energy systems used in recent years were discussed. Various configurations of renewable energy generation are optimally designed by different optimization algorithms (Hamanah *et al.,* 2020; Kumar *et al.,* 2020). A novel approach-based social spider optimization algorithm (SSO) has been adopted for size optimization of PV/WT/Battery/DG integrated MG. The PSO and non-dominated sorting genetic algorithm were utilized to find out the optimum number of PV panels, wind turbines, and batteries subjected to minimization of the levelized cost of energy and satisfying reliability constraint loss of power supply probability (Radosavljevic *et al.,* 2020). In 2020 recent approach-based social spider optimizer for optimal sizing of hybrid PV/wind/battery/diesel integrated microgrid has been proposed. Also, cost-effective grid-connected GES considering the influence of grid availability, has been proposed (Rehman *et al.,* 2020). The HRE system sizing and the microgrid's energy management issues have been carried out with a new approach, a parallel hybrid genetic algorithm-particle swarm optimization algorithm (PGA-PSO). The author proposed a method mine blast algorithm to optimize PV/WT/FC integrated hybrid system (Fathy *et al.,* 2020). An energy management strategy for grid-connected hybrid energy sources has been proposed. The combination of PV/WT/different electrochemical storage hybrid system optimal cost analysis is carried out with the Jaya algorithm, and compared with ALO and GWO, the Jaya algorithm shows superiority. Also, the HBBBC algorithm was developed to optimize PV/wind/battery HRES to minimize the total cost and meet the load demand (Jung *et al.,* 2020; Murty & Kumar, 2020). The firefly algorithm (FA) was applied to evaluate the optimal PV/WT/FC hybrid systems incorporated with an electrolyzer for hydrogen. An Optimal combination and sizing of a standalone hybrid energy system using a nomadic people optimizer was proposed in 2020 (Semshchikov *et al.,* 2020; Mohammed *et al.,* 2020). In this study, the optimization based on TLBO has been performed for standalone systems, and the obtained results are compared with PSO for a case study purpose.

System Components Modeling

The hybrid renewable energy system comprises photovoltaic (PV) panels, wind turbines, batteries, inverters, etc. Renewable energy sources such as solar and wind have been considered due to their high potential. Each system component or energy source needs to be practically designed and modeled separately to determine the performance of each system component and the overall performance of the hybrid power system. The architecture of the hybrid power system is shown in Figure 1.

Photovoltaic Module

A Photovoltaic (PV) cell is a p-n junction diode with a very large surface area under light illumination. Photovoltaic cells

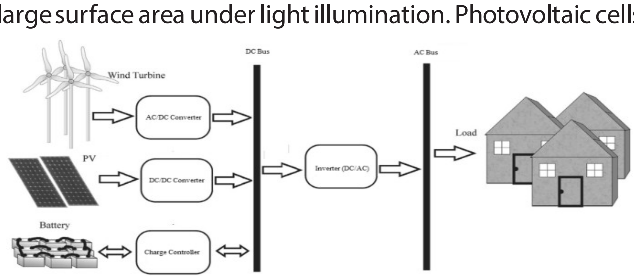

Figure 1: Architecture of hybrid power system

convert solar energy directly into direct current electricity. These cells are also known as solar cells. The output voltage of the cell is approximately 0.7V. In general, each module consists of 36 cells connected in series. The series or parallel connection of the cells depends on the required output voltage and current of the PV module. The power output of the modules depends on geographical locations and weather conditions. The solar panel generates power only during the daytime. The output of the PV module fluctuates due to its dependency on weather conditions.

Photovoltaic Effect

The photovoltaic effect is due to the presence of sunlight. When the sunlight falls on the photons, the electrons in the PV cell get stimulated and produce current when electrons flow from one semiconductor to another semiconductor. To collect the energy of a photon in the form of electrical energy, the potential energy of carriers must be increased or the separation of charge carriers must occur. When there is a difference in energy levels, then the PE of electrons increases and keeps electrons at a higher energy level. A layer of positive and negative charges appears when the p-n junction forms, which is called the depletion region. The presence of an electric field causes a drift current to flow. The rate of minority carrier generation depends on the intensity of light.

Wind Turbine

Wind turbines capture the kinetic energy present in the wind in a rotor mechanically coupled to an electric generator. This rotor is connected to the shaft of the generator which converts mechanical power into electrical power. It is affected by geographical position and height above ground level. Wind speed characteristics and the geographic dispersion of wind farms mainly influence the fluctuation in the output of wind power. The output power of wind turbines doesn't follow any pattern and fluctuates throughout the day.

Inverter Modeling

The hybrid renewable energy system consists of both AC and DC components. A converter converts all components outputs into any form, i.e., AC/DC. An inverter is a power electronic interfacing device for converting DC to AC to supply the load. The inverter rating depends primarily on the peak load demand. The rated capacity of the system inverter used in this study is 800 kW.

Standalone Hybrid Renewable Energy Systems

System configuration

The remote areas are not connected to the central grid and therefore, the power is generated through conventional sources such as diesel generators which lead to high purchase and transportation costs. To overcome this problem, they are exploring renewable energy resources which are efficient and reduce operating costs. Another main reason behind the exploitation of renewable energy sources is global warming due to greenhouse gas emissions from conventional energy sources, but renewable has high installation costs and poses stability and reliability problems in power systems. Standalone HRES is more common in remote areas where it is not accessible to the conventional grid. The power generated from PV and winds is intermittent, so the use of a single source for standalone applications is considered unreliable. Integration of PV and wind establishes a reliable hybrid system for diesel-free generation in standalone applications**.**

The proposed standalone hybrid system comprises PV panels, wind turbines, a battery, and an inverter. The typical configuration of a standalone HRES is shown in Figure 2**.**

Optimization problem formulations

The optimization problem of HRES is to minimize the levelized cost of energy (LCE) subject to various system constraints. The number of PV panels, wind turbines, and batteries is taken as the decision variable that must be optimized to minimize the LCE that covers the load demand. System design and sizing are necessary to get the full benefits of available sources, decrease air pollution, and have higher reliability and stability.

Economic modeling

The hybrid system's total annual cost includes expenses such as investment cost, operation, and maintenance cost, replacement cost, the total cost of the system, and LCE: The ratio of the hybrid power system total cost to the total energy supplied by the system is defined as the LCE. In other words, it is the cost per kilowatt-hour of the energy produced by the hybrid system over the system's lifetime.

Objective function

The hybrid system design problem is formulated as an optimization problem to minimize the Levelized energy cost or per unit cost of electricity subject to reliability and size constraints. In other words, the objective is to provide an optimal design and sizing of HRES to meet consumer demand and ensure the optimal electrical energy cost. Loss of power supply probability, loss of energy expected, dump energy, and unmet load are the parameters to be considered for optimal sizing.

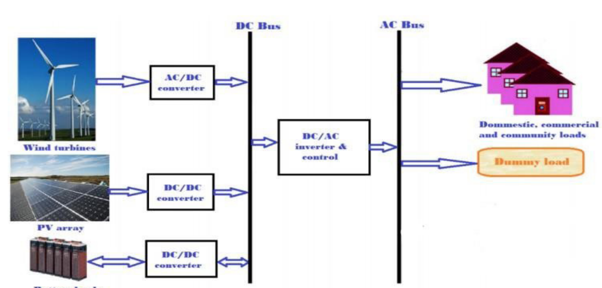

Figure 2: Typical Configuration of the standalone hybrid system

Energy management strategy

An energy management strategy (EMS) is required to maintain the power balance between renewable energy sources and load under variable weather conditions as the uncertainty in renewable energy. Therefore, EMS is incorporated into the hybrid energy system to manage the energy flow among system components. EMS controls the power flow in various conditions to supply the load. It coordinates and controls all actions in a hybrid system. EMS helps in enhancing the use of renewable energy sources and maximizes system efficiency with significant cost benefits**.** Figures 3 & 4 shows the flowchart of the proposed EMS for a standalone system and TLBO optimization followed in this work.

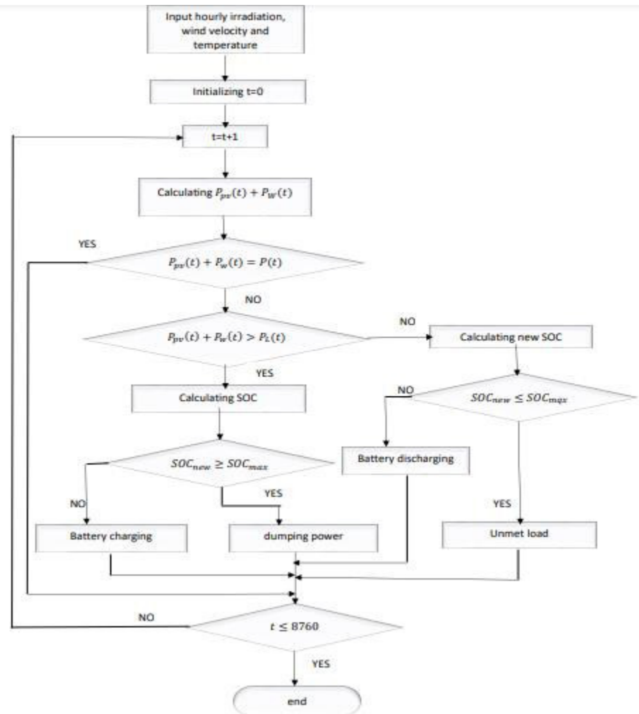

Figure 3: Flowchart of proposed EMS for SA system

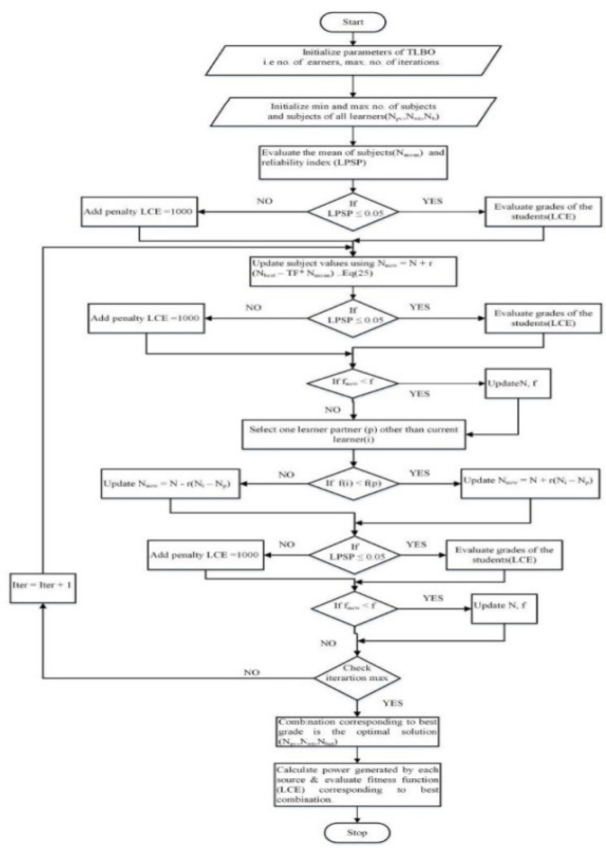

Figure 4: Flowchart of TLBO optimization

Optimization Techniques

Introduction

During the design of the hybrid system, optimization is a challenging task to obtain the optimal system configuration. Optimization is the process of designing the system as effectively as possible. At every instant of time, proper coordination between the powers from each component is required to satisfy the customer's requirement. Therefore, the modeling has been done to obtain an economical solution and converge to the standard optimal solution. The optimization was performed to evaluate the required count of each component and satisfy reliability constraints to ensure the stable operation of the power system with an optimal economic solution. In this study, the HRES is mathematically formulated using meta-heuristic techniques to determine the best economic system size. In this technique, there is an iterative correction of solutions which means the population is updated at every iteration by particular algorithm operators by random search on agents of the present population, whereas the initial population is randomly generated in the search space. The optimal sizing minimizes the LCE and increases investment in renewable plant installation. Optimization techniques must perform effectively to provide a better solution to avoid over-sizing or under-sizing the system as system cost increases due to oversizing and unreliability in power supply due to under-sizing.

Optimization algorithms

Single-objective or multi-objective strategies can employ optimal sizing of the HRES. The optimization problem can be solved using classical techniques such as iterative methods, numerical methods, analytical, probabilistic, graphical construction methods, evolutionary algorithms or metaheuristic techniques, and modern techniques such as artificial and hybrid methods. Metaheuristic techniques are more acceptable and widely used to solve optimization problems because of their ability to find global optima and faster convergence speed than traditional techniques. The sizing of HRES is complex because of the presence of two or more components and the stochastic nature of the resources. The optimal solution is obtained by using differential calculus in classical methods.

Proposed optimization algorithm

TLBO algorithm was inspired by the group of students in a particular class improving their grades by the teacher's influence. The student grades are updated only when the new grade is better than the existing one. This process continues until the convergence is obtained or maximum iterations are reached. The student with the best grade is the solution to the optimization problem. The proposed methodology incorporates TLBO to determine the optimal sizing of the HRES.

The case study

The metrological data, such as solar irradiation, temperature, and wind speed, change depending on the location. This data of a study location can be obtained using an online specialized website. These weather patterns can evaluate the performance and energy production of the HRES.

Location

The location considered for the case study is east Godavari district in Andhra Pradesh (AP), India. The study location is at a latitude of 16.44° and longitude of 81.97713° at a height of 19 m from mean sea level. Metrological data such as solar irradiation, ambient temperature, and wind speed of east Godavari district in AP, India, has been taken from the PVGIS-SARAH radiation database for one year between 01 January 2014 to 31 December 2014.

Solar Potential

The study location has maximum solar radiation of 1065.12 W/m^2. The average irradiation and the temperature of the study area during the mentioned period are 248.6935 W/m^2 and 299.5929 K, respectively. The inclination angle is taken as 8°, and the azimuth angle is 1° as these are the optimum values for the study area. The highest radiation is recorded in March, which is 1065.2 W/m^2, as shown in Figure 5. 29.91°C is the highest temperature recorded in March, and 23.06°C is the lowest temperature recorded in January, as shown in Figure 6.

Wind Potential

The minimum and maximum wind speed of the study area is 0.08 and 14 m/s, respectively. The average wind speed of the study location is 8.0993 m/s. From the Figure, it can be observed that the highest and lowest wind speed is recorded in June and March, respectively. Wind speed with 1-hour resolution over a year is shown in Figure 7.

Load Profile

The optimal design and sizing of the reliable hybrid system depend mainly on the load pattern as it must be met reliably. The load demand shows how energy consumption varies with time and seasons. Depending on the energy requirement and consumption pattern, a period of one year is divided into four seasons. Each season consists of several days corresponding to the months of the season. For each season, a typical day consisting of 24 hours is considered. The load data has been taken from, and this seasonal load is taken for one year with a 1-hour resolution, as shown in Figure 8. The average annual load is 466.787 kW, and the peak load is 779 kW.

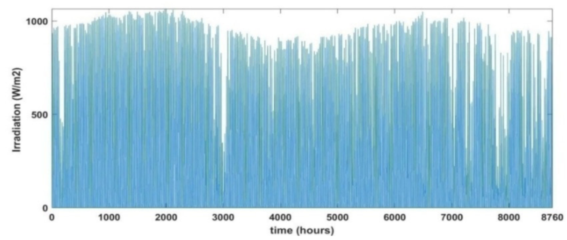

Figure 5: Annual hourly solar radiation

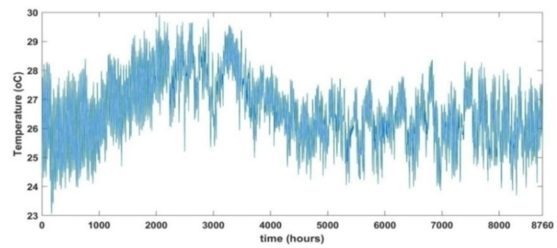

Figure 6: Annual hourly temperature

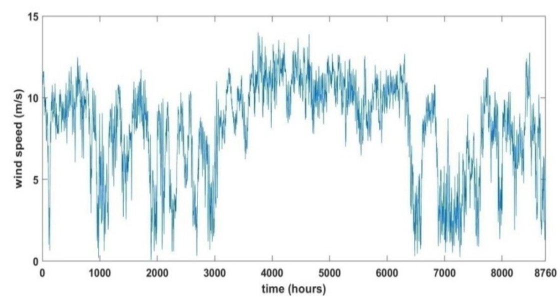

Figure 7: Annual hourly wind speed

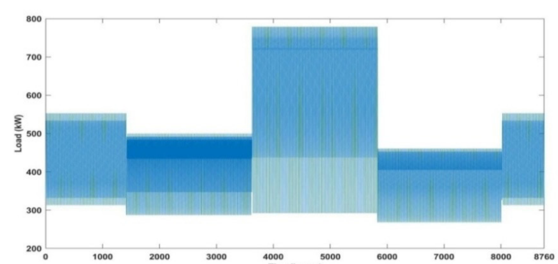

Figure 8: Annual hourly load

System Components and their Description

The technical and economic details of the PV panel, wind turbine, battery bank and inverter used in this study are shown in Table 1. The purchase rate from and sell rate to the grid are 0.325 and 0.163 $/kWh, respectively' are 0.325 and 0.163 $/kWh, respectively.

Table 1: Technical and economical details of system components

Parameter	*Value*
PV PANEL	
Module	MTS355P-144
Maximum power	355 W
Open circuit voltage	47 V
Short circuit current	9.71 A
Module efficiency	17.63%
temperature coefficient of power	-0.38 %/°C
STC	Irradiance – 1000 W/m^2 Cell temperature – 25°C
NOCT	45
Capital cost	$220
Maintenance cost	0
Replacement Cost through the life span of the project	0
Life Cycle	25 years
Wind turbine	
Wind Turbine Manufacturer	Sunning wind power ltd
Rated power	5000 W
Cut-in speed	3 m/s
Cut-out speed	20 m/s
Rated speed	12 m/s
Capital Cost	$3000
Maintenance cost	10 $/year
Replacement cost	$3000
Life Cycle	20 years
Battery	
Battery Type	12 V Mono block-Tubular 61M2001
Nominal capacity	200Ah
Efficiency	≥ 90%
Self-discharge rate in one hour	0.01%
Cmax	2400 Wh
Capital cost	$250
Maintenance cost	0
Replacement Cost	$250
Life Cycle	10 years
Battery Type	12 V Monoblock – Tubular 61M2001
Nominal capacity	200Ah
Efficiency	≥ 90%
Self-discharge rate in one hour	0.01%
Cmax	2400 Wh
Capital cost	$250
Maintenance cost	0
Replacement Cost	$250
Life Cycle	10 years
Inverter	
Rated Power	10000 W
Efficiency	≥ 90%
Capital cost	$3367
Replacement cost	0
Maintenance cost	20 $/year
Life Cycle	25 years
Capital cost	$220
Maintenance cost	0
Replacement Cost through the life span of the project	0
Life Cycle	25 years

Results and Discussion

The formulated optimization method is applied to the HRES design problem is solved using TLBO, and the results obtained are compared with PSO. The solar radiation intensity, wind velocity, and temperature data over a year is considered input data. The population size and the maximum number of iterations are assigned 50 and 100, respectively, which are kept the same for each optimization algorithm.

The study location has high wind speed and solar irradiation. The main objective is dealt with in terms of minimum LCE and maximum reliability for the proposed HRE system. The project lifetime is 20 years, and the annual rate of interest is 6%. To avoid battery over-discharging and overcharging and increase the life of the battery, the minimum and maximum SOCs are between 20 and 90% of the battery capacity, respectively. The reliability constraint LPSP is limited to 0.05 for a standalone system, whereas GPAP and SSER are limited to 0.1, 0.15 respectively, for the grid-connected system.

Standalone System

The optimal solutions using PSO and TLBO are shown in Table 2. It can be observed that all algorithms succeeded in satisfying the load, but the proposed TLBO obtains an economic solution. Therefore, the proposed TLBO algorithm is effective in finding the optimal solution for the standalone hybrid system. Different techno-economical parameters are determined, such as LCE, LPSP, unmet load, total annual cost, and dumped power. The convergence characteristics of different optimization algorithms for the hybrid system.

The power generated by the PV panel over a year with a 1-hour interval is shown in Figure 9. Similarly, the power generated by the wind turbine over a year with 1-hour intervals is shown in Figure 10. Battery SOC over one year is shown in Figure 11, and it can be observed that it is always within minimum and maximum SOC limits. The battery power at each hour is shown in Figure 12. Positive power indicates the battery is in discharge mode, and negative power indicates the battery is in charge mode.

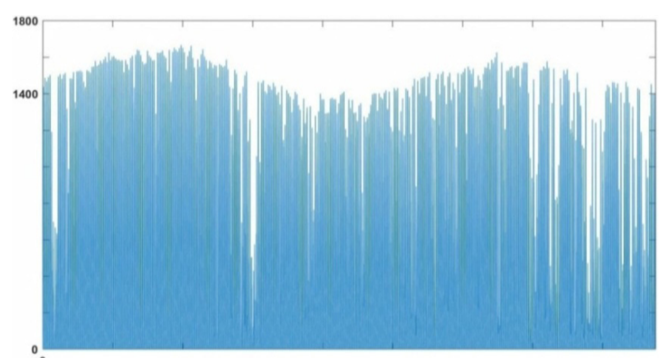

Figure 9: PV panel output power

Table 2: Optimization results for the standalone system by different optimization algorithms

Optimization algorithm	No. of PV panels	No. of wind turbines	No. of batteries	LCE ($/KWh)	LPFT	Annual Cost ($*10^5)	Dumped Power (KW*10^7)
PSO	5110	787	1166	0.2112	0.05	8.2040	1.3702
TLBO	4553	867	1132	0.2104	0.0499	8.1734	1.4716

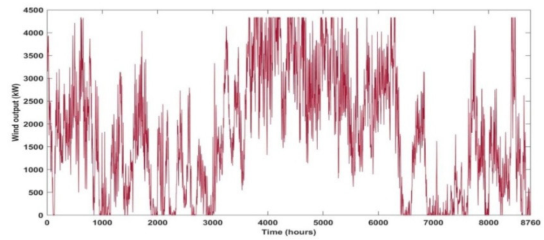

Figure 10: Wind turbine output power

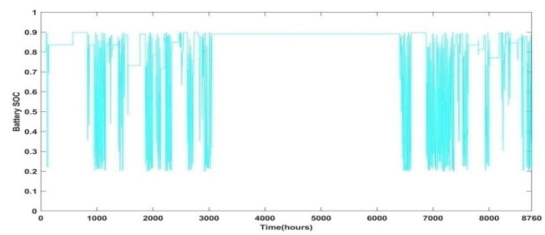

Figure 11: Annual battery SOC

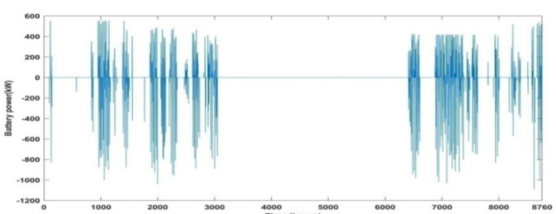

Figure 12: Annual hourly battery power

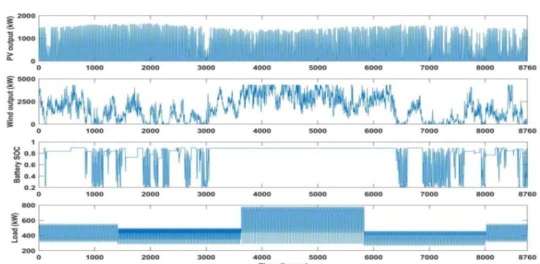

Figure 13: Output power of each component

The bar graph of LCE and LPSP by various optimization algorithms is shown in Figure 13.

Conclusion

This paper proposed the TLBO algorithm to determine the optimal sizing of PV/wind/battery hybrid renewable energy systems. The power electronic converters are connected to integrate system components to the AC bus, whose efficiency is assumed as 100%. The objective of the optimization problem is to determine the optimal sizing of the hybrid renewable energy system by minimizing the LCE while maintaining the system constraints and satisfying the load reliably. The optimization problem was formulated for standalone mode. The reliability indices are LPSP in standalone mode. Annual hourly solar irradiation, temperature, and wind speed data are collected from the PVGIS- SARAH radiation database. Seasonal load variation throughout the year with a 1-hour resolution has been considered for analysis. An EMS has been implemented to manage the power flow among the system components due to variable renewable generation and load demand. The proposed TLBO algorithm's performance has been compared with that of another well-known optimization algorithm, PSO. It provides better solutions in solving an optimization problem that is economical and reliable, and the convergence is obtained in a fewer number of iterations in the case of both standalone and grid-connected systems. The results show that the grid-connected system has low LCE than the standalone system, and it has decreased by 30% in the grid-connected system compared to the standalone system. The proposed approach performs better in designing economical and reliable HRES, which the optimization results can confirm.

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