Techno-Economic Analysis of Hybrid Renewable Energy System for Rural Electrification in India

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***Abstract*— This paper discusses a Hybrid Renewable Energy System (HRES) on basis of energy resources available for the location. The technical reliability and economic feasibility of HRES for a single household in an off-grid location is analyzed. The HRES modelled for the house constitutes a 100 percent renewable fraction and is proposed to serve a load demand of approximately 2.835 - 4.965 kWh/d over the three seasons. The results obtained reveal that HRES has the potential to overcome the issue of intermittent power and can balance load demand throughout the year by reducing unmet load and capacity shortage for the household at the same time being an economically feasible solution in terms of cost of energy studied over a projected lifespan of 25 years. This analysis is first of its kind in the state of Jharkhand, India and can be used as a framework to improve electricity infrastructure in electricity deprived communities.**

Keywords— HRES, unmet load, capacity shortage, state of charge (SOC), net present cost (NPC), cost of energy (COE).

I. Introduction

Energy is accepted as intrinsically linked with environmental, social and economic dimensions of sustainable development. Providing reliable and secure electricity supplies, reducing environmental impacts and providing access to electricity to all have been recognized as the key challenge for all the electricity sectors globally [1]. Energy management is thus one of the most important aspects any government has to deal with [2]. Individually, rural sectors or hamlets may not be very important energy markets with sensible critical mass, but taken together, they are presently the largest niche market in the world for renewable energies (RE). In fact, at present, the largest percentage of the RE in the energy balance is also to be found in villages and rural areas [3].

On the other hand, the progresses made by rural sectors in developing countries are often found to be inefficient and inappropriate as they often become non-functional after few years of installation due to variety of reasons. There are also political, financial, legal and knowledge barriers preventing the optimum exploitation of renewable energy technologies(RETs), which must be overcome in order to create a favorable socio-economical and technical environment for electrification in rural sectors [4], [5]. In this regard in-depth study on techno-economic aspects of RETs for electrification in rural sectors for providing clean reliable energy is important [6].

As per the Government of India's 2006 rural electrification policy, a village is deemed 'electrified' if basic infrastructure such as distribution transformer and distribution lines has been set up in the inhabited locality, including a 'Dalit Basti' [7]. If government data is anything to go by, nearly all villages in the country or 98.7 per cent of them, to be precise have been electrified. But a closer look at the electrification data from the hinterland especially from states such as Bihar, Uttar Pradesh, Assam, Jharkhand and Odisha show that a sizeable number of the households in villages across most states are still in the dark, without access to electricity [8]. Approximately one-third of the populations living in India do not currently have access to electricity, and most of these individuals reside in rural areas [9].

The Indian government has declared that one of their core priorities is to provide electricity to every household in India[10]. While gradual progress has been made in extending the central electricity grid, reaching all rural households through such efforts is not a viable solution. A promising approach to the challenge of rural electrification is to increase the deployment of decentralized energy generation through the use of microgrids, which refers to a smaller-scale electric grid combined with a local generation source [11], [12].

The focus of this paper is to scale up the deployment of microgrids in all those villages where it is deemed the best option for rural electrification. It is essential to ensure that microgrids projects are both technically reliable, financially feasible and socially sustainable. In order to achieve this the steps of analyzing a microgrid project for any location is carried out in chronological order described below:

1. Assessment of Resources
2. Selecting System Parameters
3. Load Profile Assessment
4. Technical Assessment
5. Economic Assessment

This paper presents the technical and economic assessment of a HRES for a single household with a load demand of approximately 4kWh that can be utilized as a framework to provide electricity in village named Sapra, Jharkhand, India. The HRES system consists of PV, wind and a suitable storage unit making the system 100 % renewable energy based system.

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The remaining sections of the paper is organized as: section 2 concentrates the resource assessment of the specified location, section 3 deals with the methodology followed by section 4 as results and observations with concluding notes in section 5.

II. ASESSMENT OF THE LOCATION

A. Solar and Wind Resource Asessment

The selected off-grid remote rural village for the analysis is Sapra, (22°47′N 86°12′E) in the Indian state of Jharkhand. The selected village is a plateau having abundant solar radiant and wind energy to be utilized for power generation. The solar irradiance (kW/m^2), ambient temperature, PSH (peak sun hours), wind data for the location selected has been resourced from NASA Surface Meteorology [13]. The highest PSH of 6.40 is obtained in April with the lowest PSH value of 4.084 is recorded in December with a scaled annual average of 5.01 (kWh/m^2/d) and an average clearness index of 0.541 as shown in Fig 1. The annual average wind speed for the location is 2.39 m/s as can be seen in Fig 2.

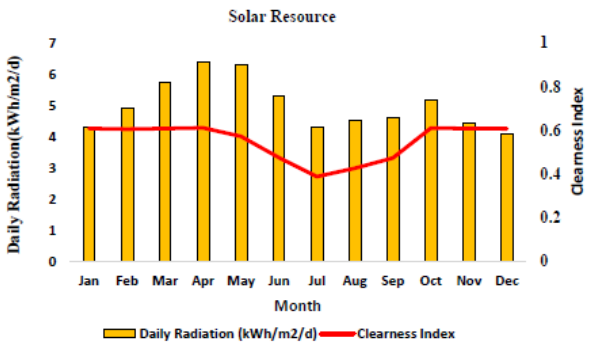

Fig 1. Solar Resource of the selected site [13]

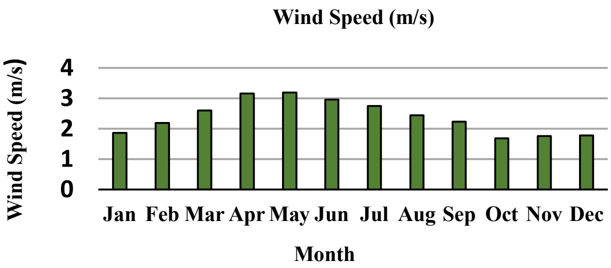

Fig 2. Wind Resource of the selected site [13]

B. Load Profile for Single Household

The HRES system is modelled for a single household to balance a load demand of 4.08 kWh/d with a peak demand of 0.55 kW. As the household considered is in an off-grid based rural location with long dry spells of summers followed by the monsoon and the winters the usage pattern of the electricity varies accordingly and a seasonal profile of load is considered as seen in Fig 3. Also, the load profile varies as per the lifestyle of the people [14][15]. It is an instrumental task for the techno-economic design's load profile to ascertain the type of appliances to be used [16]. As such, the basic appliances that are considered are AC devices such as CFL bulbs, incandescent bulbs, ceiling fans, table fans, radio, mobile charger and a television.

Fig 3. Seasonal based load profile of the household on a 24 hour time line basis

III. METHODOLOGY

As seen in Fig 4. a schematic system configuration diagram showing the design of the selected RET's for the single household. The standalone PV-wind based HRES system contains both PV and wind turbine serving as power generation unit with storage battery bank, converter and a DC and AC bus.

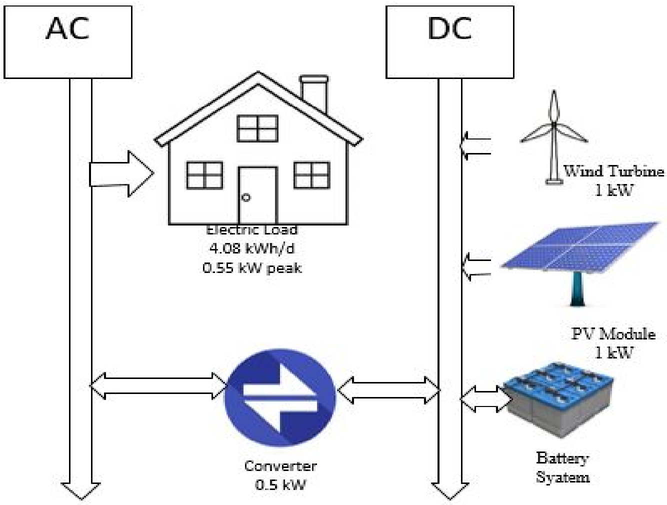

Fig 4. Architecture and Model of a Hybrid Renewable Energy based system

A. System Parameters

1) PV system: As for technical assessment of the system, the size of the PV module considered for the present work is 1 kW and has a lifetime of 25 years with no tracking system. The ground reflection and the derating factor associated with the PV array is assumed to be 20% and 90%, respectively. The temperature coefficients of power, nominal operating cell temperature, and efficiency at standard test conditions is considered to be (-0.5%/˚C), 47˚C, and 13%, respectively. For economic assessment the value of per kW capital cost of the PV module and replacement cost is considered to be $1330 USD with maintenance cost assumed to be zero [15][17].
2) Wind Turbine: As for technical assessment a SW Whisper 200 wind turbine, manufactured by Southwest Wind Power, has been chosen for the simulation work. The rated DC output power of the wind turbine is 1 kW with rotor diameter of 2.7m and the turbine lifetime assumed to be 25 yr. The power generated by the wind turbine is at a hub height 24m. The capital cost of wind turbine is

assumed to be $1500 USD and replacement cost of $1800 USD with zero annual maintenance cost.

3) Battery System: The Trojan L16P battery models are chosen for the present simulation work. The nominal capacity and voltage of the battery are 360 Ah, 6V, respectively, while the rated capacity is 2.16 kWh. The simulation is carried out assuming that the properties of the battery remain constant throughout its lifetime and are not affected by the external factors such as temperature. The battery string considered has a lifetime throughput of 1075 kWh with a round trip DC-storage-to-DC energetic efficiency of battery and the SOC below which battery should never be drawn is 85% and 30%, respectively, with 10 yr float life. The capital cost and replacement cost of batteries are considered as $170 USD and $130 USD respectively.
4) Converter: A converter is, basically, a power electronic component is an essential element of renewable energy system which can function as rectifier. In the present study, an inverter of 0.5kW is used. The capital cost per kW, replacement cost, and OM cost are taken as $300 USD, $300 USD, and $0, respectively.

Table 1. System Parameters

System Components	Sizes Considered	Capital Cost (USD)	Replacement Cost (USD)
PV Array	1 kW	1330	1330
Wind Turbine	1 kW	1500	1800
Battery	6V,360 Ah	170	130
Converter	0.5 kW	300	300

B. Technical and Economic Analysis of HRES for Single Household

The technical and economic analysis of the HRES considered for a single household has been carried out in Hybrid Optimization of Multiple Electric Renewables (HOMER) software. It performs multiple optimizations under a range of input assumptions to gauge the effects of uncertainty or changes in the model inputs. In this present scenario the inputs that have been considered are the solar and wind resources for the location, followed by the load profile for the single household and the specified system components that make up the basic HRES model for the single household.

IV. RESULTS AND DISCUSSION

The results of a techno-economic analysis HRES for a single household is presented here.

A. Technical Aspects

As the most advantageous strategy for any HRES is based on hourly operational cost where an entire year is divided into 8760 hours. The results obtained for the analysis consists of the AC primary load obtained for the household over the year in terms of 8760 hours as can be seen in Fig 5. The electrical profile for the system designed depicts a PV output power as in Fig 6 and wind turbine output power as in Fig 7 having a yield of approximately 1563kWh/yr and 1194 kWh/yr accounting for 56.69 percent PV and 43.31 percent wind power output. An excess electricity production of 1029.1 kWh/yr is achieved which is mainly due to the suitable amount of the wind flowing in the selected region during the summer and the monsoon season as per the wind profile obtained.

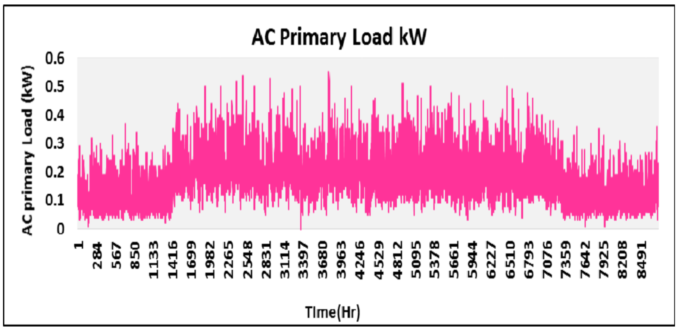

Fig 5. AC primary load of the household considered based on 8760 hours timeline

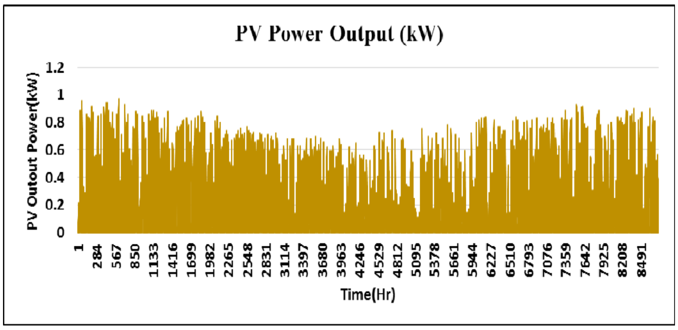

Fig 6. Hourly based average electric power generated from in a HRES

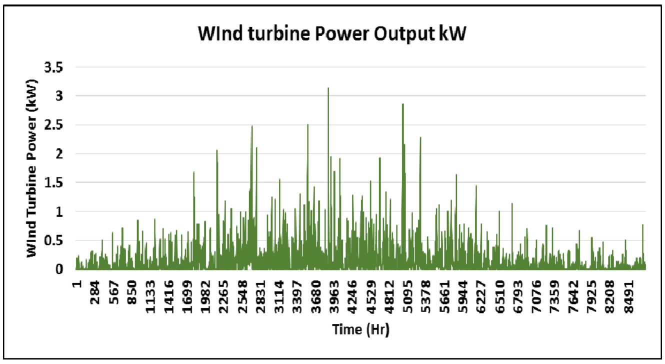

Fig 7. Hourly based average electric power generated from wind turbine in HRES

Due to this phenomenon of the wind profile in the region the over dependence of the PV system reduces as so the intermittency. The reduction in intermittency can be seen as the unmet load of the system is just is 0.5 kWh/yr even during peak energy requirements during the summer season when the cooling load is maximum. As observed the unmet electric load as shown in Fig 8. with respect to the AC load of the household in Fig 9. has an annual capacity shortage of just 1.7 kWh/yr.

The electric profile obtained depicts the battery profile of the system where the battery is seen to have expected life of 9.44 year. This is owing to the state of charge (SOC) of the battery unit which is observed to be in healthy state of approximately 95 percent for most time of the year as seen in Fig 10. and as evident from the D-Map in Fig 11. It is also observed that the least SOC level reached for the battery system is 40 percent for approximately less than two percent in a year. All these factors leads to the battery autonomy of 47.14 hour, usable nominal capacity of 8.01 kWh with a lifetime throughput of 6868 kWh.

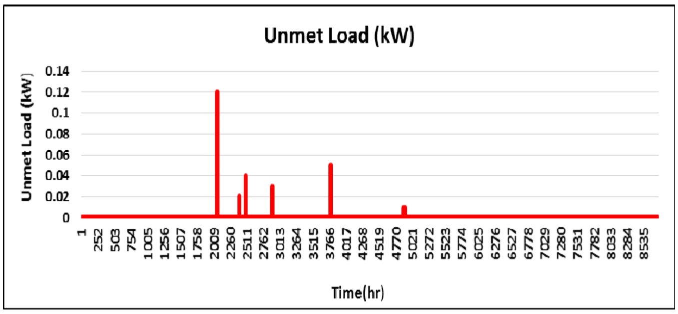

Fig 8. Unmet load of the household in a HRES

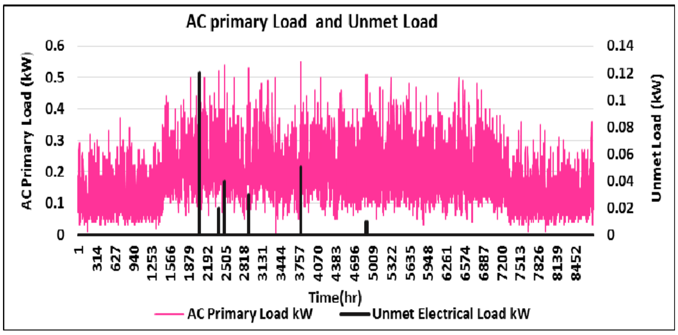

Fig 9. Comparison of the AC load and unmet load for the single household

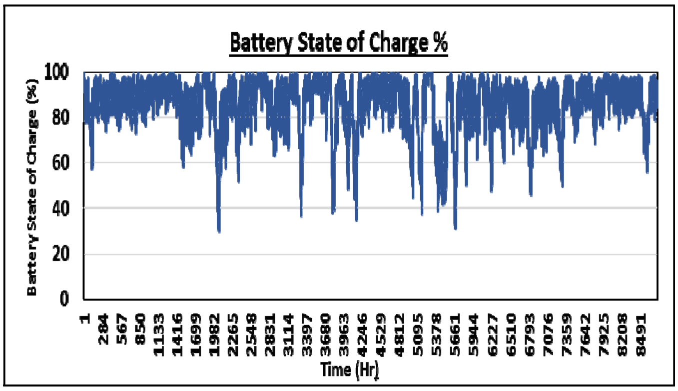

Fig 10. The state of charge of battery for HRES

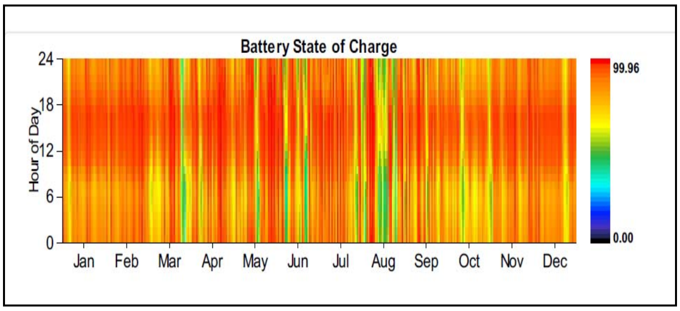

Fig 11. DMap of the state of charge of battery for HRES

B. *Economic Aspect*

The technical analysis of the HRES discussed above leads one to analyze the economic aspect of the system as the system needs to be economically feasible in order to be accepted by the consumers for their electricity generation and usage. The economic analysis of a microgrid system is based on the total net present cost (NPC), levelized cost of energy (COE) and operating cost of the system. The basis of analyzing the system for economic feasibility is done over a project lifetime of 20-25 years. The NPC is defined as present value of all the costs that it incurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue.

The economic analysis of the HRES is also based on the technical functionality of the system which when referred to the storage system based on annualized cost type shows the capital cost, replacement cost and total cost on a yearly basis over a lifetime of 25 years which in this study shows $52.60 USD, $37.12 USD and $86.33 USD . The HRES based model stands to be an economically feasible solution based on the COE (the average cost per kWh/yr of useful electrical energy produced by the system) value of $0.216 USD and operating cost of $37.73 USD.

The economics of the HRES on a component level can be studied on the basis of the net present cost and the annualized cost type which is tabulated in Table 2 and Table 3.

Table 2. Net present based component cost

Component	Capital (USD)	Replacement (USD)	Salvage (USD)	Total (USD)
PV Module	1330	0	0	1330
Wind Turbine	1500	0	0	1550
Battery	680	480	-44	1116
Converter	150	64	-12	202
System	3660	544	-56	4148

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Table 3. Annualized based component cost

Component	Capital (USD)	Replacement (USD)	Salvage (USD)	Total (USD)
PV Module	103	0	0	103
Wind Turbine	116	0	0	116
Battery	53	37	-3	86
Converter	12	5	-1	16
System	283	42	-4	321

V. CONCLUSION

This paper presents the case study of a HRES for an off grid household located in Jharkhand, India. It reports the techno-economic analysis for the HRES that has been utilized to support a peak daily demand of 0.55 kW using 100 percent renewable fraction as sources of energy. The technical and economic assessments have been done emphasizing on the unmet load of the house, state of charge of the battery and the net present cost. This work will be considered as a frame work for extending the clean electricity facilities and infrastructure to the entire village consisting of approximately 40-50 houses, community centers, agriculture and public assess buildings and in remote off grid location. For further analysis the life cycle assessment of the system, carbon emissions, load growth factors and varying can be considered which will provide a more realistic analysis considering the electricity solution to be provided to an entire off-grid based community as part of the Clean Development Mechanism defined in the Kyoto Protocol.

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