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Techno-Economic Analysis and Optimal Planning of Hybrid Renewable Energy Systems

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Abstract: The global climate change and rapidly growing population over the decades are creating an enormous burden on conventional energy sources. Global environmental concern is expected for proper planning of renewable sources to increase a positive impact on global warming. The hybrid renewable energy system is proposed for optimum sizing, costing, quality and reliability of supply for the standalone system. This research study also includes a multi-objective optimization of the net present cost, fuel cost, operating cost and cost of energy of the hybrid system. A hybrid renewable energy system has been designed which includes solar, wind, battery and diesel generator for a standalone off-grid. The simulation and techno-economic analysis of case studies indicate that the hybrid system decreases the operating cost according to meteorological conditions. The employed algorithm for power management, results in minimum use of diesel generator and a reduction in fuel cost. Furthermore, the proposed system shows better results when analyzed for loss of power supply probability, renewable factor, carbon content and sensitivity. Thus, the proposed model proves that minimum utilization of diesel generator requires maximum utilization of renewable energy sources, thereby reducing the emission of greenhouse gases and reducing global warming.

Key words: Photovoltaic, wind energy, battery, hybrid system, off-grid, optimization

INTRODUCTION

The rapidly growing population and increased industrialization have a significant role that electricity plays in the economy of the country. The fulfillment of basic need of power supply has been reported in numbers of literature required for the development of the country. The demand for energy keeps increasing progressively and is creating a massive burden on energy sectors. Therefore, it is pre-request to meet daily changing power demand by maximum integration of renewable energy sources (Salehin *et al*., 2016). The technical, economic and environmental benefits of renewable energy sources have increased maximum utilization of PV and wind turbine generator for power generation at all the segments of the power system (Das *et al*., 2017). Many international organizations have set new benchmarks and due to this, several countries have been encouraged to construct micro-grid power generation facilities to provide electricity to remotely located areas (Siddaiah and Saini, 2016).

In India, the total power generation capacity of renewable has reached 310 GW. The power generation comprises of a combination of 69.4% of thermal, 14.8% of renewable energy, 13.9% of hydro and 1.9% of nuclear energy. The renewable generation has achieved 2 level after thermal energy and further expanding its range at a very high rate.

The target of renewable power capacity has increased by the government of India to 175 GW consists of wind, solar, bio and small hydro, 60, 100, 10 and 5 GW, respectively. It is to be accomplished by the year 2022. wind energy capacity generated till 31 March 2018 was 34,046 MW and it took India to the fourth position in the world. Figure 1 shows the source of wise power and renewable power installed capacity taken from the source.

Using hybrid renewable energy systems, Caballero *et al*. (2013) have suggested a technique for the optimal design of grid-connected hybrid PV and wind energy system. Also, Bilil *et al*. (2014) introduced a method of optimization of the yearly cost of renewable energy and reliability indices of the power system using a multi-objective genetic algorithm.

To find out a planning approach (Adefarati and Bansal, 2016), proposed a pseudo dynamic planning scheme for the estimation of the impact of reliability of the distributed system. The referred literature indicates that only a few works have been carried out in the integration of renewable energy sources into the power system to reduce annual cost and study of optimization techniques.

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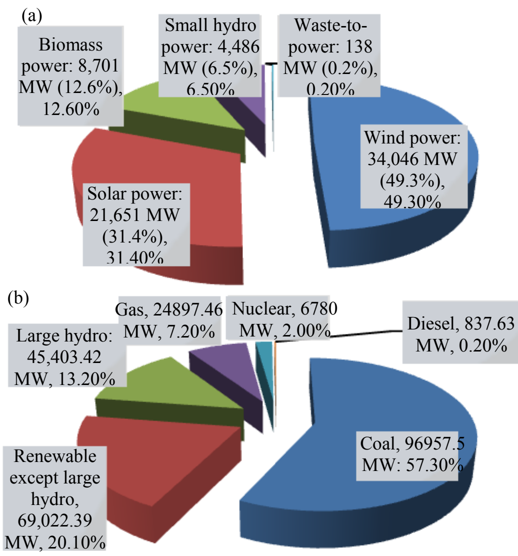

Fig. 1(a, b): Source wise power and renewable power installed capacity 2018

In this point of view, the presented research work provides a techno-economic analysis of hybrid renewable for a standalone off-grid system. The techno-economic analysis is carried out by using MATLAB simulations to determine the multi-objective optimization of Cost of Energy (COE) and Net Present Cost (NPC). The algorithm carried out, here in this research has been very useful for proper implementation of power management strategies which provides maximum utilization of renewable energy sources and minimum use of diesel generator to reduce fuel cost and positive impact on the reduction in net present cost. The results have been shown a multi-objective optimization of cost of energy, loss of power supply probability and minimum fuel cost and reduction in global warming effects by minimizing the emissions of greenhouse gases like CO_2.

The presented research study focuses on the assessment of estimation of residential community load data and metrological data of remotely located sites. Three case studies were carried out for techno-economic analysis of optimally designed integrated system components of hybrid renewable sources. The integrated hybrid renewable system consists of a solar, wind, battery and diesel generator. The main objective of research work is the development of a new viable methodology for off-grid electrification for remote areas. The system is incorporated with diesel generator and storage battery backup to ensure continuity of supply. The remainder of this study is organized as follows. In section 2, hybrid renewable system modeling, multi-objective optimization and techno-economical analysis of hybrid renewable system are introduced. This research provides a Mechanism for Clean Energy Development (MCED) by providing a consistent level of energy security, power balance management strategy and reliability of supply using an integrated mix of complementary nature of hybrid generation system. In section 3, we summarize the techno-economical parameter analysis of three different locations in our country and finally, economic analysis is performed for the planning of hybrid renewable systems.

MATERIALS AND METHODS

System model and preliminaries

Hybrid renewable system design: The arrangement of the hybrid renewable system in case study includes PV and wind system investigated for different array sizes of PV and wind. A hybrid system of power generation for an off-grid system is shown in Fig. 2. If renewable power output is in excess after fulfilling the load demand an excess amount of renewable power is fed to charge batteries. In case renewable hybrid energy insufficient to fulfill demand, stored energy in the battery is used to fulfill the remaining unmet load. A diesel generator is used in power outage conditions and delivers power for most essential loads:

$$\Delta P = P_{RE}(t) - P_{L(t)}$$

where, P_{RE} and $P_{L(t)}$ is total renewable power generated by a combination of PV and wind energy and total variable load demand throughout the day, respectively. If $\Delta P \geq 0$, battery charging state, $BCS_{(t)} \leq BCS_{MAX}$.

The excess power utilizes for charging the bank of battery and process remains to continue till complete charging position:

- If $\Delta P \geq 0$, $BCS_{(t)} \geq BCS_{MAX}$, additional power utilized through the dump load (Deshmukh and Deshmukh, 2008)
- If $\Delta P \leq 0$, grid connection is used
- If $\Delta P < 0$, $BCS_{(min)} \leq BCS_{(t)}$, the shortage energy supplied for back up of battery bank till the condition
- $BCS_{(min)} = BCS_{(t)}$
- If $\Delta P < 0$, $BCS_{(min)} > BCS_{(t)}$, diesel generator will supply deficient power

The following control strategy is utilized in the optimization of a cost function using PSO. Hybrid system components modeling is executed by using MATLAB to determine techno-economic analysis.

Modeling of components in a hybrid energy system

Wind system: The wind Power output (P_{WT}) expression is given by Eq. 1:

$$P_{wt} = \begin{cases} 0_{(t)} \leq_{(cut\,in)} or_{(t)} \geq_{(cut\,out)} \\ Pr_{(t)} \leq \dfrac{(cut\,in)}{r^{-}(cut\,in)}{}_{(cut\,in)} <_{(t)} <_{r} \\ Pr \qquad {}_{r} <_{(t)} <_{(cut\,out)} \end{cases} \tag{1}$$

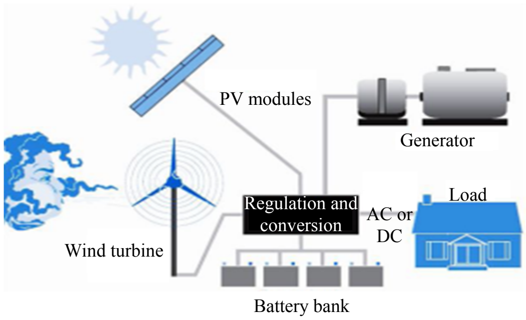

Fig. 2: Hybrid power generation for an off-grid system

Where:
v : Wind speed
P_r : Rated power

Cut in cut out, rated speed and number of a wind turbine are denoted by $V_{cut\ in}$, $V_{cut\text{-}out}$, Vr, N_{wind}, respectively. The overall power of wind turbine is given by Eq. 2:

$$P_{WT(t)} = N_{wind} P_{WT(t)} \quad (2)$$

Photovoltaic system: The power output of the PV system from the radiation of solar at a time 't' is given by:

$$P_{pv(t)} = I(t) * A * \eta_{PV} \quad (3)$$

where, I, A, η_{PV} represents radiation of solar, PV area of the overall PV panels and DC to DC converter efficiency. It is supposed that PV panels have MPPT system. N_{pv} is number of PV panels. The overall output power of PV is given by Eq. 4:

$$P_{pv(t)} = P_{pv} * P_{pv(t)} \quad (4)$$

Diesel generator: The diesel set fuel consumption is given by Eq. 5:

$$Cons_D = B_D * P_N^D + A_D * P_D \quad (5)$$

$$C_{fuel} = P_{fuel} * Cons_D \quad (6)$$

where, rated power P_N^D power output of diesel generator P_D, B_D = 0.0845 (L/kWh) and A_D = 0.246 (L/kWh) are consumption coefficients. Fuel price is denoted as P_{fuel} and Eq. 6 presents hourly diesel fuel cost.

Battery model: The battery bank charging capacity at time 't' can be expressed as:

$$E_{Battery}(t) = E_{Battery}(t\text{-}1) * (1\text{-}\acute{\alpha}) + \left[\left(E_{PV}(t) + E_{wt}(t) - \frac{E_{Load}(t)}{\eta_{inv}}\right] * \eta_{Batt} \quad (7)$$

where symbol $E_{Battery\,(t)}$ and $E_{Battery\,(t\text{-}1)}$, $\acute{\alpha}$, $\dot{\eta}$ inv, E_{Load}, $\dot{\eta}_{Batt}$ are battery bank charge capacities at time t and (t-1), discharge rate hourly, inverter efficiency, demand, charge efficiency, respectively:

$$E_{Battery}(t) = E_{Battery}(t\text{-}1) * (1\text{-}\acute{\alpha}) \left[\left(\frac{E_{Load}(t)}{\eta_{inv}} - E_{pv}(t) + E_{wt}(t)\right]\quad (8)$$

$$C_B = \frac{E_{Load*} A_D}{DoD * \eta_{inv} * \eta_{Batt}} \quad (9)$$

The following control strategy is utilized in the optimization of a cost function using PSO. Hybrid system components modeling is executed by using MATLAB to determine techno-economic analysis.

Multi-objective optimization of hybrid renewable system: Utilization of a single energy source is unreliable due to weather depending condition. Therefore, to meet energy demand and to address unreliability issues, hybrid renewable sources can be utilized which provides the reliability of electric power and provides quality of service. In recent years probabilistic, heuristic and analytical methods have been applicable for optimum sizing of hybrid renewable systems.

Optimization of hybrid renewable system is gaining use of Genetic Algorithm (GA), simulated annealing and Particle Swarm Optimization (PSO) methods for minimizing cost of installation, CO_2 emission and fulfill the daily changing load condition, therefore, evolutionary multi-objective algorithm used to find out most optimum combination of components of hybrid energy system and control strategies to control the power output.

Multi-objective problem is a linear function and satisfies inequality constraints to achieve a single objective for the best suitable solutions as Paratoo front. The hybrid renewable system is integrated with PV generation, wind power generation, battery as a storage backup device and for power quality concerns a diesel generator is provided by using PSO optimization technique. PSO optimization technique uses global optima to find the best solution with high computational efficiency, high-quality solution and shorter calculation time. The parameter selection is based on a population-based algorithm. PSO depends on no of a selection of parameters of acceleration and range of velocities. It has a stable conversion characteristic (Fig. 3).

Multi-objective problem is a linear function and satisfies inequality constraints to achieve a single objective for the best suitable solutions as Paratoo front (Deshmukh and Deshmukh, 2008):

$$\text{Fitness} = \min\left\{\sum_{i=1}^{w} Wi \frac{Fi(x)}{fi\max}\right\} \text{with } Wi \geq 0 \quad (10)$$

And:

$$\sum_{i=1}^{k} Wi = 1$$

And constraints are defined as min gig (x)≥0 for:

$$i \in \{1,...,m\} \tag{11}$$

Analysis of cost: COE is a constant total electricity price per unit of energy and calculated by Eq. 12:

$$COE\left(\frac{\$}{kWh}\right) = \frac{\text{Total net present cost}(\$)}{\sum_{h=1}^{h=8760} \text{Pload}(h)(k_{Wh})} * CRF \tag{12}$$

CRF is the ratio of the present value system component for a provided period of time, taking into consideration its interest rate. It is given by the following expression:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{13}$$

where, i and n denote real interest rate and life period of the system (Fig. 3).

Analysis of system reliability: The Power Supply Loss of Probability (LPSP) is a static parameter which indicates failure of probability either due to less renewable output or unable to fulfill the load demand by a technical failure:

$$LPSP = \frac{\sum P_{Load} - P_{PV} - P_{wind} + P_{Soc\,Min} + P_{Diesel}}{\sum P_{Load}} \tag{14}$$

Renewable factor: The renewable factor is diesel-generated energy as compared to renewable energy. The 100% renewable factor means the ideal system with renewable energy sources only. However, 0% renewable factor refers that diesel generator power supplied is equal to power from renewable energy resources:

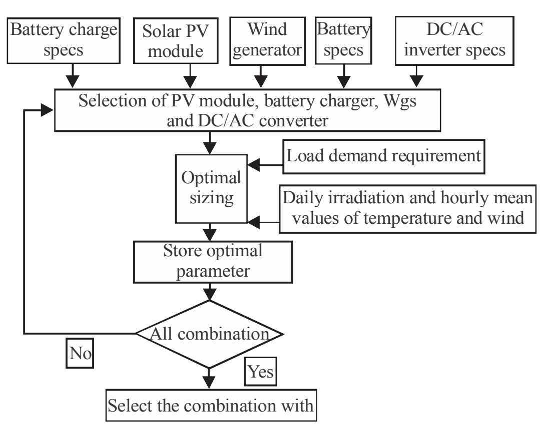

Fig. 3: Optimization methodology flowchart

$$\text{Renewable factor}(\%) = \left(1 - \frac{\sum P_{diesel}}{\sum P_{pv} + \sum P_{wind}} \times 100\right) \tag{15}$$

Renewable resources and component details: Three locations in India, namely, Gujarat, Rajasthan and Tamil Nadu metrological stations are considered for the investigation of cost optimization analysis of hybrid renewable system. A rural areas daily load with a peak of 2-5 kW and of 15-20 number of houses are used the daily load profile is shown in Fig. 4-10 Table 1-3.

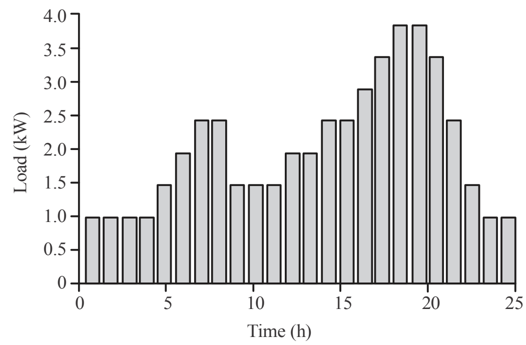

Fig. 4: Load profile

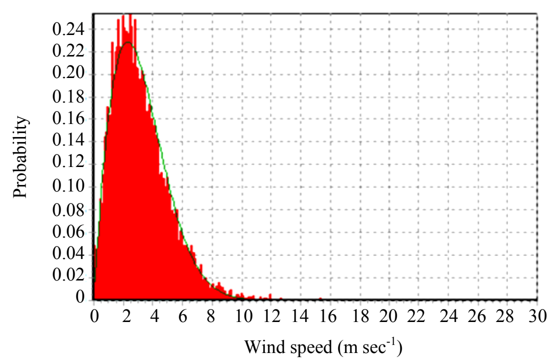

Fig. 5: Wind speed and time

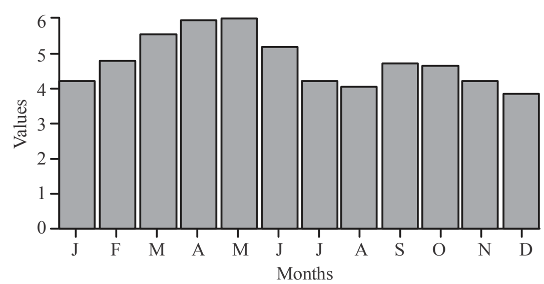

Fig. 6: Solar irradiation and time; monthly average daily irradiation, horiz, surface

Table 1: Average wind speed and solar radiation in selected locations

Location	Average wind speed (m sec^{-1})	Average solar radiation (kWh m^2/d)
Gujarat	3.30	5.32
Rajshthan	2.64	5.00
Tamilnadu	2.92	5.20

Case 1. Location-Gujarat

Table 2: PV panel parameters

PV			Economic parameters (Life: 25 years)		
Input parameters	Units	Values	Input parameters	Unit	Values
PV panel regulator efficiency	%	94%	Rate of discount	%	8.5
Total lifetime	year	25	Rate of interest	%	12
Initial capital cost	Rs/KW	238000	O and M and running cost	%	20
Rated panel power	kWh	7.4	An inflation rate of fuel	%	5

Table 3: Input data for wind, battery and diesel generator system

Wind			Battery			Diesel generator		
Input parameters	Units	Values	Input parameters	Units	Values	Input parameters	Unit	Value
Wind regulator cost	Rs	70000	Battery efficiency	%	85	Rated power	kW	4
Turbine blade dia	m	6.5	Battery lifetime	year	15	lifetime	hours	25000
Turbine swept area	m^2	128.5	Battery initial cost	Rs/kW	19600	Initial capital cost	Rs/kWh	70000
Wind generator efficiency	%	94	Battery rated power	kWh	15			
Wind cut out speed	m sec^{-1}	40	Inverter data					
Wind cut in speed	m sec^{-1}	2.6	Inverter efficiency	%	90			
Wind rated speed	m sec^{-1}	9.0	Inverter lifetime	year	25			
Wind rated generator power	kW	10	Inverter initial cost	Rs/kWh	13500			
Price	Rs/kW	14000						
Project lifetime	Year	25						

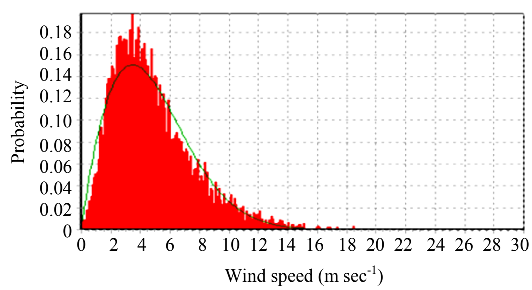

Fig. 7: Wind speed and time (Case 2. Location-Rajasthan)

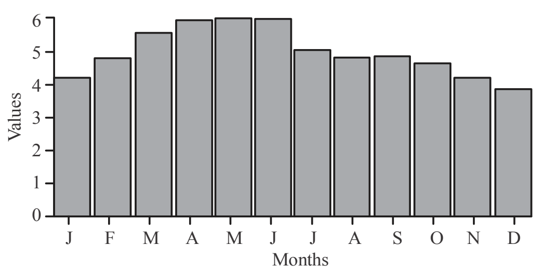

Fig. 8: Solar irradiation and time; monthly average daily irradiation, horiz, surface

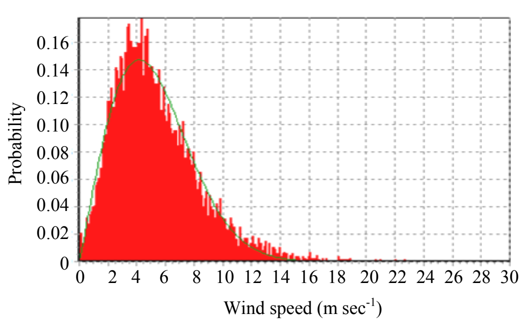

Fig. 9: Wind speed and time (Case 3. location-Tamil Nadu)

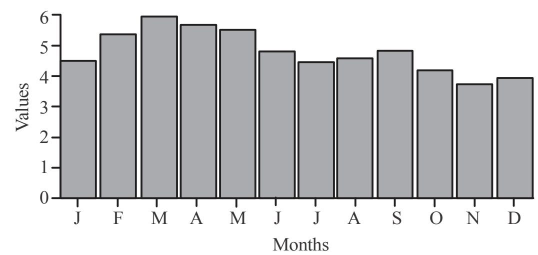

Fig. 10: Solar irradiation and time; monthly average daily irradiation, horiz, surface

RESULTS AND DISCUSSION

Case 1; multi-objective optimization results with fixed boundaries: As per the comparative analysis of three different locations, Tamil Nadu has COE of 6.2 with a renewable factor of 96% as compared to Gujarat and Rajasthan. Also, results show that in Gujarat location have a better renewable factor and less percentage of loss of power supply probability as compared to the other two locations which shown in Table 4.

Case 2; multi-objective optimization with variable boundaries: For variable boundary values of different metrological locations by using multi-objective optimization for finding LPSP and cost of Electricity. Comparative LPSP and COE are shown in Table 5.

Case 3; multi-objective optimization results for hybrid renewable systems: Invariant nature of renewable sources such as solar irradiations, wind speed and temperature of three different metrological stations affects contribution to fulfilling load demands.

Table 4: Comparative location results

Parameter	Gujarat	Rajasthan	Tamil Nadu
No. of iterations	100.0	100.0	100.0
N of particles	100.0	100.0	100.0
N_{PV} panels	5.0	5.0	5.0
No. autonomy days	1.0	1.0	1.0
No. of wind turbines	3.0	3.0	3.0
No. of diesel	1.0	1.0	1.0
No. of houses	20.0	20.0	20.0
LPSP (%)	7.0	9.0	8.0
COE(Rs/KWh)	6.0	6.8	6.2
Renewable factor	96.6	95.0	96.0

Table 5: Comparative optimized result

Location	Gujarat	Rajasthan	Tamil Nadu
No. of iterations	100	100	100
No. of particles	100	100	100
Power of PV panels	60	60	60
Days of autonomy	3	3	3
No. of wind turbines	10	10	10
Power of diesel generator (kW)	1	4	1
LPSP (%)	4%	5 %	3.8%
COE (Rs/kWh)	5.2	5.8	5.4
Renewable factor(%)	98	96	97

Table 6: Cost comparison of the hybrid system

PV	Wind	Diesel	Battery	Converter	Gujarat_gen/fuel cost (Rs)	Rajasthan_gen/fuel cost (Rs)	Tamil Nadu_gen/fuel cost (Rs)
y	y	y	y	y	1646696	1647865	1647413
	y	y	y	y	1667056	1668123	1667325
y		y	y	y	1661345	1661782	1661438
		y	y	y	1681966	1682033	1681984
	y	y			2054379	2054412	2054398
y	y	y			2041368	2041475	2041391
		y			2063873	2063905	2063896
y		y			2050561	2051023	2050763

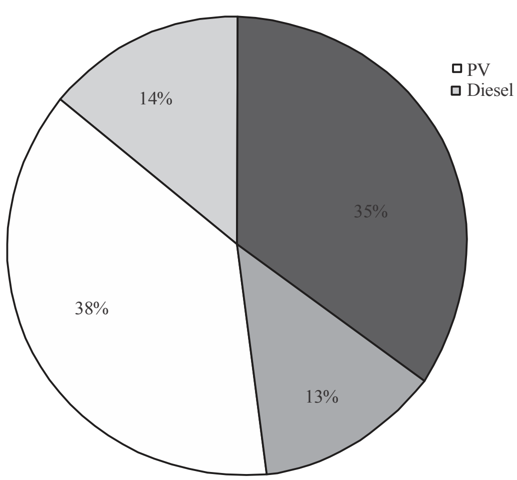

Fig. 11: Power output contribution of PV, wind, battery, diesel for Gujarat metrological location (Location 1: Gujarat)

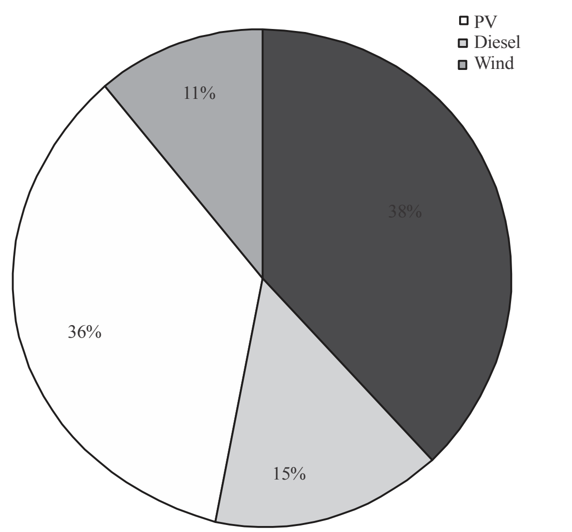

Fig. 12: Power output contribution of power output PV, wind, battery, diesel for Rajasthan location (Location 2: Rajasthan)

These variations also affect the cost of electricity. Wind power output is higher in Tamil Nadu due to higher wind speed in this area as compared to Rajasthan and Gujarat (Fig. 11-13). Table 6 shows a fuel cost comparison of a single renewable source and

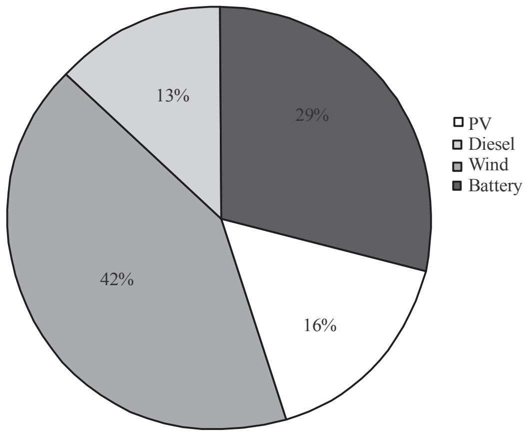

Fig. 13: Power output contribution of power output PV, wind, battery, diesel for Tamil Nadu location (Location 3: Tamil Nadu)

hybrid renewable system for rural electrification. Results shows that fuel cost is minimized by adding hybrid combinations of renewable energy sources.

CONCLUSION

The hybrid combination of renewable sources reduces the cost of energy, LPSP, renewable factor and reduce the emission of greenhouse gases contributing to global warming. The optimized hybrid renewable system enables optimum use of renewable sources and minimizes the use of a diesel system. A liter of diesel consists of 720 g carbon and consumes 1920 g of oxygen to the combustion of CO_2. Hence, the reduction of fuel consumption reduces CO_2 emission. Maximum utilization hybrid renewable energy system directly impacts on greenhouse gases emission and help to reduce global warming challenges. The renewable energy produces about 14.9% total power generation of the country and the optimized system can play a vital role in the reduction of CO_2 emission. Therefore, hybrid energy sources are an excellent alternative as compared to single renewable sources to enhance the living standard of remotely located areas with optimum costing.

The meteorological data of three stations in Gujrat, Rajasthan and Tamil Nadu are tested for this study. Loss of Power Supply Probability (LPSP) and Cost of Electricity (COE) are defined in the objective function. PSO optimization provides optimum sizing and optimum costing and less loss of power supply probability and less renewable factor. Rajasthan has fewer wind resources as compared to Tamil Nadu and Gujarat to fulfill the demand for energy, hence, it is compulsory to add diesel generator. However, increased use of diesel generator causes of less use of renewable factor and thereby increasing the operating cost. As a result, the use of diesel generators is mandatory for such locations to meet the requirement in the load side. The results reflected the higher price of electricity as well as low renewable energy factor. The comparison tables of three stations for COE, LPSP and contribution of PV, wind, battery and diesel are shown.

Thus, proposed method can help overcome some of the technical barriers functioning of micro-grid projects and is very useful in developing an optimum design of energy sources with economic costing for remotely located places in worldwide. As an extension an optimal economic dispatch can be designed for the hybrid renewable energy model in the future.

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