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Optimization and Comparative Economic Analysis of Standalone and Grid-Connected Hybrid Renewable Energy System for Remote Location

*Siddharth Jain and Yashwant Sawle**

Department of Electrical Engineering, Vellore Institute of Technology, Vellore, India

Due to rising population growth and economic development, there is indeed a growing demand for electricity. Both in aspects of generation and transmission, conventional power firms are striving to manage these demands. Moreover, the ubiquitous utilization of electricity and other power generators, which are mainly driven from fossil fuels, seems to have some limitations, like declining performance and restricted energy production. As a result, use of renewable energy sources is incredibly important. Decentralized power generation in remote regions has become the primary requirement of society, based on renewable energy. Particularly in comparison with the electrification of urban areas, rural electrification is quite expensive. Microgrid's development utilizing hybrid power is a potential solution for the electrification of rural regions where the transmission chain of network's extension is unfeasible or inefficient. This research aims to structure a power generation model associated with different HRES combinations using a HOMER software application at a location in India. In the findings of this research, it has been observed that NPC, O&M, COEs, and RF of on-grid energy systems are better than off-grid energy systems. In the study, between eight hybrid system combinations, the lowest COE of 0.034 $/kWh is obtained with the PV-WT-MH-GRID-CT system in the on-grid scenario. This analysis shows NPC, COE, O&M, and renewable fraction are sensitive to the variation in all the considered sensitivity parameters[1,2,3,4].

Keywords: decentralized power generation, microgrids, sustainable, hybrid power, solar energy, electricity, capacity, growth

Edited by:
Muhammad Zubair,
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Reviewed by:
GM Shafiullah,
Murdoch University, Australia
Mohammad Khalil Elahee,
University of Mauritius, Mauritius

***Correspondence:**
Yashwant Sawle
yashsawle@gmail.com

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Abbreviations: BT, Battery; COE, Cost of Energy; CT, Converter; DG, Diesel Generator; FC, Fuel Cells; HRES, Hybrid Renewable Energy System; MG, Micro Grid; MH, Micro Hydro; RF, Renewable Fraction; WT, Wind Turbine.

[1]https://energy.rajasthan.gov.in/content/raj/energy-department/rvunl/en/our-plant/hydel/js.html.
[2]https://energy.rajasthan.gov.in/rvunl.
[3]https://en.wikipedia.org/wiki/Bijolia.
[4]http://www.homerenergy.com.

INTRODUCTION

Around 1.5 million people worldwide lack accessibility to electrical energy, and one of the world's most prominent issues is to provide electricity to the population. Approximately 70,000 villages as well as 1.9 billion Indians often do not have reliable electricity. Due to electrical supply instability, multiple households connected to the grids are frequently witnessing power outages. Due to a lack production as well as an outdated transmission system, erratic voltage levels as well as unreliable power supply seem to be significant problems, contributing in recurrent power interruption. In India, nearly 30–50% of electricity is wasted throughout transmission and distribution, which would be exceptionally high as compared to other developed countries.

By 2040, the overall energy consumption will grow by 30%. Around 77% of energy output is generated from conventional energy sources dependent on carbon, which face many challenges and cause many problems. Rural electrification in developing nations aids in enhancing people's standard of living. The commitment to achieving 100% electrification throughout the nation is due to both the transmission and distribution of power to less populated areas sited far from power generation plants. As a result, discovering a decentralised source of energy to provide power to such towns and villages is vital.

Environmentally sustainable renewables such as PV, FC, biogas, and MH seem to be the most increasing energy forms in developing a country with such a booming economy. In rural communities worldwide, the HES provides an appealing and realistic approach to solve energy needs. Such cost-driving variables do not influence non-conventional energy. Thus, efficient economic growth makes economic growth simpler when renewable energy is used, as energy costs decrease (Doll and Pachauri, 2010).

Even though renewable energy is currently quite expensive, it has become sufficiently effective to outperform non-renewable sources with experience accumulation. Even so, being used in a stand-alone system, the non-conventional sources of energy face a variety of restraints. Specifically, the power generated from WT and PV depends on environmental factors, whereas FC requires hydrogen-enriched fuel. The worldwide non-conventional energy scenario by 2040 is presented in **Figure 1** (Panwar et al., 2011), (Sawle et al., 2017).

For future renewable sources, FC provides tremendous capability with many advantages, such as high performance, low emission, and dynamic design (Alam and Gao, 2007). Solar and wind energy resources integrate with several resources to overcome these challenges. An HRES is produced by generating more non-conventional resources. Micro grid would provide means of incorporating the generation of cleaner renewable power into the power network (Oulis Rousis et al., 2018), (Sawle et al., 2016).

A micro grid (MG) is indeed an embedded network of distributed generation including loads which operate a controllable grid within the prescribed electrical networks. For both the function of island as well as grid connection mode, the MG network could separate or connect from the grid during different periods. There are three fundamental criteria for the system: To begin, recognizing the distribution network of a particular MG from the other networks seems to be quite simple. Second, when compared to distant resources, MG resources can be regulated, and third, the MG system can function regardless of the size of the grid linked.

The benefits of the MG system are social, economic, environmental, and technological. MG design optimization is required to attain this. These advantages could be experienced by selecting the suitable MG network technology, grid configurations, load component size, and

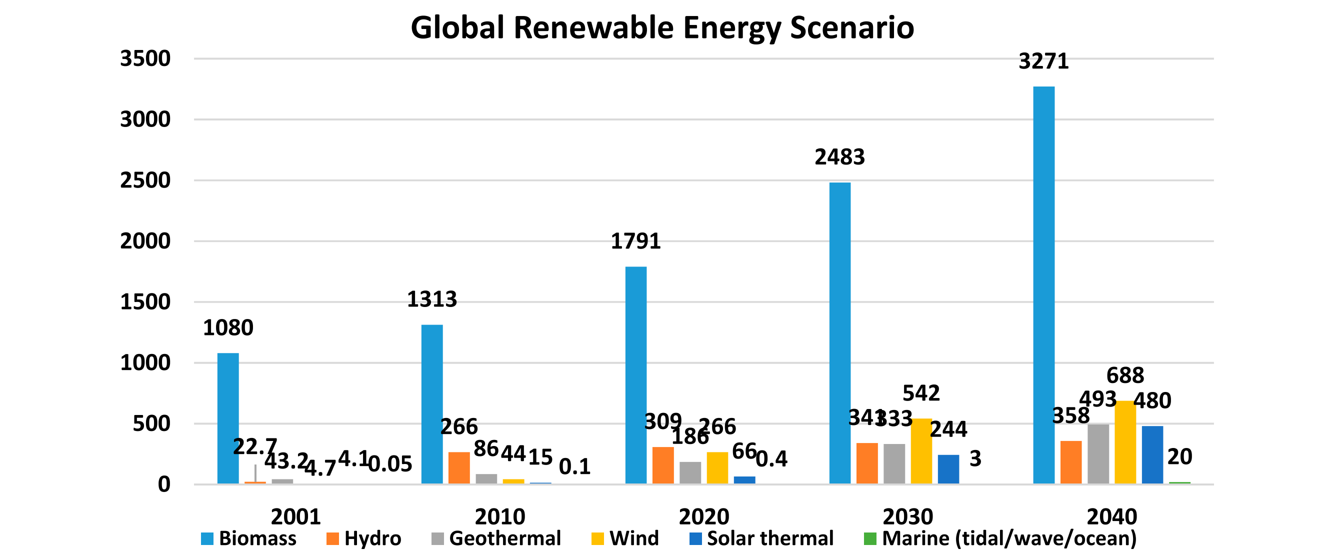

FIGURE 1 | Global renewable energy scenario by 2040.

TABLE 1 | Summary of literature review.

Reff.no	Location	Type of load	Technology	Results
Munuswamy et al. (2011)	Mamandur	Rural Health Care Load	• FC • Biogas	• It is both practical and cost-effective to operate a rural primary healthcare facility with a distributed non-conventional system • This could be less costly than grid-connected electricity
Sharma and Chandel, (2013)	Khatkar-Kalan	Solar PV plant load	• PV	• Total yields, comparative yields, as well as production ranges differed around 1.45 to 2.84 kWh/kWp-day • 2.29 to 3.53 kWh/kWp-day, as well as 55–83%
Kumar et al. (2019)	Chayangtajo Circle of East Kameng district	Remote Load	• PV • DG	A bi-directional program that utilizes analysis method as well as multi-objective optimization methods for developing countries to analyse and design a remote micro-grid with a perspective of stable growth
Bhatt et al. (2016)	Seli, Tapari, Sirani, Nailpar, Chimkholi	Rural Load	• MH • PV • Biogas • DG	A network consisting of a 6 kW biogas generator and a 60 kW of PV and 10 kW diesel generator with storage batteries is the most appropriate choice for the region under review
Jain et al. (2010)	Bacharam, Hyderabad	Rural load	• Biogas	• The economic analysis shows that the biogas plant's initial capital cost of about 303 dollars per household would effectively serve each household's energy • The rate of return for the village group operating the biomass plant is also feasible since even half of the time. The grid no longer provides electricity
Samy et al. (2019)	Egypt	Rural Load	• PV • FC	• Using the Flower Pollination Algorithm, they calculated the total annual expense (FPA) • The risk of a power supply failure is also taken into account to increase system performance
Hafez and Bhattacharya, (2012)	Egypt	Rural Load	• WT • MH • PV • DG	• For the rural community's 1183 kW peak load. A MG hybrid system based on WT, MH, PV, as well as DG was considered • This research was carried out by making unrealistic
Jahangiri et al. (2019)	Iran	City Load	• PV • DG	In comparison to a hydrogen-based system, the design for optimizing the micro-power system
Miao et al. (2020)	Northeast United Kingdom	Household Load	• PV • WT • BT • Biogas	• The best off-grid option is determined for each of the eight scenarios

specifications. As a measure, in order to achieve optimal functionality, the system must have maximum energy efficiency storage units. Renewable energy sources are being used in the MG for energy stability as well as consistent power storage. Whenever the production of energy exceeds the consumption, energy is automatically stored.

The MG system can be reviewed and analysed by using a wide range of computer-aided design methods. HOMER, a well-known software design that enables different designs to be evaluated, is widely used during the economic power system model and the experimental study. For MG analysis and model, HOMER can function in three phases: optimization, simulation, and sensitivity analysis. HOMER has a high degree of precision in all three phases of the MG economic and technological study.

HOMER is used to evaluate the off-grid and on-grid electrification problems and build a realistic system for the area. The design of the model needs a keen understanding of the components employed, such as generators, turbines, etc. In other words, rather than people migrating to cities where electricity is accessible, electricity can migrate to remote locations. Engineers must develop hybrid renewable energy systems based on size and cost and optimize their remote region's applications for electrification.

Much work was done on HRES architecture, using energy management as well as sizing techniques on HOMER software. Some of the research is displayed in **Table 1**. The main objective of this study is to simulate a microgrid using present MH, PV, wind, as well as DG at the site and conduct a cost optimization exploration to determine the finest microgrid based on the least NPC, COE, O&M, and RF percentage. The literature review makes clear that HRES is an energy source, which is cheaper as well as efficient versus traditional grid systems. Several research scientists have presented hybrid renewable energy systems in different configurations. Much research has still not been performed on the grid compared to Grid HRES, from the existing literature as well as gaps identified in the research. Various micro-grid networks, one interconnected as well as the other independent, are analysed from an economic perspective in this article. This analysis provides technological and economic viability for operation concepts. System efficiency is tested as well as contrasted through different HRES combinations for optimum NPC and COE minimum value configurations. The ideal framework is economically sustainable, has equal environmental advantages, has a reasonable payback period, and produces fewer emissions.

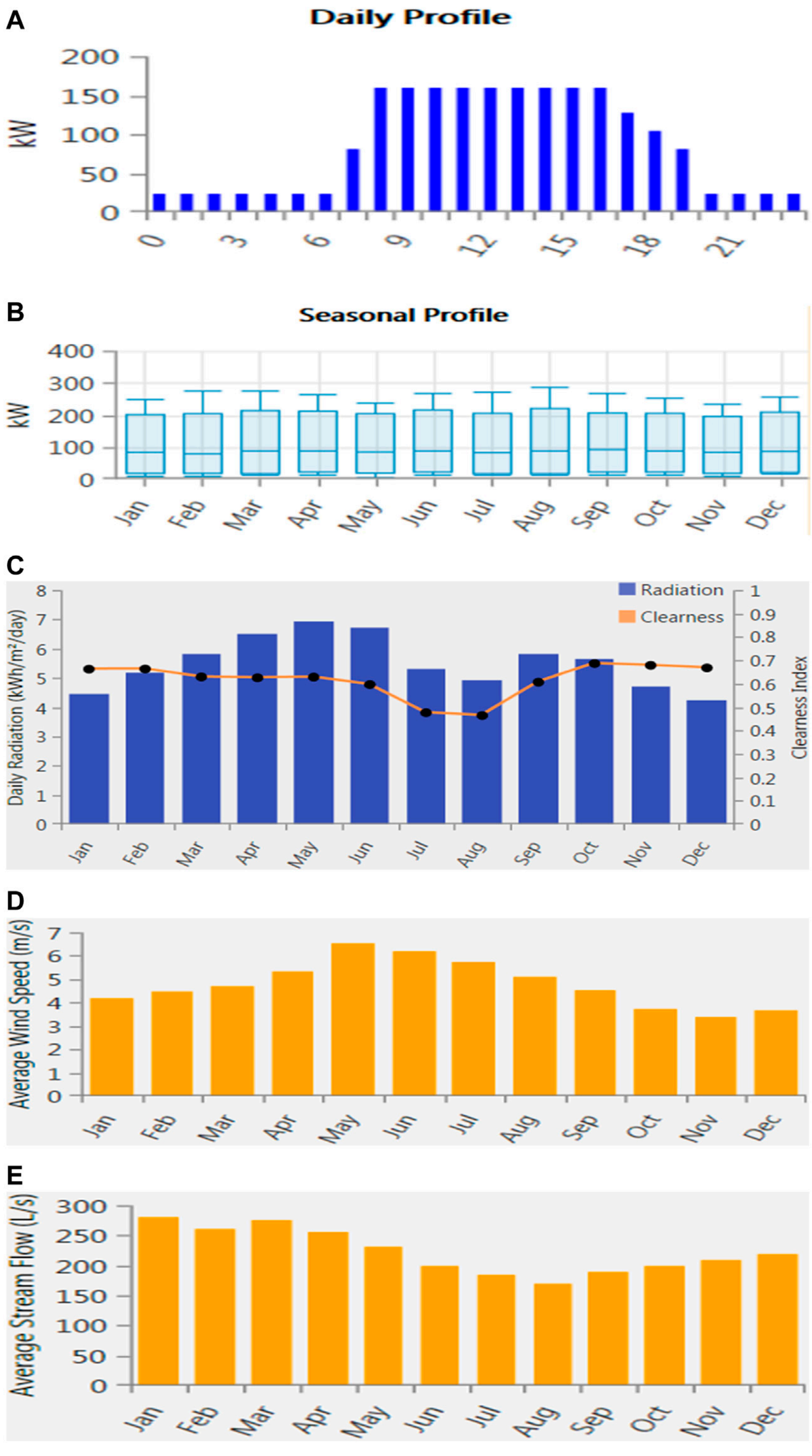

FIGURE 2 | (A) Daily load profile. **(B)** Seasonal load profile. **(C)** Monthly average solar profile. **(D)** Monthly average wind profile. **(E)** Monthly average hydro profile.

The following are the paper's key contributions:

1. A novel hybrid renewable energy system (HRES) was designed to solve scale and cost optimization challenges in remote areas.
2. The hybrid renewable energy system's COE, NPC, O&M, and RF percentage generation is kept to a minimum.
3. The proposed system provides fair environmental benefits, has a short payback period, and produces less pollution.
4. There is a comparison between on-grid vs off-grid models.

The following is the layout of this paper: **Section II** presents the methodology used in this study. **Section III** tells us about the resources used in this study. **Section IV** depicts the components used in this study and their mathematical modelling. **Section V** tells us about the system design and its costing. Simulation results and discussions are presented in **Section VI**. Sensitivity analysis results are presented in **section VII**. At last, conclusions are displayed in **Section VIII**.

METHODOLOGY

Supplementary Figure S1 shows the methods for incorporating the proposed HES into HOMER. The evaluation of the chosen site's load profile is accompanied by the determination of solar and wind potential. After that, different components are used to design the system. The financial variables, along with component dimensioning, are incorporated. NPC, O&M, COE, and RF evaluates the overall simulated outcomes to conclude whether the chosen result meets the location target (Kansara and Parekh, 2011).

Case Study

In this study, the hybrid system is designed for the electrification of Bijolia town. The town is located on the southeast of Bhilwara (https://en.wikipedia.org/wiki/Bijolia). The territorial site of Bijolia is displayed in **Supplementary Figure S2**. Comprehensive data of the location is displayed in **Supplementary Table S1**.

Energy Demand Assessment

In order to determine electricity usage, the load demand (kW) along with the time (h) of the loading phase will be considered. Primary survey data were used to determine the village's energy needs. Domestic, community, commercial, and rural enterprises are among the loads. Lighting, fans, televisions, mobile charging stations, and a water pump for drinking water are all part of the domestic load. Street lights in the village, fans in the community hall, and a device for the school are all part of the community load. When it comes to industrial loads, lighting is taken into account for shops in the village that work in the evening. The average load demand is 900 kW-h/day [(https://en.wikipedia.org/wiki/Bijolia)]. **Figures 2A,B** demonstrate daily as well as seasonal load profiles for the location.

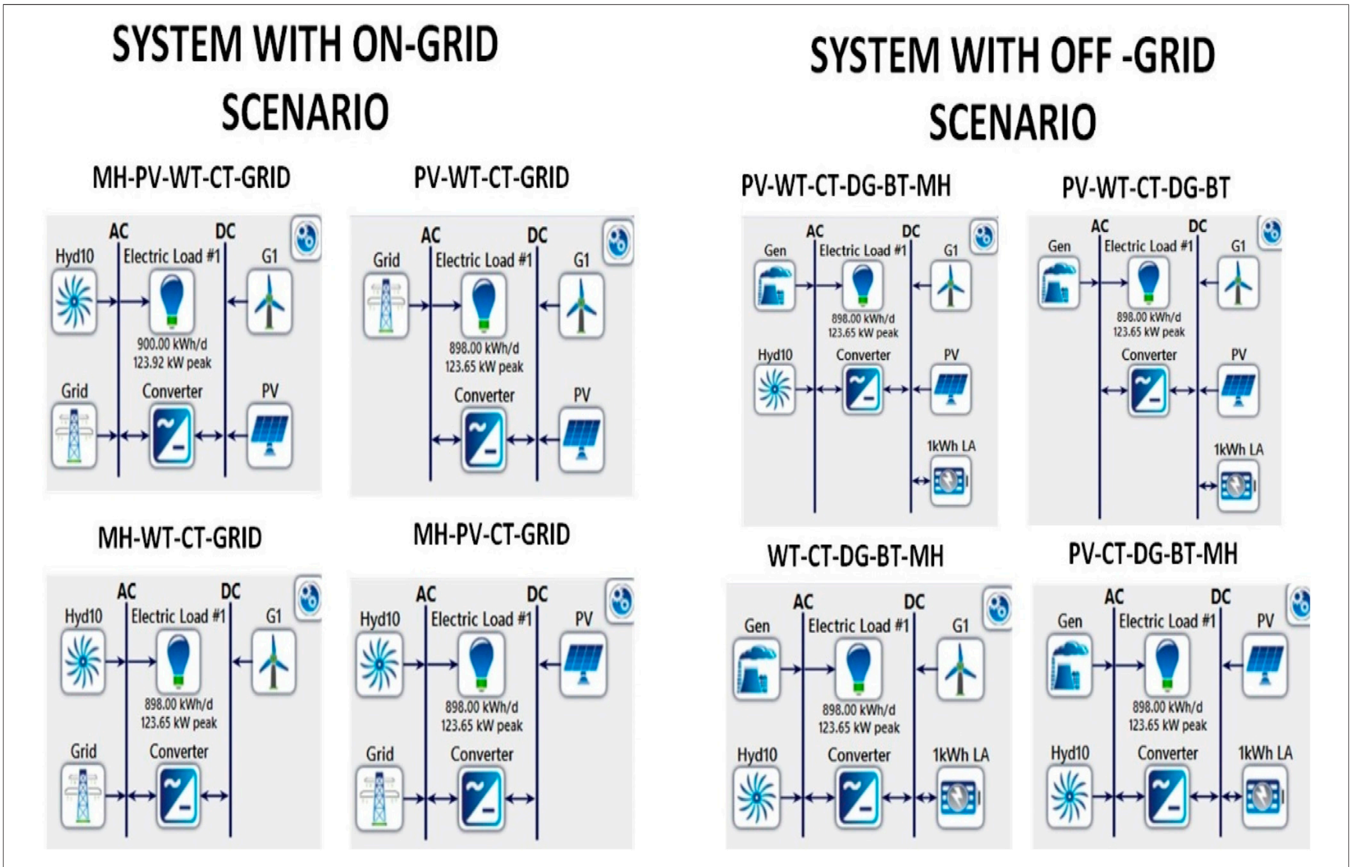

FIGURE 3 | System design.

TABLE 2 | System specifications.

Parameters	Value	Parameters	Value
PV system		**Wind system**	
Rated capacity (kWp)	1	Rated capacity (kWp)	1
Slope or tilt angle (degree)	37.5	Hub Height (m)	17
Capital cost ($)	1000	Capital cost ($)	1200
Replacement cost ($)	820	Replacement cost ($)	850
O&M cost ($/yr)	10	O&M cost ($/yr)	20
Lifetime (yr)	25	Lifetime (yr)	20
Diesel Generator System		Grid	
Rated capacity (kW)	10	Grid Power Price (US$/kWh)	0.100
Minimum load ratio (%)	25	Grid Sellback Price (US$/kWh)	0.060
Capital cost ($)	1,000		
Replacement cost ($)	800		
O&M cost ($/yr)	0.300		
Lifetime (h)	15,000		
Fuel Price ($/L)	0.8		
Battery		Converter	
Nominal Voltage (V)	12	Rated capacity (kW)	1
Nominal Capacity (kWh)	1	Efficiency (%)	95
Initial State of Charge (%)	100	Capital cost ($)	300
Minimum State of Charge (%)	40	Replacement cost ($)	300
Quantity	1	O&M cost ($/yr)	0
Capital cost ($)	300	Lifetime (yr)	15
Replacement cost ($)	300		
O&M cost ($/yr)	10		
Lifetime (yr)	10		
Throughput(kWh)	800		
Hydro System		Other economic inputs	
Rated capacity (kW)	10	Discount Rate (%)	8
Capital cost ($)	80,000	Inflation Rate (%)	2
Replacement cost ($)	40,000	Annual Capacity Shortage (%)	0
O&M cost ($/yr)	2,400	Project lifetime (yr)	25
Lifetime (yr)	25		
Nominal Capacity (kW)	10.987		
Available Head (m)	20		
Design Flow Rate (L/s)	70		
Minimum Flow Ratio (%)	50		
Maximum Flow Ratio (%)	150		
Efficiency (%)	80		

Sensitivity variables.

Parameters	Variables
Global Solar Radiation (kWh/m^2/day)	5.51, 4, 7
Annual Wind Speed (m/sec)	4.80, 3, 6.5

RESOURCE ASSESSMENT

Solar

In the environment, there is plenty of solar radiation. Solar radiation's potential is determined by the position or area. The distributed production scheme is proposed for the Indian longitudes of 25°9′50″N and 75°19′30″E. The annual average solar radiation for the design site is 5.51 kW/m^2 from the NASA resource website as shown in **Figure 2C**.

Wind

Wind energy is abundant in the architecture location of the distributed generation system (average annual resource of 4.80 m/s) from the NASA resource website as shown in **Figure 2D**. Other terms for the friction coefficient include Hellmann exponent, power-law exponent, and wind gradient. A number of variables, including wind speed, landscape irregularity, altitude above ground, local temperature, hourly data of the day, as well as the season of the year, affect the friction coefficient.

Micro Hydro

The Jawahar Sagar Dam is situated 29 km upstream of Kota. The Rana Pratap Sagar Dam is the third in a series of Chambal Valley Projects on the Chambal River. It is a 45-m-high, 393-m-long concrete gravity dam that produces 60 MW of electricity with three 33 MW units installed. The monthly water discharge is shown in **Figure 2E**. The yearly average is 222.92 L/s (https://energy.rajasthan. b).

COMPONENTS AND MATHEMATICAL MODELLING

PV Array

The PV module that is in play here is the general flat-plate PV. The following equation can be used to approximate the PV array's power output (Ramesh and Prasad Saini, 2020).

$$P_{PV} = Y_P f_P \left(\frac{I_t}{I_{STC}}\right), \tag{1}$$

Where Y_P (kW) represents PV array rated power, f_P represents PV arrays derating factor, I_t (kW/m^2) represents incident solar irradiation, and I_{STC} (kW/m^2) represent incident irradiation at standard test conditions.

Derating factor is used to scale down the power output of the PV array due to array soiling, wiring losses, shading, snow cover, aging, and other factors. The energy balance for the PV array can be determined using the equation above.

$$\tau \alpha I_T = \partial_C I_t + U_L (T_c - T_a), \tag{2}$$

Where τ (%) is the solar transmittance of PV array, α (%) is the solar absorptance of the PV array, U_L (kW/m^2) is the heat transfer coefficient to the surroundings, T_a (°C) is the ambient temperature, and T_c (°C) is the cell temperature.

The monthly average clearness index can be estimated by the following:

$$K = \frac{H_{avg}}{H_{0,\,avg}}. \tag{3}$$

where K denotes the clearness index, the average radiation on the horizontal surface of the Earth (kW/m^2/day) is denoted by H_{avg}, and radiation on the horizontal plane at the top of the Earth's atmosphere (kW/m^2/day) is denoted by $H_{0,\,avg}$.

Wind Turbine

A wind turbine module can be described as a combination of a rotor with two or more blades in coaction with an electrical generator. This combination works when the wind's kinetic energy can capture by the wind's turbine and, in turn, produce electricity. Power generated by the wind turbine system can be expressed as (Ramesh and Prasad Saini, 2020):

$$P_m = 0.5 \rho A C_p v^3. \tag{4}$$

In the above equation, C_P is the rotor efficiency, A is the area swept by the rotor, V is the speed of the wind, and P_m is the power generated by the wind module.

The key takeaways from the above equation are:

1. The output power of a wind generator is proportional to the area swept by the rotor, i.e., double the area swept by the rotor.
2. The power of the wind generator is proportional to the cube of the wind velocity.

The power equation in large-scale wind turbines where gearbox and generator efficiencies are not negligible anymore can be expressed as the following.

$$P_m = 0.5 \rho A C_p v^3 N_g N_b \tag{5}$$

Where N_g is the generator efficiency and N_b is the gearbox efficient.

Diesel Generator

The diesel generator uses a non-renewable resource (oil) to produce electricity. It can be used either as the main source or as a backup depending on the system. The amount of fuel required to produce electricity relies on factors like the fuel heat rate efficiency of the generator and the heat content of the fuel (Magarappanavar and Sreedhar, 2016), (Sawle et al., 2018c). The efficiency of the generator also depends on the load at the time.

Battery Module

Batteries are used to store electrical energy to be used during power surges and when other resources are unavailable. For the proposed system, a lead-acid type of battery has been used due to its low cost, high safety level, and recyclability. Lead-acid batteries are rechargeable (Krishan and Suhag, 2020), [(Sawle and Gupta, 2018)]. A parallel combination of batteries of the same rating is used to achieve higher voltage and current values.

The capacity of the battery is expressed as

$$C = \left(E_L * D\right)\left(\boldsymbol{\eta}_{bat} * DoD\right). \tag{6}$$

In the above expression, C (watt-hour) is the capacity of the battery, D is the daily autonomy of the battery, E_L(kWh/day) is the average daily load energy, η_{bat} is the battery efficiency, and DoD is the depth of discharge.

Mathematically the battery model is expressed as:

$$E = E_O - K \frac{Q}{Q - \int idt} + A \exp\left(-B \int idt\right). \tag{7}$$

$$V_{bat} = E - R I_{bat}, \tag{8}$$

Where E is the no-load voltage, E_O is the constant voltage, A is the ex-potential voltage, V_{bat} is the battery voltage, all expressed in volts. K (V/Ah) is the polarization constant; Q denotes the maximum ampere-hour capacity, $\int idt$ is the charge delivered by the battery (Ah), B (Ah^{-1}) is the exponential capacity; R is the internal resistance of the battery, and I_{bat} is the current in the battery.

Converter

The converter is a system that converts alternating current to direct current and vice versa. In HOMER, we can use two types of converters, rotary type and solid-state type (Canales et al., 2017), [(Sawle and Gupta, 2015); (Sawle and Gupta, 2014)]. The size of the converter depends on the converter capacity.

Grid

You can set a constant power price and a sell-back price in Simple Rates mode. We may also determine whether or not to use net metering and set grid power pollution factors. Grid Power Price ($/kWh) is the rate of purchasing electricity from the grid, expressed in dollars per kilowatt-hour. System Sellback Price ($/kWh) is the rate at which the utility pays you for the electricity you sell to the grid in dollars per kilowatt-hour (www.homerenergy.com).

SYSTEM DESIGN AND ITS DETAILS

The recommended Hybrid Energy System is incorporated into the software, as shown in **Figure 3**. **Table 2** also includes a detailed overview of each variable.

SENSITIVITY ANALYSIS

Sensitivity analysis investigates the impact of modifications in certain factors on the ideal system. Any numerical data provided into HOMER is refereed as a parameter. Any numerical data provided into HOMER is refereed as a parameter. The concept sensitivity variables are frequently used to refer to sensitivity analysis parameters. The developer inputs a set of values (sensitivity values) into HOMER for every sensitivity component. The primary sources of energy in the systems under study are wind turbines and solar arrays. As a result, sun radiation, wind speed, and fuel price can all have an impact on the best arrangement. Performing a sensitivity analysis that examined the impact of solar radiation, wind speed, as well as oil prices will provide insight into the role of HRESs in the sustainability of locations. A sensitivity analysis on the ideal system may reveal the importance of collecting these resources outside of the study area. All of these sensitivity factors and their related values are listed in **Table 2**.

SIMULATION RESULTS AND DISCUSSION

Techno-economic Study Scenarios and Optimal Power Flow Study Cases

The research's initial optimizing parameters continue as follows: Annual Average Electric Load Demand Measured is 900 kW-h/day. The annual average wind potential is 4.80 m/s, the annual average solar potential is 5.51 kW-h/m^2/day, and annual average streamflow (L/second) is 222.92. The nominal Discount Rate is 8%, and project lifetime years are (Sawle et al., 2018b). In this research, a comparison is shown between on-grid vs off-grid HRES to find a cost-effective approach that will meet local load demand while also lowering cost variables (COE, NPC, and O&M) as well as emissions. HOMER runs 1,982,235 simulations in this study, with 13,512 simulation outcomes. Each system is rated based on its NPC, COE, O&M, and RF percentages, with the best system having the lowest NPC, COE, O&M, and RF percentages while emitting a fair amount of radiation.

Case A: - PV-WT-MH-GRID-CT.
Case B: - PV-WT-GRID-CT.
Case C: - WT-MH-GRID-CT.
Case D: - PV-MH-GRID-CT.
Case E: - PV-WT-MH-BT-CT-DG.
Case F: - PV-WT-BT-CT-DG.
Case G: - WT-MH-BT-CT-DG.
Case H: - PV-MH-BT-CT-DG.

HRES with On Grid Scenario

Table 3 displays the optimal findings of all HRES for the on-grid scenario in Bijolia, Rajasthan. Among four HRES configurations, PV-WT-MH-GRID-CT is the utmost reasonable system for on-grid scenarios in terms of NPC, COE, OC, and RF. The least economic configuration is PV-WT-GRID-CT for on-grid scenarios in terms of NPC, COE, OC, and RF.

In the on-grid scenario, the optimal PV-WT-MH-GRID-CT HRES configuration to supply load demand consists of a Photovoltaic of 80 kW, WT of 20 kW, a grid of 999,999 kW, Hydro of 34.8 kW, and 62.0 kW converter. The NPC, COE, OC, as well as RF of the PV-WT-MH-GRID-CT Hybrid Energy systems are $202,733, $0.034, $288.78, and 91.5%, respectively. However, the NPC of PV-MH-GRID-CT HRES configuration is less when compared to PV-WT-MH-GRID-CT HRES configuration, but COE, OC, and RF is more when compared to PV-MH-GRID-CT, as seen from **Table 1**. Therefore, that is why PV-WT-MH-GRID-CT is placed ahead of the PV-MH-GRID-CT configuration. Detail cost analysis of the optimal HRES configuration is shown in **Table 3**.

In essence, to the other HRES, grid factor has resulted in negative operational and maintenance costs, salvage as seen in **Table 4**, effectively denoting profits rather than expenditures, which may lead to quicker payback period.

Because of the high capital and operating costs of MH, the total cost of the system components resulted in a higher total cost of $111,026. WT and CT, on the other hand, have a low overall cost and are the cheapest components in HRES. Grid earns rather than expenses, which result in faster payback, as we could observe from **Table 5** as grid purchase constitutes 8.28% when compared to grid sales which constitute 27.8% from **Table 5**. Therefore, the system earns money when it sells energy to the grid, which results in a faster payback period.

Table 5 displays the energy production of the HRES. Non-conventional energy sources are the primary sources of supply for 465,283 kWh/year.

We could observe from **Table 5** that MH and PV produce most of the energy demand for the given load profile. Due to low wind speed at the selected location, the energy generated by wind is less when compared to other sources. The PV array generates 141,153 kWh annually, with 4400 operational hours annually, as well as a COE of $0.0495/kWh. The energy output of the wind turbine is 25,089 kWh per year, with 6,757 operating hours per year, and the COE is $0.0757 per kW-hour. The hydro energy production is 260,528 kWh/year, with 8760 h of operating hours annually as well as COE of $0.0330/kWh. The converter works for 7411 h a year. **Figure 4** shows the monthly average electric share of each renewable source for an optimal HES strategy. In terms of

TABLE 3 | Performance of optimized results of HRES for ON Grid Scenario.

System Configuration	Sizing of components					Cost			RF (%)
	PV (kW)	WT (kW)	GRID (kW)	MH (kW)	CT (kW)	NPC ($)	COE ($)	OC ($/yr)	
PV-WT-MH-GRID-CT	80	20	999,999	34.8	62.0	202,733	0.034	288.78	91.5
PV-MH-GRID-CT	75	-	999,999	34.8	57.6	198,866	0.035	1,699	89.4
WT-MH-GRID-CT	-	20	999,999	34.8	15.1	244,154	0.045	10,769	68.3
PV-WT-GRID-CT	60	20	999,999	-	63.9	365,161	0.085	18,997	46.9

TABLE 4 | Detail cost analysis of HRES.

Component	Capital	O & M	Replacement	Salvage	Fuel	Total
MH	$80,000.00	$31,026	$0.00	$0.00	$0.00	$111,026
WT	$20,400.00	$2,586	$3,571	−$2,012	$0.00	$24,544
GRID	$0.00	−$48,185	$0.00	$0.00	$0.00	−$48,185
PV	$80,000.00	$10,342	$0.00	$0.00	$0.00	$90,342
CT	$18,600	$0.00	$7,891	−$1,485	$0.00	$25,006
System	$199,000	−$4,231	$11,462	−$3,498	$0.00	$202,733

TABLE 5 | Energy generation of the optimal HRES.

Source	kWh/yr	%
PV	141,153	30.3
WT	25,089	5.39
MH	260,528	56.0
GRID PURCHASE	38,513	8.28
TOTAL	448,403	100

Excess energy and consumption of the optimal HRES.

a) Excess energy consumption of HRES			b) Energy consumption of the optimal HRES		
Load	kWh/yr	%	Load	kWh/yr	%
Capacity Shortage	0	0	AC Primary Load	327,770	72.2
Unmet Load	0	0	DC Primary Load	0	0
Excess Electricity	3,043	0.654	Grid Sales	126,309	27.8

energy usage, **Table 5** shows that the best configuration plan meets 24-h load demand with no power shortage and backup surplus energy of 3,043 kWh/yr.

As seen from **Table 5**, the energy consumption from AC primary load is 327,770 kW-h/yr, which is 72.2% of total utilization. Energy consumption from Grid sales is 126,309 kWh/yr, which constitutes 27.8% of total consumption. The total energy consumption is 454,079 kWh/year. PV, wind turbine, micro-hydro, and system converter outputs of HRES with on-grid scenario are given in **Table 6**.

Table 7 shows the energy purchased (kWh) and energy sold (kWh) rates to the grid. **Figure 5** depicts the on-line energy-scheduling system, which includes generation and load profiles for April 3. The critical review of **Figure 5** shows a variety of promising possibilities for the proposed configuration plan. Solar energy generation is found to be possible, starting at 6:00 a.m. and ending at 18:00 p.m., with a high at 13:00 p.m. Since PV is not available before 06:00 and after 18:00, all load is supplied by MH. When compared to the other elements in the method, we can also see that WT only runs for a short period of time. Furthermore, surplus electricity is supplied to the grid, resulting in a quicker payback. The amount of energy purchased from the grid is minimal since PV and MH meet the majority of demand. Emissions produced by HRES are presented in **Table 8**.

HRES with Off Grid Scenario

Table 9 shows the optimal findings of all the HRES for off-grid scenario in Bijolia, Rajasthan. Among four HRES configurations, PV-WT-MH-BT-CT-DG is the utmost feasible configuration for an off-grid scenario in terms of NPC, COE, OC, and RF. The least economic configuration is PV-WT-BT-CT-DG for the off-grid scenario in terms of NPC, COE, OC, and RF. In the off-grid scenario, the optimal PV-WT-MH-BT-CT-DG HRES configuration to supply load demand consists of PV of 80 kW, Wind Mill of 20 kW, Diesel Generator of 140 kW, Hydro of 34.8 kW, 74.6 kW converter,

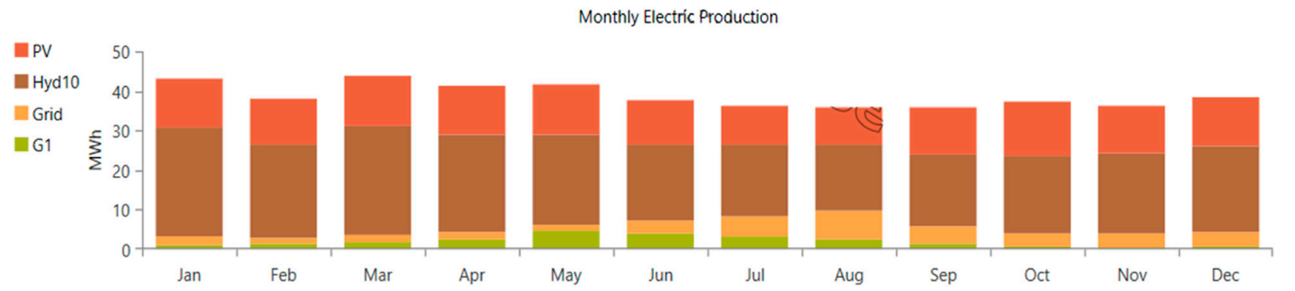

FIGURE 4 | Monthly average electric production.

TABLE 6 | PV, Wind turbine, Micro-hydro, and system converter outputs of HRES.

PV outputs			Wind turbine outputs		
Quantity	**Value**	**Units**	**Quantity**	**Value**	**Units**
Rated Capacity	80.0	kW	Rated Capacity	20.0	kW
Mean Output	16.1	kW	Mean Output	2.86	kW
Mean Output	387	kW/d	Capacity factor	14.3	%
Capacity factor	20.1	%	Maximum Output	20	kW
Maximum Output	79.0	kW	Wind Penetration	7.65	%
PV Penetration	43.1	%	Hours of Operation	6,757	h/yr
Hours of Operation	4,400	h/yr	Levelized Cost	0.0757	$/kWh
Levelized Cost	0.0495	$/kWh			
System Converter Outputs			**Micro Hydro Outputs**		
Quantity	**Value**	**Units**	**Quantity**	**Value**	**Units**
Rated Capacity	62.0	kW	Nominal Capacity	34.8	kW
Mean Output	17.7	kW	Mean Output	29.7	kW
Capacity factor	28.5	%	Capacity factor	85.4	%
Maximum Output	62.0	kW	Maximum Output	37.4	kW
Hours of Operation	7,411	h/yr	Hydro Penetration	79.5	%
			Hours of Operation	8,760	H/yr
			Levelized Cost	0.0330	$/kWh

TABLE 7 | Energy purchased (kWh) and energy sold (kWh) rates to Grid of HRES.

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Peak load (kW)	Energy charge	Demand charge	Total
January	1,908	14,860	−12,952	41.9	−$700.81	$0.00	−$700.81
February	1,518	12,568	−11,049	45.4	−$602.24	$0.00	−$602.24
March	1,885	14,059	−12,174	54.5	−$655.03	$0.00	−$655.03
April	1,791	13,295	−11,505	48.8	−$618.66	$0.00	−$618.66
May	1,680	13,157	−11,476	35.7	−$621.36	$0.00	−$621.36
June	3,210	9,479	−6,268	69.9	−$247.70	$0.00	−$247.70
July	4,779	7,797	−3,018	67.8	$10.11	$0.00	$10.11
August	7,241	6,200	1,040	89.0	$352.06	$0.00	$352.06
September	4,168	7,540	−3,372	62.7	−$35.64	$0.00	−$35.64
October	3,069	8,695	−5,625	55.7	−$214.74	$0.00	−$214.74
November	3,583	9,005	−5,422	54.2	−$182.04	$0.00	−$182.04
December	3,680	9,655	−5,975	54.4	−$211.27	$0.00	−$211.27
Annual	38,513	126,309	−87,797	89.0	−$3,727	$0.00	−$3,727

and 257 kWh Battery. The NPC, COE, OC, and RF of the PV-WT-MH-BT-CT-DG HES are $612,748, $0.145, $20,334, and 95.5%. Detail cost analysis of the optimal HRES configuration is shown in **Table 10**.

In essence, as opposed to the other HRES, this factor has resulted in negative salvage cost as seen in **Table 10**, effectively denoting profits rather than expenditures, which may result in a quicker payback period. The high capital and

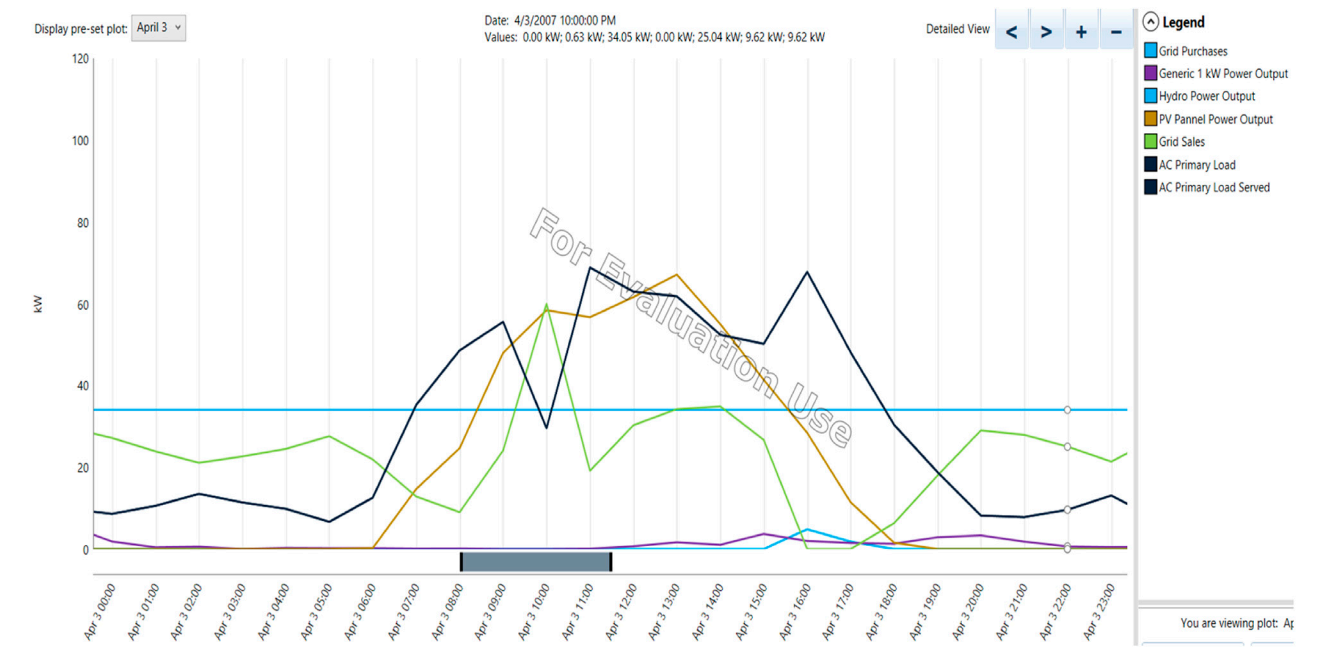

FIGURE 5 | On-line energy scheduling for April 3.

TABLE 8 | Emissions produced by HRES.

Quantity	Value
Carbon Dioxide	24,340 (kg/yr)
Carbon Monoxide	0 (kg/yr)
Unburned Hydrocarbons	0(kg/yr)
Particulate Matter	0(kg/yr)
Sulphur Dioxide	106 (kg/yr)
Nitrogen Oxides	51.6 (kg/yr)

replacement costs of BT result in a higher overall cost between system components of $220,035 due to the high cost of BT. WT and CT, on the other hand, have a low overall cost and are the cheapest components in HRES. **Table 10** presents energy generation of the optimal HRES Non-conventional energy sources are the primary sources of supply for 441,557 kWh/yr.

We could observe from **Table 10** that MH and PV produce most of the energy demand for the given load profile. Due to low wind speed at the selected location, the energy generated by wind is less when compared to other sources. DG also plays a minimum role in the energy generation of optimal HRES.

The PV array generates 141,153 kWh annually, with 4400 operational hours annually, as well as a COE of $0.0495/kWh. The energy output of wind turbines is 25,089 kWh per year, with 6,757 operating hours per year, and the COE is $0.0757 per kW-hour. The hydro energy production is 260,528 kWh/year, with 8760 operating hours per year and a COE of $0.0330/kWh. The converter runs for 4,427 h a year. The Diesel Generator produces 14,787 kWh per year and operates for 372 h per year.

Figure 6 shows the monthly average electric share of each renewable source for an optimal HRES strategy. In terms of energy usage, **Table 11** shows that the best configuration plan meets 24-h load demand with no power shortage and backup surplus energy of 98,738 kWh/yr.

As seen from **Table 11**, the energy consumption from AC primary load is 327,770 kWh/year, which is 72.2% of total consumption. The total energy consumption is 327,770 kWh/year. PV, Wind turbine, Micro-hydro, and system converter outputs of HRES with off-grid scenario are given in **Table 12**.

TABLE 9 | Performance of optimized results of HRES for off Grid Scenario.

System Configuration	Components size						Cost			RF (%)
	PV (kW)	WT (kW)	DG (kW)	MH (kW)	BT (kWh)	CT (kW)	NPC ($)	COE ($)	OC ($/yr)	
PV-WT-MH-BT-CT-DG.	80	20	140	34.8	257	74.6	612,748	0.145	20,334	95.5
PV-MH-BT-CT-DG	65	-	142	34.8	257	57.6	634,905	0.150	23,626	94.4
WT-MH-BT-CT-DG	-	10	145	34.8	282	42.8	1.06 M	0.249	60,932	70.2
PV-WT-BT-CT-DG	72	25	147	-	324	91.0	1.53 M	0.361	95,471	42.1

TABLE 10 | Detail cost analysis of HRES.

Component	Capital	O & M	Replacement	Salvage	Fuel	Total
MH	$80,000	$31,026	$0.00	$0.00	$0.00	$111,026
DG	$70,000	$20,198	$0.00	−$6,372	$52,889	$136,715
WT	$20,400	$2,586	$3,571	−$2,012	$0.00	$24,544
BT	$77,100	$33,224	$113,803	−$4,091	$0.00	$220,035
PV	$80,000	$10,342	$0.00	$0.00	$0.00	$90,342
CT	$22,378	$0.00	$9,494	−$1,787	$0.00	$30,086
System	$349,878	$97,375	$126,868	−$14,263	$52,889	$612,748

Energy generation of the optimal HRES.

Source	kWh/yr	%
PV	141,153	32.0
DG	14,787	3.35
WT	25,089	5.68
MH	260,528	59.0
TOTAL	441,557	100

Figure 7 depicts the on-line energy-scheduling system, which involves the generation and load profiles for March 6. The critical review of **Figure 7** shows a variety of promising possibilities for the proposed configuration plan. Solar energy generation is observed to be available starting at 6:00 a.m. and ending at 18:00 p.m., with a peak at 13:00 p.m. Since PV is not available before 06:00 and after 18:00, all load is supplied by BT, MH, WT, and DG. It's also worth noting that the MH's strength remains constant. We could also see that WT operates from 6:00 a.m. to 13:00 p.m. It functions for a limited amount of time when compared to other components in the system because MH and PV serve most of the load. DG functions from 14:00 p.m. to 16:00 p.m., and its peak is at 15: 00, as observed from the figure. Emissions produced by HRES are presented in **Table 13**.

SENSITIVITY ANALYSIS RESULT

As a result of this study, it is seen that NPC, O&M, COEs, and RF of on-grid energy systems are better than off-grid energy systems. In the study, between eight hybrid system combinations, the PV-WT-MH-GRID-CT system is the best optimal system.

The sensitivity parameters selected for this analysis are global solar irradiation and annual wind speed. For each sensitivity variable, the actual value (base case) was either increase or decrease. The base case (actual) values of global solar irradiation, annual wind speed were 5.51 kWh/m^2/day, 4.80 m/s respectively. The sensitivity evaluation parameters are NPC, COE, O&M, and RF for the optimal system and are presented in **Table 14**.

Observation of the sensitivity results shows that when the global solar radiation is 7 kWh/m^2/day with wind speed of 3 m/s results in less NPC, O&M and increase in RF when compared with optimal system. This is because the increase in solar radiation gives rise to increase in production of electricity by PV panel. This variable impacted the NPC, COE O&M, and RF, i.e., NPC has reduced from $202,733 to $198,630 while COE has reduced from 0.034 to 0.033, RF has increased from 91.5 to 92.3% and O&M cost has been drastically decreased from $288.78 to $118.53. For a change in the solar irradiation from 5.51 kWh/m^2/day to 7 kWh/m^2/day. When global solar radiation is 7 kWh/m^2/day with annual average wind speed of 3 m/s has the lowest O&M when compared to other sensitivity cases.

Global solar radiation at 7 kWh/m^2/day with wind speed of 6.50 m/s results in decreased NPC, COE and increase in O&M

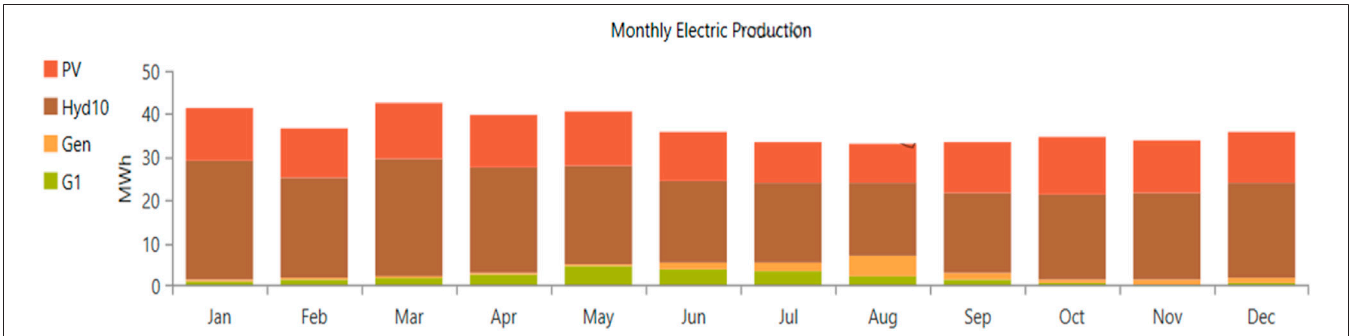

FIGURE 6 | Monthly average electric production.

TABLE 11 | Excess Energy and consumption of the optimal HRES.

a) Excess energy consumption of HRES		
Load	**kWh/yr**	**%**
Capacity Shortage	0	0
Unmet Load	0	0
Excess Electricity	98,738	22.4

b) Energy consumption of the optimal HRES		
Load	**kWh/yr**	**%**
AC Primary Load	327,770	72.2
DC Primary Load	0	0

TABLE 12 | PV, WT, MH System converter, DG, Batteries outputs of HRES.

PV outputs		
Quantity	**Value**	**Units**
Rated Capacity	80.0	kW
Mean Output	16.1	kW
Mean Output	387	kW/d
Capacity factor	20.1	%
Maximum Output	79.0	kW
PV Penetration	43.1	%
Hours of Operation	4,400	h/yr
Levelized Cost	0.0495	$/kWh

Wind turbine outputs		
Quantity	**Value**	**Units**
Rated Capacity	20.0	kW
Mean Output	2.86	kW
Capacity factor	14.3	%
Maximum Output	20	kW
Wind Penetration	7.65	%
Hours of Operation	6,757	h/yr
Levelized Cost	0.0757	$/kWh

System Converter Outputs		
Quantity	**Value**	**Units**
Rated Capacity	74.6	kW
Mean Output	15.1	kW
Capacity factor	20.3	%
Maximum Output	65.5	kW
Hours of Operation	4,427	h/yr

Micro Hydro Outputs		
Quantity	**Value**	**Units**
Nominal Capacity	34.8	kW
Mean Output	29.7	kW
Capacity factor	85.4	%
Maximum Output	37.4	kW
Hydro Penetration	79.5	%
Hours of Operation	8,760	H/yr
Levelized Cost	0.0330	$/kWh

Fuel Summary (Diesel)		
Quantity	**Value**	**Units**
Total fuel consumed	5,114	L
Avg fuel per day	14.0	L/day
Avg fuel per hour	0.584	L/h

Battery Outputs		
Quantity	**Value**	**Units**
Batteries	257	qty
Nominal Capacity	257	kWh
Usable Nominal Capacity	154	kWh
Lifetime through output	205,600	kWh
Expected Life	6.62	yr

Diesel Generator Outputs		
Quantity	Value	Units
Hours of Operation	372	h/yr
Number of starts	281	starts/yr
Operational Life	40.3	Yr
Fixed Generation costs	12.4	$/yr
Marginal generation costs	0.189	$/kWh
Electrical Production	14,787	kWh/yr
Mean electrical output	39.7	kW
Min.electrical output	35.0	kW
Max.electrical output	89.0	kW
Fuel consumption	5,114	L
Fuel energy input	50,322	kWh/yr
Mean electrical efficiency	29.4	%

and RF when compared to optimal system. This variable influenced the NPC, COE O&M, and RF, i.e., NPC has reduced from $202,733 to $161,310 while COE has drastically reduced from 0.034 to 0.025, O&M has significantly increased from $288.78 to $3,163, and RF has changed from 91.5 to 95.0%. There is a sudden change in O&M cost because PV panel is now producing 166,800 kWh/yr and wind turbine produces 52,556 kWh/yr, i.e., there is an increase of 18.16% change in

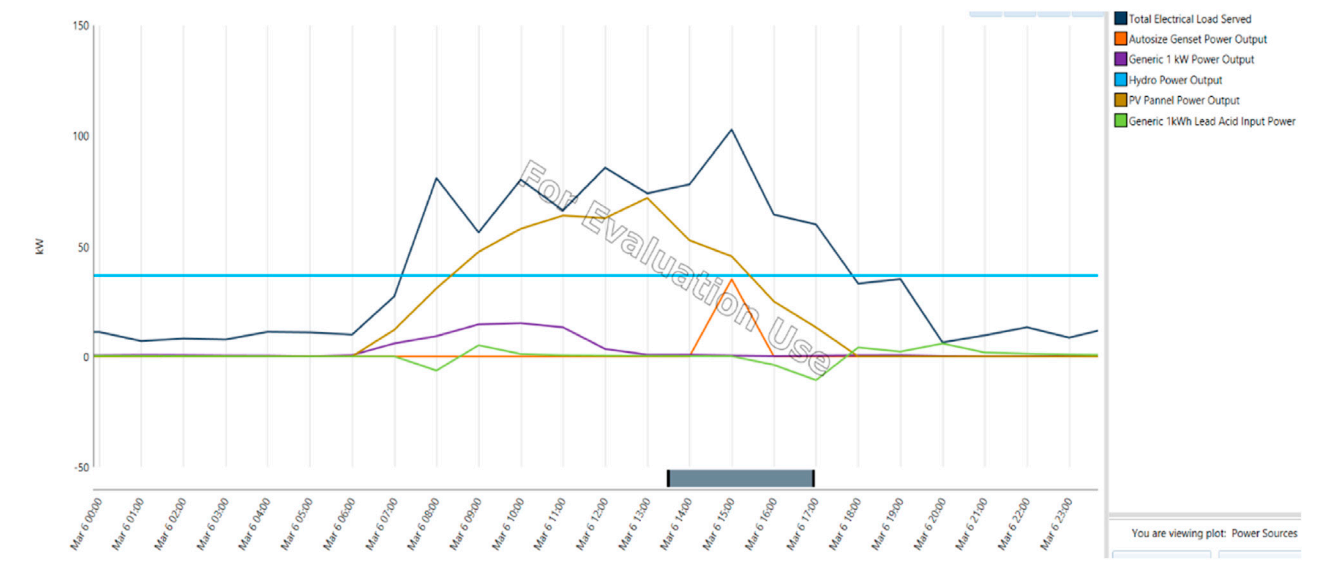

FIGURE 7 | On-line energy scheduling for March 6.

TABLE 13 | Emissions produced by HRES.

Quantity	Value
Carbon Dioxide	13,386 (kg/yr)
Carbon Monoxide	84.4 (kg/yr)
Unburned Hydrocarbons	3.68(kg/yr)
Particulate Matter	0.5111(kg/yr)
Sulphur Dioxide	32.8 (kg/yr)
Nitrogen Oxides	79.3(kg/yr)

electricity production by PV panels. There is a huge increase of 109.47% change in electricity production by wind turbines when compared with the electricity production of the optimal system. COE has drastically reduced because PV panels and wind turbine are producing more electricity. We could also see that RF has also increased drastically by 3.5% when compared to base case because PV and wind turbine when compared to micro hydro and energy purchased from grids are producing most of the electricity per year.

We could see from **Table 14** that when global solar radiation is 4 kWh/m^2/day with wind speed of 3 m/s and there is a sudden increase in NPC, COE, O&M and decrease in RF%. NPC has increased by 25.40%, COE has increased by 35.29%, O&M has increased from $288.78 to $4,723 because as the global solar radiation and annual wind speed has been reduced so most of the load demand is met by hydro and grid which results in lesser RF and increased in NPC, COE, and O&M costs.

Figures 8A–C show the optimal system plot for NPC, RF, and COE. In these graphs, we have taken annual wind speed in *y*-axis and global solar radiation in *x*-axis.

[(Sawle et al., 2018a)], [(Sawle et al., 2021)], https://energy.rajasthan.b, https://en.wikipedia.org/,https://energy.rajasthan.a.

TABLE 14 | Sensitivity analysis results.

Sensitivity variables		Evaluation parameters			
Global solar radiation (kWh/m^2/day)	Annual wind speed (m/sec)	NPC ($)	COE ($)	O&M ($/yr)	R.F (%)
	3	254,243	0.046	4,723	84.6
4	4.80	236,925	0.042	3,316	86.9
	6.50	212,363	0.037	4,802	82.1
	3	219,398	0.038	1,668	89.9
5	4.80	202,733	0.034	288.78	91.5
	6.50	180,804	0.029	1,497	93.3
	3	198,630	0.033	118.53	92.3
7	4.80	182,686	0.030	1,419	93.6
	6.50	161,310	0.025	3,163	95.0

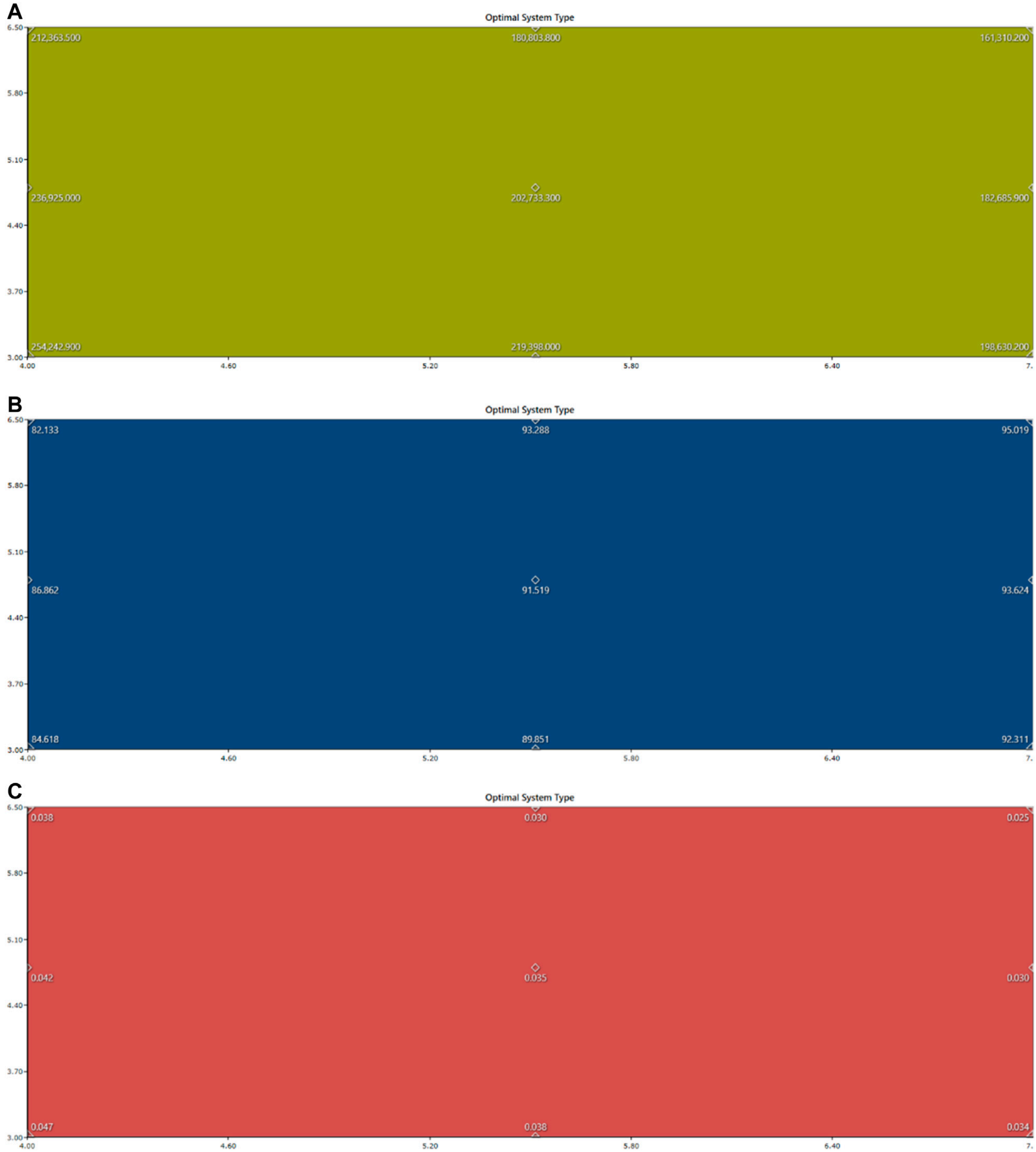

FIGURE 8 | (A) Optimal system type plot for Net Present Cost. **(B)** Optimal system type plot for RF. **(C)** Optimal system type plot for COE.

CONCLUSION

Within this research scope, meeting load demands of towns through on-grid/off-grid renewable energy systems is investigated from a techno-economic analysis perspective. As a result of this study, it is seen that NPC, O&M, COEs, and RF of on-grid energy systems are better than off-grid energy systems. In the study, between eight hybrid system combinations, the lowest COE of 0.034 $/kWh is obtained with the PV-WT-MH-GRID-CT system in the on-grid scenario. It should also be kept in mind that on-grid systems contribute to CO2 emission reduction when compared to off-grid systems. PV-WT-MH-BT-CT-DG is the utmost feasible configuration for an off-grid scenario in terms of NPC, COE, OC, and RF. The NPC, COE, OC, and RF of the PV-WT-MH-BT-CT-DG HES are $612,748, $0.145,

$20,334, and 95.5%, respectively. Global solar radiation is 7 kWh/m^2/day with wind speed of 6.50 m/s results in decreased NPC, COE and increase in O&M and RF when compared to optimal system. This variable influenced the NPC, COE O&M, and RF, i.e., NPC has reduced from $202,733 to $161,310 while COE has drastically reduced from 0.034 to 0.025, O&M has significantly increased from $288.78 to $3,163, and RF has changed from 91.5 to 95.0%.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

This research aims to structure a power generation model associated with different HRES combinations using a HOMER software application at a location in India. This research's primary goal is to examine the foremost possible HRES configuration utilizing various variations to meet the requirement for village load in a secure, permanent and sustainable way. As a result of this study, it is seen that NPC, O&M, COEs, RF of on-grid energy systems are better than off-grid energy systems. In the study, between eight hybrid system combinations, the lowest COE of 0.034 $/kWh is obtained with the PV-WT-MH-GRID-CT system in the on-grid scenario.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.724162/full#supplementary-material

Supplementary Figure S1 | Methodology used in HOMER.

Supplementary Figure S2 | Geographical map of Bijolia.

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