Modelling and analysis of a renewable energy system at various altitudes

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The study proposes a hybrid renewable energy system in India that combines solar and wind energy conversion. The system is designed to meet user load demands at specific locations, reducing electricity usage. The system is optimized using various sizing components, including climatological data, load profile, PV array parameters, wind parameters and battery parameters. The hybrid optimization model for electric renewables is used to design, analyse and optimize the system. The performance of each module, inverter, and battery is examined, considering factors such as energy production, consumption, emissions, initial cost, operating cost, net present cost, and energy cost.

Keywords: Altitude, hybrid optimization model, photovoltaic panels, solar and wind energy.

TO meet its current needs, India is facing daunting challenges to provide adequate energy supply sustainably with competitive prices. By the next 25 years[1], the country will need around 8–10% economic growth in the energy sector to tackle issues in the power sector and meet its human development goals[2,3]. To attain sustained growth, power production capacity must be improved to nearly 800,000 MW from the current 160,000 MW, including all confined plants[4–6].

In this study, a hybrid renewable electric system for the daily load demand of two cities at different altitudes has been developed using HOMER (Hybrid Optimization of Multiple Energy Resources)[7,8]. Using this software, hybrid micro-grid and grid-connected systems that integrate conventionally produced and renewable electricity, storage, and load control may be built cost-effectively and dependably[9].

In the market, various energy system modelling software are available, each having a specific advantage[10–12]. HOMER has simulations (technical, economic and environmental), emission unit factors (CO_2, NO_x, SO_2, CO, unburnt fuel and particulate matter), sizing, operation strategy optimization and life cycle status consideration. This study considers all the existing power technologies separately and in hybrid combinations to find the most cost-effective solutions to energy needs[13–15].

It compares the results from two cities, viz. Chennai and Ooty in Tamil Nadu, India, at different altitudes, for technical and environmental analyses of the best hybrid model[16,17]. The hybrid system considered in this study was proposed using meteorological data for solar radiation and wind speed collected in Chennai and Ooty (Table 1), as well as the pattern of load consumption of a typical household load profile, which was analysed and adequately modelled for optimization[18,19].

Hybrid renewable energy system

The proposed hybrid renewable system (Figure 1) is based on wind and solar power available at the study locations and comprises a photovoltaic (PV), diesel generator and wind turbine system (Figure 1).

In this simulation, we have used a 0.4 kW SW AIR X wind turbine. The specifications of the wind turbine are a rotor diameter of 1.15 m, a rated power of 400 W and tower height of 8.2, 8.8 and 13.7 m. An in-built converter was used in the wind turbine. So, the output was connected directly to a DC bus. Battery and inverter were used for backup. The lifespan of the proposed system is estimated to be 20 years, with a 6% annual interest rate. Table 2 shows the individual ratings and cost of the system components.

Study area

Location selection and climatic conditions play a key role in the type of renewable energy to be deployed in that particular location[20].

Chennai (lat. 13°04′N and long. 80°17′E) is the fourth largest metropolitan city in India, located on the coromandal coast of the Bay of Bengal. Its climate is tropical wet and dry. The coastal location of the city prevents extreme variation in seasonal temperature.

Ooty (lat. 11°24′N and long. 76°44′E), also known as Ootacamund, is one of the most attractive tourist destinations located on the border of the west coast mountains, where the weather is normally cold with an average normal temperature of 12–18°C. In winter, the average temperature is 3–15°C, whereas in summer, between March and May, it is around 15–20°C, not exceeding 23°C (maximum recorded temperature so far).

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Table 1. Monthly solar radiation and wind data

Month	Chennai			Ooty		
	Clearness index	Level of radiation (kWh/m^2/day)	Wind speed	Clearness index	Radiation level (kWh/m^2/day)	Wind speed
January	0.581	4.93	4.87	0.627	5.46	3.65
February	0.636	5.89	4.46	0.63	5.94	3.15
March	0.659	6.64	4.45	0.629	6.39	3.29
April	0.637	6.72	4.49	0.563	5.93	3.23
May	0.577	6.12	4.86	0.509	5.35	3.81
June	0.498	5.24	5.52	0.373	3.87	5.52
July	0.45	4.73	5.30	0.357	3.71	5.31
August	0.457	4.8	5.24	0.39	4.08	5.02
September	0.492	5.01	3.83	0.472	4.83	3.90
October	0.467	4.42	3.56	0.473	4.54	3.00
November	0.471	4.06	4.56	0.526	4.65	3.21
December	0.539	4.42	5.28	0.591	4.99	4.06

Table 2. Cost review

Component	Rating	Cost (INR)
PV panel	1 kW	60,000
Wind turbine	0.55 kW DC	75,000
Generator	2 kW	45,000
Battery	6 V, 225 Ah	6,500
Converter	10 kW	75,000

Table 3. Properties of diesel fuel

Property	Value
Lower heating value	43.2 MJ/kg
Density	820 kg/m^3
Carbon content	88%
Sulphur content	0.33%

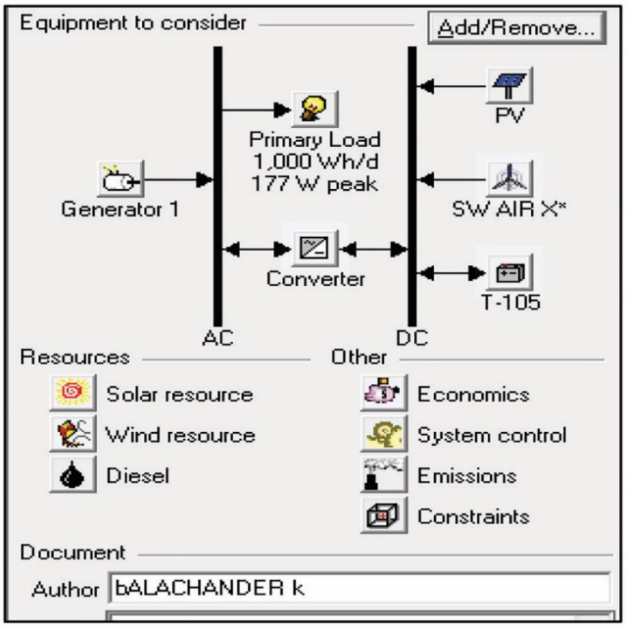


Figure 1. Proposed hybrid energy system.

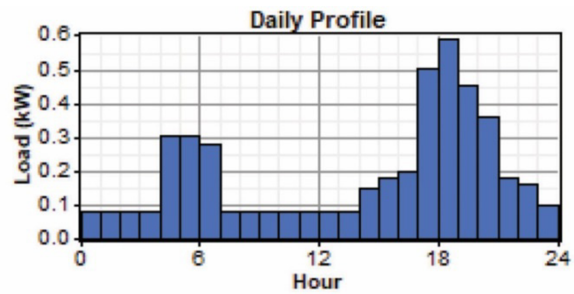


Figure 2. Daily load profile (24 h).

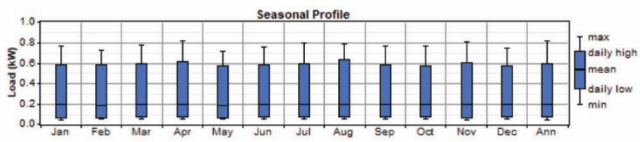


Figure 3. Seasonal load profile (January to December).

Load

For load analysis at the two locations, a typical electrical load system for a single residence was used. The overall electrical load demand was 1000 Wh/day. Figure 2 depicts the daily load, and Figure 3 describes the seasonal load profile with a peak of 177 W.

Resources and system components

In HOMER modelling, any user-specified information provided outside the system, forms the resources. The renewable energy system available at a particular location, which considerably differs from other specified locations, is vital in modelling a hybrid system[21–23]. Diesel generator and battery sources serve as backup. Table 3 lists the properties of diesel fuel.

Solar and wind power, both naturally available and intermittent, combine to develop an energy-efficient hybrid system.

HOMER modelling

In HOMER modelling, the annualized cost of producing electricity divided by the total useable electric energy production gives the cost of energy (CoE)[24].

$$\text{CoE} = \frac{[C_{\text{ann,total}}]}{[E_{\text{pry,AC}} + E_{\text{pry,DC}} + E_{\text{grid,sales}}]}, \quad (1)$$

where $C_{\text{ann,tot}}$ is the total annualized cost (€/y), $E_{\text{pry,AC}}$ the AC primary load served (kWh/yr), $E_{\text{pry,DC}}$ the DC primary load served (kWh/yr) and $E_{\text{grid,sales}}$ is the total grid sales (kWh/yr)[25–27].

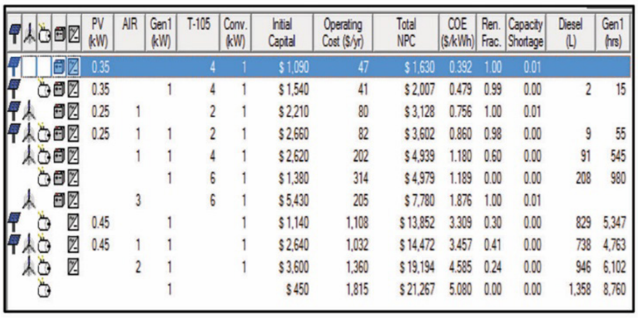
HOMER's major economic output is the total net present cost (NPC). The total NPC of a system is the present value of all the costs it incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime[28–30]. All systems are ranked to determine their NPC, and all other economic outputs are calculated to determine the same[31,32]. The total NPC is calculated by HOMER using the equation[33]

$$C_{\text{npc}} = [C_{\text{ann,total}}]/[\text{CRF}(i, R_{\text{proj}})], \quad (2)$$

where CRF is the capital recovery factor, i the interest rate (%) and R_{proj} is the project lifetime (years)[34].

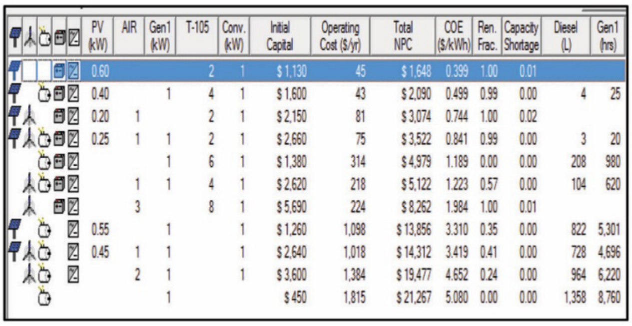
CRF is given by equation

$$\text{CRF} = \frac{i(i+1)R_{\text{proj}}}{(i+1)R_{\text{proj}} - 1}. \quad (3)$$



	PV (kW)	AIR	Gen1 (kW)	T-105	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen1 (hrs)
	0.35			4	1	$ 1,090	47	$ 1,630	0.392	1.00	0.01		
	0.35		1	4	1	$ 1,540	41	$ 2,007	0.479	0.99	0.00	2	15
	0.25	1		2	1	$ 2,210	80	$ 3,128	0.756	1.00	0.01		
	0.25	1	1	2	1	$ 2,660	82	$ 3,602	0.860	0.98	0.00	9	55
		1	1	4	1	$ 2,620	202	$ 4,939	1.180	0.60	0.00	91	545
			1	6	1	$ 1,380	314	$ 4,979	1.189	0.00	0.00	208	980
		3		6	1	$ 5,430	205	$ 7,780	1.876	1.00	0.01		
	0.45		1		1	$ 1,140	1,108	$ 13,852	3.309	0.30	0.00	829	5,347
	0.45	1	1		1	$ 2,640	1,032	$ 14,472	3.457	0.41	0.00	738	4,763
		2	1		1	$ 3,600	1,360	$ 19,194	4.585	0.24	0.00	946	6,102
			1			$ 450	1,815	$ 21,267	5.080	0.00	0.00	1,358	8,760

Figure 4. Optimization results of Chennai (technical).



	PV (kW)	AIR	Gen1 (kW)	T-105	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen1 (hrs)
	0.60			2	1	$ 1,130	45	$ 1,648	0.399	1.00	0.01		
	0.40		1	4	1	$ 1,600	43	$ 2,090	0.499	0.99	0.00	4	25
	0.20	1		2	1	$ 2,150	81	$ 3,074	0.744	1.00	0.02		
	0.25	1	1	2	1	$ 2,660	75	$ 3,522	0.841	0.99	0.00	3	20
			1	6	1	$ 1,380	314	$ 4,979	1.189	0.00	0.00	208	980
		1	1	4	1	$ 2,620	218	$ 5,122	1.223	0.57	0.00	104	620
		3		8	1	$ 5,690	224	$ 8,262	1.984	1.00	0.01		
	0.55		1		1	$ 1,260	1,098	$ 13,856	3.310	0.35	0.00	822	5,301
	0.45	1	1		1	$ 2,640	1,018	$ 14,312	3.419	0.41	0.00	728	4,696
		2	1		1	$ 3,600	1,384	$ 19,477	4.652	0.24	0.00	964	6,220
			1			$ 450	1,815	$ 21,267	5.080	0.00	0.00	1,358	8,760

Figure 5. Optimization results of Ooty (technical).

The analysis was done based on the technical properties and life cycle cost (LCC) of the system[35]. LCC comprises the initial capital cost, cost of installation and operation costs over the lifespan of the system.

Optimization results

With HOMER optimization simulation, multiple combinations of hybrid systems with PV, wind turbines, generators, batteries and converters were obtained for the study locations in India[36,37]. Figures 4 and 5 show the optimum results for Chennai and Ooty achieved by HOMER respectively. The total NPC is the primary selection tool in HOMER. The total NPC of all potential hybrid systems is presented here in ascending order[38]. From the optimization results, HOMER shows the top-ranked system configurations according to NPC (i.e. first row in the optimization results window Figures 4 and 5). The suggested best optimization results (Chennai and Ooty) are shown in Tables 4 and 5 describe the simulation results of electrical parameters. Table 6 provides details of the initial investment and CoE[39].

Table 4 summarizes the best optimal solutions for technical and economic aspects of all hybrid system configurations from the optimization procedure for both study locations, viz. Chennai and Ooty.

Figure 6 is a graphical representation of the best-optimized solutions for Chennai and Ooty.

Table 4. Best optimization results (Chennai and Ooty)

Component	Rating	Chennai	Ooty
PV panel	0.35 kW	1	1
Battery	6 V, 225 Ah	4	2
Inverter	1 kW	1	1
Rectifier	0.75 kW	1	1

Table 5. Simulation results – electrical

Location	Chennai	Ooty
Production (KWh/yr) – (PV array)	547	942
Consumption (KWh/yr)	363	360
Excess electricity (kWh/yr)	93.3	494
Unmet electric load (kWh/yr)	2.05	5.02
Capacity shortage (kWh/yr)	2.08	5.11
Renewable fraction	1	1.4

Table 6. Simulation results – economical

Location	Initial capital (INR)	Operating cost (INR/yr)	Total net present cost (NPC) (INR)	Cost of energy (CoE) (INR/kWh)
Chennai	59,950	2,585	89,650	21.56
Ooty	62,150	2,475	90,640	21.94

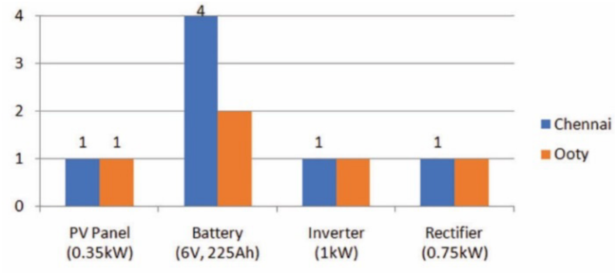


Figure 6. Graphical representation of best optimized solutions for Chennai and Ooty.

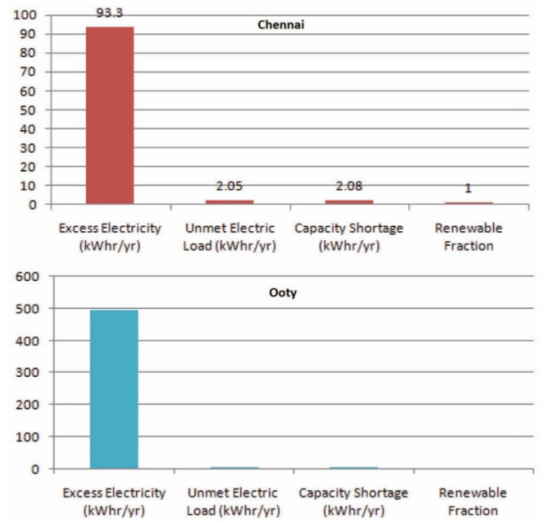


Figure 7. Graphical representation of simulation results – electrical.

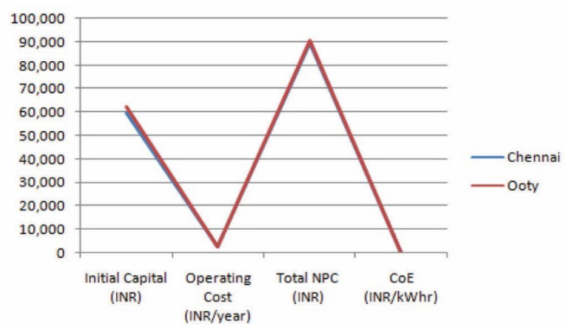


Figure 8. Cost analysis.

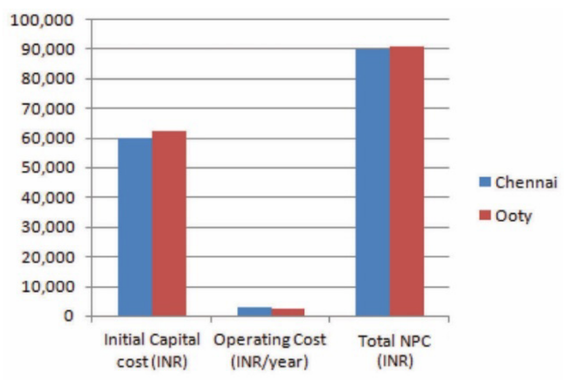


Figure 9. Cost comparison for Chennai and Ooty.

Simulation results

The optimization and sensitivity analysis of different components and resources was performed using HOMER based on technical and cost parameters, system constraints and sensitivity data over a range of exogenous variables. In the proposed model, a comparative analysis of the results is obtained for the two locations of the load condition of 1000 Wh/day, 177 W peak.

Tables 5 and 6 show that the electricity efficiency and CoE for the HOMER-recommended PV system with battery backup components are suitable to feed the power of AC single-user residential loads in both cities with a rating of 1000 Wh/day, 177 W peak throughout the year. Figure 7 is a graphical representation of the simulation results of electrical parameters. Figure 8 shows the cost analysis, and Figure 9 shows the cost comparisons for Chennai and Ooty.

Conclusion

The proposed optimized model is a possible solution to overcome the essential energy supply problem in Chennai and Ooty. Although the initial investment is relatively high, it provides electricity production at a low cost. The proposed system is the best model for AC load, and the CoE for both locations studied is almost similar with slight variation, i.e. 21.56 INR/kWh for Chennai and 21.94 INR/kWh for Ooty. There is a considerable market for standalone PV renewable energy systems for both locations in remote and highly populated areas. Installing hybrid systems in the study regions will result in a pollution-free environment with low maintenance costs.

Conflict of interest: The authors declare that they have no competing interests.

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