Sustainable Decentralised Green Energy Options for Western Ghats

Ramachandra T.V.[1,2,3*]
cestvr@ces.iisc.ernet.in

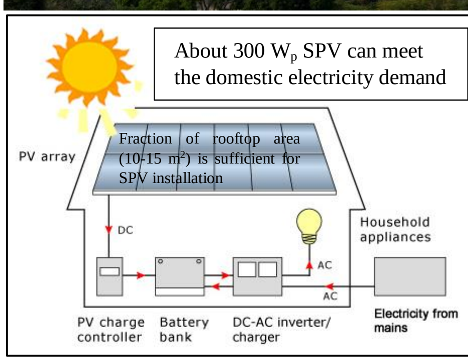
Ganesh Hegde[1]
ganesh@ces.iisc.ernet.in

[1]Energy & Wetlands Research Group, Centre for Ecological Sciences [CES]
[2]Centre for Sustainable Technologies (astra)
[3]Centre for infrastructure, Sustainable Transportation and Urban Planning [C*i*STUP]
Indian Institute of Science, Bangalore, Karnataka, 560 012, India
Web: http://ces.iisc.ernet.in/energy, http://ces.iisc.ernet.in/foss

[*]Corresponding Author: T.V. Ramachandra [cestvr@ces.iisc.ernet.in]

- Charanka Solar Park
- Patan District, Gujarat
- Installed capacity: 221 MW (planned 500 MW)
- Area: 2000 ha
- World's second largest PV power plant

Kerala has achieved 100% rural electrification through decentralised energy generation using local resources



A typical rural household consumes about 50-70 kWh electricity every month. Most of this electricity requirement can be met by a rooftop SPV of 300-500 W_p installed capacity which needs about 10-15 m^2 roof top area.

Abstract

Electricity is essential for economic and social development of a region. Dependence on the fossil fuel resources for electricity generation is eroding the resources at faster rate apart from large scale pollution of land, water and air environment. Electric energy generation from renewable energy resources (wind and solar) plays a pivotal role in the region's development, while combating global warming through the reduction of greenhouse gas (GHG) emissions. Electricity generation in India is dominated by fossil fuel based power plants (coal - 59%), gas - 8.9%, diesel - 0.5%, nuclear - 2%)), which are the prime contributors to pollution. The life cycle carbon dioxide (CO_2) emission is highest in coal based power plants, ranges from 960-1050 gCO_2eq./kWh followed by diesel (778 gCO_2eq./kWh), natural gas (443 gCO_2eq./kWh) and nuclear fuelled power plants (15 gCO_2eq./kWh). Nevertheless, thermal power plants also emit significant amount of SO_2 and NO_x which can cause acid rain and skin/lung related diseases. Most of the power generating plants are situated near the resource available area, while the load centers are sparsely located. This necessitates innovative and sustainable approaches to meet the energy demand in a decentralised way. Distributed generation (DG) with micro grids include community level standalone grids, rooftop solar photovoltaic (SPV) based energy generation, combined heat and power generation (CHP), biomass fuelled captive generation could meet the demand locally, while reducing the losses as well as supply uncertainty.

The current communication explores the available potential of renewable energy resources in Western Ghats and also the GHG footprint reduction with the effect on reduction in carbon footprint through decentralised generation. Most taluks in the Western Ghats region with solar insolation >5 kWh/m^2 and hilly terrain experiencing wind >3 m/s are highly suited for decentralised electricity interventions, which would ensure livelihood prospects through availability of electricity throughout the year. Sufficient land is available as the estimate indicate about 1-2% of current wasteland is adequate to deploy distributed electricity generation for meeting the current electricity demand. High wind power density can meet peak power deficiency in the states of WG region. Seasonal variability analysis of solar insolation and wind speeds across taluks gives the insights to generation scheduling and optimum grid operation. Decentralised energy generation using available wind and solar energy resources can meet the regional demand by reducing the transmission losses and stress on central grid.

DG mostly exploits locally available renewable energy resources, which also attribute to cutting down the GHG emission. Rooftop solar photovoltaic (SPV) and a community level (or village level) hybrid energy generation through bio-energy (biomass gasifier, wind, etc.) are technically feasible, economically viable and sustainable green energy generation option for meeting the rural energy demand. Present study proposes a standalone SPV system for un-electrified household and biomass-SPV hybrid system to meet a typical rural electricity demand. The model simulates the feasibility of rural electrification with stand-alone hybrid (using biomass, wind and Solar PV) system for reliable electricity supply. Decline in GHG emission by the simulated model is analysed, promises significant reduction in environmental pollution. Proposed model is replicable in all villages depending on the local resource availability, which can ensure meeting base load of the regional distribution station.

Keywords: Renewable energy potential, decentralised generation, Western Ghats, nano electricity generation, green energy, rural electrification.

Introduction

Electricity plays a pivotal role in the development of any sector of the society or the region. Electric energy supply, its quality and reliability is significantly associated with the regional development. Sustained supply of electricity influences human comfort, commercial and industrial development [1-3]. On the other hand, fossil fuel based electricity generation with the emissions of greenhouse gases (GHGs) is the significant contributor to the environmental pollution and global warming. Pollution of the region not only affects the local life, but also aids the global phenomenon such as increment in the earth surface temperature, acid rains, diseases related to heart and skin, large scale pollution of water resources, increment in the sea water level due to melting of glaciers and icebergs etc. [4, 5].

Electricity generation is essentially dependent on fossil fuel (coal (59%), gas (8.9%), diesel (0.5%), nuclear (2%)) based power plants [6]. The life cycle carbon dioxide (CO_2) emission is highest in coal based power plants, ranges from 960-1050 gCO_2eq./kWh followed by diesel (778 gCO_2eq./kWh), natural gas (443 gCO_2eq./kWh) and nuclear fuelled power plants (15 gCO_2eq./kWh). These generating plants also emit significant amount of SO_2 and NO_x, while letting high concentrated effluent to the water resources [7-9]. There has been a significant progress through renewable sources towards cleaner electricity generation options, which is likely to revolutionise, if dissemination of these technologies is done at decentralised levels.

Demand for electricity has been increasing due to rapid urbanisation and industrialisation with globalisation and relaxation in Indian market. Coupled with these, rural electrification has widened the supply demand gap, necessitating exploration for viable energy alternatives. Majority of Indian population (about 65%) resides in rural areas where the average electricity supply is as low as 8-10 hours per day. The provision of reliable electricity promotes rural development through employment prospects while alleviating poverty and drudgery [10]. The growing environmental concerns against fossil fuel based mega power projects with strong resistance from local public necessitates environment friendly alternatives. Thermal and nuclear power plants require lot of water for cooling and as a heat exchanging media apart from demand for land [11]. Hydro power plants make irreversible landscape changes in the region, submerging huge land (forest, agricultural fields, habitats etc.) and also severely alters the environmental flow of the river [12]. Supply of electricity to remote load centers often results in higher transmission and distribution (T & D) losses with lower energy efficiency and revenue loss.

This emphasises the need for novel sustainable technologies based on renewable resources harvested at decentralised level and efficient distribution through micro grids. Exploiting locally available renewable energy resources to meet the regional electricity demand is being attempted in many regions [13-15]. Hybrid systems through integration of local energy resources is a feasible technique to address the seasonal variability and ensure the reliable energy supply. Grid connected micro grid seems viable option as many federal governments have opted the payback tariff for supplying to the grid [16]. Rural electrification is yet to gain momentum evident from the absence of electricity supply in more than 74,00,000 households of 32,000 villages, where nano generation is viable [17]. This would also make the last consumer of the central grid ladder, an energy generator (nano generation), while increasing the decentralised renewable energy interception. This necessitates the design of a model for un-electrified households, mostly in economically poor vicinity to meet the basic lighting demand. These individual houses act as nano generating units, which can be inter connected and scaled up. The proposed nano generating units are independent of grid connection, since the load serving capability is limited to a house or cluster of few homes and mostly connected to DC load.

Though renewable energy sources are widely available, they are intermittent and variable in nature. The potential assessment of available RE sources is essential, prior to installation of generation plants. Solar energy is one of the widely available energy source which can be directly converted to electricity using photo-voltaic (PV) cells. Photoelectric effect is the phenomenon which generates electricity (electrons), when solar radiations fall on PV cells. Number of PV cells are connected in series and/or parallel to meet output requirement (Voltage and current). External circuit will be connected to the end user/loads through inverters (to convert DC to AC), transformers (to maintain required voltage level) and security (circuit breakers, fuses, surge arrestors, isolators etc.) components. Solar energy can also be used for thermal applications and electricity is produced through steam turbines. Solar cookers, dryers, water heaters, concentrated solar power (CSP) plants are some of the examples of thermal energy utilisation. However, PV cells produce electricity from solar radiations which is more convenient for installation and which is also user friendly [18, 19].

Wind is being used for mechanical applications such as water pumping, grinding etc. Innovation of electricity generation boosted up the wind turbine installation to generate electricity, all over the world. Currently, more than 200 GW of power is being generated from wind across the globe, which is the leading RE resource. Winds are generated due to the rotation of the earth and temperature gradient in the atmosphere. Energy generation from wind is highly unpredictable which depends on potential variability, wind speed, etc. Since the output power of the wind turbine directly proportional to the cube of the wind velocity, any variation in wind speed will cause power output deviation. Drastic changes in the output will create stress on transmission lines due to stranded loads. This also decreases the plant load factor leading to lesser electric energy supply. To avoid transmission line stressing and to keep the load connected to the grid, forecasting of available wind potential is essential in order schedule the generation. This necessitates the potential assessment of available wind resource which also will help in plant installation planning and optimised scheduling of electricity generation. Forecasting of wind speed requires extensive mathematical (probabilistic approach) modelling. High potential areas assessed from spatial data will promise certain number of high wind speed days which decreases the complexity of prediction [20, 21].

The present study deals with the available wind and solar energy potential assessment of taluks in the Western Ghats, one among 35 biodiversity hotspots in the world. Western Ghats (WG) is a repository of diverse endemic flora and fauna and also receives higher solar insolation for about 300 days in a year. The high altitude taluks in the region experience greater wind speed which are the high wind energy potential areas. Taluks in the planes and northern region of Western Ghats (WG) receives higher insolation which encourages the solar power plant installation. Seasonal variability across the taluks and seasons have been analysed, which helps in optimising the generation and selecting the best location for plant installation. Wind energy potential compliments the lower solar insolation during monsoon in the region. This ensures the reliable electricity generation throughout the year by hybridising the energy resources.

Further, two systems are modelled in the study, which includes, a nano electricity generating system for supplying a typical load of an un-electrified household and a hybrid system for village electrification. Earlier studies focused on rural electrification through renewable energy resources, decentralised energy generation, optimisation of locally available energy resources, etc. [22-24]. Researchers have also proposed integrated energy systems and regional integrated energy plan which analyses the energy consumption pattern to provide viable sustained solutions [25, 26]. However, there are only few studies to address the un-electrified household energy issue (nano level electricity generation) while mitigating the environmental pollution and grid dependency. The present study deals with electricity generation at the farthest end of distribution side, i.e. generation at the household, which eventually creates the building block to achieve energy independence. However, the model can also address the rural electrification in more environmental friendly way, while keeping the base load of the grid unchanged. The hybrid model using solar, wind and bio-energy, is simulated using HOMER platform to meet the village electricity load. The results are optimised for grid connected hybrid micro grid, with the sensitivity analysis of payback tariff. The probable reduction in emission is computed while the reliability of the system and minimum cost of electricity generation are optimised. Since the system is connected to the grid, energy storing devices are excluded which reduces the capital cost. Load data used are the real time data obtained by local electricity supply company (HESCOM grid), excluding industrial consumptions. The model is technically feasible, economically viable and environmental friendly with the scope for replication in all un-electrified and/or electrified villages depending on the resource availability. Reliability and better power quality is noticed with the decentralised system integrating locally available renewable energy resources, which also reduces the demand on the regional grid.

Materials and Method

Study area: Western Ghats comprising of undulating terrain is located in the western part of India, along the coast, from Kanyakumari to Tapti valley covering about 1,490 km and spreads over 1,29,037 km^2 area in Kerala, Karnataka, Goa, Maharashtra and Gujarat states. Taluks wise solar and wind energy potential analysis is carried for the Western Ghats region to analyse the seasonal variability and to identify the locations with high potential suitable for exploitation.

Renewable energy potential expedition

Spatio-temporal data are used for energy potential assessment using open source GIS platform, which also gives the seasonal and geographical variability of the energy resources. Long term data sets acquired from NASA SSE and Climate Research Unit (CRU) are reliable and depicts the seasonal variability which are closely correlated with ground measurement.

Solar energy potential assessment: NASA SSE Global insolation datasets are obtained from a physical model based on the radiative transfer in the atmosphere considering its absorption and scattering properties. The model considers visible and infrared radiation, cloud and surface properties, temperature, perceptible water, column ozone amounts and also the atmospheric variables includes temperature and pressure measured using various satellite instruments. The long wave and shortwave solar radiations recorded in the satellite sensors along with the effecting parameters are studied to generate global insolation for different locations and durations. The 0.1°X0.1° spatial resolution SSE global insolation data derived from NASA SSE web portal (http://eosweb.larc.nasa.gov/sse/), for a period of 22 years (July 1st, 1983 to June 30th, 2005) were validated (RMSE of 10.28%) with Baseline Surface Radiation Network (BSRN) data available as daily, monthly and annual averages obtained from measured values every 3 hours [27, 28].

In this study, NASA SSE monthly average Global insolation data is collected for more than 900 grids which optimally cover the entire topography of India within the latitudes 8° to 38°N and longitudes 68° to 98°E. Further, grids which essentially covers the entire Western Ghats region are extracted and a geo-statistical Inverse Distance Weighting (IDW) interpolation is employed to produce monthly average Global Hourly Insolation (GHI) maps for the region. The Direct insolation is given by

$$I = (G - D)/\sin \Phi \qquad (1)$$

where G is the Global insolation, D is the diffuse component and Φ is the sun’s elevation angle.

Wind energy potential assessment: Synthesized wind data is available from various sources, which provides overview of the wind regime of a region. Depending on the physiographical features and climatic conditions, these data help to assess wind potential in the region of interest which can be validated by long term surface wind measurements.

From earlier studies it is evident that Climate Research Unit (CRU) data are reliable and closer to the Indian Meteorological Department (IMD) surface data, which is used in the present study [29]. CRU at the University of East Anglia maintains a record of climatic average datasets of meteorological variables which also contains wind speed data for the period between 1961 and 1990, compiled from different sources. Further, inter and intra variable consistency checks are performed to minimize data consolidation errors. The Global Land One-km Base Elevation project (GLOBE) data of the National Geophysical Data Center (NGDC) were re-sampled into 10'×10' (ten minute spatial resolution or 0.16°X0.16°) elevation grids where every cell with more than 25% land surface represents the average elevation of 100~400 GLOBE elevation points. Those below 25% are considered water bodies. The climatic average of wind speeds measured at

2 to 20 m anemometer heights (assumed to be standardized during collection) collated from 3,950 global meteorological stations together with the information on latitude, longitude and elevation were interpolated based on a geo-statistical technique called thin plate smoothing splines. Elevation as a co-predictor considers topographic influence on the wind speed, whereas, proximity of a region to the measuring station improves the reliability of the interpolated data. During interpolation, inconsistent data were removed appropriately. This technique was identified to be steadfast in situations of data sparseness or irregularity [30]. The 10'×10' spatial resolution wind speed data as climatic averages were available for all global regions (excluding Antarctica) [31].

System modelling

Two scenarios are modelled and simulated which are i) a standalone system for an un-electrified household and ii) a hybrid system for a village load. Optimal share of energy resources and annual operating cost is obtained for both system. Sensitivity analysis is carried out for grid connected system with respect to the payback tariff or feed in tariff (FIT). Systems are modelled in a hybrid energy optimization software called HOMER (Hybrid Optimization Model for Electricity through Renewables), developed by National Renewable Energy Laboratory (NREL), which optimises the cost for given load profile every hour (8760 hours per year). The unit cost of electricity (COE) generated is computed considering annualised net present value (NPV) and the total annual generation. Analysis of cash flow and energy utilised throughout the year provides payback time and return on investment (ROI). Lighting is the major load in rural households which accounts for 60-70% of the total energy requirement. However, fans, television, water heaters and pumps also consume significant electric energy which are operated few times a day. Typical rural household electrical energy consumption ranges from 35 to 50 kWh per month, cooking and heating energy is normally met by biomass burning. The study analyses i) an un-electrified household which needs minimum electricity for 5-6 hours a day for lighting and fans, ii) the community or village level load using hybrid option of SPV, wind generators and biomass gasifiers.

Techno-economic analyses of these options have been carried out based on the present market prices of SPV module, wind generators, gasifiers, batteries, inverter and other electrical equipment. Economic analysis is done considering the cost of PV module as INR 80/Wp, installation cost as 5% of capital cost and soft interest of 3%. Battery is secured with charge controller and fixed maintenance expense of INR 1,000 per annum. Table 1 gives the cost details of the equipment used in the simulation. Cost of the solar PV panel, battery and lamps are obtained by market survey and life span of 20 years is assumed.

Table 1: Techno-economic specifications of the standalone SPV system

Equipment	**Rating**	**Cost[a] (INR)**	**Other details**
PV module	125 Wp	10,000	Life: 20 years No replacement cost
Battery	60 Ah	10,000	Replacement cost: INR 2500 Minimum life: 5 years

Charge controller	5 A, 12 V	2,000	Life: 20 years (Not included in simulation)
Annual maintenance cost	All equipment	1,500	Fixed
Wiring, protection etc.	Required rating	5% of capital cost	(Not included in simulation)

[a] Estimated and approximated comparing with the market value

For an un-electrified household, possible load (DC) from 3-4 compact fluorescent lamps (CFL) and a fan is shown in Fig. 1. However, the model is intended to provide basic electricity for lighting during non-sunshine hours as most of the members from villages work outside in the field during day. Load demand of the home will be higher during 6 to 11 PM due to usage of all lighting devices. During night only fan is assumed to be operated and during the day mostly no electricity consumption. In some cases loads can be switched on during sunshine period since they will be directly supplied from PV module without depending on batteries. Electricity requirement after dusk till dawn is considered in modelling and Table 2 gives hourly variation in load.

Table 2: Hourly load demand of the household

Hour	Load (W)	Hour	Load (W)
00:00 - 01:00	30	12:00 - 13:00	0
01:00 - 02:00	30	13:00 - 14:00	0
02:00 - 03:00	30	14:00 - 15:00	0
03:00 - 04:00	30	15:00 - 16:00	0
04:00 - 05:00	30	16:00 - 17:00	0
05:00 - 06:00	20	17:00 - 18:00	0
06:00 - 07:00	20	18:00 - 19:00	25
07:00 - 08:00	20	19:00 - 20:00	40
08:00 - 09:00	0	20:00 - 21:00	40
09:00 - 10:00	0	21:00 - 22:00	40
10:00 - 11:00	0	22:00 - 23:00	40
11:00 - 12:00	0	23:00 - 00:00	30

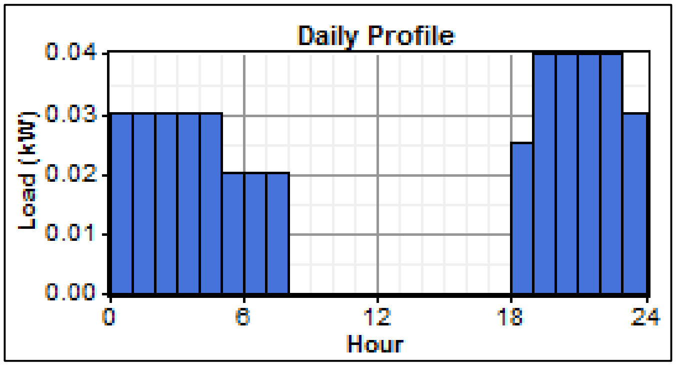


Figure 1. Hourly load profile of an un-electrified household

For the hybrid system (SPV, Wind, Gasifier), it is assumed that availability of biomass is abundant in the form of agriculture and horticulture residues, in addition to the forest biomass in the region. Load profile of the village is obtained from the regional electricity distribution company (HESCOM), in which industrial consumption is excluded. Annual electric energy requirement of the village is about 4,33,255 kWh having the peak demand of 49 kW and average daily consumption of 1187 kWh. Land use Land cover (LULC) analysis gives the available waste/barren land and rooftop area for SPV and wind generator installation. The village has about 39 ha of open land and 4.5 ha of rooftop area. The average rooftop area per household in the village is about 147 m^2, in which less than 10% would be sufficient to meet the domestic energy demand. In the present study, grid connected hybrid system is considered in order to make the system more reliable and to ensure the higher power quality. Techno-economic specifications of the hybrid system is depicted in Table 3. Assumption of maintenance by local people, waives labour charges. Annual maintenance cost of INR 50,000 is considered (gasifier, wind generator and inverter maintenance, etc.) and the battery banks are excluded since the system is grid connected.

Solar insolation data is obtained from NASA SSE and NREL for the region having coordinates 14° 36' latitude and 74° 42' longitude (Uttara Kannada, Karnataka, India) with average solar insolation of 5.41 kWh/m^2/day. Solar insolation received is higher (>6 kWh/m^2/day) from February to May (summer) and decreases abruptly resulting lower insolation (about 4 kWh/m^2/day) from June to August (Monsoon).

Table 3: Economic and technical specifications of the hybrid system

Equipment	**Rating**	**Cost[a] (INR)**	**Other details**
Gasifier and Generator	50 kW	20,00,000	Fed from only producer gas. Replacement cost is 10,00,000.
PV module	70 kWp	56,35,000	Life: 20 years No replacement cost
Wind Generator	40 kW	27,40,000	Each wind generator of 2 kW (20 nos.)
Converter/Inverter	80 kW	8,40,000	Replacement cost: INR 4,20,000
Annual fixed maintenance cost	All equipment	50,000	Including labour cost

[a] Estimated and approximated comparing with the market value

Insolation increases above 5 kWh/m^2/day till January (Post monsoon and winter) from September (Fig. 2). Wind speed in the ranges from 2.7 to 5 m/s, while the annual average wind speed is about 3.5 m/s (Fig. 2). Low speed wind turbines are optimum for the region which can complement lower solar energy during monsoon. Biomass is available throughout the year from agro-horticultural residues and also from forest litters. However, it should be stored in a dry place during monsoon for better combustion and to reduce the ash production.

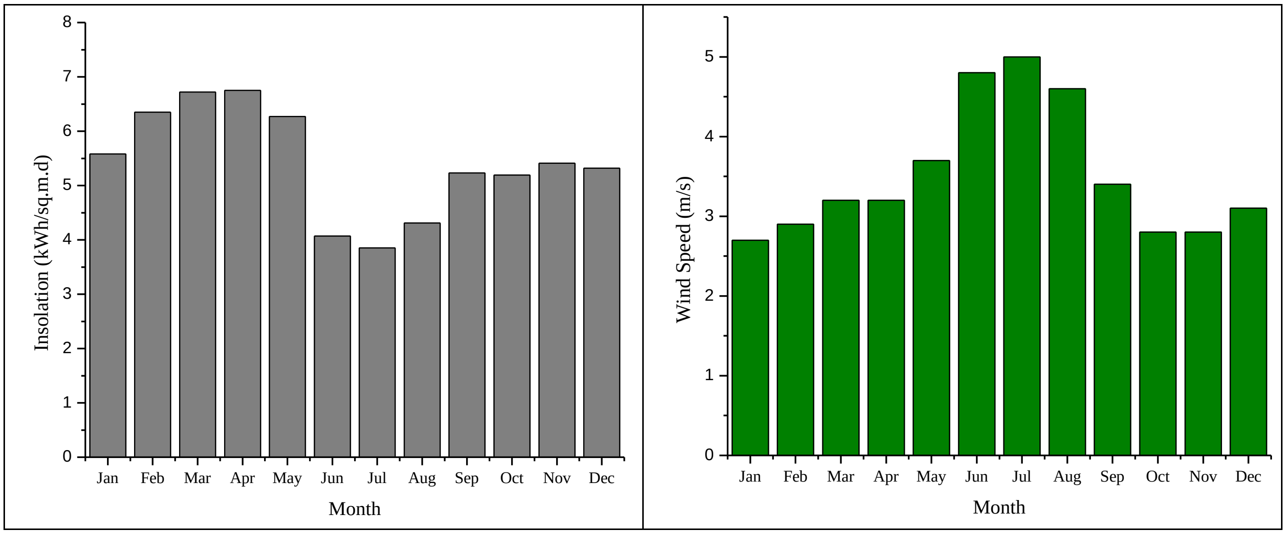


Figure 2: Monthly variation of solar insolation and wind speed

Results and Discussions

Solar potential in Western Ghats: Figure 3 shows the taluk wise distribution of solar insolation in WG region, which highlight the availability of ample solar insolation to harvest energy for meeting the local electricity demand. Annual average insolation received in the region ranges from 5.3 to 5.9 kWh/m^2/day. Taluks in the eastern and northern part of the WG receive more isolation (5.7 - 5.9 kWh/m^2/day) compared to the southern taluks (5.3 - 5.5 kWh/m^2/day). However, grid connected SPV systems are not viable in taluks with thick canopy vegetation (Evergreen/semi-evergreen). Rooftop SPV modules are viable options to meet the fundamental requirement of electricity for domestic purpose.

Figure 5 gives the seasonal distribution of solar insolation across the taluks. In summer (February to May), insolation ranges from 5.5 to 7.5 kWh/m^2/day. Sothern taluks receive higher insolation (6 – 6.6 kWh/m^2/day) in early summer (February), which moves towards northern region as summer progresses. In March and April, WG receives higher insolation in the year which ranges from 5.9 to 7.4 kWh/m^2/day in all the taluks. During monsoon (June to September), insolation ranges from 3.5 to 6.1 kWh/m^2/day, in which July receives lower insolation (3.9 to 5.6 kWh/m^2/day). From August, solar energy reception in southern taluks increases (5 - 6 kWh/m^2/day), which slowly moves towards central region as the winter approaches. In winter months (October to January), distribution of solar insolation varies from 4.1 to 6 kWh/m^2/day. In December and January, most of the central and southern taluks receive higher insolation (5.2 to 6 kWh/m^2/day) compared to the northern region (4.6 to 5 kWh/m^2/day). As the winter recedes, insolation reception increases (>5.8 kWh/m^2/day). The seasonal solar potential maps of WG reveals that, distribution of solar insolation follows a pattern which move from southern region to northern taluks (from monsoon to summer), which gives the insight for generation scheduling and secured plant operation. Forecasting of the generation from solar PV plants (in grid connected system), contributes to decide the dynamic range of grid operation and security limits. However, village level study may reveal better information to decide the precise grid operation constraint to keep the grid stress free and connected to the load reliably.

Wind potential in WG: Taluks in the higher altitude and planes experience higher wind speed compare to the interior and costal region. Annual average wind speed ranges from 2.1 to 3 m/s throughout the region, where taluks in the south-eastern region experience higher wind speed (2.7 to 3 m/s). Figure 4 shows the taluks wise wind regime of the WG region. Taluks in the central and southern region experience higher wind speed (2.5 - 3 m/s) compared to the northern region (2.1 - 2.5 m/s), annually.

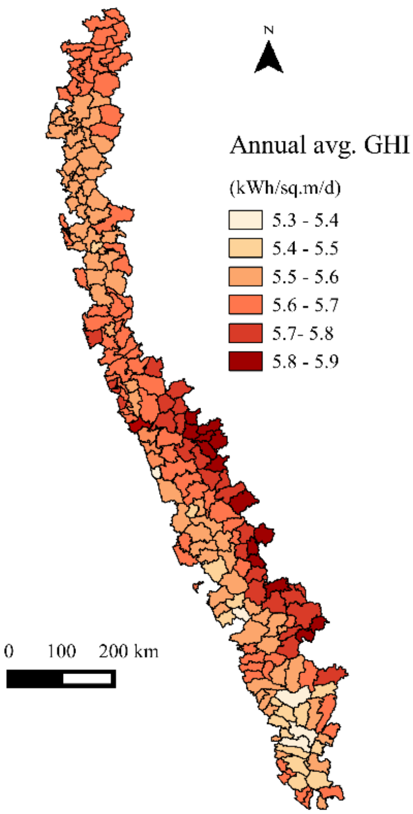


Figure 3: Taluk wise annual average solar insolation in WG region

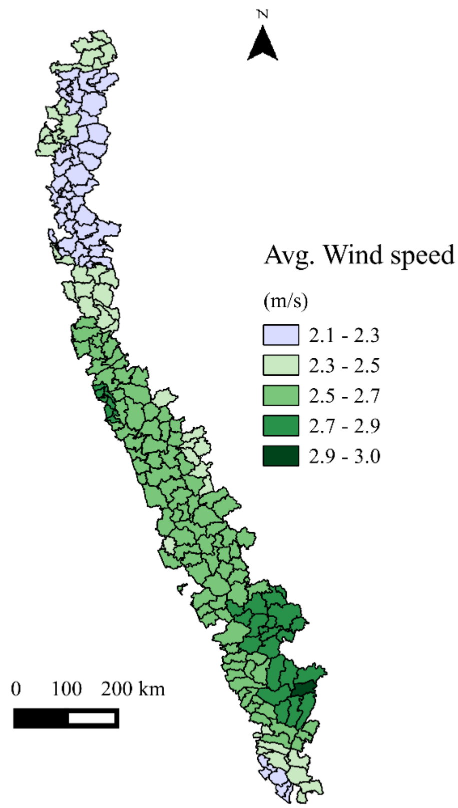


Figure 4: Taluk wise annual average wind speed in WG region

Taluk wise seasonal distribution of wind speed is given in Figure 6, which also gives the high potential areas. During summer (February to May), wind speed varies from 1.5 to 3.37 m/s, where the northern taluks experience lower wind speed (1.5 to 2.1 m/s) compared to central and southern region (2.3 to 3.37 m/s). WG region experiences higher wind speed in monsoon season (June to September) due to the south-west monsoon. Speed of wind ranges from 2.5 to 4.1 m/s (in June, July and August) which decreases (in September, 1.9 to 2.9 m/s) as monsoon recedes. The central taluks of WG receives swift winds (3.7 to 4.1 m/s) which are high potential areas. However, change in the direction of wind is not suitable for power plant installation, which gives the extreme power outputs. During winter months (October to January), average wind speed in the region varies from 1.3 to 3.1 m/s, in which northern taluks experience lower wind speed (1.4

to 1.9 m/s). Nevertheless, central and southern taluks experience higher wind speed ranging from 2 to 3.1 m/s annually. The seasonal wind speed maps of WG reveals the taluk wise energy potential in the region. The south-eastern taluks consistently showed higher potential which also include some of the hilly regions including Ooty, Elivai malai, Perumal peak, Anamudi, Munnar and valley at Palaghat. Some of these regions are biodiversity rich, having rare flora and associated fauna. Since the wind plants need vast disturbance free area, open area such as coast, planes are to chosen instead vegetated regions. However, potential analysis shows the harvestable energy of the region which gives the scope for generation forecasting, scheduling and to enhance the plant security. It also helps in village level plant installation to meet the community demand in a decentralised manner.

Seasonal variability in solar and wind potential: RE sources are intermittent in nature and the variation cause the variation in the output. Optimisisation of RE resources requires the understanding of seasonal variability including diurnal variation. Figure 7 gives the taluk wise variability in solar and wind potential in WG region. Annual average insolation in Maharashtra during monsoon (Figure 7 (a)) shows high variability compared to other states. Goa experiences lower variability in insolation reception compared to other taluks annually. Insolation reception is almost same during summer across the states, however Gujarat shows higher potential. Wind speed shows high variability and higher energy potential in all the states during monsoon months (Figure 7 (b)) compared to other seasons. Overall, wind speed is highly variable in all the season which also varies the harvestable energy potential of the region. Figure 8 shows the monthly variation of wind speed and solar insolation in WG region, which infers that higher wind speed potential compliments the lower insolation reception from June to September (monsoon). This also shows that solar insolation reception from January to May compliments the lower wind speed. This endorses the hybridisation of energy resources to have the reliable energy generation throughout the year. Study using higher resolution wind speed data may provide precise wind regime for regional level (village level) to analyse the energy potential variability analysis.

Energy generation from solar potential using available wasteland: Electric energy can be harvested directly from solar radiations using solar photovoltaic (SPV) cells (modules). These SPV modules can be mounted on rooftop (domestic supply) or can be installed in an outdoor area (wasteland/barren land) for higher capacity of generation which shall meet the irrigation and commercial electric energy demand. Land use by power plants is one of the major factors to be considered in the early stage of planning of any power plant. The assessment shows that to setup 1 kW solar power plant (SPV based) land required is about 100 m^2.

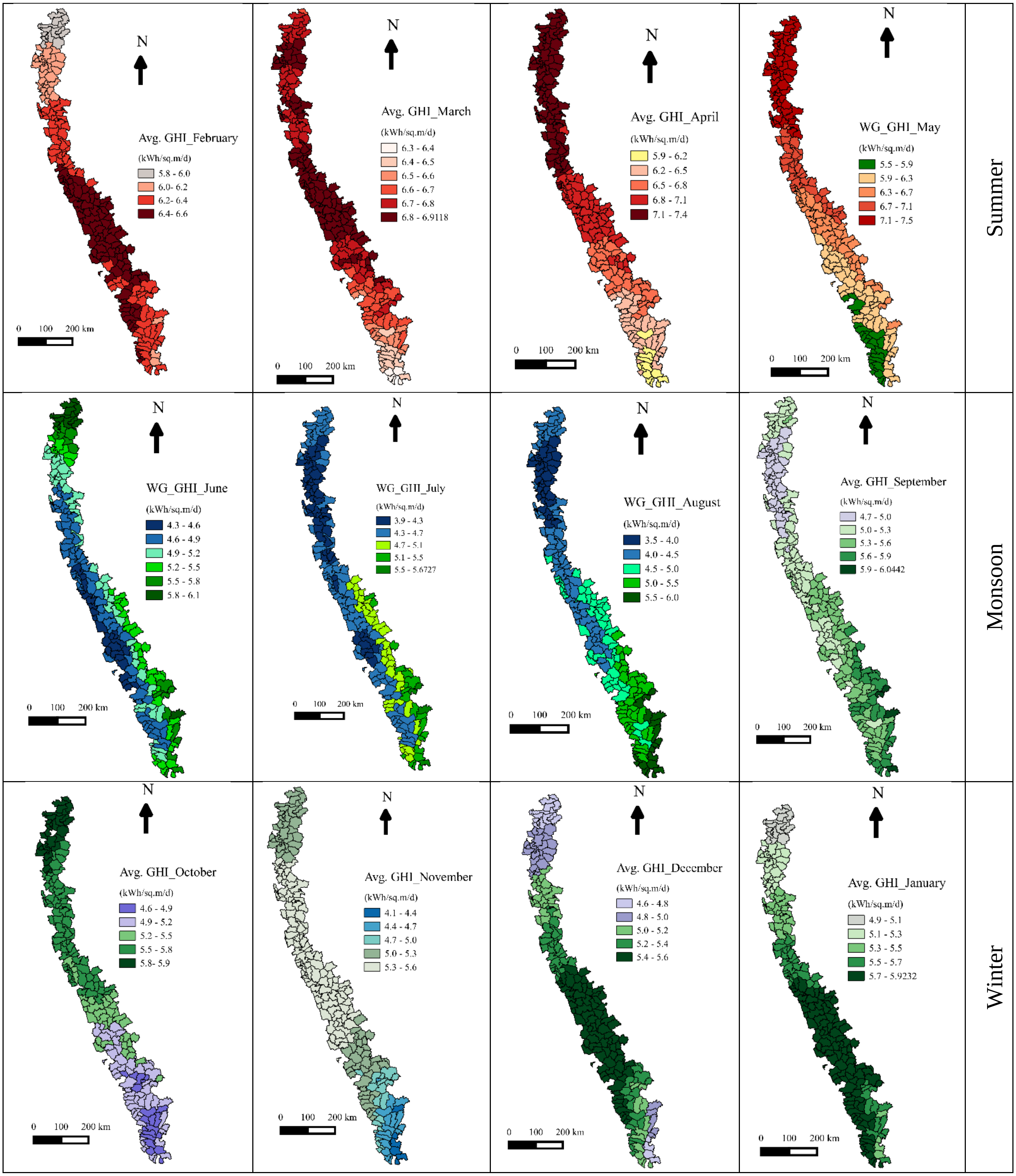


Figure 5: Seasonal distribution of solar insolation across the taluks in WG region

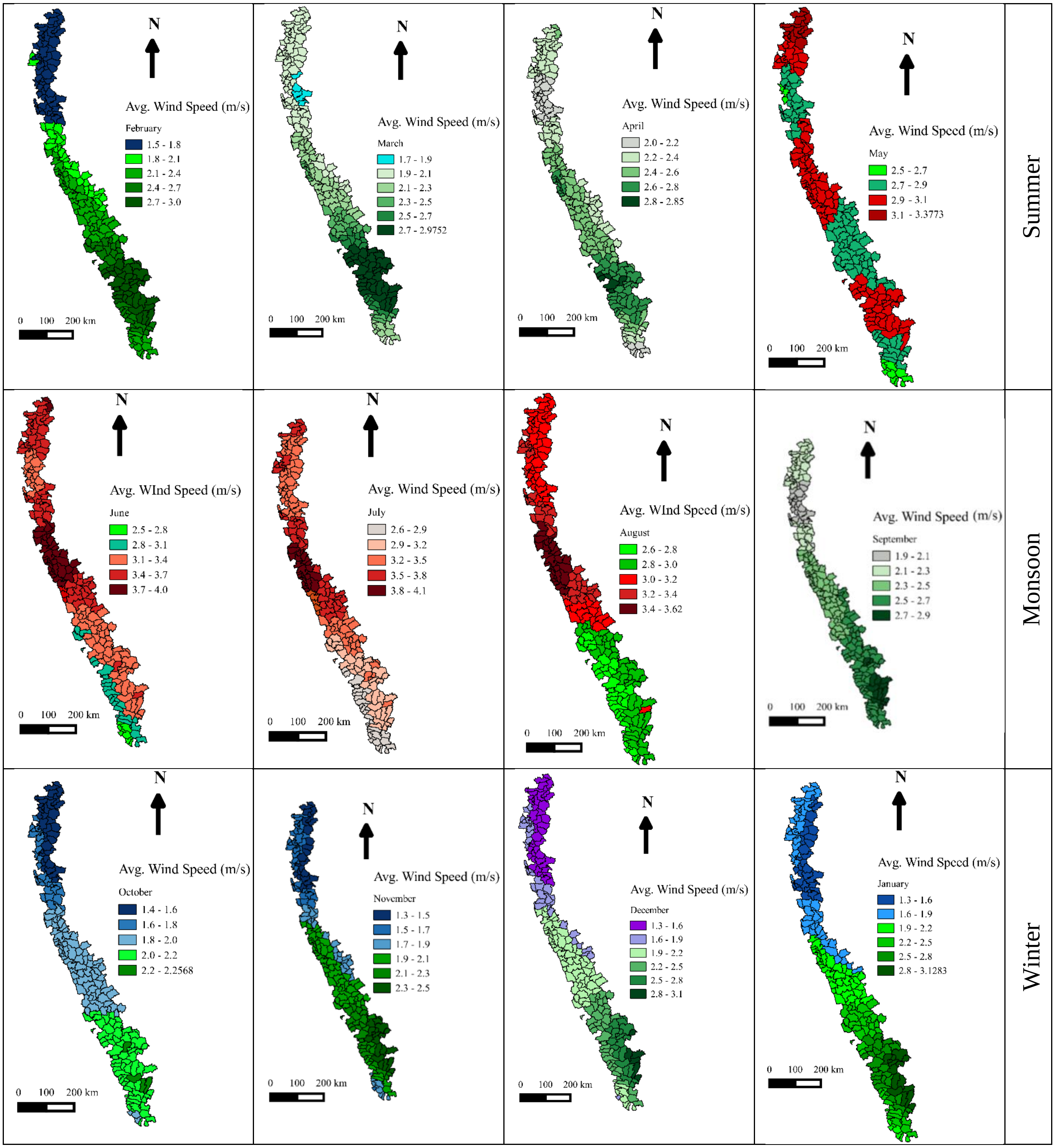


Figure 6: Seasonal distribution of wind speed across the taluks in WG region

Scope for solar energy is assessed considering the present energy demand and extent of wasteland available in the state. Figure 9 shows the month wise electric energy that could be generated using a fraction of wasteland area (Gujarat – 2%, Maharashtra – 1.5%, Goa – 2%, Karnataka – 2% and Kerala – 3%) and the monthly elctric energy demand. The electric energy consumption in the states of WG region varies seasonally. Electricity consumption is more during summer months while the solar insolation received is also higher. Energy consumption decreases during monsoon, where the insolation is lower. The figure shows that the electricity required follows the solar energy potential in all the states. Table 4 gives the wasteland area required to mee the electricity demand in all the states of WG region. Wind energy density map shows that peak power deficiency in Maharashtra, Karnataka and Kerala occur when the wind density is high. Harvesting wind would help in meeting the peak demand. The assessment shows that wind power potential can significantly contribute in supplying the peak power demand from March to August.

Table 4: State wise annual electric energy and wasteland required to supply using solar potential

State	**Available wasteland (km^2)**	**Total energy consumption in 2011 (GWh)**	**Required wasteland to meet the demand (km^2)**
Gujarat	20108.06	86485	402.16 (2%)
Maharashtra	37830	127488	567.45 (1.5%)
Goa	489.08	2785	9.78 (2%)
Karnataka	13030.62	64519	260.6 (2%)
Kerala	2445.63	20943	73.36 (3%)

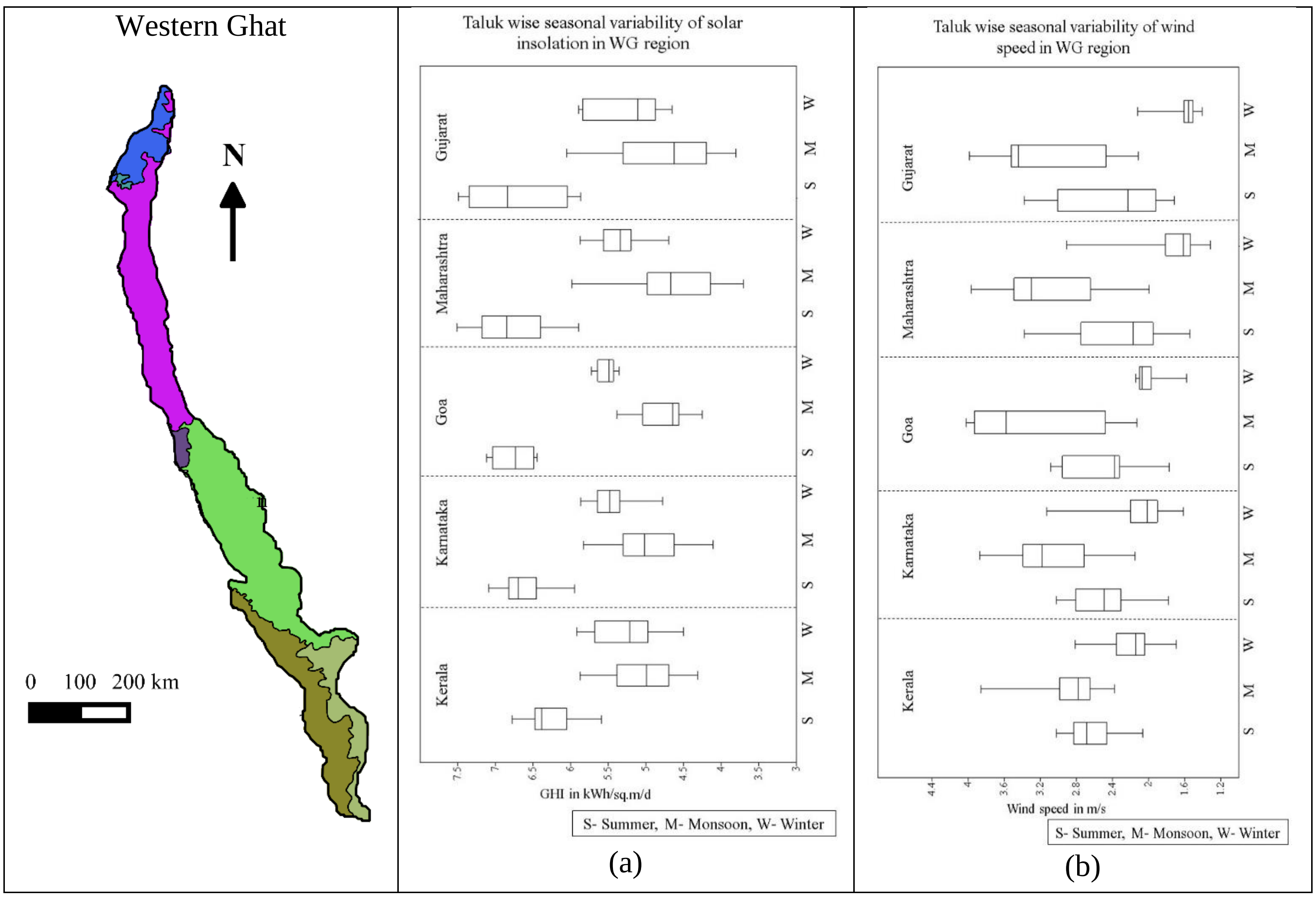


Figure 7: Variability in solar energy and wind speed potential in WG region

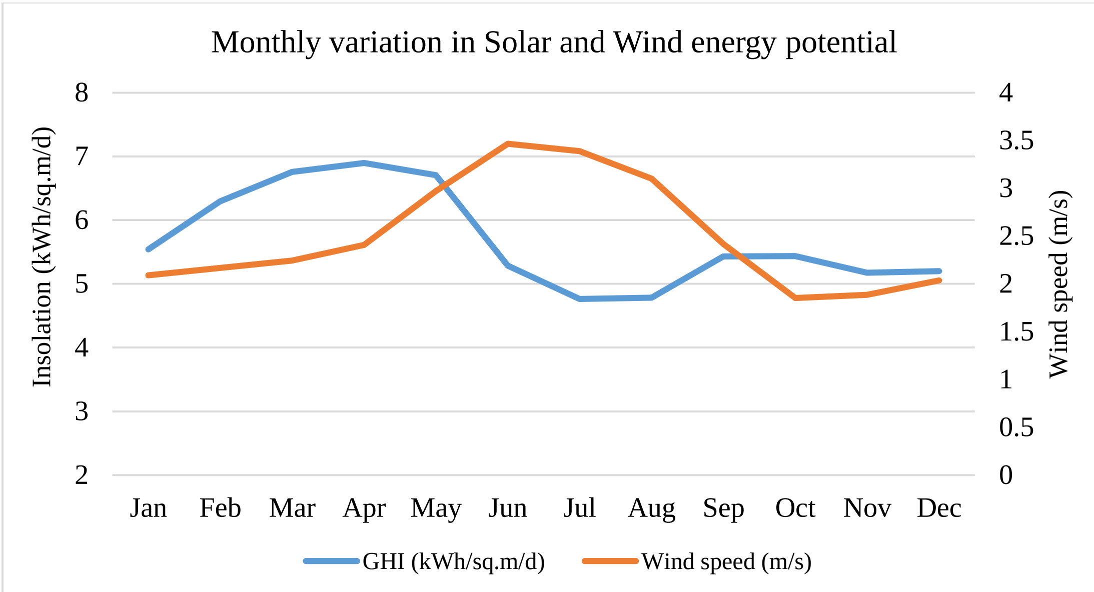
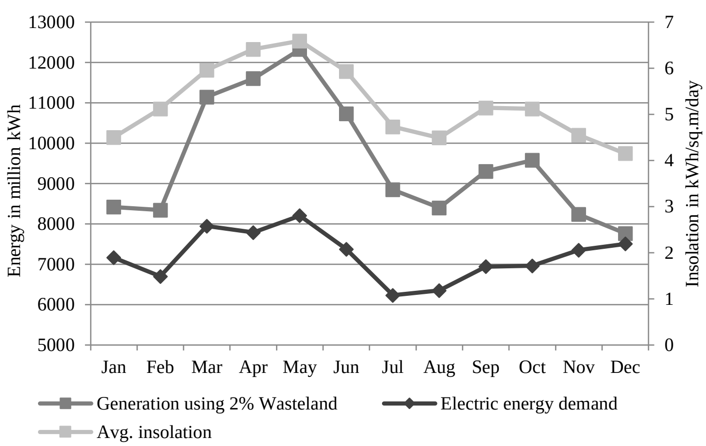
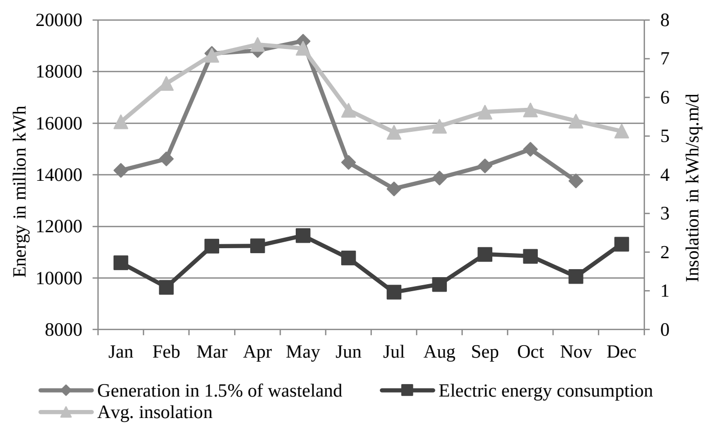


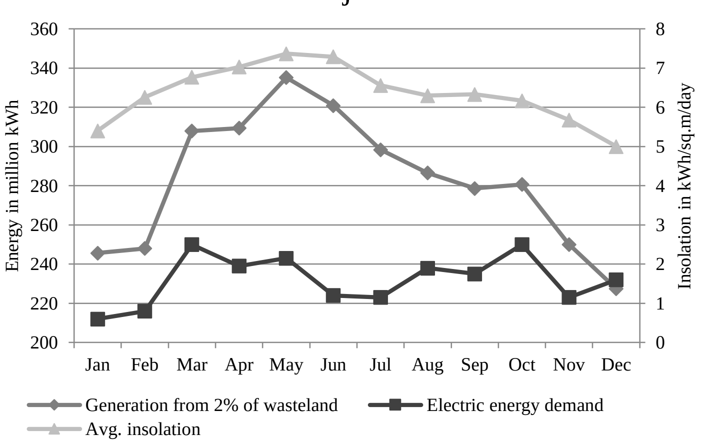
Figure 8: Monthly variation of solar insolation and wind speed in WG region



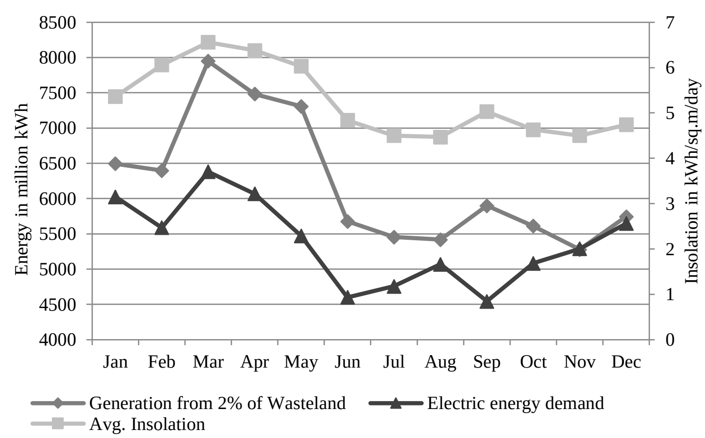
Gujarat



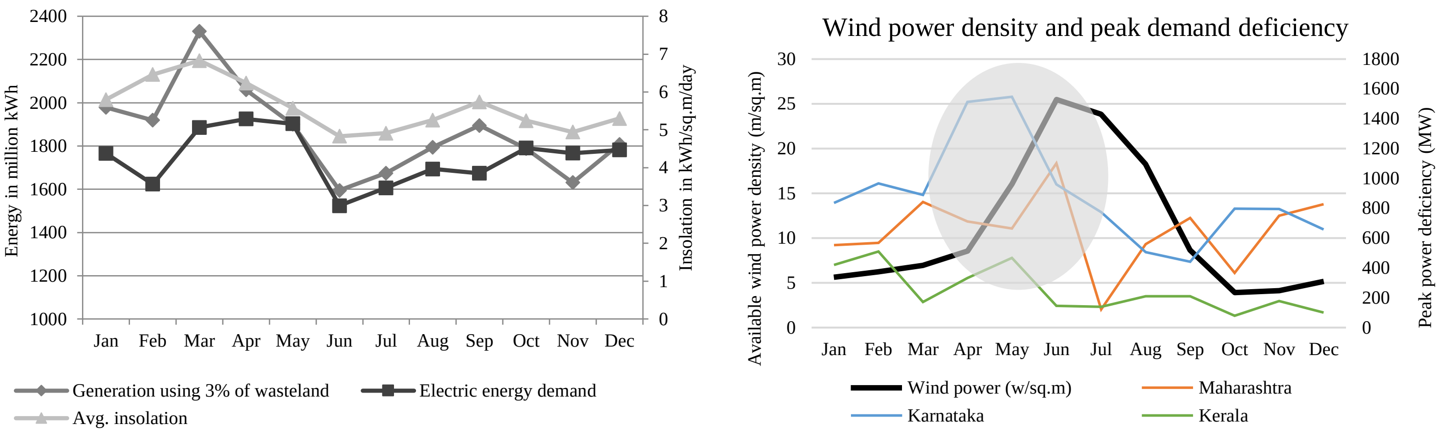
Maharashtra



Goa



Karnataka



Kerala

Figure 9: Electric generation using renewable potential in waste land (state wise)

System Simulation

Scenario 1: Rooftop SPV- for un-electrified household

System is modelled for an un-electrified home which needs minimum electricity for 5-6 hours a day, contains the loads of CFL lamps (4-5) and a fan. Figure 10 shows the simulated SPV system with peak home load of 67 W and average load of 20-30 W. This demand will be supplied for minimum of 5 hours per day and hence the average energy consumption ranges from 400 to 450 Wh/day. For the modelling of the stand-alone rooftop PV system, a peak load of 67 W and average electrical energy consumption of 425 Wh/day were considered. Constant load operation is assumed irrespective of the seasons to avoid complexities in the modelling. It will also help in optimising the PV panel and battery capacity with respect to cost.

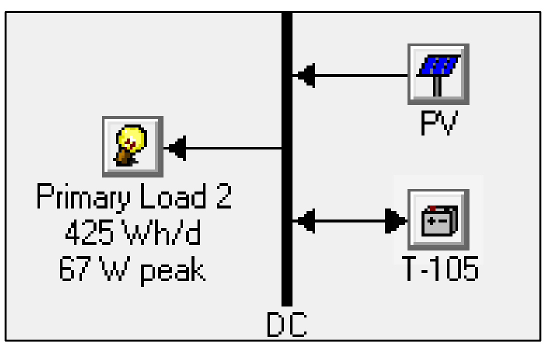


Figure 10: Simulation model diagram – Un-electrified household

HOMER simulations show that annual energy generation of about 206 kWh. Excess energy generated is about 35 kWh (25.6%) mostly during summer. Unmet demand during June to September (monsoon) is 9.52 kWh/year due to lower insolation. Initial capital cost of the system (excluding charge controller and fitting) is about INR 20,500 and total net present cost (NPC) is INR 50,500 for the operation of 20 years. Levelised cost of electricity generated is INR 23.1/kWh whereas operating cost of the system is INR 2,050 and unit cost of the electricity generated is found to be INR 9.5/kWh. Figure 11 shows the annual DC load served and unmet load. During June to August months, a fraction of load was not supplied as insolation received was lesser than 4 kWh/m^2/day. Figure 12 shows the battery status of charge (%) and the excess electricity generated from the system. During monsoon months (June to September) battery charge status found lower (30%), which may reduce the battery life and efficiency. This also would increases the unmet energy demand in the system and reduces the reliability. Figure 13 gives the Dmap (data map) of battery bank state of charge throughout the year.

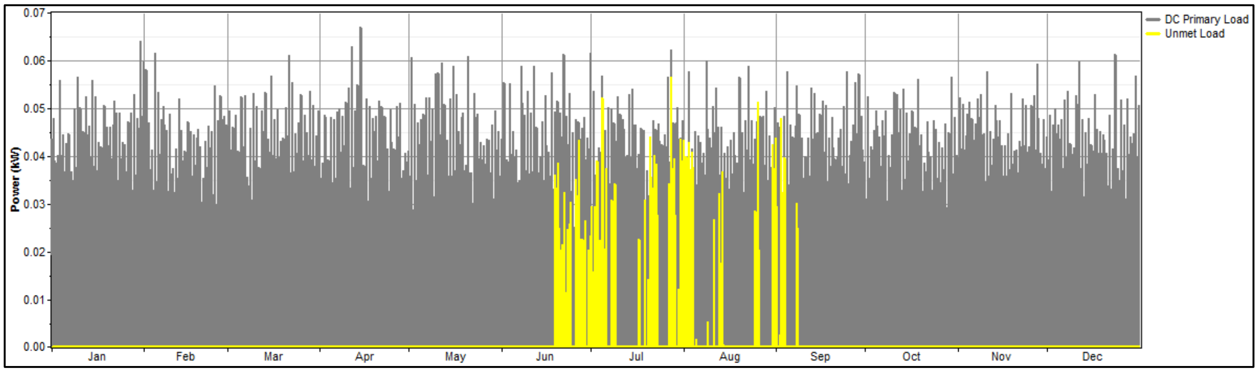


Figure 11: DC load supplied and unmet electricity in a year

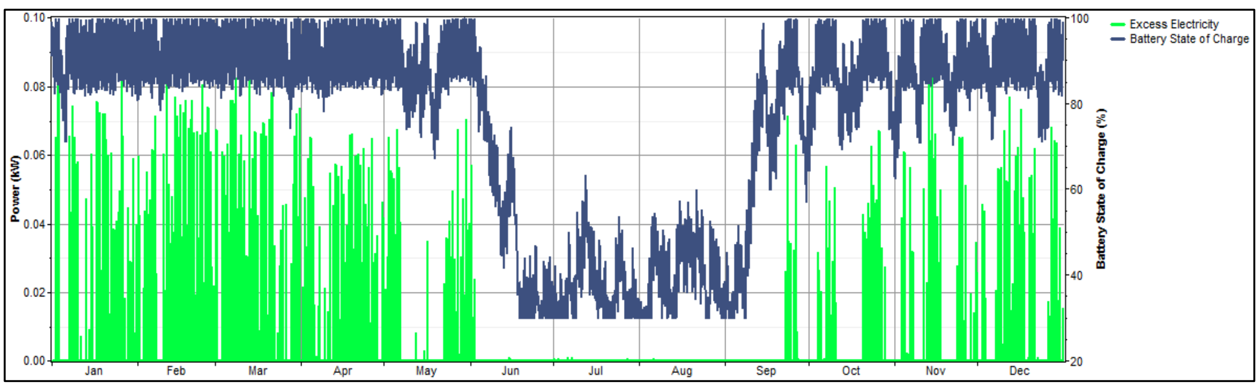


Figure 12: Battery status of charge and excess electricity generated throughout the year

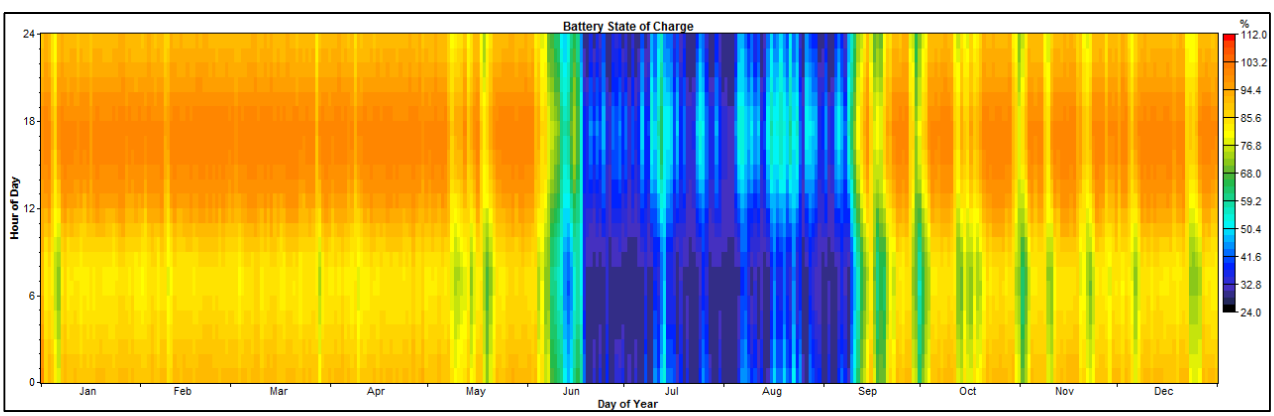


Figure 13: Hourly data of battery status of charge (%)

The system can generate about 206 kWh of green energy annually, reducing the significant greenhouse gas (GHG) emission. Table 4 gives the annual CO_2, SO_2, NO_x and CO emission reduction due to the electricity generation from SPV panels compared to other generating plants.

Table 5: GHG reduction using SPV compared other electricity generating plants

Type of GHG	Coal	Diesel	Natural Gas	Nuclear
CO_2 (tons/yr)	216.3	168.04	95.68	3.24
SO_2 (kg/yr)	0.82	0.26	0.65	0.648
NO_x (kg/yr)	0.937	3.87	0.48	0.019
CO (kg/yr)	2306.88	0.832	-	-

Source: [31-33]

Scenario 2: SPV-Wind-Biomass gasifier based hybrid generation for rural electrification

Hybrid system of energy generation is capable of providing reliable electricity supply compared to single energy source based systems. An optimal generation scheduling is possible in such systems depending on least cost of generation, which leads to lesser unit cost of energy [34]. Though RE sources are intermittent in nature, but hybrid systems of two or more sources provide continuous supply and hence are best suited for rural electrification [35]. Solar-Wind-Biomass based hybrid electricity generation system is modelled to meet the electricity demand of a village which is connected to the grid. However, the effect of Feed in Tariff (FIT) is analysed to optimise the system for least operation cost and higher renewable energy integration.

Figure 14 shows the simulated hybrid grid connected model (PV-Wind-Biomass Gasifier) to meet the demand. The system modelled to supply a typical village load of ~1187 kWh/day with a peak power demand of 49 kW. The total annual average energy requirement of the village is about 4,33,255 kWh which contains about 310 households (Census, 2001).

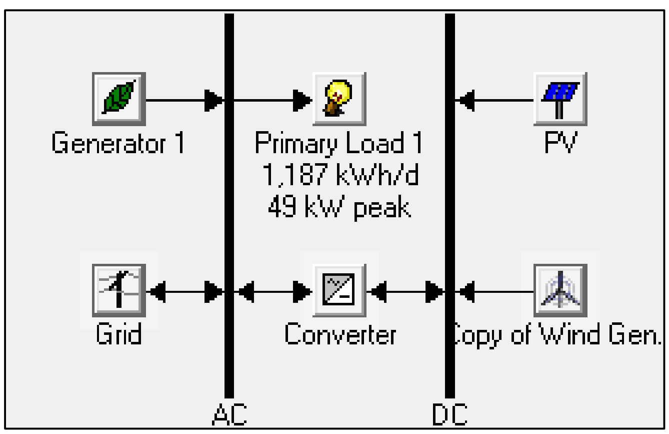


Figure 14: Simulation model diagram – Hybrid system

Technical specifications of the simulated model are given in Table 6. Gasifier based generator of capacity 50 kW is combined with a 70 kW_p PV and 40 kW wind generator. Gasifier connected generator is operated between 8 to 10am in the morning and 7-10pm in the evening when the domestic load is likely to be higher. A converter is equipped in the system which connects the DC generation to AC grid. Capacity of the converter is 80 kW which should be equipped with filters to avoid harmonics while converting DC to AC power. Available distribution network has to be employed for energy supply in the village having prior permissions from utility.

Case 1: Grid connected - without FIT

The system has been simulated in HOMER and total energy generation found to be 4,65,076 kWh per annum which can meet the required energy demand in the village. Energy purchased from grid is found to be 2,01,364 kWh (43%) and the electricity generation from renewable energy is about 2,63,713 kWh (57%). Figure 15 shows the variation in monthly electric energy generation from different energy sources.

The capital cost of the system is about INR 2,97,00,810 while the operating cost is about INR 1,372,792. Cost of electricity (COE) generated is found to be INR 5.97 per kWh which is comparable with the grid electricity.

Table 6: Technical and economic specifications of the hybrid model

Equipment	Rating	Cost[a] (INR)	Other details
Generator	50 kW	20,00,000	Replacement cost is 10,00,000
PV module	70 kWp	56,35,000	Life: 20 years No replacement cost
Wind Generator	40 kW	54,80,000	Life 20 years No replacement cost
Converter/Inverter	80 kW	8,40,000	Replacement cost: INR 4,20,000
Annual fixed maintenance cost	All equipment	50,000	Including labor cost

[a] Estimated and approximated comparing with the market value

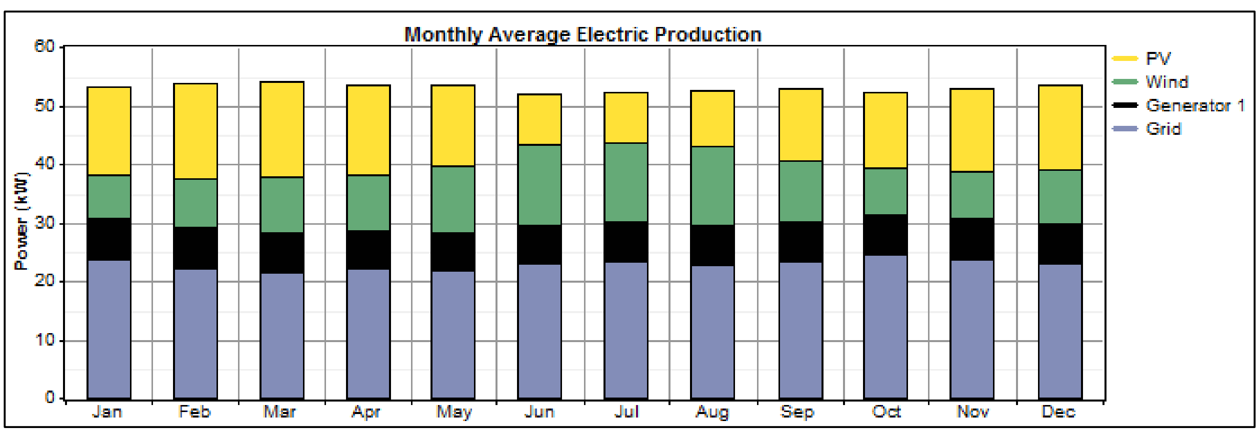


Figure 15: Variation in monthly electric energy generation from different energy sources.

Total operation duration of biomass based generator is 1,825 hours/year which consumes 337 tonnes of biomass. The specific fuel consumption is found to be ~4 kg/kWh and recorded mean electrical efficiency is 16.5%. Output from PV array found maximum (68.3 kW) from 10 am to 4 pm and varies seasonally; from June to September it was lower. The average output of solar PV is about 13.1 kW with average energy generation of 315 kWh/day. The maximum output of wind generator reached 23.1 kW during monsoon (June - August) and the average output is found to be 10.2 kW.

Case 2: Grid connected - with FIT of INR 7 per kWh

In this system with FIT of INR 7 per kWh, grid purchase is found to be 2,15,027 kWh (36%) and the electricity generation from renewable energy is about 3,80,883 kWh (64%). In this system about 25% (1,42,212 kWh) of electricity is sold to grid after meeting the connected loads. Figure 16 shows the variation in monthly electric energy generation from different energy sources. The net present cost of the system is about INR 2,48,26,564 while the operating cost is reduced to INR 9,47,833. Cost of electricity (COE) generated is found to be INR 5 per kWh which is lesser compared to the case 1.

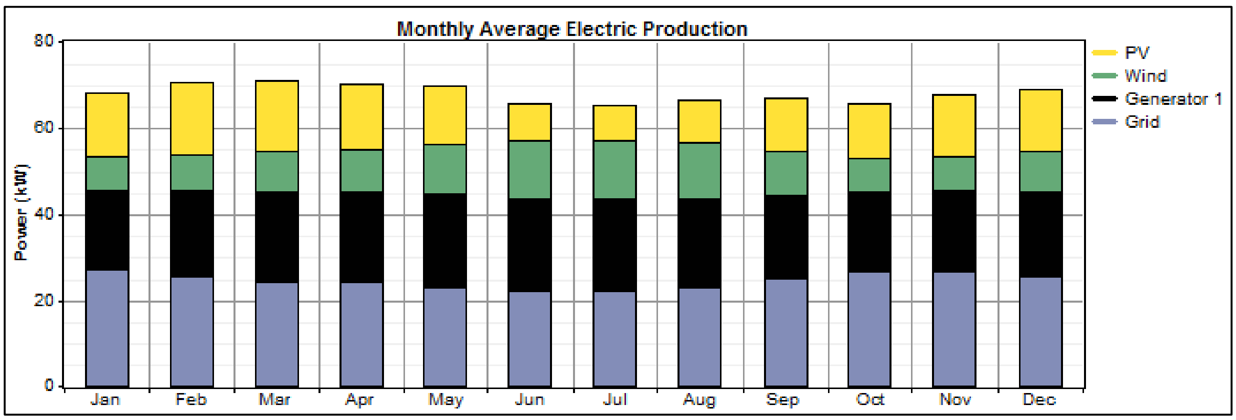


Figure 16: Variation in monthly electric energy generation from different energy sources.

Total operation duration of biomass based generator has increased to 3,529 hours/year where the generator is not operated from night 10pm to morning 6am which consumes 731 tonnes of biomass. The specific fuel consumption is found to be 2.9 kg/kWh and recorded mean electrical efficiency is 22.6%. Output from PV array found maximum (68.3 kW) between 10 am to 4 pm and varies seasonally; from June to September it was lower. The average output of solar PV is about 13.1 kW with average energy generation of 315 kWh/day, however total energy generation from PV is about 1,15,032 kWh annually. The maximum output of wind generator reached 23.1 kW during monsoon (June - August) and the average output is found to be 10.2 kW.

Case 3: Grid connected - with FIT of INR 15 per kWh

In this case, with FIT of INR 15 per kWh, purchase from grid has reduced drastically to 1,40,888 (23%) and the electricity generation from renewable energy has increased to 4,78,284 kWh (77%). But the energy sold to grid increased marginally 28% (165,473 kWh) where, most of the electricity is used to meet the local demand. Figure 17 shows the variation in monthly electric energy generation from different energy sources. The net present cost of the system decreased to INR 1,01,02,231 while the operating cost is reduced to INR 3,35,867.

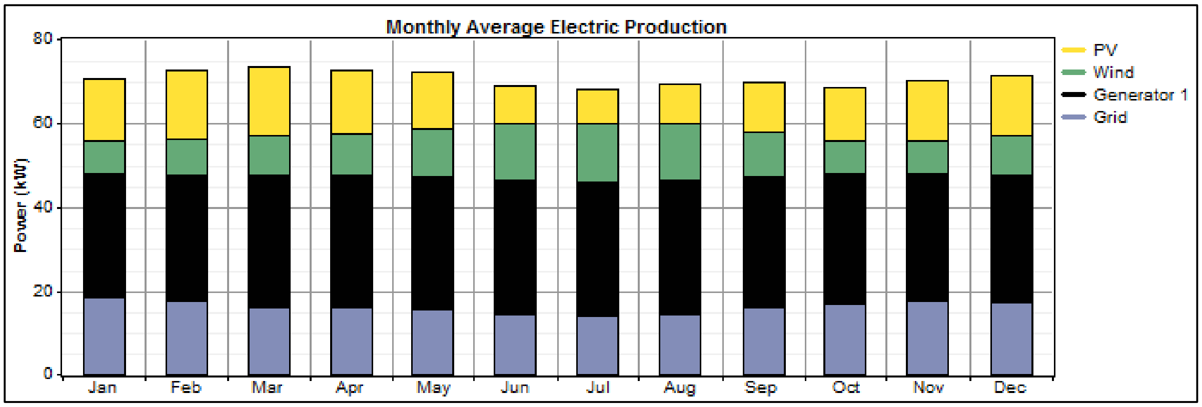


Figure 17: Variation in monthly electric energy generation from different energy sources

Cost of electricity (COE) generated is found significantly low, INR 2 per kWh which is lesser compared to the grid electricity. Total operation duration of biomass based generator has increased to 5,477 hours/year which consumes 1,135 tonnes of biomass. The specific fuel consumption is found to be 2.9 kg/kWh and recorded mean electrical efficiency is 22.6%. Output from PV array and Wind generating system remained same as that in Case 2.

Economic and Emission analysis

Table 6 describes the variation in operating costs with respect to the base case (Case 1), as FIT increases. Net present cost and the operating costs of the system decrease with the increase in the FIT. Cost of electricity (COE) is dependent on the operating cost, which reduces with increment in the FIT. Though the energy generation from renewable sources is increasing, unit cost of electricity is reducing shows that generation based incentives (GBI) and feed in tariff (FIT) could help to reduce the system cost. The reduction in GHG due the renewable energy integration to the grid is shown in Table 7. It can be seen that vast amount of GHGs can be cut down with the integration of RE sources.

Table 7: Cost variation of the hybrid system with change in FIT

	Net present cost (INR)	**Operating cost (INR)**	**COE (INR)**	**Grid purchase (kWh)**	**Energy sold (kWh)**	**RE fraction (%)**
FIT = 0	2,97,00,810	13,72,792	5.97	2,01,364	11,378	56.7
FIT = 7	2,48,26,564	9,47,833	5.0	2,15,027	1,42,212	63.9
FIT = 15	1,01,02,631	3,35,867	2.033	1,40,888	1,65,473	77.2

However, gasifier generator produces little amount of greenhouse gases which is accounted during the computation of GHG reduction from different power plants. Since the model is simulated for the real time load, can also be replicated in other villages in the country which would contribute in reducing the carbon footprint.

Table 8: Reduction in GHG emission with respect to FIT variation

	GHG reduction (tons/yr)	**Coal**	**Diesel**	**Natural Gas**	**Nuclear**
FIT=0	CO_2	276699.11	204969.17	116625.32	6393.28

	SO_2	1001.12	315.47	78.13	0
	NO_x	1143.92	4.37	619.14	1.94
	CO	2953.58	1.07	-	-
FIT=7	CO_2	399851.62	296251.17	168655.03	9445.52
	SO_2	1446.98	456.68	113.89	0.76
	NO_x	1652.78	6.90	894.82	3.40
	CO	4265.90	1.54	-	-
FIT=15	CO_2	502198.20	372104.95	211879.81	11957.10
	SO_2	1817.48	573.94	143.49	1.43
	NO_x	2075.75	8.99	1123.97	4.59
	CO	5356.78	1.94	-	-

Source: [32-34, 36]

Conclusion

Taluks in the Western Ghats region receive higher solar insolation (>5.5 kWh/m^2/d) and also experience swift winds (2- 3 m/s), makes this place suitable for decentralised electricity generation. Electricity harvesting by exploiting available renewable energy potential (avoiding coal/nuclear/hydro power plants) could also help in conserving the biodiversity of the region. A small fraction of available wasteland (1-3%) in each state is sufficient to meet the present electricity demand using SPV installation. Available wind power density shows that, peak demand deficiency can be met with wind power potential of the region. Study analyses the variability of wind and solar energy resources which also maps the energy potential of WG taluks. Decentralised electricity generation using renewable energy sources is the sustainable option to meet the future demand in an environmental friendly way.

A standalone system is promising to meet the domestic electricity (light and fan) requirements of an un-electrified remote household. It could generate sufficient energy to supply demand for more than 6 hours with excess generation of about 25.6%. The system can be installed in every rural household in varying capacities. Hybrid DG systems (SPV/Wind/Biomass gasifier) is a novel way of electrifying villages, which if implemented will revolutionise the Indian rural scenario with reliable electrification. The simulated outcome highlights of meeting the respective village's domestic electricity demand in a decentralised way through locally available abundant resources - biomass and SPV.

Adopting renewable energy technologies can address the environmental issues and energy crisis in the developing countries like India. Rooftop electricity generation using SPV panels can electrify remote household supplying the energy for lighting and other domestic applications. Present study reveals that, FIT and GBI would boost the energy generation from decentralised hybrid systems. Distributed generation and hybridisation of local energy sources can help in overcoming the resources intermittency while reducing the load of regional grid. However there is an immediate need to promote green energy generation through friendly policies and generation based incentives (GBI). Technological advancement in two way metering (net metering) and intelligent controlling of micro grid requires attention and encouragement. Green energy generation certainly ensures the local energy sustainability and global pollution control which is adoptable across the country.

Acknowledgement

We thank the NRDMS division, the Ministry of Science and Technology, Government of India, Indian Institute of Science and The Ministry of Environment and Forests, GOI for the sustained support to carry out energy research.

References

[1] Sajal Ghosh (2000), Electricity consumption and economic growth in India, *Energy Policy*, 30, 125–129.

[2] Andreas Kemmler (2007), Factors influencing household access to electricity in India, *Energy for Sustainable Development*, (11) 4, 13-20.

[3] Tariq Muneer, Muhammad Asif and Saima Munawwar (2005), Sustainable production of solar electricity with particular reference to the Indian economy, *Renewable and Sustainable Energy Reviews*, 9, 444–473.

[4] Mishra U.C. (2004), Environmental impact of coal industry and thermal power plants in India, *Journal of Environmental Radioactivity*, 72, 35–40.

[5] Panwara N.L., Kaushik S.C. and Surendra Kothari (2011), Role of renewable energy sources in environmental protection: A review, *Renewable and Sustainable Energy Reviews*, 15, 1513–1524.

[6] Central Electricity Authority (CEA) monthly reports accessed on 5th July 2014. (http://www.cea.nic.in/reports/monthly/inst_capacity/mar14.pdf).

[7] Luc Gagnon, Camille Belanger and Yohji Uchiyama (2002), Life-cycle assessment of electricity generation options: The status of research in year 2001, *Energy Policy*, 30, 1267–1278.

[8] Daniel Weisser (2007), A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies, *Energy*, 32, 1543–1559.

[9] Akella A.K., Saini R.P. and Sharma M.P. (2009), Social, economical and environmental impacts of renewable energy systems, *Renewable Energy*, 34, 390–396.

[10] Ramachandra T.V., Rishabh Jain and Gautham Krishnadas (2011), Hotspots of solar potential in India, *Renewable and Sustainable Energy Reviews*, 15, 3178–3186.

[11] Mitavachan H. and Srinivasan J., (2012), Is land really a constraint for the utilization of solar energy in India?, *Current Science*, 103 (2), 163-168.

[12] Ramachandra T.V., Subhash Chnadran M.D., Harish R. Bhat, Sumesh Dudani, Rao G.R., Bhoominathan M., Vishnu Mukhri and Bhaarth S., Biodiversity, Ecology and Socio-Economic Aspects of Gundia River Basin in the context of proposed Mega Hydro Electric Power Project, CES Technical Report 122, Energy & Wetland Research Group, Centre for Ecological Sciences, Indian Institute of Science, Bangalore - 560012, INDIA.

[13] Ramachandra T.V., Ganesh Hegde, Bharath Settur and Gautham Krishnadas (2014), Bioenergy: A sustainable Energy Option for Rural India., *Advances in Forestry Letters (AFL)*, 3 (1), 1-15.
[14] Ramachandra T.V., Ganesh Hegde and Gautham Krishnadas (2014), Potential Assessment and Decentralized Applications of Wind Energy in Uttara Kannada, Karnataka, *International Journal of Renewable Energy Research*, 4 (1), 1-10.
[15] Ramachandra T.V., Ganesh Hegde and Gautham Krishnadas (2014), Scope of Solar Energy in Uttara Kannada, Karnataka State, India: Rooftop PV for Domestic Electricity and Stand alone for Irrigation, *Productivity*, 55 (1), 103-119.
[16] Deshmukh M.K. and Deshmukh S.S. (2008), Modeling of hybrid renewable energy systems, *Renewable and Sustainable Energy Reviews*, 12 (1), 235-249.
[17] Progress Report on Rural Electrification, Central Electricity Authority, Ministry of Power, Govt. of India, accessed on 7th July 2014 (http://www.cea.nic.in/welcome1.htm).
[18] Ramachandra T.V. (2011), Renewable energy transition: Perspective and Challenges. In: Energy India 2020- A Shape of Things to come in Indian Energy Sector, Saket Projects Ltd., Ahmedabad, 175-183.
[19] Ramachandra. T.V. and Gautham K. (2011), Decentralized renewable energy options for Himalayan states in India. Paper presented in 7th National Conference on Indian energy sector "SYNERGY WITH ENERGY", November 18th-19th, AMA, Ahmedabad, 80-86.
[20] Ramachandra T.V., Rajeev K.J., Vamsee Krishna S. and Shruthi B.V. (2005), Wind energy potential assessment spatial decision support system, *Energy Education Science and Technology*, (14), 61-80.
[21] Ramachandra T.V. and Gautham Krishnadas (2012), Prospects and Challenges of decentralized wind applications in the Himalayan Terrain, J*ournal of Energy Bioscience*, 3, 1-12.
[22] Ramachandra T.V., Ganesh Hegde and Veena H.S. (2014), Sustainable Decentralised Green Energy Model for Rural India, 30th National Convention of Environmental Engineers & National Seminar on Fostering Greenovations for Green Growth, The Institution of Engineers (India), 22nd August 2014.
[23] Nouni M.R., Mullick S.C. and Kandpal T.C. (2009), Providing electricity access to remote areas in India: Niche areas for decentralized electricity supply, *Renewable Energy*, 34, 430–434.
[24] Ramkumar R., Sudhakar Shetty P. and Ashenayi K. (1986), A Linear Programming Approach to the Design of Integrated Renewable Energy Systems for Developing Countries, *IEEE Transactions on Energy Conversion*, 1 (4), 18-24.
[25] Iniyan S. and Sumathy K. (2000), An optimal renewable energy model for various end-uses, *Energy*, 25 (6), 563-575.
[26] Ramachandra T.V. (2009), RIEP: Regional Integrated Energy Plan, *Renewable and Sustainable Energy Reviews*, 13 (2), 285–317.
[27] Surface Meteorology and Solar Energy Release 6.0 Methodology, NASA. Viewed on October 17, 2012. (http://eosweb.larc.nasa.gov/sse/ documents/SSE6Methodology.pdf)
[28] NREL GHI data furnished by National Renewable energy Laboratory, 2010.

[29] World Meteorological Organization, Guide to Meteorological Instrument and Observing Practices, 4th Edition, WMO, No. 8, TP. 3 Geneva, Switzerland, 1964.
[30] Climate Research Unit, University of East Anglia, Accessed on 10th June 2013. (http://www.cru.uea.ac.uk/cru/data/hrg/tmc/).
[31] Ramachandra T.V. and Ganesh Hegde (2014), Scope for Distributed Renewable Energy Systems in South India, 2014 IEEE Global Humanitarian Technology Conference - South Asia Satellite (GHTC-SAS) 26-27 September 2014.
[32] Chakraborty N., Mukherjee I., Santra A.K., Chowdhury S., Chakraborty S., Bhattacharya S., Mitra A.P. and Sharma C. (2008), Measurement of CO_2, CO, SO_2, and NO emissions from coal-based thermal power plants in India, *Atmospheric Environment*, 42, 1073–1082.
[33] Emission Estimation Technique Manual for Combustion Engines Version 2.2, National Pollutant Inventory, Commonwealth of Australia, 2002.
[34] Moti L. Mittal, Chhemendra Sharma and Richa Singh (2012), Estimates of Emissions from Coal Fired Thermal Power Plants in India, accessed on 16th July 2014 (www.epa.gov/ttnchie1/conference/ei20/session5/mmittal.pdf).
[35] Balamurugan P., Ashok S. and Jose T.L (2009), Optimal operation of biomass/wind/pv hybrid energy system for rural areas, *International Journal of Green Energy*, 6, 104-116.
[36] Paulina Jaramillo, Michael Griffin W. and Scott Matthews H. (2007), Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation, *Environmental Science and Technology*, 41, 6290-6296.