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CONFERENCE PAPER

COST-EFFECTIVE HYBRID SOLUTIONS FOR RURAL ELECTRIFICATION IN INDIA: A TECHNO-ECONOMIC STUDY

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Abstract

This study explores a Hybrid Renewable Energy System (HRES) based on the energy resources available at the selected site. It evaluates both the economic feasibility and technical reliability of the system for a single household located in an off-grid region. The proposed fully renewable HRES model is designed to meet a daily energy demand ranging from 2.835 to 4.965 kWh across different seasons. The findings indicate that the system effectively addresses issues of power intermittency while maintaining a balanced load throughout the year by minimizing unmet demand and capacity limitations. Furthermore, considering a projected lifespan of 25 years and associated energy costs, the system proves to be economically sustainable. This study also provides a foundational framework for enhancing electrification infrastructure in underserved areas and represents one of the first such implementations in Jharkhand, India.

Introduction:-

Energy plays a fundamental role in the economic, social, and environmental dimensions of sustainable development. The global power sector faces key challenges, including ensuring a reliable and secure electricity supply, reducing environmental impacts, and achieving universal access to energy [1]. Consequently, effective energy management has become a critical priority for governments worldwide [2]. Although individual rural communities may not constitute large energy markets, collectively they represent a significant opportunity for renewable energy (RE) deployment. In fact, rural and village regions currently account for a substantial share of renewable energy utilization [3]. However, many renewable energy initiatives in rural areas of developing countries have been criticized for their limited effectiveness, as systems often fail within a few years of installation due to various technical, financial, and institutional constraints.

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Establishing a robust socio-economic and technological framework for rural electrification requires overcoming barriers such as lack of awareness, inadequate financing, policy limitations, and regulatory challenges that hinder the adoption of renewable energy technologies (RETs) [4], [5]. Therefore, comprehensive techno-economic assessments of RETs are essential to ensure reliable and sustainable electrification in rural regions [6].According to the 2006 rural electrification policy of the Government of India, a village is considered electrified if essential infrastructure—such as distribution lines, transformers, and electrification of all inhabited areas including marginalized settlements—is in place [7]. Government reports indicate that approximately 98.7% of villages in India have been electrified. Despite this progress, a considerable number of rural households still lack access to electricity, particularly in states such as Bihar, Odisha, Assam, and Jharkhand [8]. Ensuring electricity access for every household remains a top priority for the Indian government [10]. While expansion of the centralized grid has achieved notable progress, it is not a fully viable solution for reaching all remote rural areas. In this context, decentralized power generation through microgrids, integrating local energy resources with smaller distribution systems, emerges as an effective and practical approach for rural electrification [11], [12].

Assessment of Location:-

Evaluation of Solar and Wind Resources:

Sapra, located at 22°47′N 86°12′E within Indian territory of Jharkhand, is the off-grid, isolated rural community chosen for the investigation. The chosen community is situated on a plateau with plenty of sun and wind energy that may be used to generate electricity. NASA Surface Meteorology provided the location's solar irradiance (kW/m2), PSH (peak sun hours), ambient temperature, and wind statistics[13]. With a typical clearness index of 0.541 and a scaled yearly average of 5.01 (kWh/m2/d), the greatest PSH value of 6.40 is recorded in April, and minimum PSH value of 4.084 is observed in December asinFig1. As observed, the location's yearly average wind speed is 2.39 m/s depictedinFig.2.

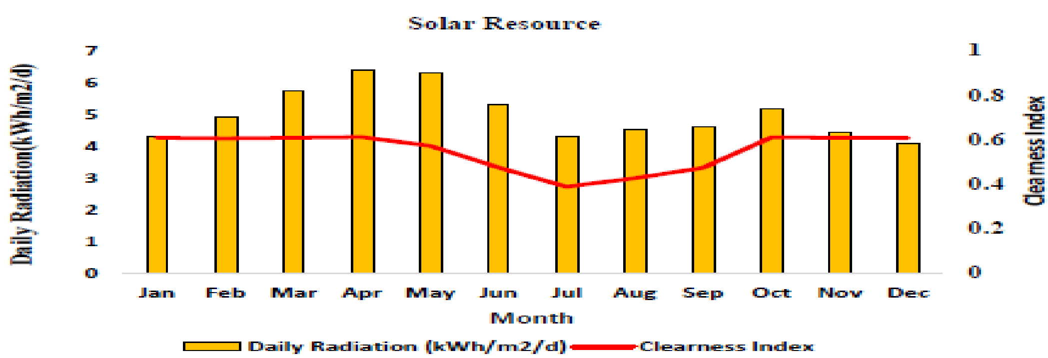

Fig1.Solar Potential at the Suggested Location

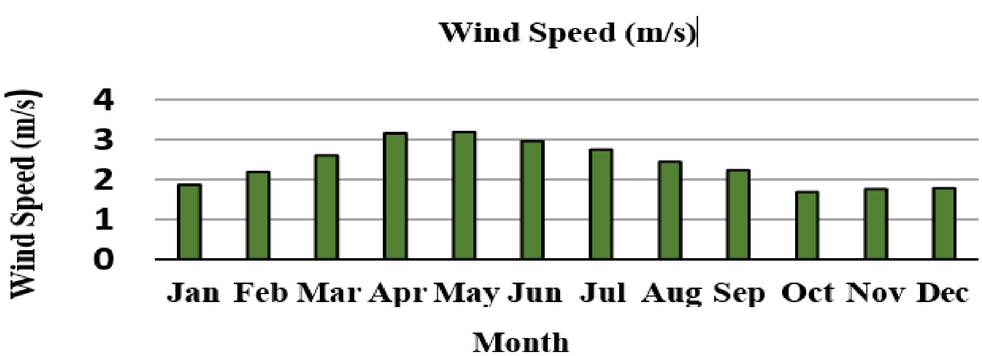

Fig2.Wind Capability of the Selected Location

Load Pattern for Individual Households:
For a single family, the HRES system is designed to balance a peak demand of 0.55 kW with load demand for 4.08 kWh/d. The home under consideration lies in an off-grid village area with lengthy dry summers complying with monsoons and winters, therefore their electricity usage patterns vary appropriately, and a seasonal outline of load is taken into account.Additionally, the load profile changes according to people's lifestyles [11][12]. To determine the kind of appliances to be utilized, the load profile of the techno-economic design is a crucial task[12]. As a result, AC gadgets like CFL and incandescent lights, ceiling and table fans, radios, mobile chargers, and televisions are regarded as basic appliances.

Methodology:-
Figure.3 displays a schematic system setup diagram that illustrates the chosen RETs' architecture for a single household.A DC and AC bus, a converter, a storage battery bank, and a PV and wind turbine both function as power producing units in the standalone PV-wind dependent HRES system.

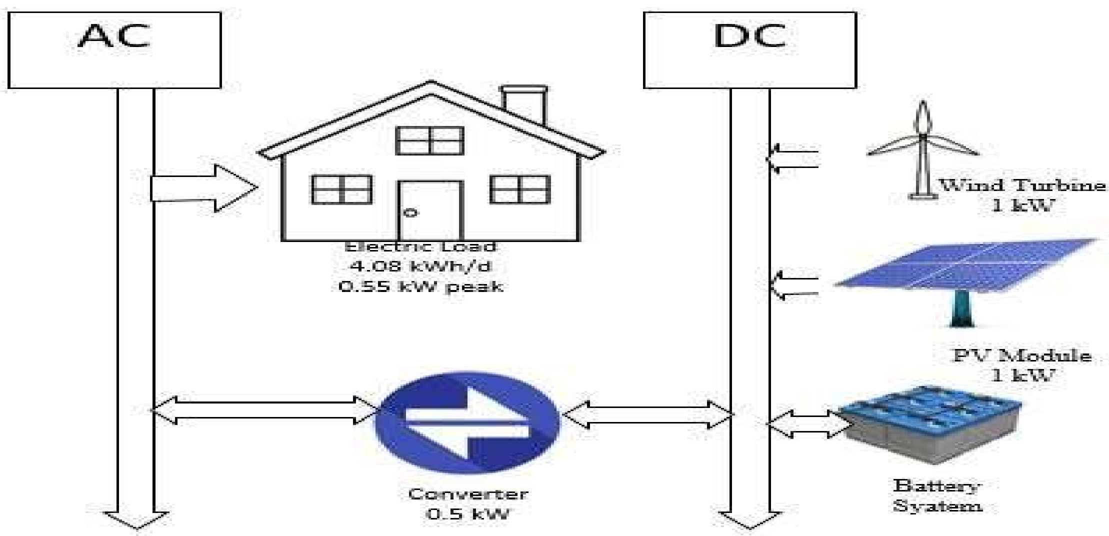

Fig3.Structure and Model of a System Based on Hybrid Renewable Energy

System Specifications:-
P-V system: Regarding the system's technical evaluation the PV module taken into consideration is 1Kw in size with 25 years of life span without a traking system.Under conventional test settings, the power, efficiency and nominal cell working temperature coefficients are regarded as (-0.5%) /^{o} C, 47^{o}C and 13% accordingly. Per Kw the P-V module's capital cost and replacement are valued at $1330 USD for economic analysis without any maintenance cost[12].

Wind Turbine:Cncerning technical evaluation aSW Whisper 200 wind turbine, designed by Southwest Wind Power is chosen for simulation purpose. The wind turbine's rated DC output is 1 Kw, rotor diameter is 2.7 m, and its estimated lifespan is 25 years. The wind turbine's hub height is 25 meters.Replacement cost of$1800 USD and capital cost assumed as $1500 with zero annual maintenance cost.

Battery System: For this simulation study, Trojan L16P batter model is choosen. The battery has rated capacity of 2.16Kwh and a nominal capacity of 360Ah, 6v accordingly.Simulation is conducted under the assumption that the battery's characteristics will not changeover time and will not be impacted with change in temperature. With a float life of 10 years and life time efficiency of1075Kwh, the battery string has a round trip of DC storage efficiency is of 85%, below which the battery should not be pulled. Battery replacement and capital costs are estimated as $130 and $170 USD accordingly

Converter: In the current method,a converter basically a power electronic component which can act as a rectifier and is an essential part of a renewable energy system. A 0.5 Kw inverter is employed. The OM cost, Replacement cost and capital cost per Kw are assumed to be $0, $300 USD and $300 USD accordingly.

Table1.SystemParameters

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

Functional and Financial Evaluation of Single-Household HRES:-

The Hybrid Optimization of Multiple Electric Renewables (HOMER) software has been used to do a techno-economical study of HRES taken into consideration for a single home. Several optimizations are carried out under various input assumptions in order to assess the impact of ambiguity or modifications to the model inputs. The inputs taken into consideration in this scenario include the location's solar and wind resources, the single household's demand profile, and the designated system components that comprise the single household's basic HRES model.

Results and Discussions:-

Here are the findings of an HRES techno-economic analysis for a single family.

TechnicalAspects:-

The hourly operational cost approach, which divides a year into 8760 hours, is the most beneficial approach for any HRES. As can be observed, the analysis's findings include the household's annual AC primary load is of 8760 hours as in Fig 5. P-V output power is shown in the system's electrical profileinFig6andpower output from wind turbines inFig7with an annual output of roughly 1563 kWh and 1194 kWh, which correspond to 56.69% of P-V and 43.31% of wind power, respectively. A surplus power output of 1029.1 kWh/year is accomplished, for which thanks primarily to the appropriate quantity of wind flowing within the specified region throughout summer and monsoon seasons, as determined by the wind profile.

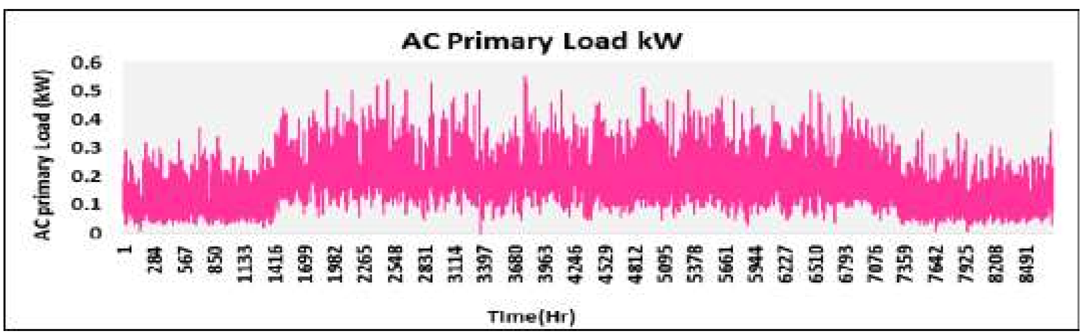

Fig4.The family's AC primary load was calculated over a period of 8760 hours.

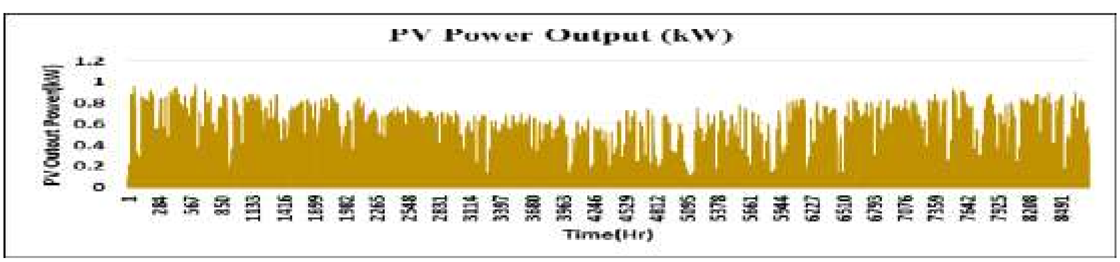

Fig5.Average electric power produced in an HRES on an hourly basis

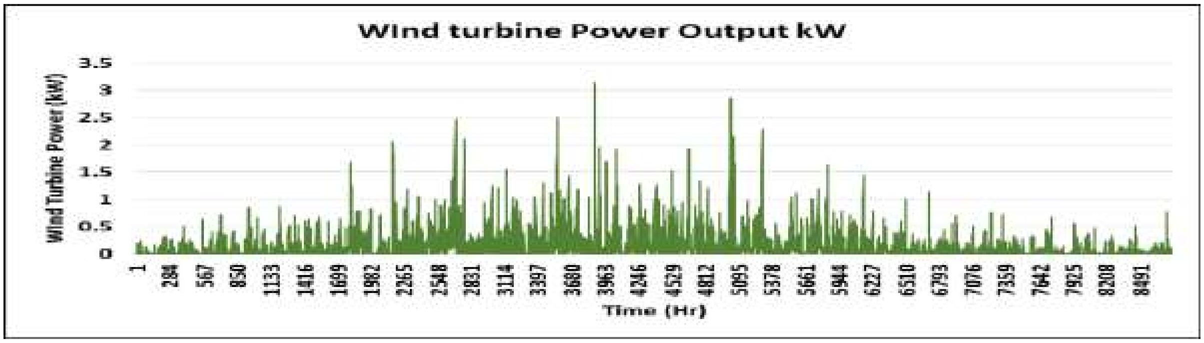

Fig.6. Average hourly electricity production from wind turbines in HRES

As a result of this local wind profile occurrence, the PV system's over-reliance and intermittency are decreased. The system's unmet load is just 0.5 kWh/year, even duringsummer months whencooling load is at its highest, indicating a reduction in intermittency. In relation to the household's AC demand, the unmet the electrical load is depicted in With an expected 9.44-year battery life, the system's battery characteristic is displayed in the electric profile that was obtained. This is because, the battery unit's state of charge (SOC), as depicted in Fig. 9 and the D-Map in Fig. 10, is in a healthy state for most of the year, roughly saying as 95 percent. The lowest state of charge (SOC) of the battery system is 40% lower than 2% of the year, it is also observed. Together, these components provide the battery's 6868 kWh lifetime throughput with 8.01 kWh of effective nominal capacity, and 47.14-hour autonomy.

Fig7.Unmet household load in an HRES:-

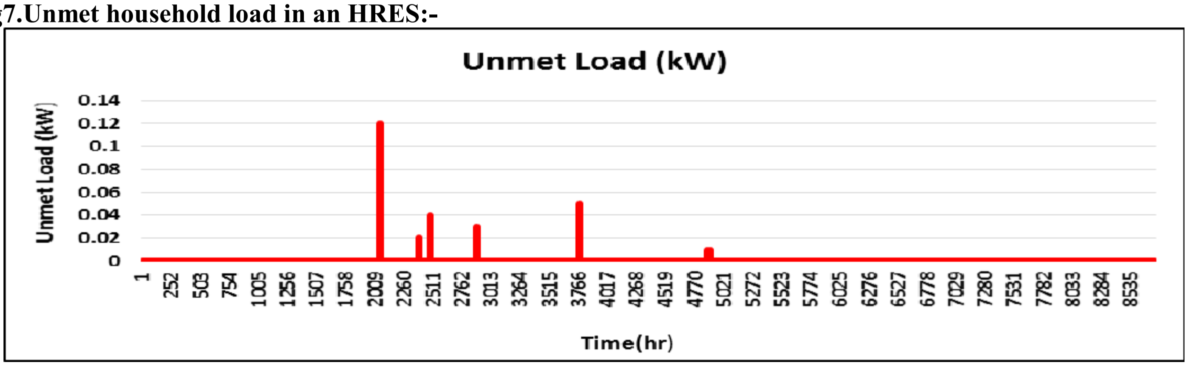

Figure 7. In Fig 8reveals an annual capacity shortfall of only 1.7 kWh.

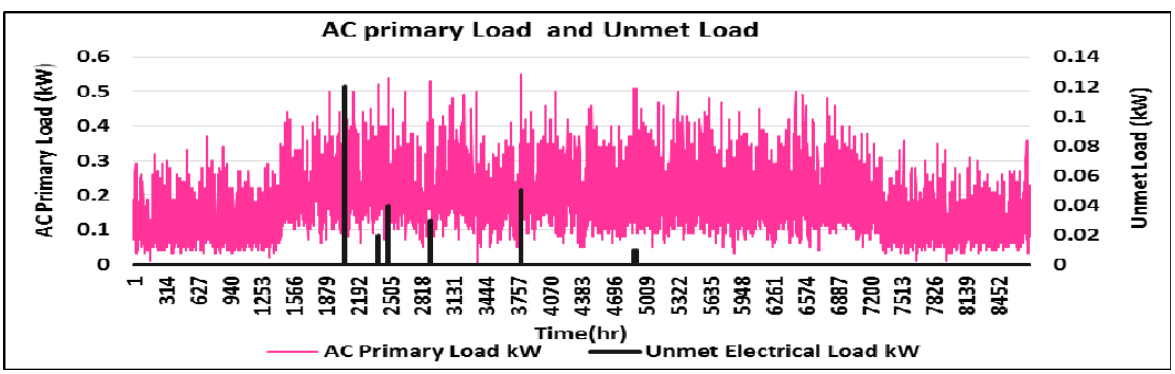

Fig8. AC load versus unmet load for a single family

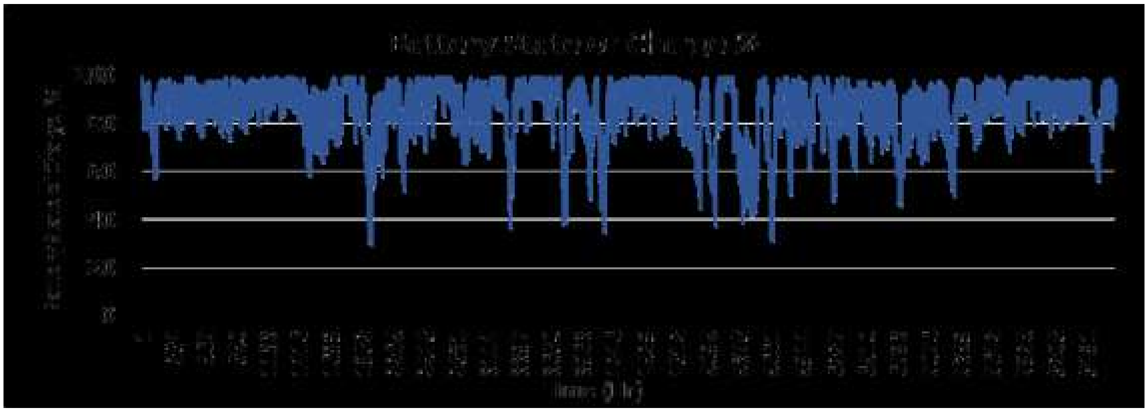

Fig9. Battery's charge level for HRES

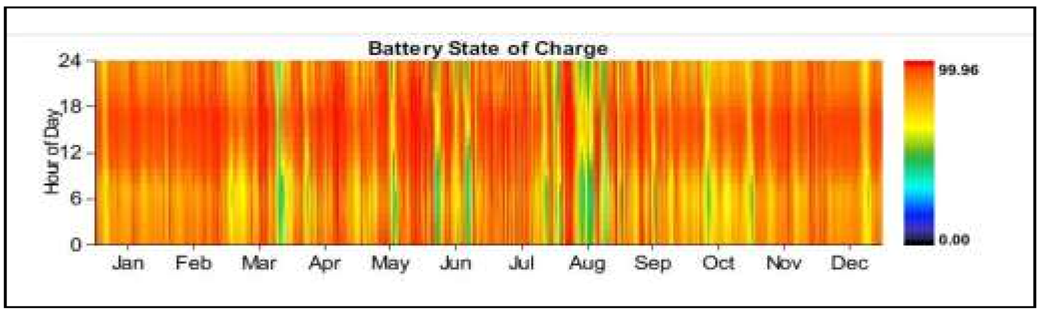

Fig10.D Map showing the battery's level of charge for HRES

Economical Considerations:-

The technical examination of the HRES that was previously described leads to an analysis of the system's economics because the system must be financially viable for consumers to accept it for the generation and use of electricity. The levelized cost of energy (COE), total net present cost (NPC), and system operating costs serve as the foundation for an Economic modelling of a microgrid. The system is first examined for economic viability during a 20–25year project lifespan. NPC is calculated by subtracting the present value of all revenue earned over the course of its existence from the present value of all costs incurred. Costs include those associated with capital projects, replacements, operations and maintenance, fuel, pollution fines, and purchasing electricity from the grid. Grid sales revenue and salvage value are included in revenues.

Tables 2 and 3 tabulate the yearly cost and the net present cost, which may be used to study the HRES's economics at the component level.

Table2.NetApproximatecomponentcost

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

Table3.Annualized component cost

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

Conclusion:-

This study presents a case analysis of an off-grid household in Jharkhand, India, powered by a Hybrid Renewable Energy System (HRES). It focuses on the techno-economic evaluation of the system, which relies entirely on renewable energy sources to meet a peak average daily demand of 0.55 kW. The assessment highlights key performance indicators, including unmet load, battery state of charge, and net present cost.The findings provide a basis for scaling up clean energy infrastructure across the entire village, encompassing approximately 40–50 households, along with community centers, agricultural facilities, and public utility buildings in remote off-grid regions. Furthermore, in line with the Clean Development Mechanism under the Kyoto Protocol, the study emphasizes a more comprehensive evaluation of electrification strategies by incorporating life cycle analysis, carbon emissions, demand growth, and system variability for sustainable energy planning.

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