Design of wind-PV based hybrid standalone energy systems for three sites in central India

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ABSTRACT

The aim of this study is to design renewable energy based hybrid standalone systems to supply two rural and one urban sites of Madhya Pradesh state in India. These locations characterize different load profiles and wind and solar resources. The wind speed data measured at these sites and solar radiation data obtained from NASA are utilized to carry out the analyses of these systems using HOMER Pro. These systems are designed to cater for domestic electricity demand of one rural site, domestic and agricultural demand of another rural site and residential load demand of staff quarters of an urban institution. The pattern of power consumption of the loads considered for these sites is suitably modelled and different combinations of hybrid systems are simulated to identify the optimal system based on least life cycle cost. Results show that the most economically feasible system to supply the load demand of the three sites is comprised of different combinations of renewable energy sources viz. only wind, wind- solar and only solar based systems. Each design also includes diesel generator back up and battery storage to ensure reliability of power supply and a converter to maintain the energy flow between ac and dc components.

Keywords: Weibull shape factor, Probability Distribution function, Solar radiation, Net present cost, Hybrid energy systems

1. INTRODUCTION

Energy is vital for the progress of any nation. The fast depletion of fossil fuels and the environmental concern worldwide has necessitated the use of clean and renewable forms of energy sources [1]. India is a developing nation with a huge population and its energy demand is increasing at a high rate. More than 30000 villages in India are un-electrified and over 200 million people do not have access to electricity [2]. The cost of installing transmission and distribution lines to remote un-electrified areas is very high. Moreover, it also results in high transmission and distribution losses. Standalone systems based on renewable-based energy offer a cost effective and environment friendly alternative to grid extensions in remote areas [3, 4]. Renewable energy based off grid systems are also attractive options for supplying load demands of some urban establishments [5]. The green energy generated from these systems helps to reduce the pollution, which has become a cause of concern especially in large cities in India. A number of combinations, based on various alternative energy sources and energy storage devices have been used in the literature to design standalone hybrid systems to supply load demands for different applications in the world, which include solar, wind, micro hydro, fuel cell, diesel and battery based systems [2–9]. However, wind power and photovoltaic driven stand-alone systems are the most promising technologies for generating clean and sustainable energy and are suitable for electrification requirements of remote rural areas and isolated alternative energy systems for urban applications [10–12]. India is blessed with a good wind and solar energy potential which can be exploited in these areas. However, wind and solar energy are highly variable in nature and the systems based on wind or solar power alone can result in poor reliability of these systems. A hybrid energy system comprises of more than one power source so that the deficit of power from one source can be compensated by the other sources. Hybrid systems based on wind and photo voltaic (PV) energy combine the complementary characteristics of wind and solar sources, thus enhance the system reliability [13–15].

Madhya Pradesh (MP), a state in central India is blessed with a good solar potential and has a medium wind resource potential [16, 17]. A number of villages in MP are un-electrified [2]. Moreover, the reliability of supply in grid connected areas in MP is not good in rural and urban areas both, as supply shut down rate is high due to load shedding, maintenance and faults. The wind and solar energy potential is not exploited yet in un-electrified remote areas of MP. Solar and wind potential can also be harnessed in urban areas of the state by grid connected or small standalone energy systems. In this study hybrid wind-solar off grid energy systems have been designed for two remote rural areas and one urban location of MP. One rural site selected for this study is a small village Purtala situated in south of MP state, with only 65 households [2]. The village is covered under the rural electrification scheme of government of India [18] in which it is proposed to electrify this village by erecting a low-tension line up to this village to release connections

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to 26 houses. In this study a hybrid wind-PV standalone system is proposed as an alternative to grid extension to supply the domestic load of 25 households of this village. A standalone wind solar based system to supply the residential and agricultural load of another small village Mandawa, in Madhya Pradesh is also proposed here. This system is designed to fulfil the domestic electricity demand of nearly all the village and provide electricity for irrigation of the farms. Additionally, a system including biomass as energy source is also considered here for optimization. Biomass is a more reliable source of renewable energy which is free of fluctuations as compared to solar and wind source. However, it is not a preferred renewable energy source till now because of the challenges involved in ensuring a reliable biomass supply chain. This is due to large change in its physical properties and uncertainty in availability due to dependence on cropping patterns. As the Indian economy is mainly based on agriculture, the Ministry of New and Renewable Energy (MNRE), government of India [27] has realized the potential of biomass energy and has initiated a number of programmes for the promotion of efficient use of biomass energy.

The third off grid wind-PV based system in this study is designed to supply the residential sector of an urban educational institute of Bhopal. This institute, Maulana Azad National Institute of Technology (MANIT) situated in capital of the state has around 350 staff quarters which constitutes 15-20 % of the total electricity bill of the campus. The proposed system will help in making the residential sector self-sufficient in energy, ensuring reliability of supply and reduction in emissions. Wind monitoring stations are installed in Purtala and Mandwa and the monthly average wind speeds available from the centre for wind energy technology [19] are used in this study. The Centre of Wind Energy Technology (CWET) is an autonomous organization that was setup under MNRE, India to serve as a technical focal point for development of wind power in India. The 10-minute averages of wind speed values recorded at the urban institute MANIT are utilized to design the third system. The solar radiation data for these sites based on latitude and longitude of the sites as downloaded by HOMER via internet have been used here. As the wind and solar energy are intermittent they may not be able to match the load variation on a 24-hour basis throughout the year. Therefore, diesel generators and battery banks are also included in these systems to ensure system reliability. The optimum combinations of systems based on net present cost for each case are identified using Homer Pro software. Homer Pro by the US National Renewable Energy Laboratory (NREL) is a powerful tool for optimizing hybrid renewable energy system designs.

2. DESCRIPTION OF THE SITES

2.1 Purtala

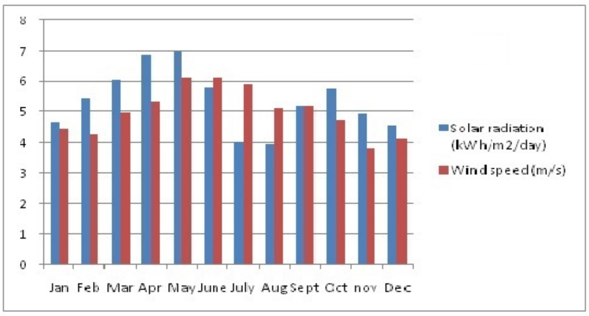
Purtala is a small village located in Tamia block of Chhindwara district in the south of Madhya Pradesh state. The village has only 65 households with a small population of 351 [2]. The village is not electrified and is covered under rural electrification scheme ‘Deendayal Upadhyay gram jyoti yojana’ of the government of India [18]. It is proposed to erect 0.85 km, 11 kilovolt line and 0.45 km low tension line and install one 25 KVA transformer to release 26 household connections in this scheme. A wind monitoring station is installed in Purtala and the wind data for the site recorded at 30 and 50 m height is available from Centre for Wind Energy Technology, India [19]. The annual wind speed average at 30 m height for this site is 4.46 m/s and is 5.02 m/s at 50 m measurement height. The residents of the village belong to very low socio-economic status and around 50 % of the population works as farmers and labourers [2]. The proposed system is designed to supply the basic domestic electricity requirement of 25 households of the village.

2.2 Mandawa

Mandwa is also a remote rural village of Madhya Pradesh. It is located in Jhiranya Tehsil, of Khargone district. This village has 136 households with a population of 625 [2]. A wind monitoring station is installed in Mandawa and the wind data for the site recorded at 10, 30 and 50 m height is available from CWET. The annual wind speed average at 10 m height for this site is 3.63 m/s, is 4.48 m/s at 30 m and is 5.12 m/s at 50 m measurement height. The residents of this village are also of poor economic status and are engaged in minor works [2] and agricultural work. It is proposed to design a renewable energy based system for the village to supply the electricity demand for daily needs of 130 houses and also, for the irrigation of farms.

2.3 MANIT

MANIT is a premier technical government institute of India. It is situated in the middle of Bhopal city which is the capital of Madhya Pradesh. The institute is situated in a comparatively open, widespread, hilly area. The institute has a large campus encompassing several blocks for educational, administrative use and other needs. The institute has many residential blocks which include hostels for students, guest houses and quarters for faculty and supporting staff. It is proposed to install an off-grid hybrid renewable energy based system to supply the load demand of 300 staff quarters of the institute.



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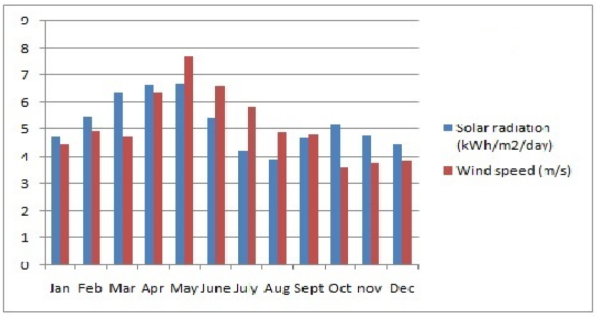

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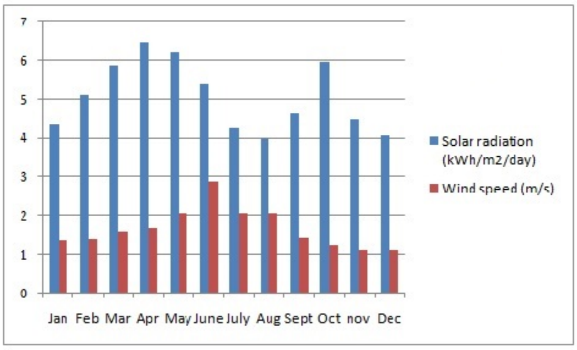


(c)

Fig.1: *Wind and solar resource- Yearly variation in (a)Purtala, (b) Mandawa (c) MANIT, Bhopal.*

3. RESOURCES

3.1 Wind resource

The monthly averages of wind speeds recorded at 50 m heights in Purtala (April 2005–March 2006) and Mandawa (December 2007–November 2008) available from CWET have been used as input to Homer Pro, to synthesize time series data for analyses of these two rural sites. This data created by Homer Pro, is able to characterize the actual data with sufficient accuracy. The 10-minute averages of wind speed measured at a height of 11.5 m measured by a 3-cup anemometer are obtained from the third site MANIT. The meteorological mast is installed on the terrace of the institute. The institute is situated on a plateau in a comparatively open area in the middle of the city. The time series dataset covers a period of one year (July 2013- Jun 2014). The wind speed was recorded by NRG systems Symphonie PLUS3 data logger. In addition to wind speed averages, four more inputs viz. the Weibull shape factor k, the autocorrelation factor, the diurnal pattern strength and the hour of peak wind speed are also required to generate the artificial data. In this study the power law profile is used to describe the variation of wind speed with height. The power law exponent for the two rural sites is taken to be equal to 0.14 as given in [17] for these locations. This default value is also used for the third site. The variation of wind speed in a certain region, over a period of time is represented by a probability distribution function (PDF). A number of PDFs have been proposed by various researchers to describe the wind speed data of different locations [20–23]. In Homer Pro, the wind speed data is represented by a Weibull probability distribution function (PDF) which is the most widely used and accepted distribution worldwide [22]. Default values of Weibull shape factor k=2, autocorrelation factor=0, diurnal pattern strength=0.25 and hour of peak wind speed=15.00 are used as inputs for all the sites considered here.

3.2 Solar resource

As the measured solar radiation at these sites is not available, monthly average solar radiations based on latitude and longitude of the sites as downloaded by Homer via internet have been used. From these monthly average values, Homer synthesizes realistic hourly solar radiation data.

The geographical features and solar and wind resource details of the three sites are given in Table 1. Fig. 1 shows the monthly plot of solar and wind resource for the three selected sites. It can be seen, that maximum solar radiation is obtained in the months of May and June due to the summer season in central India and lowest is obtained in July and August due to the rainy season. Good solar radiation is also received in October. Maximum average wind speed is encountered in Purtala in May and June (monsoons) and the minimum average wind speed is recorded in November. The highest average wind speed is recorded in June in Manadwa village whereas a lowest average occurs in October. A wind speed average above 3.5 m/s is recorded in both the villages throughout the year. The plot for MANIT shows that a good solar resource is available in the institute however the wind speed recorded is always below 3 m/s at the measurement height of 11.5 m. It can be said that poor wind speed is encountered at this site and the wind speed will seldom go above 3 m/s even if the wind turbine is installed at a higher height.

4. LOAD PROFILE

An important consideration in design of any power generating system is load [24]. The load profiles of the

Table 1: *Geographical features and solar and wind resources of the three sites dentification.*

Name of site	Geographical features of site			Wind speed data description		Solar radiation data (kWh/m^2/day)
	Latitude	Longitude	Altitude (m)	Measurement (m)	Yearly average height (m/s)	
Purtala	22° 32' N	78° 44' E	787	50	5.02	5.04
Mandawa	21° 27.9' N	75° 56.44' E	181	50	5.12	5.21
MANIT, Bhopal	23.21° N	77.41° E	568	11.5	1.6721	4.99

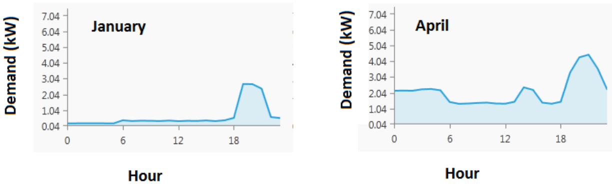


Fig.2: *Hourly load profile for winter (January) and summer (April) months for Purtala.*

three selected locations are discussed here.

4.1 Purtala

The energy system for Purtala is designed to cater to the power needs of 25 houses of the city. A hypothetical load which represents the power consumption pattern for typical rural households of central India is considered for this study. A rural house needs a small quantity of electrical energy. It generally requires electricity for lighting, cooling, entertainment and mobile charging etc. A load of two ceiling fans (40 W each), two CFLs (20 W each), one CFL (8 W) and one TV (40 W) for each house is considered here. An additional load of 15 W for other requirements (from 6 am to 12 pm) is also considered. The temperature in central India is high in summers. Fans are essential for cooling, in the months of April, May and June. It is assumed that more fans are used in the evening and night as around half of the population works outdoors from morning to evening. There is sufficient daylight up to late evenings in summers and no lights are required up to 7 pm. Daily average load profile of summers and other months of the year, is shown in Fig. 2.

4.2 Mandawa

Mandawa is also a rural village in Madhya Pradesh. The proposed system for this village is designed to fulfil the electricity need of almost all the houses of the village and agricultural needs of 50 small farms. The power consumption pattern of a house of this village is assumed to be similar to Purtala. Electricity for agriculture is mostly required for irrigation of farms. Generally, two types of crops are grown in this area. Kharif crops which includes rice crop are grown from July to October. However, irrigation in this season is mostly dependent on monsoon and monsoon rains in central India are good from mid-June to August. Also, irrigation is not required when the crop is ready. Another crop rabi is sown in October. The rabi crop grown in this area mainly includes wheat and gram. It is assumed that a total of 3 tube wells having 2 kW pump each and 8 dug wells with a 3 kW pump each are sufficient for irrigation needs of the farms of this village. The agricultural electricity demand is high in rabi season and low in kharif season as kharif is grown during monsoons and much watering of crops is not required. The hypothetical agriculture load demand considered here, takes into account the typical hourly and monthly pattern of irrigation of this area.

4.3 MANIT

The load demand of 300 staff quarters of the institute is considered for design of the energy system in this study. The residents of the quarters are employees of the institute belonging mostly to middle socio-economic status. With one staff quarter having 2 to 3 bedrooms, one hall kitchen, 2 latrines and bathrooms, veranda etc. Electricity is required for lighting, cooling heating, cooking and entertainment etc. Tube lights, CFLs, refrigerators, fans, coolers, television sets and water heaters are used by almost every family. Computers, air conditioners, washing machines and microwaves and induction heaters for cooking etc are also used by many residents here. Load is high in summer months due to requirement of cooling. In winters water heaters (morning) and room heaters in a few houses are used for limited duration. Load is high in evening due to lighting. Electricity demand in the afternoon is not much as most of the employees and their family members leave the houses for their respective works.

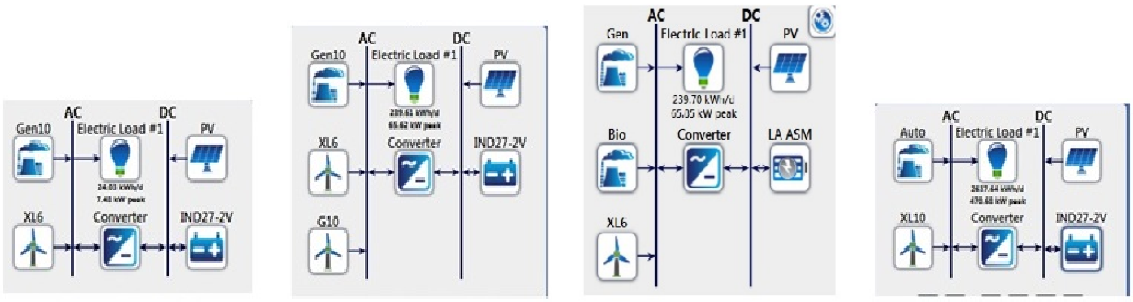
The load demands of the three sites are summarized in Table 2.

5. SYSTEM DESCRIPTION AND COMPONENTS

The hybrid systems for all the sites simulate different combinations of components selected for the respective sites. The system simulated for Purtala consists of a 6 kW Bergey Excel wind turbine genera-

Table 2: *Load Profile of the three sites.*

Name of site	Load Profile		
	Type of load	Peak load (kW)	Average energy consumption (kWh/day)
Purtala	25 Rural household	7.48	24.03
Mandawa	130 Rural households and agriculture	65.62	239.61
MANIT, Bhopal	Urban residential-300 houses	470.68	2637.6



(a) (b) (c) (d)

Fig.3: *Schematics of hybrid- standalone systems for (a) Purtala (b) Mandawa 1 (c) Mandawa 2 (d) MANIT, Bhopal*

tor (WTG), PV arrays, and battery as power sources and power converter to match ac and dc energy.

The load of Mandawa in comparison to Purtala is higher. Also, the wind resource at this site is good. To take in to account these factors the system design (Mandawa 1) for this village includes a Generic 10 kW WTG in addition to the above components considered for Purtala for optimization. Village Mandawa is located in Khargone district of the state. This village and the surrounding villages are situated in the basin of Narmada river and in addition to monsoon the region is irrigated well throughout the year by the water available from the river. Hence, additionally a system including biomass generation is also designed for this village. It is proposed to collect the waste from crops of this village and nearby villages to generate power. This system (Mandawa 2) includes PV, wind turbine generator and bio generator as energy sources. The biofuel mainly comprising of rice husk is available when the kharif crops are harvested. Rice husk contains about 30–50 % of organic carbon and has a high heat value of 13–16 MJ per kg.

The peak load and energy demand of the third site MANIT is high. As seen earlier the wind speeds at this site are very low, hence a Bergey Excel 10 wind turbine is used for optimization. This turbine has a lower cut-in speed compared to other available options. The generator included in the system is autosizing, which automatically sizes itself to meet the load demand. It also adjusts its fuel curve to match its sizes.

Schematics of the systems for these three sites are shown in Fig. 3. The load demand is fulfilled by the renewable energy sources (PV and WTG) during normal operation. The diesel generator is used as backup when the generation from wind and PV is not sufficient to supply the load. When the generation exceeds the load demand the excess energy is stored in the battery. PV arrays without a tracking system are used for simulation in these systems. A slope equal to latitudes of the location is selected to maximize the energy production for these fixed- slope PV system. Diesel generators are included in all the three systems to ensure reliability of power supply. The generators will supply the load when generation from wind and PV is not sufficient to fulfil the load demand. Battery banks are used for storage in the systems. When the generation exceeds the load demand the excess energy is stored in the battery. The cycle charging dispatch strategy is used here in which the generator operates with full capacity with surplus power going to charge the battery bank. A set point state of charge of 80% is applied so that once the system starts to charge the battery bank it will not stop until the battery bank charging reaches this set point. This setting reduces the amount of time spent by the battery at a low state of charge. It also reduces the number of generator starts and the number of battery charge-discharge cycles occurring in a year. As the components used in systems are of both ac and dc types, it is necessary to include a power converter in the designs to maintain the flow of energy between ac and dc components.

Table 3: *Components considered for optimization for the three sites.*

Site	Components considered for optimization		
	Components	Model	Sizes/Numbers considered for optimization
Purtala	Wind turbine	Bergey Excel 6	0,1 no
	Solar PV	Generic flat plate	0,5,10 kW
	Generator	Generic 10 kW	10 kW
	Battery	Trojan 2V, 2008 Ah	0,5,10 no
	Converter	Generic	5,6,7 kW
Mandawa 1	Wind turbine	Bergey Excel 6	0,1 no
	Wind turbine	Generic 10 kW	0,1,2 no
	Solar PV	Generic flat plate	0,20,40,50 kW
	Generator	Generic	10,25,40,50 kW
	Battery	Trojan 2V, 2008 Ah	0,15,20,30,40,50 no
	Converter	Generic	10,30,40,50,60,70 kW
Mandawa 2	Wind turbine	Bergey Excel 6	0,1 no
	Solar PV	Generic flat plate	0,20,40,50 kW
	Bio gas generator	Generic 500 kW	0,1
	Generator	Auto size	-
	Battery	Generic 2V 1 kWh	0,15,20,30,40,50 no
	Converter	Generic	10,30,40,50,60,70 kW
MANIT, Bhopal	Wind turbine	Bergey Excel 10	0,1,2,3,4 no
	Solar PV	Generic flat plate	0,5,10 kW
	Generator	Auto size	-
	Battery	Trojan 2V, 2008 Ah	0,5,10,20,30,40,50 no
	Converter	Generic	300,400,500,600 kW

6. OPTIMIZATION AND ECONOMIC CONSIDERATIONS

The sizing and cost optimization of a hybrid power system is a challenging task due to a large number of design options and uncertainty in key parameters such as fuel prices, load demand and intermittency of renewable power sources [24, 25]. Simulation and optimization software identify the optimum configuration by comparing the performance of different feasible combinations based on different criteria which include energy production, emissions and economic criteria such as cost of energy and net present cost. In this paper, different combinations of WTGs, PV, DG and battery array are analysed, for each of the three sites and the most feasible design for each site based on the least net present cost is determined using Homer software. Economics plays an important role in the simulation process as the optimization software searches for system configuration with the life cycle cost [26]. The net present cost is defined as the total present value of the time series of cash flows, which includes the initial cost of all the system components, the cost of any component replacements occurring within the project lifetime and the cost of maintenance. HOMER uses total net present cost to represent the life-cycle cost of the system. The components considered for optimization for all the three cases are given in Table 3. The sizes, numbers and combination of components which result in minimum net present cost to meet the load demand of for each site, are optimized by Homer Pro. The cost assumptions and lifetimes of various components used in these designs are given in Table 4.

7. RESULTS AND DISCUSSIONS

Different system configurations were simulated in Homer Pro. The optimum sizes of the components which meet the load demand for the available dataset of site resources have been determined for these sites and the optimum system for each case which offers least net present cost is identified. The optimization results of the three sites are summarized in Table 5 and are discussed here.

7.1 Purtala

The optimization results based on the least life cycle costs of the system as given by Homer Pro for Purtala are given in Fig. 4. In addition to this sensitivity analyses using diesel price, solar radiation and wind speed as sensitivity variables are also done for this site.

7.1.1 Economic analysis results

It can be seen that the hybrid system with one 6 kW Bergy Excel WT, a 10 kW DG, 10 Trojan batteries and a 5 kW converter is found to be the most feasible system for Purtala. This system gives a net

Table 4: *Cost assumptions and lifetimes of various components.*

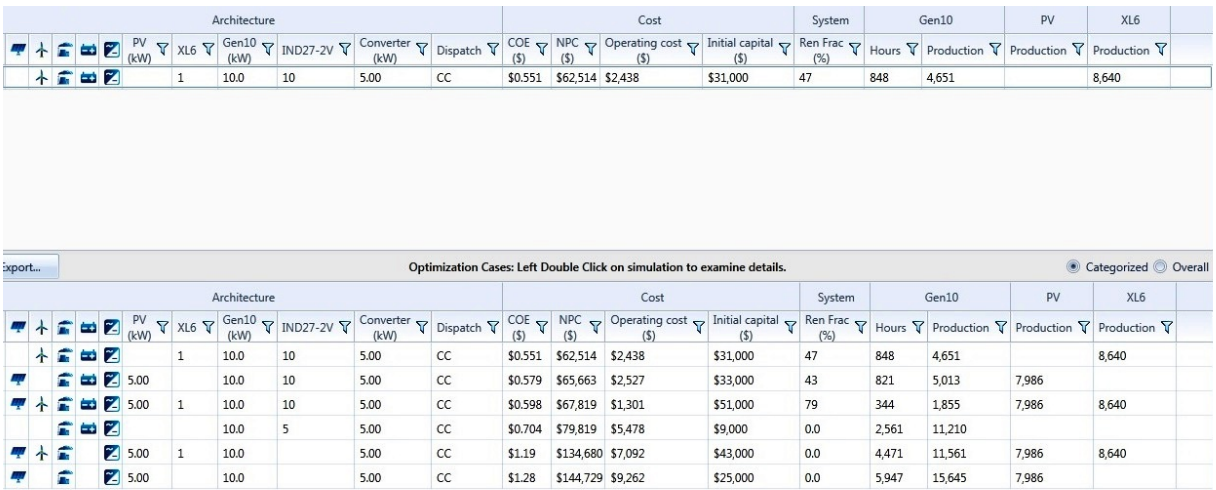
Component	Capital cost	Replacement cost	Operation and maintenance cost	Lifetime
Wind turbine (Bergey Excel 6)	18000 $/unit	15500 $/unit	15 $/year	20
Wind turbine (Bergey Excel 10)	30000 $/unit	20000 $/unit	30 $/year	20
Solar PV	4000 $/kW	3000 $/kW	8 $/year	25 years
Generator (Generic)	250 $/kW	200 $/kW	0.03 $/hr	15000 hrs
Generator (Autosize)	250 $/kW	200 $/kW	0.03 $/hr	15000 hrs
Bio generator	250 $/kW	200 $/kW	0.02 $/hr	20000 hrs
Battery	800 $/ unit	650 $/ unit	6 $/year	20 years
Converter	500 $/kW	350 $/kW	-	15 years

hr: Hour

Table 5: *Optimum systems for three sites based on least NPC.*

Site	Optimum system based on least NPC			Dispatch stragy	NPC ($)	COE ($)	Renewable fraction	Generator hours	Unmet Load (kWh/yr)	Excess energy
	Components	Model	Sizes/ Numbers							
Purtala	Wind turbine	Bergey Excel 6	1 no	CC	62514	0.551	47%	848	0 kWh	18.2 %
	Generator	Generic 10 kW	10 kW							
	Battery	Trojan 2V,2008Ah	10 no							
	Converter	Generic	5 kW							
Mandawa 1	Wind turbine	Bergey Excel 6	1 no	CC	517277	0.458	46%	1694	18.3	17.3 %
	Solar PV	Generic flat plate	40 kW							
	Generator	Generic	10 kW							
	Battery	Trojan 2V,2008Ah	50 no							
	Converter	Generic	30 kW							
MANIT, Bhopal	Solar PV	Generic flat plate	400 kW	CC	7.63M	0.613	0%	6594	0	40.4 %
	Generator	Auto size	520 kW							
	Battery	Trojan 2V,2008Ah	50 no							
	Converter	Generic	300 kW							

no: Numbers, yr: Year



Architecture						Cost				System	Gen10		PV	XL6
PV (kW)	XL6	Gen10 (kW)	IND27-2V	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)	Hours	Production	Production	Production
	1	10.0	10	5.00	CC	$0.551	$62,514	$2,438	$31,000	47	848	4,651		8,640

Export... Optimization Cases: Left Double Click on simulation to examine details. Categorized Overall

Architecture						Cost				System	Gen10		PV	XL6
PV (kW)	XL6	Gen10 (kW)	IND27-2V	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)	Hours	Production	Production	Production
	1	10.0	10	5.00	CC	$0.551	$62,514	$2,438	$31,000	47	848	4,651		8,640
5.00		10.0	10	5.00	CC	$0.579	$65,663	$2,527	$33,000	43	821	5,013	7,986	
5.00	1	10.0	10	5.00	CC	$0.598	$67,819	$1,301	$51,000	79	344	1,855	7,986	8,640
		10.0	5	5.00	CC	$0.704	$79,819	$5,478	$9,000	0.0	2,561	11,210		
5.00	1	10.0		5.00	CC	$1.19	$134,680	$7,092	$43,000	0.0	4,471	11,561	7,986	8,640
5.00		10.0		5.00	CC	$1.28	$144,729	$9,262	$25,000	0.0	5,947	15,645	7,986	

Fig.4: *Optimization results for the hybrid standalone system of Purtala .*

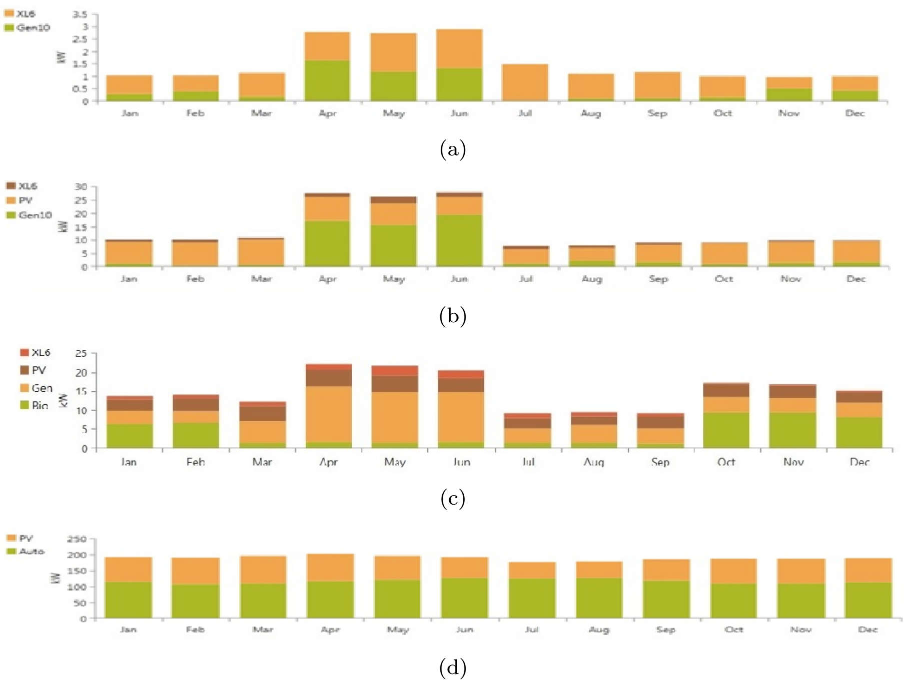


Fig.5: *Monthly average energy production - Share of energy sources (a) Purtala (b) Mandawa 1 (c) Mandawa 2 (d) MANIT, Bhopal*

present cost of \$62514 and cost of energy is 0.551 \$/kWh. With this system configuration the unmet load is 0 kWh/year. Excess energy of 18.2 % is generated which will be wasted due to lack of demand. The optimum system identified on the basis of least life cycle cost, uses the wind turbine generator and diesel generator to meet the load demand. The share of energy yield from each energy source is shown in Fig. 5(a). About 65% energy is being supplied by renewable green energy source. It can be seen, that most of the demand is fulfilled by the wind generator from July to October. Generation from diesel source is required in other months and a high share from DG source is required in summer months from April to June when the energy demand for cooling is high due to high temperatures in this area. A total of 1737.40 L and an average of 4.76 litres/day diesel, is consumed in a year and the DG set runs for 848 hours in a year. A total of 4575 kg/year CO_2, is emitted by this system.

The categorized system in the third row (Fig. 4) is identified as a third option based on lowest NPCs. This system includes both solar and wind renewable sources. In this system a 5 kW PV, one Bergey Excel 6 WT and a 10 kW DG backup source are used to supply the load. Although the NPC (\$ 66819) and cost of energy (0.598 \$/kWh) of this combination is higher, about 90% of the energy is being supplied by green energy sources and the DG set runs for only 344 hours in a year leading to lesser CO_2 emission of 1831.80 kg/year. DG is required in summers only and the solar and wind generation are able to meet most of the load demand in other months. In this system low energy generation by solar source during monsoon months is compensated by good energy production by wind source, and in post winter months when wind is dull, solar PV takes over.

7.1.2 Sensitivity results

Homer Pro facilitates sensitivity analyses by entering multiple values of selected variables. It performs the optimization process for each variable and allows a number of parameters to be displayed against the sensitivity variation for identifying an optimal system. In this study sensitivity analyses are performed using diesel prices (0.6, 0.7, 0.8, 0.9, 1.0, 1.1 and 1.2 \$/L), solar- average radiation (3.5, 4, 4.5, 5 ,5.5, 6, 6.5 kWh/m^2/day) and wind speed (3, 4, 5, 6, 7 m/s) as sensitivity input variables. A total of 13230 sensitivity cases were simulated.

Fig. 6 shows the sensitivity analysis results in terms of solar radiation and diesel prices with fixed average wind speed of 5 m/s and in Fig. 7 optimal systems in terms of wind speeds and diesel prices with fixed solar radiation of 5.00 kWh/m^2/day superimposed with NPC, is displayed. Fig. 6 shows the wind-DG system is the optimal combination in comparison to PV-wind system for most of the diesel price and solar radiation inputs. The PV-DG system is suitable for high solar average radiations. Fig. 7 shows that the wind-DG system is optimal for average wind speeds above 4.6 m/s and for wind speeds below this PV-DG system, are optimal. From the sensitivity result the optimum combination of systems for different

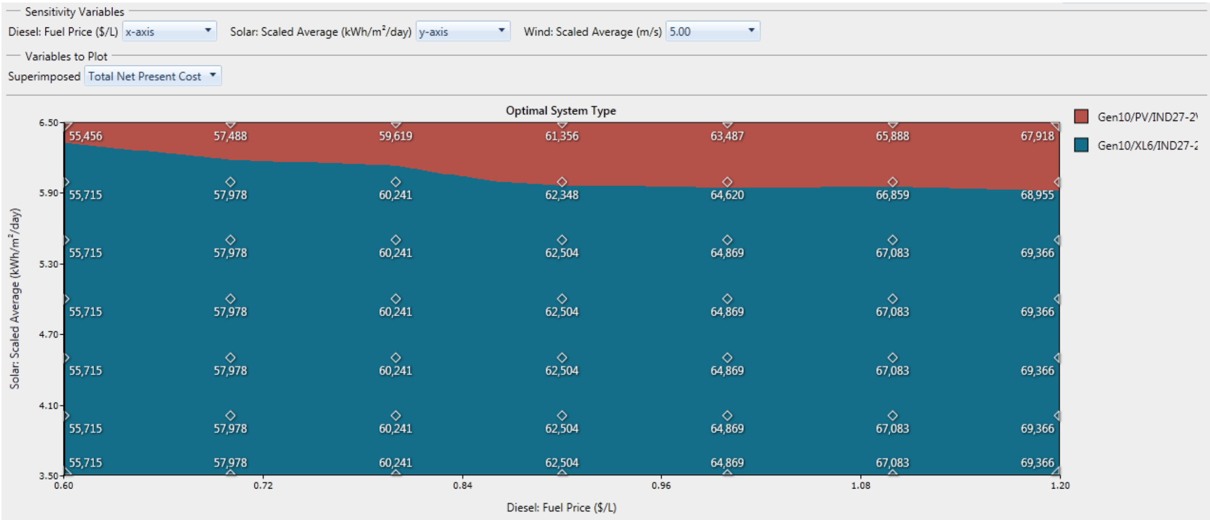


Fig.6: Sensitivity analysis in terms of solar radiation and diesel prices for Purtala.

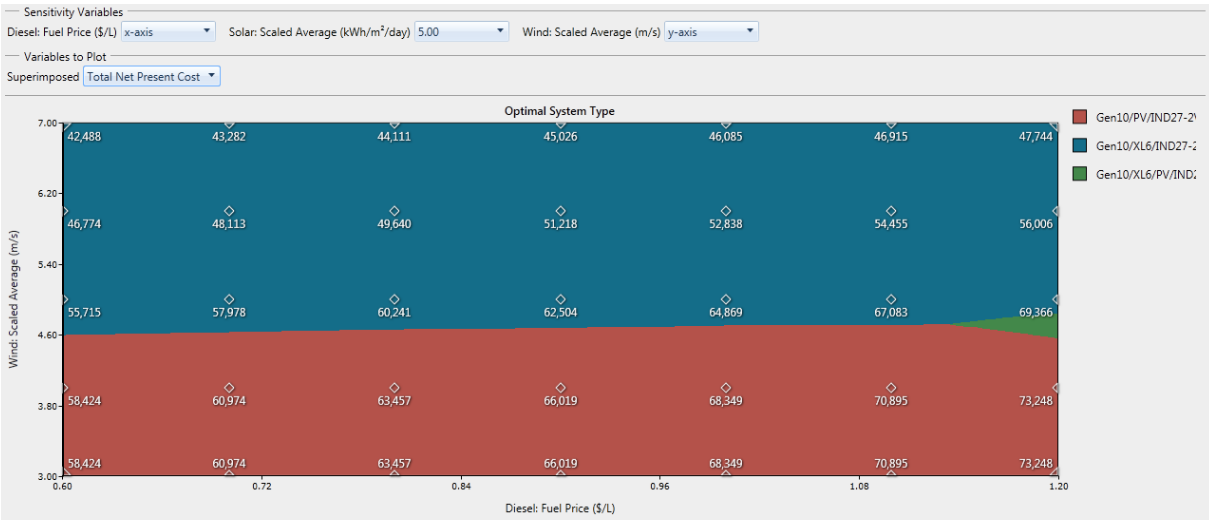


Fig.7: Sensitivity analysis in terms of wind speeds and diesel prices for Purtala.

wind and solar resources of this area can be identified.

7.2 Mandawa

The system designed for Mandawa (Mandawa 1) includes the load of rural households like Purtala. In addition to this the system is expected to supply the agricultural load of the village. As seen from Table 2 the peak load demand and energy consumption requirement of this system is higher than Purtala. This rural site is also situated in central India with slightly higher yearly average solar radiation and wind speed than Purtala. The optimization results show that the optimum system for this site includes both solar and wind based renewable sources. About 61 % of the energy is being supplied by green energy sources. The share of each energy source in production (Fig. 5) shows that only a small proportion of production is supplied by WTG throughout the year. The PV contributes almost evenly in the whole year. Most of the requirement of DG is in summer months when the load demand is higher than the other months.

Another optimum system (Mandawa 2) designed for this village includes one Bergey Excel 6 WT, 20 kW PV, and one 500 kW bio gas generator with diesel generator and batteries for backup. The bio generator supplies a larger share of the power from October to February due to larger availability of bio fuel as compared to other months. The NPC of this system is $ 609990 which is greater than the above system. The bio generator is supplying 27.1 % energy.

7.3 MANIT, Bhopal

The optimization results of this site show that the optimum system consists of PV, 520 kW DG, 50 batteries of the selected model and a 300 kW converter. The share of PV and DG in yearly average energy production shows that the PV gives mostly uniform energy output throughout the year except in monsoon months in which the energy production is slightly lower. DG set runs for 6594 hours in the year. This urban site has the highest load demand among the three locations analysed. WTG is not included in the optimum system. This is expected as wind speed recorded is always below 3 m/s at the measurement height of 11.5 m at this site. It can be said that poor wind speed is encountered at this site and the wind speed will seldom go above 3 m/s even if the wind turbine is installed at a higher height. The cut-in wind speed of most of the horizontal axis wind turbines is in the 2-4 m/s range, therefore these turbines will not start power production until this speed is achieved. The poor wind resource in this site makes it unsuitable for a wind based system with horizontal axis wind turbines. However, a vertical axis wind turbine for small amount of power production can be considered. It can be said that a standalone off grid system to supply the selected load needs the running of a fossil fuel based diesel generator for long hours, hence the standalone system will not be a feasible option for supplying this load. However, the renewable energy based system to aid the grid supply may be considered so that a reliable supply can be ensured.

8. CONCLUSION

Standalone renewable energy based hybrid systems to meet the load demands of three different locations have been designed. These three locations selected here represent different types of load profiles and wind and solar resources. These three systems are proposed to supply the domestic load of 25 households of a small village Purtala, the domestic load of 130 households and agricultural load of another village Mandawa, and the residential load of 300 staff quarters of an urban institute MANIT in central India respectively. The study indicates that the two rural sites considered here are blessed with good solar and medium wind energy potential. The urban site has a poor wind resource but has a good solar energy potential. The optimal model which offers least life cycle cost is obtained from Homer Pro simulations. The optimal system of Purtala consists of wind based green energy source and diesel generator. Another hybrid system based on solar and wind energy sources and fossil diesel source, which also offers low net present cost is identified as an attractive option for Purtala as less operating hours of fossil fuel based source in this system result in less greenhouse gas emissions. Due to the complementary characteristics of wind-PV energy this system provides more consistent renewable energy production throughout the year thus needs less operational hours of fossil fuel based generation. The least cost system for Mandawa village has both wind and solar renewable sources and DG source. The additional system designed for Mandawa which includes biomass generation has a higher NPC than the above system. The power from biomass is dependent on cropping pattern. There is a need to have robust institutional and market mechanisms for efficient procurement of the required quantity of biomass and safe storage till it is finally used. The least cost system identified for MANIT does not include wind source and is composed of PV and DG energy sources only. The most feasible systems for three sites consist of different combinations of renewable energy sources. These systems use battery banks for energy storage. The renewable energy sources combined with DG and battery storage ensures good reliability. Deployment of renewable based standalone energy generation systems in comparison to diesel based system only will result in less emission of greenhouse gases and less fuel cost as the prices of diesel are high in the country. It can be concluded that the solar and wind based standalone energy systems are attractive options to supply remote un-electrified areas of Madhya Pradesh. The solar and wind potential can also be exploited in urban areas of the state thus enhancing the reliability of supply and reduction in emissions.

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