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Techno-economic analysis of hybrid renewable power generation system under different climatic zones in India

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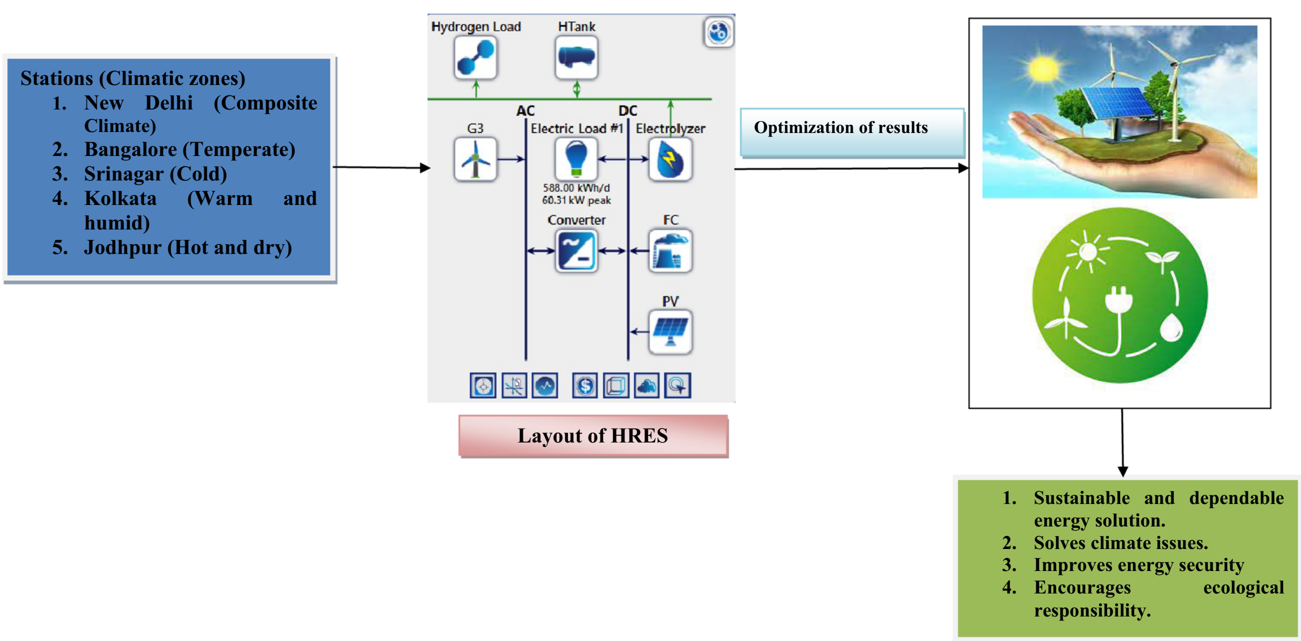
Abstract

Power is becoming more crucial all across the world because of the limited supply of fossil fuels. Therefore, it is critical to develop some alternative non-renewable energy frameworks that can reduce dependency on conventional energy assets. Increased adoption of renewable energy sources (RES) has recently aided in achieving environmental and sustainable energy goals. To overcome the technical difficulties posed by their erratic and intermittent nature, the combination of RES and their costs may provide a cheap, clean and effective alternative energy supply source. This research focuses on the techno-economic analysis of hybrid renewable energy systems (HRESs) for power generation under different climatic zones, i.e. composite, temperate, cold, warm and humid and hot and dry. The system is modelled for an average load demand of 588 kWh per day and a peak load of 60.31 kW and simulated based on meteorological data of New Delhi, Bangalore, Srinagar, Kolkata and Jodhpur. It consists of a solar photovoltaic system (PV), a wind turbine, a fuel cell, a converter, an electrolyser and a hydrogen tank. Srinagar has the highest total net present cost (NPC) of 57,44,105.53 US$, whereas Bangalore has the lowest NPC, i.e. 34,01,103.82 US$. The hydrogen production range is between 1955 and 1963 kg/year for all climatic zones. The Jodhpur station is the most suitable one with the lowest LCOE, i.e. 1.14 $/kWh, and a payback period of 5.9 years. Therefore, installing an HRES according to the climatic conditions will provide a sustainable and dependable energy solution that solves climate issues, improves energy security and encourages ecological responsibility.

Graphical abstract



Keywords Hybrid renewable energy system · Climatic zones · HOMER · Power generation · Capacity factor

List of symbols

A_E and B_E	Coefficient of consumption curve (kW/kg/h)
$C_{ann,tot}$	Total annualised cost ($/year)
C_{AT}	Total annualised cost (US$)
C_{NPC}	Net present cost (US$)
CC_T	Capital cost of hybrid energy system component (US$)
C_{rep}	Component replacement cost (US$)
$E_{prim,AC}$	AC primary load served (kWh/year)
$E_{prim,DC}$	DC primary load served (kWh/year)
$E_{grid,sales}$	Total grid sales (kWh/year)
E_{nerst}	Nernst voltage (V)
E_{ocv}	Open circuit voltage (V)
f	Yearly inflation rate (%)
F	Faraday constant (96,485 s/mol)
ΔG	Activation energy barrier (J)
h	Planck's constant (6.626×10^{-34} J s)
H	Solar radiation (W/m^2)
H_{ref}	Solar radiation at reference conditions (H_{ref} = 1000 W/m^2)
i_{hf}	Fuel cell current (A)
i_o	Exchange current (A)
i_r	Real interest rate
k	Boltzmann's constant (1.38×10^{-23} J/K)
N	Number of years
N_{fc}	Number of fuel cell
OMC_T	Operation and maintenance cost of HRES component (US$)
P	Component of HRES (fuel cell/hydrogen tank/solar PV/wind turbine system/electrolyser/system converter)
P_{H2}	Partial pressure of oxygen inside the stack (atm)
P_{input}	Input power from/to converter (W)
P_L	Project life (20 years)
P_{O2}	Partial pressure of hydrogen inside stack (atm)
P_{output}	Output power from/to a converter (W)
P_{PV}	Power output from the PV cell (W)
P_R	Rated power at reference conditions (W)
P_r	Rated power of wind turbine (kW)
$P_{WT}(t)$	Output energy of a wind turbine at the time (t) (kW)
Q	Hydrogen mass flow (kg/h)
R	Gas constant (8.3145 J/mol K)
ReC_T	Replacement cost of HRES component (US$)
R_{comp}	Component life in year
R_{rem}	Component remaining life in year
R_{Td}	Response time at 95% of final value (s)
S	Tafel slope (V)
SR_T	Number of replacements
S_p	Temperature coefficient of maximum power for solar cell
S_T	Number/Size of HRES
T_C	Cell temperature (K)
T	Temperature of operation (K)
T_{ref}	Temperature at reference conditions (K)
v_{anem}	Wind speed at anemometer height (m/s)
v_{cin}	Cut-in wind velocity of selected wind turbine (m/s)
v_{cout}	Cut-off wind velocity of selected wind turbine (m/s)
V_f	Fuel cell voltage (V)
v_r	Wind speed at wind turbine height (m/s)
W_c	Voltage constant at nominal condition
z	Number of moving electrons ($z = 2$)

Extended author information available on the last page of the article

Greek symbol

α	Coefficient of charge transfer

Abbreviations

COE	Cost of energy
CRF	Capital recovery factor
HFC	Hydrogen fuel cell
HRES	Hybrid renewable energy system
LCOE	Levelised cost of energy
NPC	Net present cost
NREL	National Renewable Energy Laboratory
PEM	Proton exchange membrane
PV	Photovoltaics
RES	Renewable energy sources
RF	Renewable fraction

1 Introduction

In today's globalising world, around one billion people are not able to access electricity [1]. The rising demand for energy due to population growth and industrialisation is largely satisfied by fossil fuels that release greenhouse gases like methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) [2]. Currently, interest in producing power via RESs is growing in the public and private sectors, because of an enormous rise in the cost of fossil fuels and the threats to the environment produced by the usage of traditional fuels [3]. As a result, RESs are viable options for generating power since they are dependable, environmentally friendly, and freely available [4]. This technology provides safe, clean, and ecologically beneficial energy [5]. Another significant advantage of this technology is its minimal maintenance and running expenses, as it contains no moving components. These characteristics make this technology suitable for producing energy for a wide variety of applications. Renewables, particularly solar PV and wind have gained the greatest ground of all forms of energy this decade, accounting for 43% of global power output in 2030, up from 28% currently [6]. The aforementioned structure is intended to be an environmentally friendly solution since it seeks to increase the use of RESs. PV generators are simple devices that convert sunlight into electrical energy [7]. From an operational perspective, the production power of PV power generation varies greatly due to weather variability. Another disadvantage is that PV is sunlight-dependent, and its production does not meet load demand throughout the year [8].

An approach to overcoming this challenge is to combine the solar framework with additional power sources like fuel cells, wind power, electrolysers, hydrogen tanks and converters, to ensure a continuous 24-h power supply. Ram et al. presented an in-depth study of the capabilities and limits of various HRES software, claiming that HOMER can do a techno-economic analysis [9]. Baghel et al. investigated the effect of tilt angle and albedo on the specific production of solar PV systems. Results indicate a linear relationship between albedo, tilt angle and specific production [10]. Aykut et al. [11] investigated grid-connected HRESs. The optimal system's NPC is determined to be US$ 5.612.501, while the LCOE is 0.067 $/kW and also reduces greenhouse gas emissions. Kumar et al. [12] looked into the viability of a PV/diesel HPS from an economic standpoint in diverse climate zones of Tamil Nadu. Kanyakumari is the ideal climate zone in Tamil Nadu for setting up a PV/diesel HRES based on the NPC, renewable fraction (RF), carbon emission in tons/year and diesel consumption in lit/year. Kallio et al. investigated the HRES using MATLAB/Simulink to identify the individual COE of items. The charges vary greatly on a monthly and regional basis. The lowest yearly specific cost of electricity is 0.29 €/kWh in the southernmost region, while the lowest specific cost of heat products is 0.319 €/kWh_{ex} (0.034 €/kWh) and overall exergy efficiency is 13–16% [13].

Babatunde et al. [14] investigated an off-grid hybrid PV, micro-wind turbine and RES with hydrogen and battery storage. In South Africa, the total NPC and LCOE of the ideal energy system were 8771 US$ and 0.701 US$/kWh, respectively, compared to 9421 US$ and 0.756 US$/kWh in Nigeria. Turkay et al. [15] evaluated the economics of standalone and grid-connected HRES. Results reveal that grid-connected HRESs are more likely to adapt than independent (100% renewable system) designs. Nallolla et al. [16] investigated an HRES by evaluating the lowest possible LCOE: 0.244 $/kWh, NPC: $7.01 M, and the high RF: 84.1%. This ideal HRES set-up offers a consistent power supply with no unfulfilled loads. Lau et al. [8] examined an HRES containing PV/BS (417 batteries, 1476 kW solar PV, hydrogen tank 20 kg, electrolyser 200 kW and 59.6 kW converter) by evaluating the lowest feasible LCOE: 0.244 $/kWh, NPC: $7.01 M, and the highest RF: 84.1%. It became clear that adopting a hybrid PV/diesel system with batteries could produce considerably cheaper NPC and COE than an independent diesel system with a 25-year projected horizon and a 6% annual interest rate. Ismail et al. [3] examined a system that consists of solar panels, a battery bank and a diesel generator; the COE is 0.239 US$/kWh with a contribution from the sun of 90% and a battery bank of 0.4 AD. When CO_2 emissions were considered, it was observed that a diesel generator produces more CO_2 when in operation, than a PV, battery and diesel generator HRES. Koussa et al. [17] analysed the design of an HRES that combines wind and solar energy with battery storage. Basu et al. [18] found that the hybrid structure is the most practicable, where electricity demand is moderate. Bhayo et al. [19] investigated and optimised a standalone HRES for powering a 3.032 kWh/day dwelling unit. Table 1 compiles the relevant HRES previously conducted studies using HOMER software to develop the best system for remote places depending on the availability of renewable sources.

1.1 Why HOMER is selected for the simulation?

HOMER can simulate grid-connected and off-grid systems that meet electric and thermal demands and can be made up of any number of different photovoltaic (PV) modules, wind turbines, small hydro, biomass power, fuel cells, batteries and hydrogen storage. Based on the numerous design options and the ambiguity surrounding important aspects like load size and fuel price in the future, studying and designing these systems can be challenging. The intermittent, seasonal, non-dispatchable and uncertain availability of renewable energy sources further complicate the problems. To address these issues, HOMER was developed. The main tasks performed by HOMER are simulation, optimisation and sensitivity analysis. The best possible optimised results are produced by HOMER when it simulates the operation of a particular hybrid renewable energy system.

1.2 Advantages of HRES

- Multiple renewable energy sources, such as solar, wind and fuel cell are combined in HRES. This diversification decreases the system's reliance on a single energy source, making it more dependable and resilient to intermittent power generation or equipment breakdowns.
- By making the best use of various energy sources, HRES can increase energy efficiency. When renewable energy production is limited, excess energy from one source can

Table 1 Various HRES designs using HOMER software

S. no	Authors	Year	Components	City	Result
1	Sawle et al. [20]	2021	PV/WT/BG/DG	Gujarat	NPC-831,217 $, LCOE-0.196 $/kWh, RF-81.2%
2	Pujari et al.[21]	2022	PV/WT/DG /BS	Andhra Pradesh	NPC-5.48M, LCOE-0.272 $/kWh, RF-91.6%
3	Baseer et al. [22]	2019	PV/WT/DG/BS	Saudi Arabia	NPC-$555,492M, LCOE-$0.25/kWh, RF-100%
4	Sahu et al. [23]	2021	WT/PV/BS	Orissa	NPC-$454,242, LCOE-0.278 $/kWh
5	Hassan et al. [24]	2022	PV/FC	Iraq	NPC-$10,166, LCOE-0.23 $/kWh, RF-91.8%
6	Krishnamurthy et al. [25]	2020	PV/WT/BM	Pondicherry	NPC-Rs.11.9M, LCOE-Rs.8.231, RF-100%
7	Li et al. [26]	2020	PV/WT/BGDG/BS	West China	NPC-$456,388, LCOE-0.206 $/kWh
8	Fazelpour et al. [27]	2016	PV/WT/DG/BS	Iran	NPC-$888,500 LCOE-0.36 $/kWh

be used to generate hydrogen, which can be utilised during periods of low renewable energy generation

- HRES considerably reduces environmental pollution and greenhouse gas emissions. By replacing fossil fuel-based power generation, they aid in reducing climate change while encouraging clean air.
- HRES supports environmental programmes and sustainability goals at the local, state, and federal levels. They are financially appealing because they are generally eligible for government incentives, subsidies and tax credits.

According to the literature, no detailed techno-economic analysis based on meteorological data for different climatic zones in India utilising HOMER has been performed. The effect of climatic conditions on power generation using solar PV, wind energy, fuel cells and electrolysers has been carried out for five different stations, i.e. New Delhi, Bangalore, Srinagar, Kolkata and Jodhpur. The present investigation is completed using the National Renewable Energy Laboratory's (NREL) HOMER model. For Bangalore, Kolkata, and Jodhpur, wind power generation is commendable. However, Srinagar does not benefit from wind energy power generation. Additionally, it has been found that installing such a system as per the local climate can greatly reduce emissions, encourage environmental sustainability and improve power generation. The study's findings will aid investors and policymakers in identifying climatic conditions based on expertise that will deliver the best return on investment for significant projects in the residential and industrial sectors.

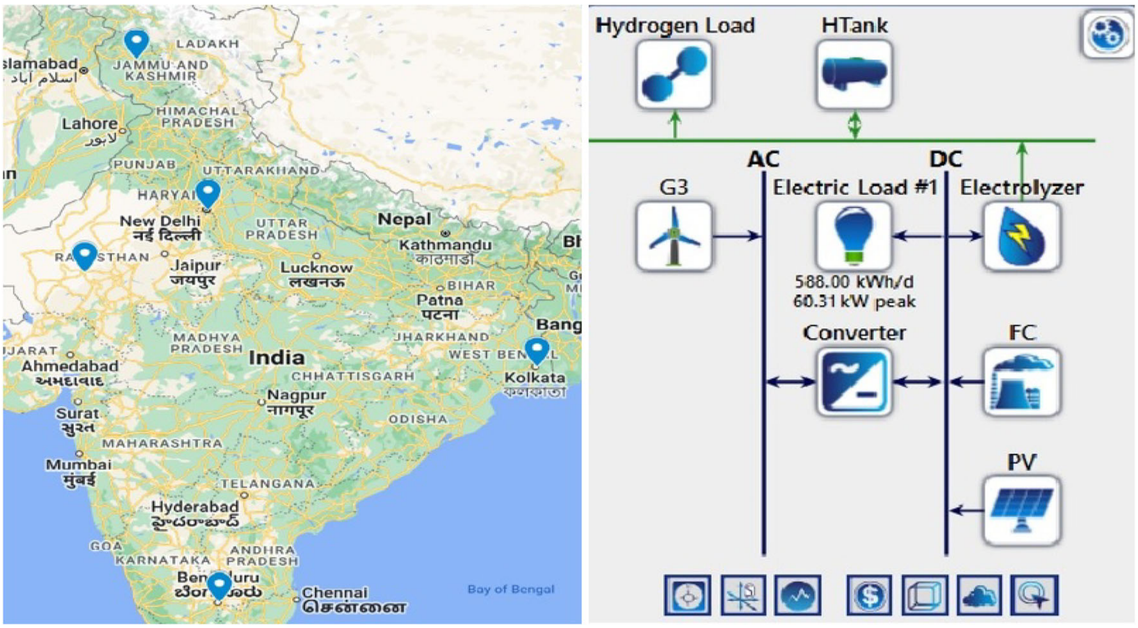
2 Material and methods

2.1 Site selection

India has five distinct stations, each with a wide range of climates. The following subsections provide a brief description of these zones, which have unique climates that are intended to be hot and dry, warm and humid, temperate, composite and cold. The five stations that correlate to the five climatic regions of India are New Delhi, Bangalore, Srinagar, Kolkata and Jodhpur as given in Table 2 and the location of the selected site is shown in Fig. 1a. The HRES is intended for a load of 588 kWh per day and a peak load of 60.31 kW. The primary goal of the system is to supply electricity and produce hydrogen to balance out the irregular nature of RESs. Figure 1b shows the layout of HRES, and it consists of the solar PV system, a wind turbine, a fuel cell, a converter, an

Table 2 Five stations of five climatic zones of India [28]

S. no	Station	Zone	Latitude (N)	Longitude (E)	Altitude (m)
1	New Delhi	Composite	28.6429°	77.2191°	273
2	Bangalore	Temperate	12.9716°	77.5946°	921
3	Srinagar	Cold	34.0837°	74.7973°	1585
4	Kolkata	Warm and Humid	22.5726°	88.3639°	5
5	Jodhpur	Hot and Dry	26.23°	73.02°	217



(a) (b)

Fig. 1 **a** Selected site locations in India and **b** Layout of HRES

electrolyser and a hydrogen tank. The DC bus combines the DC output from the fuel cell and solar panels, whereas the AC bus combines the power from the wind turbine. The hydrogen generated by the electrolyser is kept in a hydrogen tank. HRES comprised of solar PV, wind and hydrogen technologies can be designed and optimised with the help of HOMER. It helps in making decisions about system connection strategies and guides the operation of the system to maximise efficiency, minimise costs and achieve renewable energy and sustainability goals. The size and cost of the HRES must be optimised to achieve an optimal cost–performance ratio for different climatic zones of India.

2.2 Availability of resources at the selected stations

Table 3 depicts the vast potential of available annual average solar radiation, annual average wind speed and daily temperature of the selected stations. As per the NASA prediction data, Bangalore station has the highest potential for solar radiation and wind speed and Srinagar has the lowest potential for the same. Figures 2 and 3 show the NASA prediction of the worldwide energy resource database for solar global horizontal irradiation resources and monthly average wind speed at 50 m above the surface of the earth.

2.3 System components

2.3.1 Solar PV system

Solar PV panels transform sunlight into electric energy. PV panel's current output is a function of voltage and solar radiation. The solar PV panel's power output is estimated by multiplying the current and voltage. The power supplied by the solar panel is given by Eq. (1) [29].

$$P_{PV} = P_R \times \left(\frac{H}{H_{ref}}\right) \times \left(1 + S_p(T_C - T_{ref})\right) \quad (1)$$

Table 3 Potential of solar radiation and wind speed of different selected stations

S. no	Station	Annual average solar radiation (kWh/m^2/day)	Annual average wind speed (m/s)	Daily temperature (°C)
1	New Delhi	5.06	4.55	25.61
2	Bangalore	5.26	5.54	24.00
3	Srinagar	4.63	2.41	07.65
4	Kolkata	4.67	4.65	25.92
5	Jodhpur	5.21	5.26	26.65

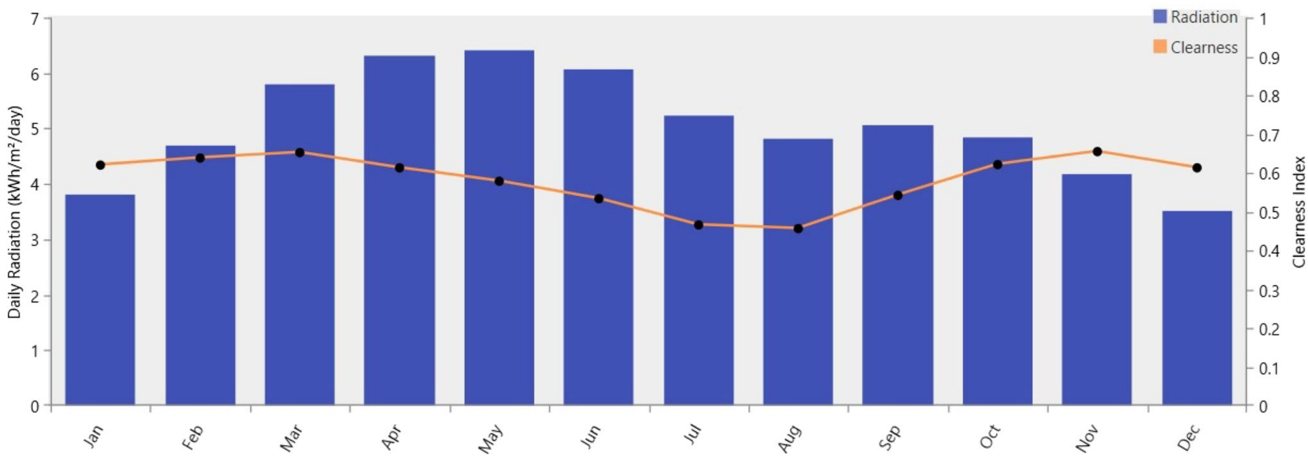


Fig. 2 Solar global horizontal irradiation resource

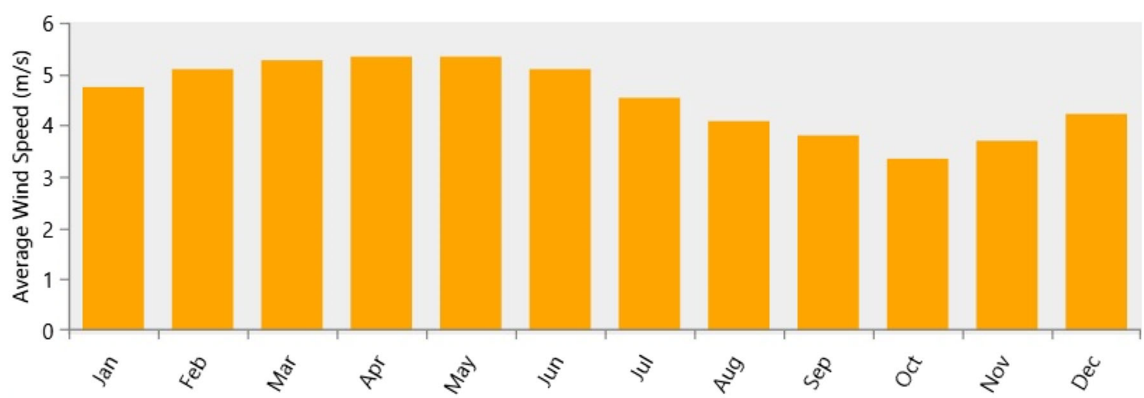


Fig. 3 Monthly average wind speed data

The installation and replacement costs of a 1 kW solar PV energy system are estimated to be US$ 3000 for each and a 90% derating factor. The solar PV arrays are supposed to have a life cycle of 25 years.

2.3.2 Hydrogen fuel cell

Hydrogen fuel cells (HFCs) are electrochemical devices that use an electrochemical reaction with oxygen to convert the chemical energy of hydrogen fuel into electrical energy. Water and heat are the by-products of this chemical process. Every HFC must connect electrodes, one positive and one negative, referred to as the cathode and anode, respectively. Hydrogen is the main fuel used in fuel cells; however, oxygen is also required.

Due to their high power density, precise power, low operating temperature, durability, efficiency and ability to perform well in dynamic environments, proton exchange membrane (PEM) fuel cells are among the best options for distributed generation in HRES. Fuel cells use hydrogen as their main fuel, but they also need oxygen. Tanks filled with compressed gas are the standard method for storing hydrogen. Fuel cells use hydrogen as their main fuel, but they also need oxygen. In tanks filled with compressed gas, hydrogen is often stored. An HFC voltage is given by Eq. (2) [30].

$$V_f = E_{ocv} - \left\{ N_{fc} \times S \times \ln\left(\frac{i_{hf}}{i_0}\right) \times \frac{1}{\frac{R_{Td}}{3} + 1} \right\} - (r_{int} \times i_{hf}) \tag{2}$$

$$\therefore S = \frac{R \times T}{z \times \alpha \times F}$$

The E_{ocv} and i_o are given by Eqs. (3) and (4), respectively [30].

$$E_{ocv} = W_c \times E_{nerst} \tag{3}$$

$$i_o = \frac{z \times F \times k\left(P_{H_2} + P_{O_2}\right)}{R \times h} \times e^{\left(\frac{-\Delta G}{R \times T}\right)} \tag{4}$$

UtH_2 and UtO_2 stand for utilisations of hydrogen and oxygen, P_{ffuel} and P_{fair} for supply pressures of fuel and air, respectively, V_{ffuel} and V_{fair} for flow rates of fuel and air, respectively, and $x\%$ and $y\%$ for the proportions of hydrogen and oxygen in the fuel oxidant, respectively. The UtO_2 and UtH_2 are given by Eqs. (5) and (6), respectively [30].

$$UtO_2 = \frac{60,000 \times R \times T \times i_{hfc}}{z \times F \times P_{fair} \times V_{fair} \times y\%} \tag{5}$$

$$UtH_2 = \frac{60,000 \times R \times T \times i_{hfc}}{z \times F \times P_{ffuel} \times V_{ffuel} \times x\%} \tag{6}$$

2.3.3 Electrolyser

An electrolyser is an apparatus that electrolyses water (H_2O) to separate it into hydrogen (H_2) and oxygen (O_2), using electrical energy. Two electrodes are submerged in an electrolyte solution in an electrolyser. The electrodes connected to the positive and negative terminals of a power source are referred to as anode and cathode, respectively. Water molecules at the cathode undergo reduction to produce hydrogen gas (H_2) when an electric current is supplied, whereas water molecules at the anode experience oxidation to release oxygen gas (O_2). According to Eq. (7), modelling is done for the input electrical energy dependence on the hydrogen mass flow [30].

$$Cons_E = B_E.Q_{N-E} + A_E.Q \tag{7}$$

2.3.4 Wind turbine

A wind turbine system having a rated capacity of 3 kW and a maximum output of 150 kW is modelled. The power output of a wind turbine is determined at each time step by HOMER using hourly wind speed and direction data for that particular region. Usually, a meteorological station provides this data. To predict the power output of the wind turbine under typical temperature and pressure circumstances, HOMER first determines the hub height and wind speed. The anticipated power value from the power curve is multiplied by the air density ratio by HOMER to take into consideration the actual environmental circumstances. If the wind speed at the hub height is greater than the range allowed by the power curve, the turbine is unable to produce any electricity. In this instance, it is presumed that wind turbines cannot generate power at wind speeds beyond the maximum cut-off or below the cut-in. By applying linear interpolation to locations where the power curve is recorded, HOMER calculates the wind turbine yield. A power curve illustrates the entire amount of power produced by the wind speed at the centre point height. The turbine's output is zero, outside of the power curve. When the required wind speed for operation is too low to produce energy, the turbine shuts off to prevent damage. In this investigation, a 3 kW G3 turbine with a 17 m hub height is employed. The capital cost is US$ 18,000 and 20 years lifespan. The power output of a wind turbine is calculated as in Eq. (8), and the wind speed acting on the wind turbine is calculated as in Eq. (9) [2].

$$P_{WT}(t) = \begin{matrix} 0 & V_{cin} \geq v(t) \text{ or } V_{cout} \leq v(t) \\ P_r \frac{v(t) - v_{cin}}{v_r - v_{cout}} & V_{cin} \leq v(t) \leq v_r \\ 0 & V_r \leq v(t) \leq v_{cout} \end{matrix} \tag{8}$$

$$v_r = v_{anem}\left(\frac{z_{hub}}{z_{anem}}\right)^{\gamma} \tag{9}$$

2.3.5 Converter

Power converters are the main components of HRESs. Power electronics devices are significant. Throughout the AC and DC segments, a power electronic converter is expected to maintain power upstream. A 60 kW capacity converter is used for this system. The capital cost of the converter is 300 US$, and the replacement cost is also 300 US$ for 1 kW. A unit's lifespan is estimated to be 15 years with a 95% efficiency. Converter efficiency is calculated by Eq. (10) [16].

$$\eta_{conv} = \frac{P_{output}}{P_{input}} \tag{10}$$

2.4 Cost analysis of hybrid renewable energy system

In the cost-advancement approach, HOMER duplicates each framework design in the search space and displays the potentially viable ones in a diagram, arranged with NPC. Therefore, it only displays the least-cost configuration inside each system category or type, revealing only a portion of these overall optimisation findings. The cost of the HRES is the sum of the costs of each of its components. As an example, the cost of a fuel cell (C_{FC}), hydrogen tank (C_{Htank}), solar PV system (C_{SPV}), wind turbine system (C_{WTS}), electrolyser (C_{Elect}) and system converter (C_{Conv}) is the total cost of an HRES given by Eq. (11).

$$C_{HRES} = C_{FC} + C_{Htank} + C_{SPV} + C_{WTS} + C_{Elec} + C_{Conv} \tag{11}$$

The cost of each component of HRES is found by using Eq. (12),

$$C_p = S_T \times [CC_T + (R_e C_T + SR_T) + OMC_T] \tag{12}$$

The first thing HOMER does is to assess the system's specific achievability and capacity to handle the load demand. Secondly, it evaluates the total NPC of the system, which represents the system's life cycle costs, comprising initial set-up costs (IC), replacement costs (RC), fuel costs (FC), operation and maintenance costs (OM) and the costs associated with obtaining power from the network. NPC of the HRESs is given by Eq. (13) [11], and capital recovery factor (CRF) is given by Eq. (14) [7].

$$C_{NPC} = \frac{C_{AT}}{CRF(i_r P_L)} \tag{13}$$

$$CRF = \frac{i_r(1+i_r)^N}{(1+i_r)^N - 1}. \tag{14}$$

2.4.1 Interest rate

One of the inputs used by HOMER is the yearly real interest rate, often known as the real interest rate or simple interest rate. It is the discount rate applied when one-time costs are converted to annualised costs. Equation (15) connects the nominal interest rate to the annual real interest rate [31].

$$i = \frac{i' - f}{1 + f} \tag{15}$$

2.4.2 Levelised cost of energy (LCOE)

To assess the financial sustainability of the HRES, the LCOE is calculated by using Eq. (16) [31].

$$LCOE = \frac{C_{ann,tot}}{E_{prim,AC} + E_{prim,DC} + E_{grid,sales}}. \tag{16}$$

2.4.3 Salvage value

Salvage value is the price of a power system component that is still functional at the end of the project's lifespan. To determine the value of each component at the end of the project's life cycle, HOMER utilises Eq. (17)[32]:

$$\text{Salvage} = C_{rep}\frac{R_{rem}}{R_{comp}}. \tag{17}$$

2.4.4 Payback period

The payback period may be described as the duration of time required to repay its initial cost and expenses and the cost of investment done for the project to reach a time where there is no loss no profit, i.e. breakeven point. It is given by Eq. (18).

$$\text{Payback period} = \frac{\text{Cost of investment}}{\text{Average annual cash flow}} \tag{18}$$

2.4.5 Total annualised cost

The annualised cost is computed by multiplying the net present cost by the capital recovery factor, as illustrated in Eq. (19) [31].

$$C_{ann,\,tot} = CRF\left(i,\ R_{proj}\right) \times C_{NPC,\,tot} \tag{19}$$

A detailed description of technical specifications, capital cost, replacement cost and maintenance cost of various components is given in Table 4.

3 Results and discussion

With the help of the HOMER software, simulation has been done according to the input parameters and limitations mentioned above. According to the total NPC and the necessary power demands for a specific station under its existing energy resources, HOMER Pro simulates the available resources according to the different selected stations and every system arrangement in search space and assesses the more feasible ones. Figure 4 shows the power output of the flat plate PV throughout the year with 100–200 kW rated capacity of solar PV panels. The total rated capacity of wind turbines varies from 150 to 300 kW for all the stations. The lowest wind penetration is found in Srinagar, while the highest is in Kolkata as shown in Fig. 5. Fuel cell generator capacity ranges from 0 to 60 kW. Figure 6 shows the generator power output for each hour of the day throughout the year. Electrolyser input power capacity ranges from 0 to 60 kW as shown in Fig. 7.

Table 4 Technical specifications and economic parameters of the proposed HRES

S. no	Component	Rated power	Lifespan	Capital cost(US$)	Replacement cost (US$)	Maintenance cost
1	PV module	100, 200 kW	25 years	3000	3000	10 $/year
2	Wind turbine	3 kW	20 years	18,000	18,000	180 $/year
3	Electrolyser	60 kW	15 years	2000	2000	–
4	Converter	60, 100 kW	15 years	300	300	–
5	Fuel cell	100 kW	40,000 h	3000	3000	0.10 $/op.hr
6	Hydrogen tank	50 kg	25 years	1500	1500	–

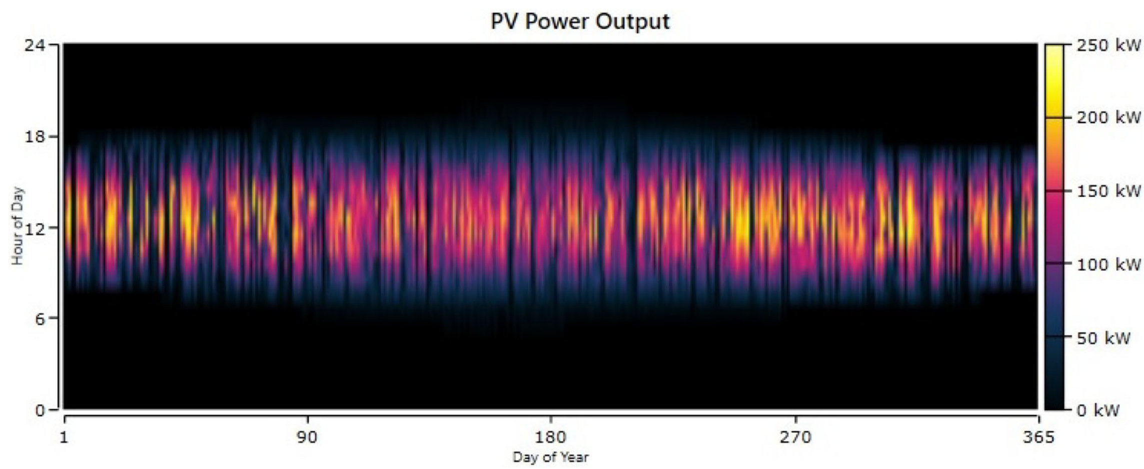


Fig. 4 Power output of generic flat plate PV

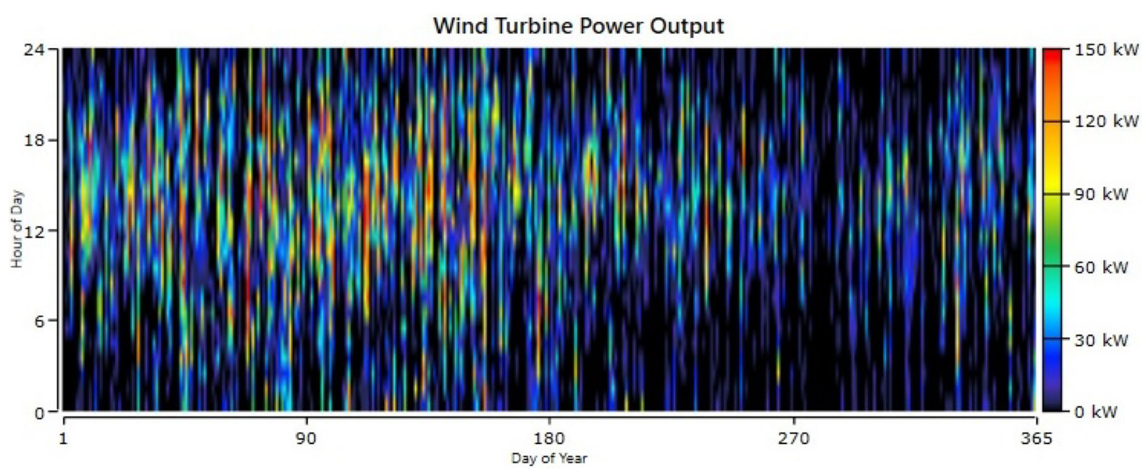


Fig. 5 Power output of wind turbine

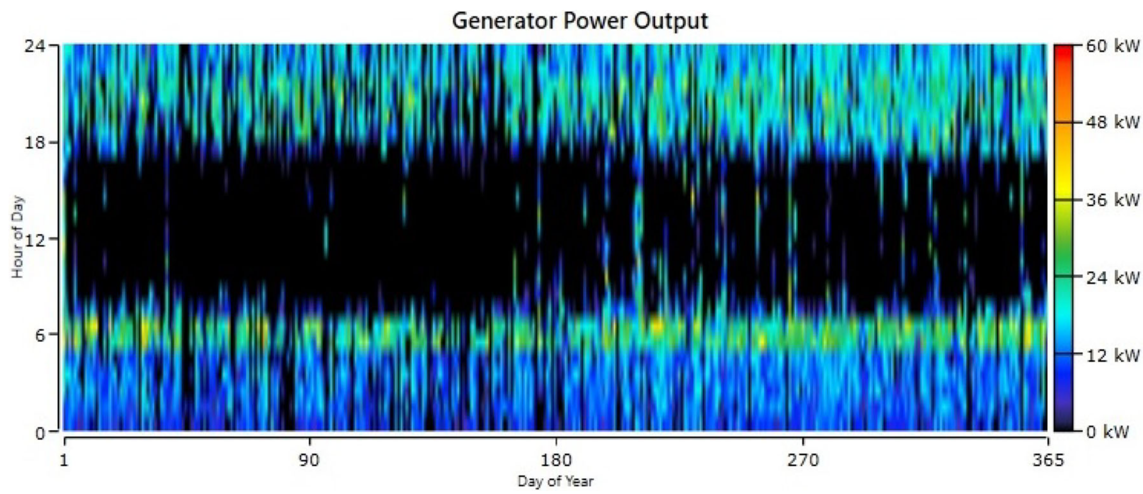


Fig. 6 Fuel cell generator power output

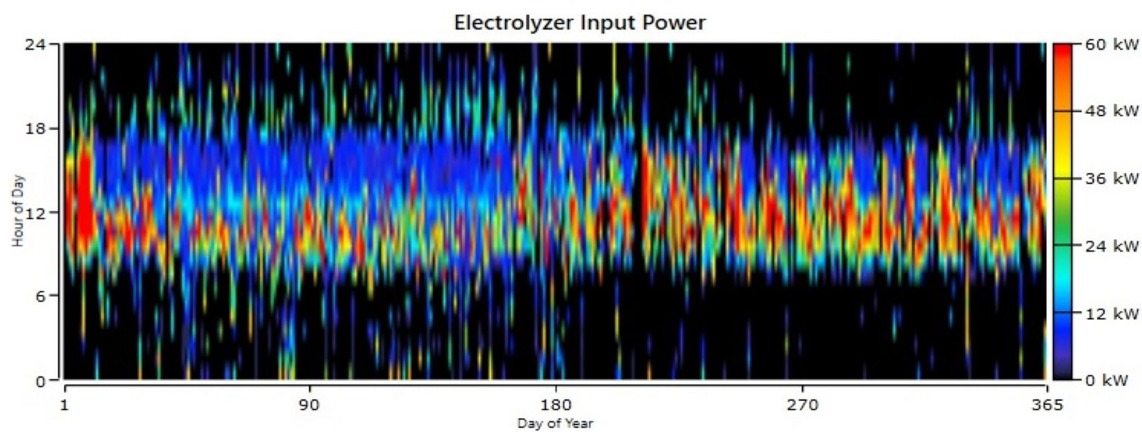


Fig. 7 Input power of electrolyser

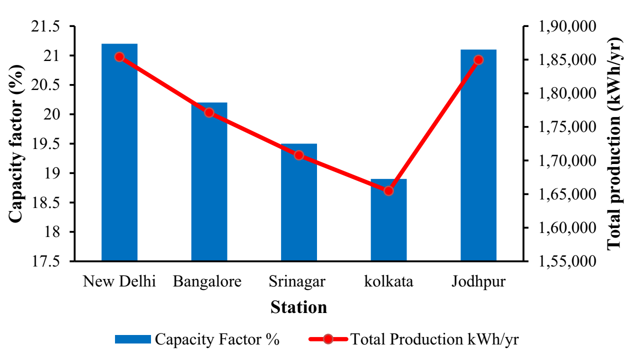


Fig. 8 Total production and capacity factor of solar PV for all the stations

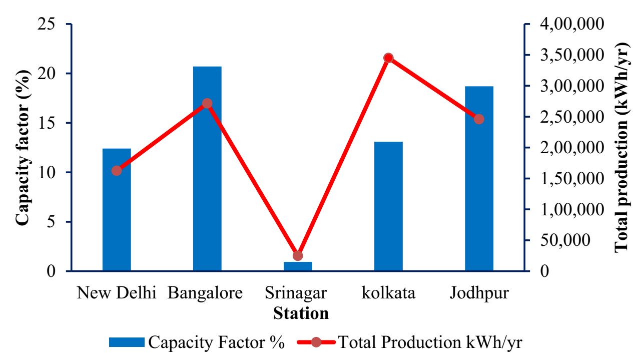


Fig. 9 Total production and capacity factor of wind turbine for all the stations

As shown in Fig. 8, the capacity factor for New Delhi is 21.2%, whereas 18.9% for Kolkata. Total production of Kolkata has decreased by 10.84% as compared to New Delhi. The wind turbine capacity factor is extremely low in Srinagar. However, the annual average wind speed is 2.41 m/s, i.e. also very less as compared to all other stations. LCOE of Srinagar is 6.14 US$/kWh, and it is 94.95% more than the LCOE of Jodhpur. The capacity factor of Bangalore is 20.7%, i.e. the highest capacity factor, while Srinagar's capacity factor is 0.945. Therefore, wind power generation is not a good choice for cold climatic zones (Fig. 9).

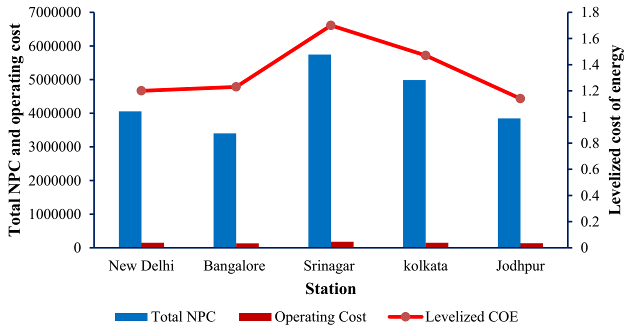


Fig. 10 Overall total NPC, operating cost and levelised COE of all stations

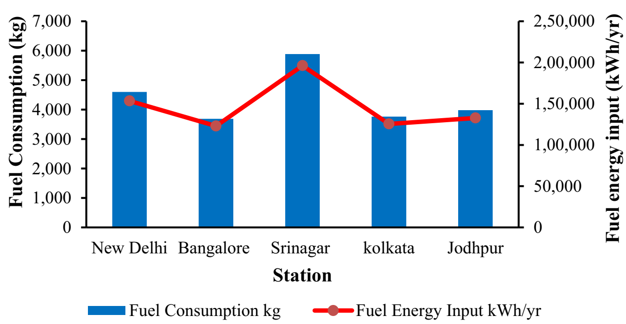


Fig. 11 Fuel consumption and fuel energy input for all stations

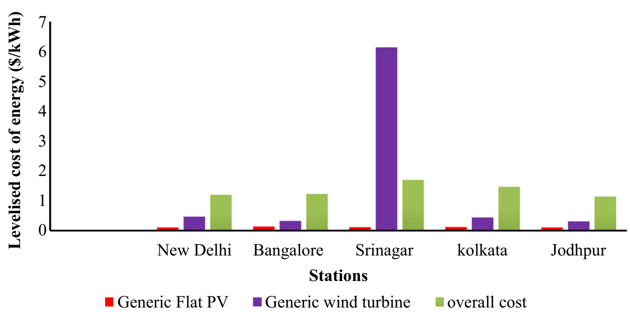


Fig. 12 LCOE for PV, wind turbine and the overall system

Figure 10 depicts the total NPC, operating cost and LCOE of all the stations. Jodhpur has the lowest LCOE, i.e. 1.14 US$, and Srinagar has the highest LCOE, i.e. 1.7 US$. Also, the operating cost of HRES in Srinagar is very high and Bangalore station has the lowest operating cost among all stations. Fuel consumption is less in Bangalore as compared to other stations. Srinagar has 37.32% more fuel consumption as compared to Bangalore and vice versa with the fuel energy input as shown in Fig. 11.

As depicted in Fig. 12, LCOE based on generic flat plate PV for Jodhpur and New Delhi is equivalent, i.e. 0.108 US$/kWh, and on the other side the LCOE of Bangalore is 21.16% greater than the Jodhpur and New Delhi. Generic wind turbine is a viable option for Jodhpur, and hence, it is

Table 5 Payback period and LCOE of all stations

S. no	Station	Payback period (Years)	LCOE (US$/kWh)
1	New Delhi	10.76	1.2
2	Bangalore	12.8	1.23
3	Srinagar	10.3	1.7
4	Kolkata	16.6	1.47
5	Jodhpur	5.9	1.14

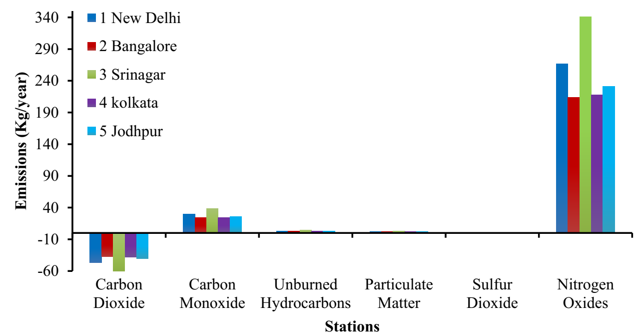


Fig. 13 Annual emissions produced from the HRES

suitable for hot and dry climatic zones. Srinagar station has the highest overall LCOE as compared to the other stations. Jodhpur station has the lowest payback period, i.e. 5.9 years and the lowest LCOE (Table 5).

Contrasting RESs, HRES and conventional fuel energy sources are associated with certain amounts of emissions like carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulphur dioxide and nitrogen oxides regardless of the reduction in greenhouse gas emissions. However, they are very low compared to the emissions generated by the conventional power generation system (Fig. 13).

According to the simulation findings, there are numerous feasible solutions, and the optimised solution with the lowest NPC has been selected. The availability of renewable resources at various locations will vary depending on the climate zones, and hence, there will be a variation in the cost for various stations. The overall NPC, capital cost and cost of energy (COE) of all the stations, i.e. New Delhi, Bangalore, Srinagar, Kolkata and Delhi, are evaluated through simulation. The proposed HRES system for Srinagar has the highest total NPC, i.e. 57,44,105.53 US$, and the proposed system is very cost-effective for Bangalore. The capital cost is also very high for Srinagar, whereas the capital cost is the same for the three stations, i.e. New Delhi, Bangalore and Jodhpur, as given in Table 6.

Figure 14a shows the details about the total NPC of all the stations. Results show that the capital cost of installing an HRES in Srinagar is 41.19% higher than New Delhi,

Table 6 Total optimised NPC of HRES in 25 years of operation at different stations

Station	Capital	Replacement	O&M	Fuel	Salvage	Total (US$)
New Delhi	17,13,000.00	12,34,078.98	13,46,042.30	72,494.75	− 3,08,220.17	40,57,395.86
Bangalore	17,13,000.00	8,90,039.26	9,85,076.76	47,694.60	2,34,706.80	34,01,103.82
Srinagar	29,13,000.00	17,90,376.28	15,89,731.88	92,714.58	6,41,717.21	57,44,105.53
Kolkata	20,13,000.00	12,02,136.41	12,56,883.74	63,408.15	3,55,954.76	41,79,473.54
Jodhpur	17,13,000.00	11,99,254.14	12,32,310.00	62,714.67	3,59,968.47	38,47,310.34

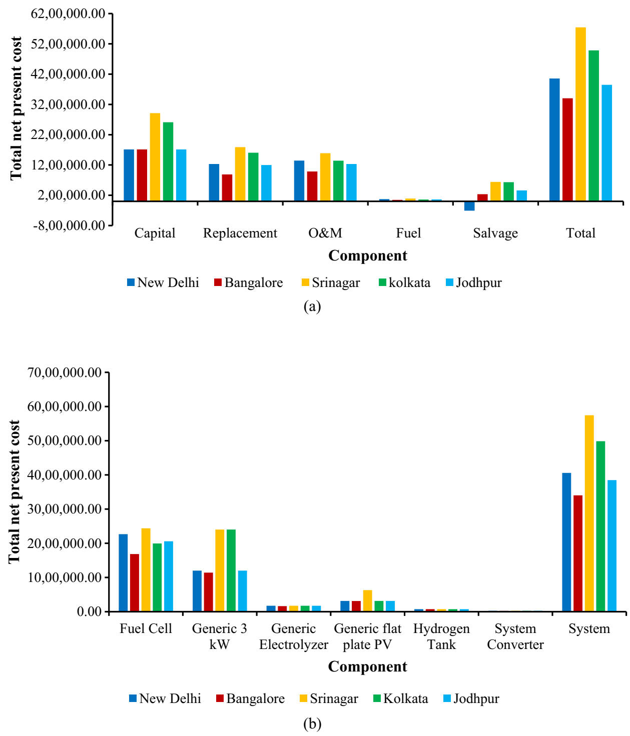


Fig. 14 Total NPC of all stations of HRES **a** based on different types of cost, **b** based on various components of the system

Kolkata and Jodhpur stations. The replacement cost of Bangalore station is very feasible, i.e. 8,90,039.26 US$, whereas 17,90,376.28 US$ for Srinagar. Overall total NPC for Srinagar station is 57,44,105.53 US$, and Bangalore has the 40.78% lowest NPC as compared to Srinagar. The detailed cost analysis based on the various components is shown in Fig. 14b. In 2012, the cost of per unit power from conventional power plants was roughly 11.02 US$/kWh; however, in this HRES, the average cost of per unit power is 1.348 $/kWh [33]. The USA's conventional power plants produced 2043 million metric tonnes of emissions in 2014, whereas this HRES produced only 243.246 kg/yr average emissions [34].

Figure 15 illustrates the monthly electricity generation for all the stations. Here, Srinagar is contributing 74% of the total electricity generated by solar PV, while Kolkata is contributing the least. All of the station's average electricity generation from fuel cells ranges from 11 to 21%. It is feasible to produce electricity using wind turbines in New Delhi, Bangalore, Jodhpur and Kolkata, and for the Srinagar station, wind power is not very ideal.

3.1 Validation of the proposed system results with published work

This study has developed a new HRES configuration that differs from previous studies discussed in Table 1 [20–27], in terms of component sizes, load requirements and renewable resources. As a result, a precise comparison of those systems is unachievable. However, a comparison based on the economic design of the systems can be considered valid and acceptable. The NPC and COE of this proposed system have been compared with the results of other research that have been published (Fig. 16).

4 Conclusion

Techno-economic analysis has been carried out based on five different climatic zones, i.e. hot and dry, warm and humid, composite, temperate and cold via meteorological data of five cities, namely New Delhi, Bangalore, Srinagar, Kolkata and Jodhpur. A system made up of Solar PV, wind, fuel cell, electrolyser and converter has been modelled, simulated and optimised using HOMER to find out the best suitable station for HRES. The following conclusion has been drawn based on the analysis:

- Srinagar has the highest LCOE, i.e. 1.7 US$/kWh, whereas Jodhpur has the lowest LCOE, i.e. 1.14 US$/kWh. The total NPC for Srinagar is 57,44,105.53 US$, whereas Bangalore has the 40.78% lowest NPC as compared to Srinagar.
- Wind power is not suitable for colder zones, and it is found very suitable for hot and dry climatic conditions. LCOE of wind energy power generation in Srinagar is 6.14 US$/kWh, whereas 0.31 US$/kWh for Jodhpur.

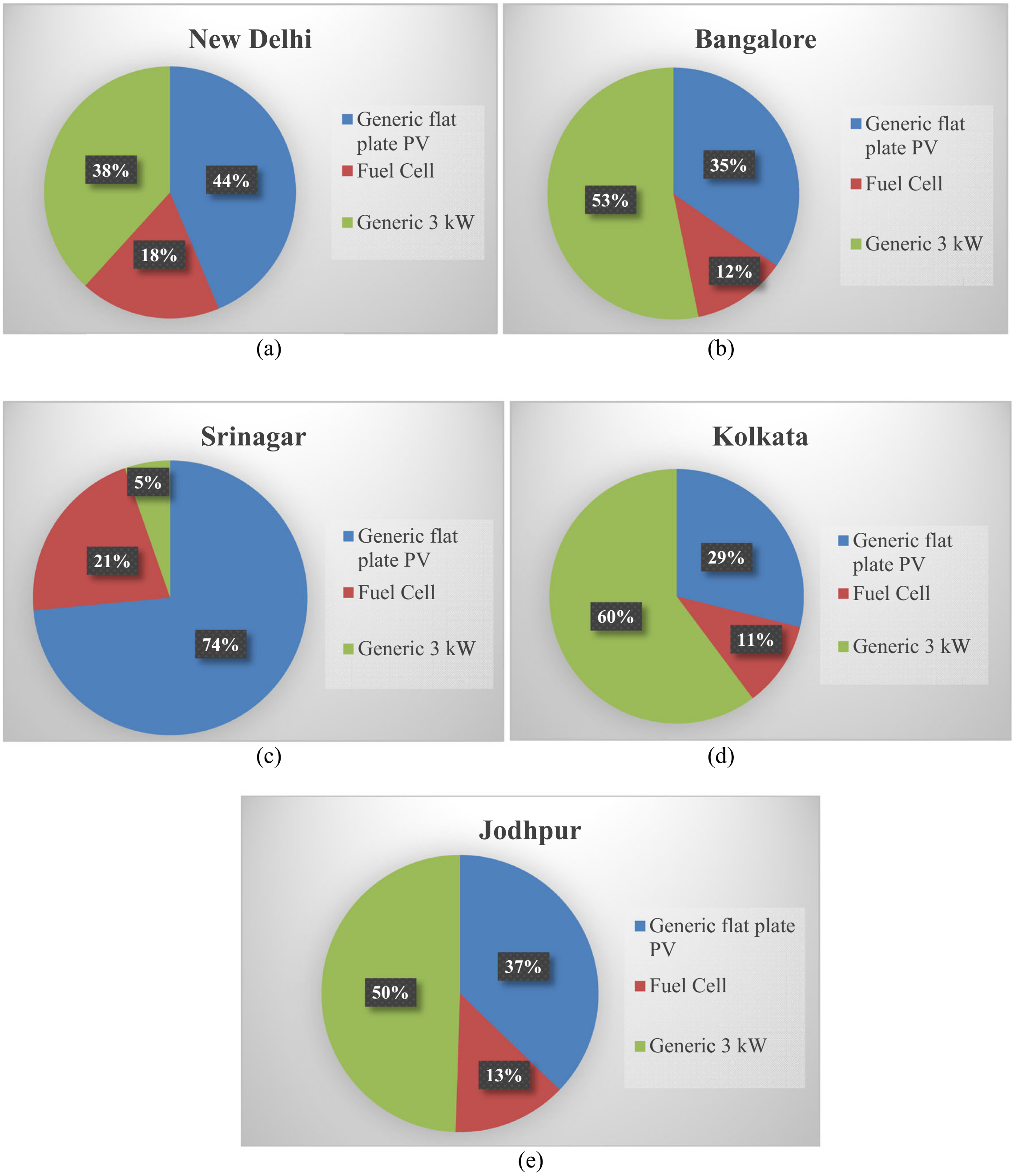


Fig. 15 Monthly electricity production **a** New Delhi, **b** Bangalore, **c** Srinagar, **d** Kolkata, **e** Jodhpur

- Fuel consumption is highest in New Delhi, i.e. 4,602 kg under composite climatic conditions, whereas lowest for Bangalore, i.e. 3689 kg. The capacity factor of the electrolyser is 17.3%, and its value is the same under all climatic conditions, However, the hydrogen production is lowest in Srinagar, i.e. 1955 kg/yr, and highest for Bangalore and Kolkata, i.e. 1963 kg/yr.
- Electricity production using solar PV is 44% and 74% in New Delhi and Srinagar, respectively, whereas 60%, 50% and 53% use wind power. Results show solar PV is a good choice for all climatic zones; however, wind power generation is restricted to warm and humid, temperate, hot and dry climatic zones.
- Jodhpur station is the most suitable one for the HRES. It has the lowest LCOE, i.e. 1.14 \$/kWh with a payback period of 5.9 years.

As per the findings, the goal of climatically appropriate HRES design is to produce an effective and dependable

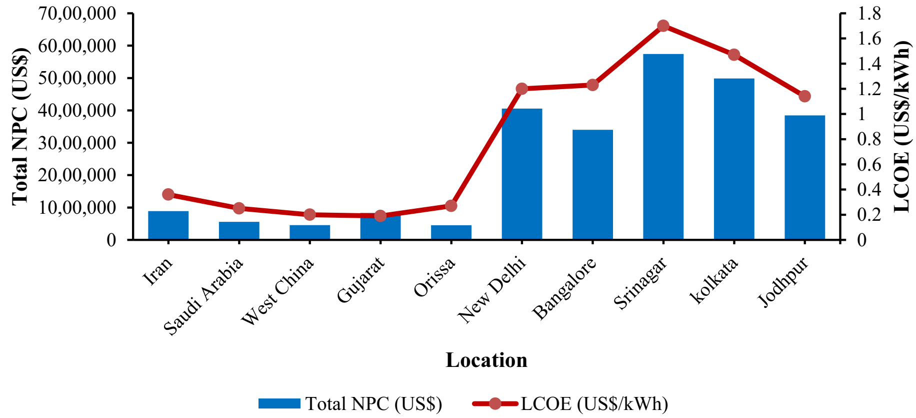


Fig. 16 NPC and COE of the optimal HRES at various locations [20–27]

energy generation system that maximises the use of available RESs while taking into account the region's unique climatic characteristics. In conclusion, adapting HRES to climatic zones has many benefits, such as improved resource utilisation, efficiency, reliability, and reduced environmental impact. It provides more resilient and sustainable energy systems with maximum energy production that can adapt to changing environmental circumstances while also benefiting local economies.

Future research could optimise hybrid renewable power production system design and integration for efficiency and reliability across climate zones by utilising sophisticated modelling methodologies, machine learning algorithms and simulation software to consider diverse factors such as solar irradiation, wind speed, temperature fluctuations and load demand. Anticipating the ecological consequences, land-use demands and carbon emissions of hybrid renewable power generation systems could be the subject of forthcoming research, given the escalating concerns regarding climate change and environmental sustainability. This may entail conducting life cycle assessments and environmental impact assessments to provide information for decision-making and ensuring the promotion of sustainable development.

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Declarations

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Code availability (software application or custom code) Not applicable.

Ethics approval (include appropriate approvals or waivers) Not applicable. Additional declarations for articles in life science journals report the results of studies involving humans and/or animals.

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