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ABSTRACT

6 Power is becoming more vital all across the world due to the limited supply of fossil fuels. Therefore, it is important to develop some alternative to non-renewable energy frameworks that can lessen the dependency on conventional energy assets. To overcome the technical difficulties posed by their erratic and intermittent nature, the combination of renewable energy sources (RES) and their costs may provide a cheap, clean and effective alternative energy supply. The study of optimised energy systems that can meet the needs of diversified climatic regions is necessary.

2 This thesis offering a Techno-Economic and Environmental Assessment of Hybrid Renewable Energy Systems (HRES) in India's different climatic zones, i.e., composite, temperate, cold, warm and humid, and hot and dry. The assessment combines combinations of solar photovoltaic (PV), wind turbines, biomass generators, and battery storage units, simulated using modelling software like HOMER Pro (hybrid optimisation model for electric renewable), PVsyst and Design Expert. Key performance metrics like
2 Levelized Cost of Energy (LCOE), Renewable Fraction (RF), Net Present Cost (NPC), and CO_2 emissions are evaluated in each region. The result suggests that the system performance and viability are highly influenced by climatic conditions, resource availability, and load patterns. Solar-wind-fuel cell hybrid power generation systems, for instance, are optimised for five climatic zones, while solar PV and solar PV with biomass gasifier integration are optimised for a composite climatic zone.

5 Solar PV, wind and fuel cell system are 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 comprises of a solar PV system, a wind turbine, a fuel cell, a converter, an electrolyser, and a hydrogen tank. Srinagar has the highest total 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 to 1963 kg/yr 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.

11 In the second case, the performance of solar PV systems using PVsyst and Response Surface Methodology (RSM) for composite climatic conditions is analysed. Two critical parameters, i.e., tilt angle and albedo, have been investigated. Specific production
7 increases as the albedo and tilt angle increase. Optimum tilt angle is 25º at 0.54 albedo with a maximum specific production of 1643.3 kWh/kW$_P$/year. Payback period is 5.8 years, return on investment (ROI) is at 469.2% and the LCOE is 0.027 \$/kWh. During its lifetime, the system reduces 3470.5 tCO_2 carbon emissions compared to the conventional plant. Therefore, installing such a system will drastically reduce CO_2 emissions, encourage environmental sustainability and enhance the number of claimed carbon credits.

Third case analyses and optimises a solar PV and biomass gasifier HRES for the building of Department of Mechanical Engineering, Delhi Technological University (located at 28°44' N and 77°06' E). The HOMER software is employed for simulation, and the
27 analysis primarily focuses on the techno-economic and environmental assessment of the system. HRES is designed to fulfill the daily energy consumption of 588 kWh at a peak of 65 kW. The system generates 3,76,780 kWh of power every year. The COE is 0.207 US\$/kWh, and the gross NPC is 5,07,737 US\$. Throughout a lifetime (25 years) contributions to the total energy production from biomass gasifier and solar PV are 23.4% and 76.6%. Around 161 metric tons of CO_2 are prevented from entering the atmosphere.

Result provides region-specific recommendations for policymakers, investors, and developers to design low-cost and low-carbon energy systems, driving India's transition to sustainable energy infrastructure. Therefore, installing a 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.

Keywords: Hybrid renewable energy system; Climatic zones; HOMER; Power generation; Capacity factor; Solar Photovoltaic; Economics; Specific Energy Production; Carbon emissions; Response Surface Methodology; Environmental sustainability

CHAPTER: 1

INTRODUCTION

1.1 Background

Energy has been recognised as a vital component of human welfare, societal progress, and economic expansion. Since their discovery, conventional energy has remained the primary energy source. With the growing drift of modernisation and industrialisation, the world's energy demand is correspondingly rising faster. To cope with the increasing demand, most developing countries are switching from conventional energy resources to non-conventional energy resources. This puts an extra burden on the economy. Exploration of potential alternatives to traditional energy resources has become necessary due to a number of factors, including increased industrialization, rising energy consumption, depleting reserves of the current energy stock, and rising environmental degradation. In Southeast Asia, rural areas are only around 51% electrified, while urban areas are 90% electrified.

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
23 satisfied by fossil fuels that release greenhouse gases like nitrous oxide (N_2O), methane (CH_4), 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 price 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 photovoltaic (PV) and wind,

have gained the greatest ground of all forms of energy over the last decade, accounting for 43% of global power output up to 2030 [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-hour power supply. Ram et al. presented an in-depth study of the capabilities and limits of various HRES software, claiming that HOMER can perform an optimised solution and a detailed 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]. Kallio et al. conducted a study on a HRES using MATLAB/Simulink to determine the COE for individual components. They found significant variations in costs depending on the region and month. The lowest annual specific electricity cost was 0.29 €/kWh in the southernmost area. For heat production, the minimum specific cost was 0.319 €/kWhex (equivalent to 0.034 €/kWh), with the overall exergy efficiency ranging between 13% and 16%. [11]. Babatunde et al. 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 [12]. Turkay et al. 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 [13]. Nallolla et al. 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 setup offers a consistent power supply with no unfulfilled loads [14]. Lau et al. 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: $7.01 M, and the highest RF: 84.1%. It became clear that adopting a hybrid PV/diesel system with batteries could produce considerably cheaper NPC and COE than an independent diesel system with a 25-year projected horizon and a 6% annual interest rate [8]. Ismail et al. examined a system that consists of solar panels, a battery bank, and a diesel generator; the COE is 0.239 US$/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 [15]. Koussa et al. analysed the design of an HRES that combines wind and solar energy with battery storage [16]. Basu et al. found that the hybrid structure is the most practicable where electricity demand is moderate [17]. Bhayo et al. investigated and optimised a standalone HRES for powering a 3.032 kWh/day dwelling unit [18]. Thus, it is important to perfrom a comprehensive techno-economic and environmental assessment of HRESs in order to utilize resources at optimal level, at the lowest cost, and the least environmental impact. The present study seeks to compare different HRES configurations under different scenarios to determine the most sustainable options. The insights gained will support informed decision-making for future energy planning and policy development.

1.2 Harnessing Earth's Energy: An Introduction to Renewables

Renewable energy is defined as energy that is produced from natural resources that are perpetually replenished and cannot be exhausted, at least within the human lifespan. RESs, in divergence to fossil fuels (which include coal, natural gas and oil) do not release damaging greenhouse gases or pollutants when they are utilized. As a result, they are both sustainably and environmentally benign. It depends on Earth's ecosystem, like geothermal, solar and wind. Today, India is generating power from solar, wind, biomass and hydro etc. Renewable Energy Sources are intermittent; such as solar provides energy only in the daytime, and wind energy also depends on air flow. The performance of renewable energy resources is affected by various environmental conditions. Therefore, a HRES is necessary for the continuous power generation supply. Its generation improves public health and environmental quality and reduces climate change. It also reduces the dependency on fossil fuels, gas and oil reserves and ensures stability in fluctuation. RESs are commonly used to reduce the gap between production and demand all over the world. Characteristics of renewable energy are as follows:

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- **Naturally Replenished:** Renewable energy resources are replenished naturally over a humanoid timescale. Some examples are sunlight, wind, rain, tides, geothermal heat, and biomass.
- **Environmentally Friendly:** They emit minimal or no greenhouse gas emissions or pollutants during consumption, which means they are cleaner and safer for the environment than fossil fuels.
- **Sustainable:** These resources are renewable for ongoing utilisation, since they are not consumed when employed (e.g., the sun will always shine, and the wind will always blow).
- **Low Operating Costs:** Operational and maintenance expenses are normally low after initial installation. Fuel expenses are also minimal or zero (e.g., sunlight and wind are not costly).
- **Energy Security and Independence:** Dependence on foreign fuels is less, and national energy security is boosted.
- **Decentralised Production:** Renewable technologies (solar and wind power in particular) can be implemented at small and large scales, facilitating decentralised production of power, perfect for rural or remote communities.
- **Technology-Driven Efficiency:** Efficiency, performance, and storage capacity are constantly being enhanced through technological developments, making renewable energy more feasible and competitive.

- **Resource Variability:** Most renewable sources are variable or intermittent in nature. Solar and wind are weather and time-dependent and must be backed up with energy storage or hybrid systems to be reliable.
- **Aligns with Climate Objectives:** Renewable energy is instrumental in lessening climate change through the reduction of carbon emissions and the encouragement of cleaner substitutes.

1.3 Estimated Renewable Energy Potential in India

In terms of electricity generation capacity, India's renewable energy sector has grown significantly over time. One of the most important factors for a country's well-being and economic development is power. The development of a sufficient electricity sector is necessary for the Indian economy to grow sustainably. The demand for power in the nation has grown quickly and is expected to continue to rise in the years to come. The installed production capacity must be greatly increased in order to fulfill the nation's growing demand for power. Over the past five years, the Indian economy has been impacted by renewable energy. Over the past few years, India's renewable energy sector has perceived significant changes in the policy framework. Specifically, initiatives to raise the solar and wind energy sectors' share of India's overall energy contribution are being expedited and ambitiously implemented.

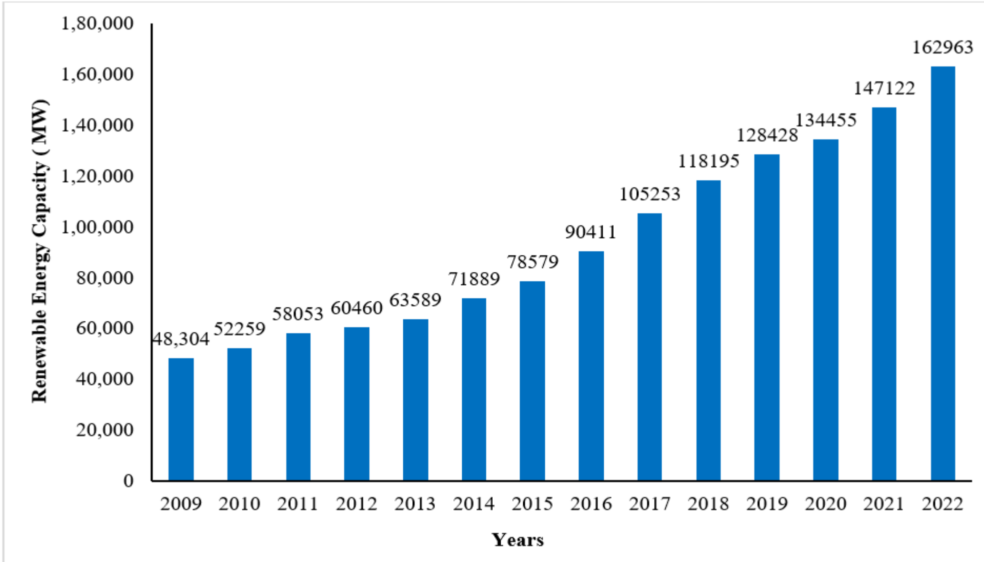

Figure 1. 1: Renewable energy capacity in India from 2009 to 2022 [20]

In terms of installed renewable energy capacity, India is rated fourth globally (including fourth for solar power, wind power, and large hydro). At COP26 (UN Climate Change Conference), the nation increased its objective to 500 GW of energy derived from non-fossil fuels by 2030 [19]. India's installed non-fossil fuel capability has increased by 396 per cent over the past 8.5 years. It makes up 43% of the nation's total capacity, or more than 179.322 gigawatts, as of July 2023 (including huge hydro and nuclear). The installed solar energy capacity is 67.07 GW in July 2023, having grown by 24.4 times over the previous nine years. The installed capacity of RESs, including large hydro, has enhanced by around 128% since 2014. India's renewable energy capacity status from 2009 to 2022 is shown in Figure 1.1, and it is evident that it is steadily growing [20]. The increase in installed renewable energy capacity in India signifies the beginning of a new period of energy conversion and sustainability.

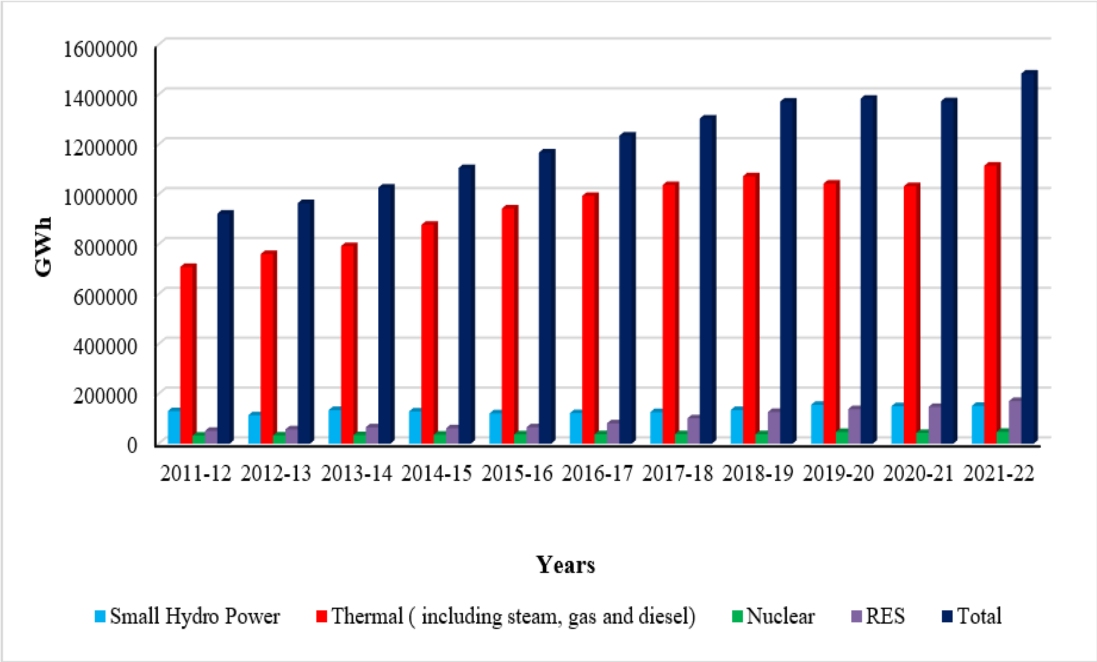

Figure 1.2 Gross power generation growth using various utilities

As India progresses towards its ambitious renewable energy goals, the focus is not only on producing kilowatts but also on accelerating a cleaner and brighter future for future generations. Figure 1.2 shows the gross power generation utilising the various forms of renewable energy, including thermal energy. It is also indicated that renewable energy contributed a major amount to the total power generation in India. The total accumulative capacity of RESs in India up to 2023. Solar power and wind power contributed a huge share to the total power generation in India (Figure 1.3).

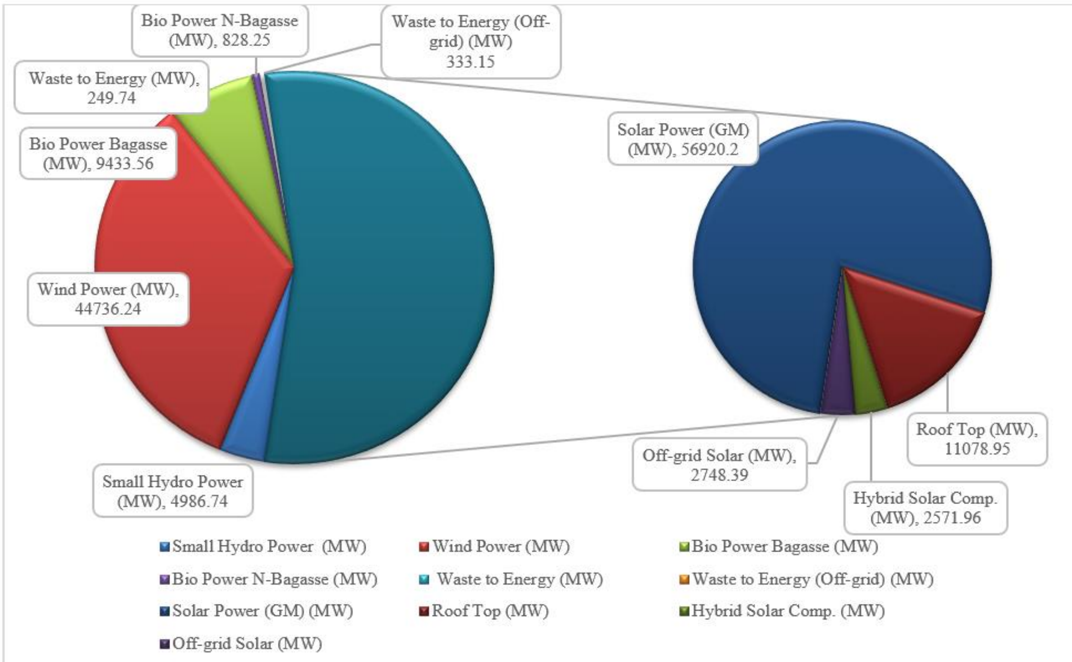

Figure 1. 3 Total accmulative capacity of renewable energy sources in India up to 2023

1.4 Need for Renewable Energy Shift

The shift to renewable energy is not an option anymore but a paramount necessity for a variety of compelling reasons:

- **Mitigation of Climate Change:** Greenhouse gases are primarily contributed by fossil fuels. A shift to renewable sources such as solar, wind, and hydropower cuts down carbon footprints heavily, slowing down global warming.
- **Energy Security:** Renewables decrease reliance on imported fuel, increasing national energy security and stability. Environmental Conservation: Renewable energy reduces air and water pollution, land contamination, and ecological disturbance relative to traditional energy sources.

- **Finite Character of Fossil Fuels:** Oil, coal, and natural gas are finite. Renewables provide a long-term, sustainable solution. Economic Development and Employment Creation: The renewable energy industry generates more employment per unit of electricity produced than fossil fuels, developing regional industries and stimulating innovation.
- **Public Health Benefits:** Improved air and water quality lowers the rates of respiratory and cardiovascular conditions, enhancing public health.
- **Global Policy and Targets:** Global pacts such as the Paris Agreement call for drastic emissions reductions made mostly by going renewable.

1.5 Ongoing Government Schemes for Renewable Energy Expansion in India

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- **PM Muft Bijli Yojana:** The PM Surya Ghar: Muft Bijli Yojana, which was rolled out in February 2024, is a flagship program by the Government of India to encourage the large-scale installation of rooftop solar power systems by domestic households. With a target outlay of ₹75,000 crore, the scheme's fundamental aim is to offer as much as 300 units of permitted electricity (free) every month to one crore families through the installation of rooftop solar panels, especially in urban and rural middle-class households.

  Through the scheme, a large subsidy of up to ₹78,000 is given to households for setting up solar systems, along with assistance in low-interest collateral-free loans and easy digital application processes through a national solar rooftop portal. Not only does this scheme lower the burden on families in terms of electricity, but it also enables them to become energy-independent and contribute excess power back to the grid and earn with net metering. As of mid-2025, more than 11 lakh families have already installed rooftop systems under this scheme, and over ₹5,400 crore in subsidies have been released. The scheme is also anticipated to generate more than 17 lakh green employment opportunities, increase local production of solar devices, and assist India in moving towards its 500 GW non-fossil energy capacity by 2030.

By aligning clean energy access with economic advantages, the PM Surya Ghar Yojana is a revolutionary move towards a low-carbon, sustainable, and inclusive energy future [21].

- **Production Linked Incentive (PLI) Scheme:** One of the most prominent programs
15 that the Government of India has implemented is called the Production Linked Incentive (PLI) Scheme for Higher-Efficiency Solar PV Modules. The primary objective of this program is to improve the domestic manufacturing ecosystem for solar energy components. It is initiated under the larger umbrella of the "Atmanirbhar Bharat" (Self-Reliant India) initiative, the initiative aims to curb India's high reliance on imported solar cells and modules, specifically Chinese, and at the same time enhance local production and generate green employment. With a total investment of ₹24,000 crore, ₹4,500 crore under Tranche-I and another ₹19,500 crore under Tranche-II, the PLI scheme offers performance-based monetary incentives to manufacturers depending on the efficiency and domestic value addition of solar modules.

The scheme encourages the setting up of completely integrated manufacturing facilities in the entire value chain of solar from polysilicon, wafers, cells, and
9 modules and used by the Indian Renewable Energy Development Agency (IREDA) under the Ministry of New and Renewable Energy (MNRE). Firms that produce all the components, from raw material to the end solar module, are given increased incentives. By 2025, the program will have enabled a huge boost in local manufacturing capability, solar module capacity will increase from 38 GW in 2024 to 74 GW in 2025, and solar cell capacity will increase from 9 GW to 25 GW. It has encouraged more than ₹41,000 crore worth of investments and generated more than 11,000 direct and 35,000 indirect jobs. The PLI scheme not only enhances India's role in the international solar manufacturing business but also supports its ambitious
34 goal of developing 500 GW of non-fossil fuel capacity by 2030.

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- **National Green Hydrogen Mission:** The National Green Hydrogen Mission, unveiled by the Government of India in January 2023, is a game-changing one to make India a world leader in the production, usage, and trade of green hydrogen and its derivatives. With an overall initial investment of ₹19,744 crore, the mission aims at less fossil fuel dependence, decarbonising strategic sectors like industry and transport, and making India a global leader in clean energy technology. The key objective of the mission is to generate 5 million metric tonnes of green hydrogen yearly by 2030, backed by the installation of at least 125 GW of renewable energy capacity for hydrogen production. Green hydrogen is made from renewable electricity and water via electrolysis and is a clean energy carrier with broad applications and the potential to substitute fossil fuels in various industries. The mission is not just to decarbonise India's energy sector but also to produce more than 6 lakh jobs, lower fossil fuel imports by ₹1 lakh crore annually, and eliminate almost 50 million metric tonnes of CO_2 emissions every year by 2030. India aims to spearhead the world's green hydrogen revolution, bring in enormous investments, and secure a low-carbon, sustainable, and energy-secure future through this mission. Additional important projects are listed below:

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- **Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan, or PM-KUSUM:** It is a program that promotes solar energy for irrigation and other purposes in order to guarantee farmers' energy security [22].
- **National Solar Mission:** The expansion of solar energy in India has been greatly aided by the National Solar Mission.

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- **Creation of Solar Parks and Ultra Mega Solar Power Projects:** The goal of this project is to create expansive solar parks that will make it easier to use solar energy.
- **Green Energy Corridor:** The goal of the Green Energy Corridor project is to fortify the transmission network to evacuate electricity from states that are abundant in renewable energy.

- **Programs for Biomass and Bioenergy:** These initiatives encourage the production of energy from biomass and biogas.
- Research and development in the field of renewable energy is supported by the Renewable Energy Research and Technology Development (RE-RTD) program.
- Training and skill development in the field of renewable energy are the main objectives of the Human Resource Development Scheme.

1.6 Different Climatic Zones in India

India has an enormous quantity of renewable resources, but due to the sporadic nature of these renewable resources and the different climatic conditions of India, continuous power generation is not possible. Solar radiation, air humidity, ambient temperature, wind speed, precipitation, and sky conditions are some of the factors that determine the climate and weather of any given location. Other environmental parameters include wind speed and wind direction. The climates of India can be divided into five distinct regions, each of which covers a wide range of diversity. These zones, which are supposed to have unique climates, are designed as hot and dry, temperate, warm and humid, composite, and cold. The following subsections provide a brief description of each of these zones. The five stations that are chosen for the study are Jodhpur, Kolkata, Bangalore, New Delhi, and Srinagar. These stations are chosen because they are representative of the five different climate regions that are found in India, as shown in Figure 1.4.

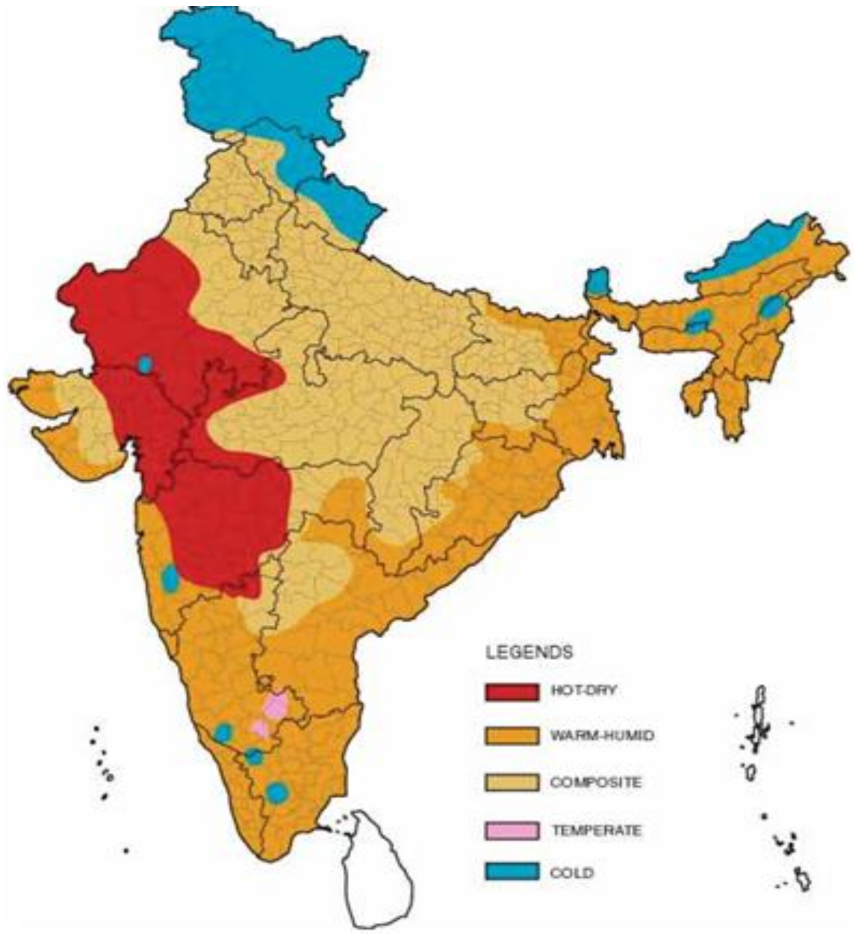

Figure 1.4 NBC climatic region (Bureau of Indian Standards, 2016) [25]

a) Hot and Dry Climatic Zone

The Hot and Dry climatic zone, covering parts of western and central India such as Jodhpur, is characterized by intense solar radiation (800–950 W/m²), extremely hot summers with daytime temperatures reaching 40–45°C, and cooler nights ranging from 20–30°C. Winters in this zone are relatively mild with daytime temperatures between 5–25°C and night temperatures dropping as low as 0–10°C. This region has low relative humidity (25–40%) and receives minimal rainfall, typically less than 500 mm annually.

b) Warm and Humid Climatic Zone

The Warm and Humid zone, found in coastal regions like Kolkata, experiences high levels of cloud cover leading to significant diffuse solar radiation, although direct radiation is strong on clear days. Summer temperatures typically range from 30–35°C during the day and 25–30°C at night, while winter remains warm with temperatures between 25–30°C (day) and 20–25°C (night). The relative humidity is consistently high, between 70–90% during the year.

c) Temperate Climatic Zone

Temperate or Moderate climatic zone includes elevated and plateau regions like Bangalore, where solar radiation levels are fairly consistent year-round. Due to the altitude, temperatures remain moderate, with summer days reaching 30–34°C and nights cooling to 17–24°C. Winters are slightly cooler, with daytime temperatures ranging from 27–33°C and nighttime values of 16–18°C. Humidity levels fluctuate from 20–55% during dry months to as high as 90% during the monsoon season.

d) Composite Climatic Zone

Composite climatic zone, represented by cities such as New Delhi, exhibits varied conditions with extremely high solar radiation during summers and significant diffuse radiation during monsoons. Summers are intense with daytime temperatures from 32–43°C and warm nights of 27–32°C, while winters are much cooler, ranging from 10–25°C in the day and 4–10°C at night. Humidity in this zone is quite dynamic, ranging from 20–25% in the dry season to 55–95% in the monsoon.

e) Cold Climatic Zone

Cold climatic zone, which includes high-altitude areas like Srinagar, is marked by harsh winters with low solar radiation and a large share of diffuse sunlight. Winter temperatures remain low, reaching only around 8°C during the day and dropping to a maximum of 4°C at night. Summers are comparatively mild and pleasant, with daytime temperatures between 20–30°C and nighttime temperatures from 17–27°C. This zone typically maintains high humidity levels, ranging from 70–80%. These climatic variations across the country have significant implications for energy planning, building design, and the implementation of renewable energy systems.

1.7 Hybrid Renewable Energy System: Why?

HRES, i.e. the amalgamation of renewable and non-renewable energy sources, can be used in rural as well as urban areas for continuous power generation. HRES sources are used as primary sources, and non-renewable resources are used as secondary sources. Non-renewable sources can be used when no renewable energy is present; for example, in the case of a solar and diesel engine system, a diesel energy system can be used during night or when solar energy is unavailable. It increases the possibility of reliable voltage all the time, whether renewable energy resources are present or not. Figure 1.5 shows the schematic representation of components of Hybrid renewable energy systems as an example. Here, PV Array, Wind Turbine and Biogas are used for power generation, including biogas as a backup generator.

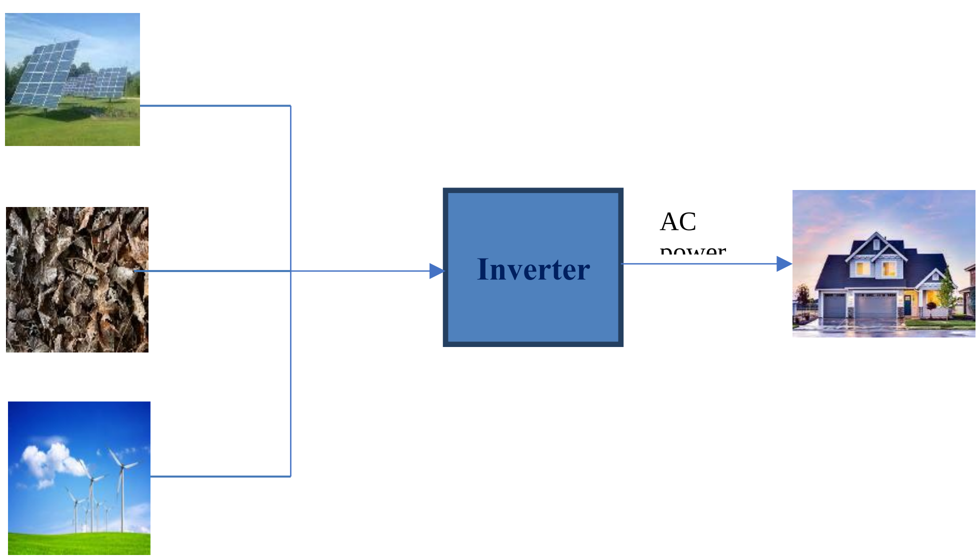

Figure 1. 5 Hybrid Renewable Energy Systems

1.8 Characteristics of HRES

Depending on the availability of various present sources at the site, there can be many possible combinations of different energy sources. Some characteristics of HRES are given as:

- Alternating between energy sources when one becomes inactive helps minimize the variability associated with renewable energy and enhances the reliability of the electricity supply. As a result, a consistent power output at the supply point is maintained.
- It requires less maintenance.
- Less expensive and easily accessible.
- Reduces global warming.
- Less pollution as compared to other conventional sources.

RESs are intermittent in nature, such as solar provides energy only day time and wind energy is also dependent on the flow of air. The availability of various RESs varies according to the climatic conditions of the particular area. Various environmental conditions affect the performance of RESs; therefore, HRES is necessary for the continuous power generation supply.

1.9 Advantages of HRES

- Several RESs, such as solar, fuel cells and wind 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 be used to generate hydrogen, which can be utilised during periods of small renewable energy generation.

- HRES considerably reduces environmental pollution and greenhouse gas emissions. By swapping 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.

1.10 Software selection for simulation and analysis

A comprehensive overview of the existing HRES concepts and software tools, and their strengths, limitations, user requirements, and choice for investigations is required. The essential characteristics of software designed for HRESs are reviewed, along with a relative evaluation.

1 Singh et al. [23] simulated, analysed and optimised a HRES using HOMER pro. Zhou et al. [24] have described HOMER, HYBRID2, HOGA, and HYBRIDS, which were used to evaluate the hybrid solar-wind system performance. Ammari et al. [25] focused on four key aspects of HRESs, i.e., sizing, optimisation, control, and energy management. Gokcol et al. [26] determined and assessed optimum stand-alone and grid-connected HRESs with varying minimal RPRs in depth using HOMER software and compare them, incorporating COE, total NPC, and emission rates into account. Furthermore, a sensitivity analysis assessed the cost of producing clean renewable energy using HRESs. A framework of various software was established for efficiently using these tools in diverse research investigations; therefore, with a focus on HRES, some software is identified and discussed as:

a) **HOMER:** HOMER is a simulation tool. HOMER is the greatest extensively used, publicly accessible, and user-friendly program. It is suitable for quick feasibility, optimisation and sensitivity analysis in numerous alternative configuration options. The National Renewable Energy Laboratory (NREL) USA developed

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HOMER for both off-grid and on-grid systems in 1993 [27]. It will try to simulate a reliable system for all feasible component arrangements you desire to explore. Figure 1.6 shows the schematic diagram of HOMER software. HOMER can imitate thousands of systems, subject to how you can set up your challenge. HOMER simulates the functioning of a HRES for a whole year in one-minute to one-hour time intervals. HOMER analyses all feasible configurations in a single session and then arranges the configurations according to the optimisation criteria. HOMER Pro includes our new optimisation method, which greatly simplifies the design process for determining the lowest-cost choices for microgrids and other distributed production electrical power systems. HOMER Optimizer™ is a patented "derivative-free" optimisation method created particularly for HOMER.

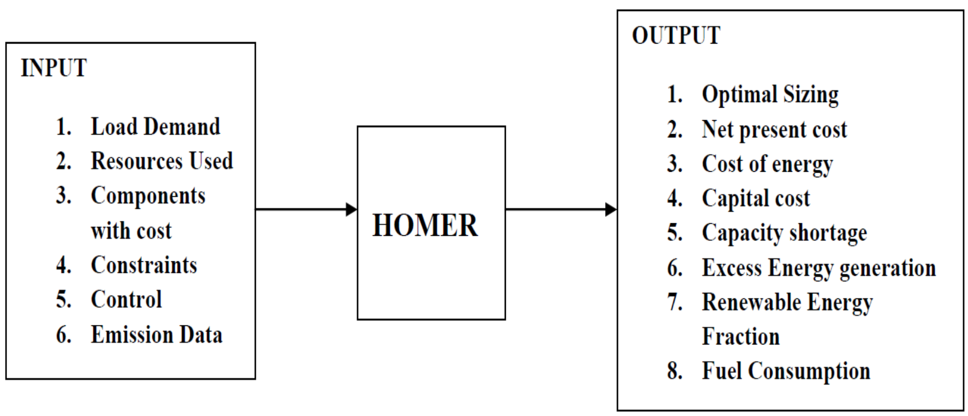


Figure 1. 6 Schematic diagram of HOMER Software

b) **HYBRID 2:** Hybrid2 was created as a highly versatile and user-friendly tool for estimating possible hybrid energy-generating systems' long-term performance and cost. The developers give enough structure for individuals with less expertise in hybrid systems to consider it one of their electrification alternatives while allowing for extensive analysis for users with greater design experience. Hybrid 2 is not a comprehensive system design tool, but rather an intermediate phase that provides preliminary system performance forecasts before the final system design is completed. The system may contain loads on both the AC and DC buses using Hybrid 2 [3]. The Code also allows for three levels of accountability: main, deferrable, and optional. The Site/Resource module allows you to combine resource data and site characteristics for use in various applications. In Hybrid2's simulation run 2, three forms of resource input data may be used: wind speed, sun irradiance, and ambient temperature. Time series averages represent each input data type. This software programme has restricted parameter access and is rigid; however, it does provide a library of distinct resource data files. A pin is necessary to install the HYBRID2 demo version.

c) **RETScreen:** Natural Resources Canada's RETScreen is a free research tool that may be downloaded, which provides financial and environmental evaluations of various renewable energy technologies at any location on a global scale. Consider both the expenses and the advantages. The design for RETScreen software, launched in 1998 for on-grid applications. Off-grid PV applications are also addressed by the PV model RETScreen, which comprises stand-alone, hybrid, and water pump systems [10]. A database including global climate data from approximately 6000 ground stations (monthly data for yearly solar radiation and temperature), energy resource maps (e.g., wind maps), hydrological data, and product data such as PV module information [11]. Wind Turbine Power Curve provides a link to the NASA climate database RETScreen is a Windows based energy management software tool for evaluating energy performance. This product requires Microsoft .NET, Microsoft Windows 2000, and Microsoft Excel 2000. Framework 2.0 or later versions are required, and VirtualBox for Mac can also be used to run on Apple Macintosh computers. Table 1.1 gives the schematic representation of HYBRID 2, RETScreen, iHOGA and TRNSYS. Some primary limitations of RETScreen are as follows:

- The impact of temperature on solar PV performance assessment is not taken into account.
- Importing time series data files is not possible.
- Only a few options are available for searching, retrieval, and visualisation.
- Data exchange is a concern.
- Does not facilitate more complex computations.

Table 1. 1 Details of HYBRID 2, RETScreen, iHOGA and TRNSYS

Software	Input Parameters	Output Parameters
HYBRID 2	• Load demand • Resources • Power system component details • Financial data	• Technical analysis • Sizing Optimisation • Financial evaluation
RETScreen	• Climate database • Project database • Product database • Hydrology database	• Technical, financial and environmental analysis • Sensitivity & Risk analysis • Energy efficiency • Cogeneration
iHOGA	• Constraints • Resource • Components • Economic data	• Multi-objective optimisation • Life cycle emission Probability analysis • Buy-sell energy supply analysis
TRNSYS	• Meteorological data • Models from own library	• Dynamic simulation behaviour of thermal and electrical energy systems.

d) **iHOGA:** It is a C++-based hybrid system optimisation software application called Improved Hybrid Optimisation by Genetic Algorithm (iHOGA), which was created by the University of Zaragoza in Spain and was formerly known as HOGA (Hybrid Optimisation by Genetic Algorithm). iHOGA is used to optimise the size of hybrid energy systems, including solar, wind, hydropower, fuel cells, H_2 tanks, electrolysers, storage systems, and single and multi-objective optimisation [25].
In addition to calculating lifetime emissions, probability analysis, and optimising PV panel slope, iHOGA can also buy and sell energy possibilities to the electrical grid via a net metering system. Degradation effects, sensitivity analysis, extra limits, a database of various components, currency conversion, and other features are now included in the most recent version of iHOGA. It includes two types: PRO and EDU. Unlike EDU, which is free and can only be used for learning or educational purposes and is not authorised in projects, engineering work, installation work, or any work involving commercial activity, PRO is a paid version that may be used without limits and with full technical help.

e) **TRNSYS**: The Transient Energy System Simulation Programme (TRNSYS) was developed in 1975 in collaboration with the Universities of Wisconsin and Colorado in the United States. TRNSYS was initially created to model thermal systems; however, throughout the course of more than 35 years, this programme has been improved and changed. It has evolved into a hybrid simulator by including PV, thermal solar, and other systems. Using the FORTRAN programming language, this simulation tool was developed to model thermal energy fluxes. [28].

1.11 Organisation of Thesis

An overview of the five-chapter of thesis titled "Techno-Economic and Environmental Analysis of Hybrid Renewable Energy System" is as follows: an introduction; a literature review; a methodological section (including a sequence of follow-up); and modelling and simulation of hybrid renewable energy system according to different climatic zones of India, the results and discussion, the conclusions and recommendations for future work, references, list of publications, and curriculum vitae are the following sections that are included in the report. In addition, the following is a representation of the schemes that are used throughout the entire chapter.

Chapter 1 depicts a realistic background of renewable energy and how it is harnessed from the earth, and also explores the current status of renewable energy installation in India. This section also sheds light on the various ongoing government schemes for renewable energy expansion in India. This chapter also gives a detailed review of the different climatic zones of India and the importance of HRES integration for the sustainable future. It is anticipated that these findings would aid in strategic decision-making regarding the development of renewable energy, particularly for areas aiming for climate resilience and energy security.

Chapter 2 provides an overview of various techniques used for the performance, economic and environmental analysis of hybrid renewable energy systems, including their historical background and current developments. It also provides a brief overview of the design, modelling and optimisation of a hybrid renewable energy system for power generation under different climatic conditions. This chapter identifies the problem description, the proposed research gap, and the specific goals of the current study, which was conducted at Delhi Technological University (DTU), Delhi. Additionally, the scope and social impact of the research have been outlined in this chapter to support the technology's benefits to society and, consequently, to nationwide.

Chapter 3 accomplishes the study goals outlined in Chapter two, and the methodology of analysis is established in Chapter three using a series of procedures. Modelling and simulation of a solar, wind and hydrogen fuel cell model using HOMER has been done for different climatic zones of India. A detailed techno-economic and environmental analysis of a solar PV rooftop installed system has been done for a composite climatic zone. Installed system and simulated system results have been compared to overcome various existing performance losses using PVsyst and Design Expert software. A solar PV and biomass gasifier system has also been designed and modelled to optimise the power generation of the academic institute located in a composite climatic zone.

Chapter 4 presents the results and discussion for the three designed systems, first, namely solar PV, wind and fuel cell systems; second, is installed rooftop solar PV system on an academic building; and third one is solar PV system with a biomass gasifier. These include the assessment of the system's performance, specific production, yield, system efficiency, capacity factor, performance ratio, operational performance, economic analysis, and pollution emission mitigations, as well as their environmental analysis has been done. Response surface methodology (RSM) is used to optimise the process parameters of a solar PV system, i.e., albedo and tilt angle. Additionally, validation of all the suggested systems and earlier research based on comparable parameters of various systems has also been done.

Chapter 5 concludes the observations for all the suggested systems studied in this thesis. In addition, each of the observations has been summed up with recommendations for studies to be conducted in the future. These recommendations are intended to urge the researchers to continue investigating the possibility of making improvements in this field for the sake of human civilisation and the environment.

The next chapter discusses the fundamentals of hybrid renewable energy systems technology, from its inception to the latest developments, for the integration of various renewable energy sources for power generation. Literature survey is also briefly reviewed to gain an understanding of the potential of available renewable energy sources in the different climatic zones. Technological developments in hybrid renewable energy sources and its performance analysis, optimisation techniques, thermal modelling, economic analysis and environmental evaluation is also reviewed in detail. This chapter defines the problem statement, the suggested research need, and the specific goals of the current study effort conducted at Delhi Technological University (DTU), which is situated in Delhi. Furthermore, the extent of the research and its contribution to society have been demonstrated in this chapter to support the positive impact of this technology has on society as well as on the nation.

CHAPTER: 2

LITERATURE REVIEW

2.1 Introduction

Traditional energy generation has long been a concern in many countries owing to increased demand and limited supply. This predicament compels all governments worldwide to look for other energy sources. The most admired energy-generating method is Hybrid renewable energy technology if it is utilised according to the different climatic conditions of the region. Due to rising electricity prices, rural electrification, and rapid global climate change over the last decade, research into hybrid renewable energy systems has garnered major attention in Asia, the Middle East, and Africa [29].

Energy consumption is directly proportional to the advent of manpower with the rising population, improving humanity's standard of living and the economic prosperity of emerging countries. With the rise in demand for energy, there is a subsequent need to increase and diversify energy production and energy sources. Global warming is increasing greenhouse gas (GHG) emissions, and the depletion of non-renewable energy sources has raised interest in protecting the world's energy supplies [30]. However, according to World Economic Outlook 2020, 940 million people, or 13% of the global population, face a shortage of grid power or other energy sources [31]. However, as a result of urbanisation and population growth, electricity demands are increasing. Therefore, more energy is needed when the population grows, which comes from fossil fuels but also generates emissions. Utilising cutting-edge, suitable machinery and sustainable energy sources in rural regions is a very efficient approach to reducing fossil fuel use [32]. The main issue with non-grid autonomous systems is the unpredictability of the electrical supply, which may be addressed by combining renewable and conventional technologies. Over the past ten years, research into HRESs has drawn significant attention in the Middle East, Asia, and Africa as a result of rising electricity costs, rural electrification, and rapid global climate change. Sheikh et al. explored the thermal control of a solar cell that was being cooled by a phase-change material. When phase change material is used for cooling, electrical energy efficiency rises by 4.82, 8.1, and 7.17%, respectively, while power output rises by 5.12, 8.4, and 7.29% [33]. Singh et al. estimated the COE of a biomass gasifier generator set, solar PV, and fuel cell crossover energy system is 15.064 ₹/kWh, with a total net current cost of ₹51,89,003, and the suggested framework's plentiful power is 36 kWh/year with zero tariffs for unmet electrical load [7]. Turkay et al. discussed the economics of standalone and grid-connected HRESs. Results reveal that grid-connected HRES are more likely to adapt than standalone configurations [34]. Decentralised green energy is becoming more feasible to supply electricity to one billion people where no access to the power grid [35]. While government regulations cut back on emissions of agricultural waste, solar energy prices are declining. In India, more than 70% of the population resides in isolated areas deprived of access to grid-connected power [36].

HRES is an amalgamation of many components relating to power production equipment like generators, power storage systems, and various sources, including renewable energy. Using renewable sources, as opposed to traditional fuels, is becoming prevalent. However, several problems are faced when using renewable energy sources. They are scattered, challenging to produce, expensive and usually unpredictable due to their intermittent nature. These are the limiting factors because they have not been able to replace fossil fuels on a large scale. Merging the various technologies into a hybrid energy system can optimise the overall system and hold many potential benefits [37]. A major limitation in HRESs is the lack of a fixed optimal structure of the HRES. Simulation and modelling are based on the ease of access to traditional and non-traditional sources, existing base structures, cost of building and manufacturing, etc. As a result, proper design of HRES needs a comprehensive survey of the planned project location and resources in addition to the renewable energy sources.

2.2 Identified Research Work

The literature review is carried out in terms of the following two categories:

a. Design and modelling of a hybrid renewable energy system for power generation under climatic conditions.
b. Optimisation, techno-economic and environmental analysis of a hybrid renewable energy system for power generation.

2.2.1 Design and modelling of a hybrid renewable energy system for power generation under climatic conditions

Ghenai et al. investigated the available renewable resources in Sharjah to find the best configuration for meeting the city's intended power loads. In Sharjah city, a hybrid system may meet up to 14% of the entire yearly electrical demand, with PV panels contributing 74% and a biogas generator for 26% of the total electrical demand [35]. Kumar et al. analysed that with the rising impact on the environment and the rapidly dwindling fossil fuel supplies, hybrid power systems consisting of two or more renewable energy sources such as solar PV, wind, biomass, ocean thermal, with or without the backup of a diesel generator have emerged [36]. Jha et al. proposed a dual energy generation system for integrated grids to reduce energy waste [37].

Ludwig et al. examined technical opportunities and challenges of combining a wind and solar PV power plant into an integrated hybrid plant [38]. Jenkins et al. assessed a wind-solar hybrid power generation system for a specific site. Grid-connected power generation systems generate electricity using solar PV or wind turbines. The installation of ten 100 kW wind turbines and 150 kW solar PV arrays was determined as the most viable and cost-effective design to deliver average load linked to the grid with a design payback time of 2.6 years [39]. Sen et al. suggested residential, institutional, commercial, agricultural, and small-scale industrial needs in the pre-HOMER analysis. Utilising HOMER, the article determines the best off-grid solution and compares it to traditional grid expansion [40]. Maouedj et al. analysed the operation of a PV-Wind hybrid system test bench [41]. Roy et al. discussed numerous hybrid energy storage system coupling technologies, emphasising their key benefits and drawbacks [42]. Kumar et al. investigated several parts of a grid-connected PV system, their functioning, and the design parameters to be observed during installation [43]. Sharma et al. entailed a parametric study as well as PV system modelling based on varied load situations in a building to obtain maximum power, performance ratio, and efficiency and to obtain more specific production and improved system efficiency, a comparative evaluation of the system is performed for one laboratory load of fixed tilt with varying azimuth angles [44]. Wibowo et al. compared the performance of fixed-panel versus solar-tracking solar panel applications for PV systems at PT. Pertamina (Persero) RU-III Plaju [45]. Benti et al. investigated the viability of employing integrated PV/diesel/battery systems to run a fairly remote school in southern Ethiopia [46].

Ibrik et al. evaluated the long-term performance of a roof-mounted solar PV system built at one of An-Najah National University's buildings [47]. Rehman et al. analyzed various hybrid power systems and related theoretical studies conducted in different climatic zones worldwide to determine the most suitable hybrid configurations for enhancing Saudi Arabia’s current energy mix. The most widely adopted systems include wind/solar-PV (28%), wind/solar-PV/diesel (22%), and solar-PV/diesel setups with or without battery storage (21%). These systems are primarily utilized by remote communities, followed by installations on islands and communication towers. The average energy costs for the wind/solar-PV, wind/solar-PV/diesel, and solar-PV/diesel systems are approximately 0.458, 0.355, and 0.349 US$/kWh, respectively [28]. Kallapan et al. analysed four locations with 2kWh/day and 350W peak for simulation, and the result suggests that the hybrid system (PV, Battery) had the lowest cost of energy i.e, 68.90 Rs/kWh for Mumbai, and it was also observed that COE is low for PV, Battery system in all configurations [48]. Table 2.1 indicates the key findings of the Design and modelling of a hybrid renewable energy system for different climatic conditions.

Table 2. 1 Design and modelling of a hybrid renewable energy system for different climatic conditions

S. No.	Authors	Key Findings
01.	Maouedj et al., 2014 [41]	• Demonstrated the capacity of the system to supply energy demands for public lighting at night with an average daily energy consumption of 2640 Wh. • Study suggested that the power supplied by the PV array (84%) was more than the power obtained from the wind turbine (16%). • Average wind speed was observed to be higher between 10:00h and 18:00h.
02.	Ghenai & Janajreh, 2016 [49]	• Analysed the performance and the cost of the proposed hybrid microgrid system. • The findings indicated that the solar-biomass hybrid system could supply up to 14% of Sharjah's annual electrical consumption, with PV panels accounting for 74% and biogas generators for 26% of the total.
03.	Sharma et al., 2018 [44]	• Analysed PV system on diverse load conditions and orientations in a building to achieve maximum power, performance ratio, and efficiency of panels. Specific production was found to be maximum, i.e., 1679 kWh/kWp/year, when the system had zero azimuth angle.
04.	Benti et al., 2022 [46]	• Aimed to find the most appropriate and least costly alternative while considering the environmental impact of each system scheme. • With an NPC of 32,019$ and COE of 0.254$/kWh, a hybrid system including 7.50 kW of PV panels, 11 units of batteries, 7.30 kW of DG capacity, and a 6.60 kW power converter was determined to be the most economically viable option.
05.	Roy et al., 2022 [42]	• Reviewed existing wind-solar hybrid renewable energy resources, in which the system modelling and the optimal design algorithms were studied.

06.	Jha et al., 2022 [50]	• Analysed energy-efficient hybrid power system model based on solar and wind energy for integrated grids. • The suggested setup was determined to have a total installation cost of 49,500 US dollars, while the other systems cost 66,000, 56,500, and 56,300 US dollars.
07.	Kelvin Edem Bassey, 2023 [51]	• To forecast performance under various climatic situations, the study integrates data from wind and solar power systems and models hybrid renewable energy systems using machine learning techniques. • Results suggested that the HRES performance forecasts are improved using ML models and also improve energy storage planning and optimization.
08.	Cheng chen et al.,2009 [52]	• Discusses the dynamic modeling of a HRES that integrates solar cells, wind turbines, fuel cells efficiently handling variable climatic circumstances to assure stable power supply and manage variations.
09.	Saleh et al., 2022 [53]	• Study enhances energy output and efficiency by combining wind and photovoltaic solar energy of HRES. It suggests flexibility in response to changing weather patterns, guaranteeing dependable electricity production even when each energy source isn't always available.
10.	Kumar et al., 2024 [54]	• Assess a wind and solar-based hybrid energy system under different operating conditions, using simulation tools and mathematical modeling to determine performance and viability. • Improve energy sustainability and reduce greenhouse gas emissions and ensure a consistent supply of electricity.

2.2.2 Optimisation, techno-economic and environmental analysis of a hybrid renewable energy system for power generation

In this literature survey, various types of hybrid systems operating strategies, optimisation, economic analysis, environmental analysis and case studies were discussed in detail. Sawle et al. gave an overview of hybrid system architecture, modelling, renewable energy sources, hybrid system optimisation criteria and control methodologies, and software utilised for optimal sizing [35]. Chadel et al. offered an approach for modelling and optimising the hybrid system utilising both methodologies, demonstrating that the method's worst month results in a greater system cost than the monthly average values per year [55].

Koussa et al. showed that the principal advantage of PV/wind/diesel hybrid with battery storage is used together, enhancing the system's reliability [56]. According to Zhou et al.'s analysis, standalone hybrid solar-wind power generating systems are acknowledged globally as a competitive substitute for conventional fuel-based remote area power sources or the grid. For off-grid applications, it is typically more appropriate than systems with a single energy source for electrical supply [24]. Heydari et al. indicated that the PV/biomass system is economically better than a PV-alone system or a biomass-alone system [57]. Dalton et al. indicated that wind energy conversion systems (WECS), rather than photovoltaics, are the most economically viable RES for large-scale operations. Large-scale WECS (over 1000 kW) are more efficient and economical than multiple small-scale wind energy conversion systems (0.1–100 kW) [58]. Turkay et al. showed that grid-connected hybrid RE systems have a higher probability of adaptation than the standalone (100% renewable system) configurations [34].

According to Shahzad et al.'s cost analysis, the optimal option for this case study is a mix of 10 kW PV modules, 8.0 kW biogas-fueled generator, 32 storage batteries, and a 12 kW converter. The initial capital expenditure is PKR 2.64M, with a total NPC of PKR4.48M. Since the cost of electricity from the grid for agricultural applications is 10.35 PKR/kWh, this hybrid system saves around 4.84 PKR/kWh while providing consumers with electricity at a low cost of 5.51 PKR/kWh [59]. Jahangir et al. demonstrated that as solar panels degrade and diesel prices rise, biogas consumption increases by 7% and diesel consumption decreases by 14% in the optimal scenario [60]. Kirim et al. estimated that the grid-connected system, including PV and biomass, is more feasible than the stand-alone biomass system in terms of total NPC, ROI, energy cost, and annual worth [61].

Najjar et al. found that using solar PV and biomass generators can effectively generate clean and sustainable energy while significantly addressing emission issues. Their findings showed a substantial decrease in carbon dioxide and sulfur dioxide emissions. Specifically, carbon dioxide emissions were reduced to one-sixth of the amount typically emitted by a conventional power plant for producing the same quantity of electricity [62]. Aykut et al. emphasized that due to the harmful effects of fossil fuels on both human health and the environment, the studied system relies entirely on renewable energy sources that produce minimal pollution. The simulation incorporated photovoltaic, wind, and biomass energy options; however, the most efficient configuration was identified as a grid-connected hybrid system combining wind and biomass. This optimal setup includes a 1000 kW grid connection, a 1000 kW biomass generator, and a 1500 kW wind turbine. The NPC of the system was estimated at 5,612,501$ with a COE of 0.067 $/kWh. Additionally, the system significantly reduces greenhouse gas emissions [63]. Adaramola et al. examined the technical and economic assessment of hybrid energy system viability in rural communities of Ibadan in the south-west region of Nigeria using HOMER software. The results show that the cost of generating electricity using a Wind/PV/Generator/Battery hybrid energy system is significantly cheaper than using only a generator-based energy system (with and without battery) [64]. Ghussain et al. designed a system that includes 1.79 MW of solar PV, 2 MW of wind power, and 0.92 MW of biomass, supported by a hybrid energy storage setup comprising 24.39 MWh of pumped hydro storage and 148.64 kWh of batteries. This configuration achieved a fuel reduction (FR) of 99.59%, a demand supply factor (DSF) of 98.86%, and a cost of electricity of $0.1626/kWh. The simulation demonstrated that integrating hybrid storage with the PV/wind/biomass system enables an exceptionally high level of energy independence, reaching nearly 99% [65].

Kumaravel et al. analysed the economic feasibility of a solar PV/biomass/pico-hydro hybrid energy system to meet the annual average load of 56 kWh/d in the study area. The optimal hybrid system design is realised by satisfying the load demand, non-linear seasonal variations, and equipment constraints. The optimal hybrid system explored has the least COE and is found to be Rs 7.274 (0.164 US$) per kWhr. The annualised average energy resource values are solar radiation of 3.89 kWh/m^2/day, stream flow of 51.7 L/s, and biomass availability of 0.692 t/d. Li et al. demonstrate that a hybrid renewable energy system that comprises solar, wind and biomass is reliable and cost-effective regarding sustainable rural electrification. Moreover, this system can also acquire environmental and social benefits [66]. Ammari et al. analysed that the hybrid renewable energy system is meant for the electrification of isolated areas, feeding the main grid, saving energy, reducing emissions, and reducing the levelized energy cost [25].

Saha et al. presented a comparison analysis of the proposed HRES model performance with conventional utility grid extension and found it cost-effective, efficient and environment-friendly. Simulated results show the total NPC is 99, 32,723.00 with COE of 20, 77,035.00. The operation cost was observed to be 1, 32,764.80 [67]. Gokcol et al. analysed a gradual increase in total NPC and COE that occurred in regions where RPRs were between 0 and 70%, and that there were dramatic increases in both the total NPC and COE for the RPRs above 70%. Moreover, CO_2, SO_2 and NOx emission rates decrease as RPR increases from 0% to90% and decrease linearly until RPR is 80%, while they are nearly zero for values more than 80% [26]. Busaidi et al. analysed that hybrid energy systems can significantly reduce the total life cycle cost of standalone power supplies in many situations, and the COE is less, i.e. 0.182 $/kWh with PV-wind-diesel hybrid system and high, i.e. 0.189 $/kWh with wind–diesel hybrid system [68]. Table 2.2 shows the important findings of various published results of optimisation, techno-economic and environmental analysis of a hybrid renewable energy system.

Table 2. 2 Optimisation, techno-economic and environmental analysis of hybrid renewable energy system

S. No.	Authors	Key Findings
01.	Kalappan & Ponnudsamy, 2013 [48]	• Analysed four locations with 2kWh/day and 350W peak load for simulation. • Result suggested that the hybrid system (PV, Battery) had the lowest cost of energy, i.e., 68.90 Rs/kWh for Mumbai. It was also observed that the COE is low for the PV and battery system in all four configurations.
02.	Gokcol & Dursun, 2013 [26]	• Designed a hybrid system based on PV-biomass gasifier-diesel and grid, and optimised the system configuration for different load profiles. COE was calculated for different peak loads, energy demand profiles and grid availability. • Concluded that the cost of energy for a grid-connected hybrid system is lower compared to an off-grid hybrid system for similar load profiles.
03.	Heydari & Askarzadeh, 2016 [57]	• Optimised the size of a biomass-based PV power plant in Bardsir, Kerman • Nominal power of the PV and biomass systems was 75.2 kW and 180 kW, respectively, and the values of LCOE and LPSP were obtained at 0.1855 $/kWh and 1.9997%, respectively • Concluded that combining biomass systems with PV technology could make a reliable and cost-effective energy system for supplying the electrical demand of off-grid areas.
04.	Al Busaidi et al., 2016 [68]	• Study suggested that hybrid energy systems could significantly reduce the total life cycle cost of stand-alone power supplies in different conditions. • COE was lower, i.e. 0.182 $/kWh with PV–wind–diesel hybrid system and higher, i.e. 0.189 $/kWh with wind–diesel hybrid system.

05.	Chadel et al., 2017 [55]	• Analysed two sizing methods of hybrid PV/wind power systems, results showed that the worst month of the method gives a higher cost of the system compared to the average monthly values per year. • Also concluded that the use of a wind energy system as a backup system with a PV system increases the cost of the hybrid system.
06.	Shahzad et al., 2017 [59]	• Analysed hybrid system provided electricity at a low cost of 5.51 PKR/kWh, saving about 4.84 PKR/kWh at the grid's electricity cost of 10.35 PKR/kWh for agricultural purposes. • HRES generated about 65,593 kWh/year with excess electricity generation of 3221 kWh/year, making the studied area grid independent. • System had a NPC for the projection period of 25 years and an estimated payback period of 9.5 years.
07.	Bhatnagar et al., 2019 [69]	• Proposed a new classification of climatic zones based on hierarchical cluster analysis of 60 Indian locations grouped into 8 climate zones • Analysis used climate indices such as HDD, CDD, and annual mean relative humidity as variables for clustering analysis.
08.	Aykut & Terzi, 2020 [63]	• Analysed a wind/biomass system consisting of 1000 kW grid, 1000 kW biomass generator, and 1500 kW wind turbine. • NPC of the optimised system was calculated as $5.612.501 while COE was 0.067$/kW with a decrease in emission of greenhouse gases.
09.	Ammari et al., 2021[25]	• It was analysed that HRES was meant for the electrification of isolated areas, feeding primary grids, energy saving, emission reduction, and reducing the levelized energy cost.

10.	Saha et al., 2022 [67]	• Presented a comparative analysis of proposed HRES model performance with conventional utility grid extension and found it to be cost-effective, efficient, and environment-friendly. • Simulated results showed the total NPC was Rs. 99,32,723 with COE of Rs. 20,77,035 and an operation cost of Rs. 1,32,764.

Table 2.3 compiles the relevant previously conducted studies of hybrid renewable energy systems at various locations to develop the best system for remote places, depending on the availability of renewable energy sources.

Table 2. 3 Solar PV, wind, biomass and fuel cell hybrid system for power generation

S.No	Authors	Findings
1.	Najideen et al., 2017 [70]	• With a capital cost of $117,000 and a payback period of about 5.5 years, the analysis showed that the Engineering Faculty at Mu'tah University consumed 96 MWh annually. • To meet this demand, an on-grid PV system with a capacity of 56.7 KW could be installed, producing 97.02 MWh of electricity to feed into the grid.
2.	Kavuma et al.,2022 [71]	• Analysed grid-connected solar PV in Uganda for viability by evaluating the performance ratio of the already installed solar systems using the System Advisor Model. • The total annual energy was estimated at 69.52 GWh. The capacity factor ranges from 13.1% to 17.5% and the performance ratio of 0.76.
3.	Kamali et al.,2009 [72]	• Evaluated a grid-connected PV system at the University of Malaya. Different scenarios of interest rates and costs are proposed. The energy demand of the Engineering Tower is approximately 800-900 kWh/day. HOMER

		simulation shows the technical viability of PV modules.
4.	Ibrik et al.,2020 [47]	• Average annual performance ratio of the installation was found to be 84%, due to weather conditions, especially on sunny days. • Average efficiency of the module, system, and inverter over a year was 14.8%, 13.7%, and 92.5%, respectively. The average daily final yield of the PV system in Palestine is higher than the average daily final output of other systems in other publications.
5.	AbdelHady et al.,2017 [73]	• Economic savings when the system is connected to the national grid are exponentially higher compared to the savings of the real system when feeding the local grid. Therefore, to encourage private and governmental agencies to expand on solar energy production.
6.	Ludwig et al.,2020 [38]	• By permitting a curtailment of roughly 0.07% of the overall yield, the connecting power line capacity for a hybrid system with 50% PV and 50% wind capacity can be as low as 70% of the hybrid power plant's nominal capacity. • In contrast, a separate wind and PV system facility of the same size may have needed a curtailment loss of roughly 3.6% and 6.2% of the overall output, respectively.
7.	Gangopadhyay et al.,2022 [74]	• Firstly, encourage the deployment of solar-wind hybrid systems tailored to the unique advantages of each region. Secondly, address periods of low renewable energy generation at the national level by enhancing the national grid infrastructure and fostering inter-regional exchange of renewable energy."

8.	Deshmukh et al.,2006 [75]	• Describes methodologies to model HRES components, HRES designs and their evaluation. • In addition to boosting the power value of conventional generation, this HRES integration creates a market for the adoption of renewable energy systems.
9.	Al-Ghussain et al.,2021 [65]	• The designed system includes 1.79 MW of solar PV, 2 MW of wind power, and 0.92 MW of biomass, supported by a 24.39 MWh pumped hydro storage unit and 148.64 kWh of battery storage. It achieves a Fractional Reliability (FR) of 99.59%, a Demand Supply Factor (DSF) of 98.86%, and a levelized cost of electricity of $0.1626 per kWh. • Simulation outcomes confirm that combining hybrid energy storage with PV, wind, and biomass sources results in a highly autonomous system, nearing 99% energy self-sufficiency."
10.	Al-Badi et al.,2022 [76]	• The proposed hybrid system removes CO_2 emissions at US$ 0.436/kWh. • Oman will invest in 30 gigawatts of green hydrogen production. • The proposed method has a levelized cost of 0.436 $ per kWh.
11.	Albarrak et al.,2025 [77]	• Neom's wind profile minimises hydrogen storage needs compared to Riyadh's fluctuating speeds. • The 100 kW PV system achieved 88 kW under standard conditions. Real conditions yielded approximately 52 kW output in both regions. • Hybrid systems improve energy security and reduce fossil fuel reliance.
12.	Godfrey Nnabuife et al.,2024 [78]	• Hybrid system produces 6988 kWh/year, meeting energy demand effectively. It reduces CO_2 emissions by 5273.14 kg annually.

		• The study highlights the potential for optimising renewable energy systems. It can lower hydrogen production costs from EUR 3.5 to EUR 8.9/kg.
13.	Hassan Fathabadi, 2017 [79]	• A novel hybrid solar/wind/fuel cell power system is developed. • Achieves high MPPT efficiencies of 99.60% and 99.28%. Short tracking convergence times of 12 ms and 15 ms. • The hybrid system efficiently produces electric energy under various conditions.
14.	Manickam et al.,2014 [80]	• Hybrid power system improves power quality and reliability. It effectively manages the optimal utilisation of primary energy sources. • It addresses fluctuating energy demands in isolated and grid-connected modes.

The comparative techno-economic analysis of different hybrid renewable energy systems for different geographical locations is depicted in the Table 2.4. These systems are usually integrated with PV, wind turbines, diesel generators, biomass, fuel cells, and battery storage at a cost-optimising and reliability basis of NPC, LCOE, and Renewable Fraction as performance metrics. In India, Sawle et al. (2021) formulated a PV/WT/BG/DG system for Gujarat with a high renewable fraction of 81.2% and an LCOE of $0.196/kWh. Along similar lines, Pujari et al. (2022) achieved an even higher RF of 91.6% for Andhra Pradesh using PV/WT/DG/BS at a slightly higher LCOE of 0.272$/kWh. In contrast, Sahu et al. (2021) formulated a PV/WT/BS system in Orissa with a marginally higher LCOE of 0.278$/kWh. Krishnamurthy et al. (2020) rolled out a PV/WT/BM hybrid in Pondicherry with a 100% RF, meaning pure dependence on renewables, although the LCOE was comparatively higher at Rs. 8.231/kWh. At the global level, Baseer et al. (2019) reached a 100% RF fully in Saudi Arabia with PV/WT/DG/BS, with an LCOE of 0.25$/kWh. Hassan et al. (2022) employed a combination of PV/FC with a low NPC of $10,166 and LCOE of 0.23$/kWh with an RF of 91.8% in Iraq. Li et al. (2020) in China studied an integrated mix consisting of PV, WT, BG, DG, and BS, which had an LCOE of 0.206$/kWh. Finally, Fazelpour et al. (2016) employed a system of PV/WT/DG/BS in Iran, which had the highest LCOE of 0.36$/kWh. These comparative observations highlight the impact of site, component arrangement, and system design on HRES economic and renewable performance and stress the importance of regional optimisation.

Table 2. 4 Various HRES designs using HOMER software

S. No.	Authors	Year	Components	City	Result
1.	Sawle et al. [81]	2021	PV/WT/BG/DG	Gujarat	NPC-831,217 $, LCOE-0.196 $/kWh, RF-81.2%.
2.	Pujari et al.[82]	2022	PV/WT/DG /BS	Andhra Pradesh	NPC-5.48 M, LCOE-0.272 $/kWh, RF-91.6%.
3.	Baseer et al. [83]	2019	PV/WT/DG/BS	Saudi Arabia	NPC-555,492$ LCOE-0.25 $/kWh, RF-100%.
4.	Sahu et al. [84]	2021	WT/PV/BS	Orissa	NPC-454,242$, LCOE-0.278 $/kWh.
5.	Hassan et al. [85]	2022	PV/FC	Iraq	NPC-10,166$, LCOE-0.23 $/kWh, RF-91.8%.

6.	Krishnamurthy et al. [86]	2020	PV/WT/BM	Pondicherry	NPC-Rs.11.9 M, LCOE-Rs.8.231, RF-100%.
7.	Li et al. [87]	2020	PV/WT/BGDG/BS	West China	NPC-456,388$, LCOE-0.206 $/kWh.
8.	Fazelpour et al. [88]	2016	PV/WT/DG/BS	Iran	NPC-888,500$ LCOE-0.36 $/kWh.

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 electrolyzers 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.

2.3 Research Gaps

Research gaps in the field of renewable energy are very wide. Renewable energy sources are intermittent; combining two or more renewable energy sources is very important to meet the power demand. Some points are discussed as follows:

- Most research has been carried out on grid-connected hybrid renewable systems for specific climatic zones. Limited research has been carried out on designing hybrid renewable energy systems for different climatic zones. Therefore, there is significant potential for designing a hybrid renewable energy system for different climatic zones to optimise the share of available renewable energy resources in that location.
- More research work has been carried out for the hybrid renewable energy system with less than 100 kW capacity. Few research works have been done for the larger microgrid-connected system.
- Few work has been carried out in deciding the unavailability of natural resources, which have seasonal variations and getting support from the grid electricity and back-up generators. Hence, there is more scope in the different locations to determine the availability of renewable energy and back-up electricity optimisation.
- Less research is available on the economic and environmental feasibility of hybrid renewable energy systems for different climatic zones.

Furthermore, the research shows hybridised systems have superior features as compared to standalone renewable energy systems. Thus, the best-suited hybrid system should be developed according to the energy requirement and seasonal variations.

2.4 Research Objective

The main objectives of the present study are as follows:

- To design and simulate a 1 MW hybrid renewable energy system for different climatic zones of India.
- Economic analysis of a 1 MW hybrid renewable energy system for different climatic zones of India.
- Environmental analysis of a 1 MW hybrid renewable energy system for different climatic zones of India.

2.5 Research Scope

This research is concerned with the techno-economic and environmental analysis of hybrid renewable energy systems (HRES) with an aim to contribute towards the increasing need for clean, dependable, and decentralised energy solutions. The necessity for such a study is most critical in a geographically varied nation like India, with different climatic regions stretching from arid deserts and sea-coastal humid regions to mountainous terrains and productive plains, making a one-size solution is not feasible. As shown in the tables, lots of researchers have also researched in this field with specific research gaps and have run into them in the form of a glimpse. Therefore, one can increase power generation production according to the climatic zones by completing the research gap (performance evaluation, process parameter improvement).

Therefore, hybrid systems utilising solar, wind, biomass and fuel cells and other resources are becoming increasingly vital to provide site-appropriate energy reliability and efficiency. This research entails the modelling, simulation, and performance analysis of hybrid systems considering component sizing, energy conversion efficiency, and technical feasibility. Economic analysis encompasses initial investment and operating costs, levelized cost of energy (LCOE), and financial metrics like net present value (NPV) and payback period, employing software like HOMER Pro, PVsyst and Design Expert. Environmental effects are also analysed to estimate carbon emissions and sustainability. A different case study approach is adopted to show the viability of the systems in the chosen Indian climatic regions. The studies are confined to large-scale systems (up to 1 MW) and focus on technical, economic, and environmental factors only. The conclusions seek to inform energy planners, engineers, and policymakers to design cost-effective, location-optimised, and sustainable hybrid energy solutions suited to India's varied climate and power generation requirements.

2.6 Research Contribution

This study contributes significantly to the field of hybrid renewable energy systems (HRES) by offering an integrated techno-economic and environmental assessment that is adapted specifically to India's unique meteorological circumstances. Comparing various system architectures under regionally specific load profiles and climatic data helps to better understand how well they work in various geographic zones. With the aid of modelling tools like HOMER Pro, PVsyst and Design Expert, the study provides an economic cost-benefit framework utilising measures like LCOE, NPV, and payback period. The research illustrates practical viability and directs the selection of suitable hybrid systems for particular Indian locations by utilising a case study-based methodology. The results help engineers, developers, and legislators make decisions by bridging the gap between theoretical modelling and practical deployment of economical, environmentally beneficial, and efficient renewable energy systems. Research contributions of the existing study are as follows:

- Addressed the impact of India's numerous climatic zones by simulating hybrid systems under various environmental conditions, allowing for location-specific energy system planning.
- Established an extensive framework for evaluating hybrid renewable energy systems (HRES) performance that concurrently takes into account system performance, economic viability, and environmental impact using HOMER Pro, PVsyst and Design expert.

In order to accomplish the research goals outlined in Chapter Two, the simulation and modelling technique is established in the next chapter using a series of procedures. This study examines the performance parameters of solar PV, wind and fuel cell systems according to different climatic zones in India. It explores the detailed analysis of solar PV installed systems with varying tilt angle and albedo to optimise the specific production, and also analyses the solar PV and biomass gasifier system for the composite climatic zone. It includes extensive assumptions, *performance parameters, system descriptions, and specifications that will be used in the analysis using HOMER Pro, PVsyst and Design Expert software.*

CHAPTER: 3

METHODOLOGY

3.1 Introduction

This chapter describes the approach used to determine the objectives to be accomplished. Hybrid renewable energy systems have been the subject of extensive environmental, economic, and technical studies. In this chapter, three cases have been covered first one in which five distinct climate zones, i.e., hot and dry, warm and humid, moderate, composite, and cold, have been taken for modelling and simulation. To accurately reflect the five distinct climatic zones, five stations have been selected for the modelling and simulation. In the second case, a solar PV rooftop installed system at an academic building in Delhi has been taken for simulation and modelling, and the last one is one in which solar PV, biomass gasifier and battery have been taken for the analysis under composite climatic conditions.

As per the literature survey, HOMER found to be suitable for the techno-economic and environmental analysis of HRES. 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 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. Intermittent, seasonal, non-dispatchable, and uncertain availability of renewable energy sources further complicates 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.

3.2 Site selection according to the five different climatic zones

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 3.1, and the location of the selected site is shown in Figure 3.1 (a). 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 3.1 (b) shows the layout of HRES and which consists of the solar PV system, a wind turbine, a fuel cell, a converter, an 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 comprises solar PV, wind, and hydrogen technologies that 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.

Table 3. 1 Five selected stations of different climatic zones of India [24]

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

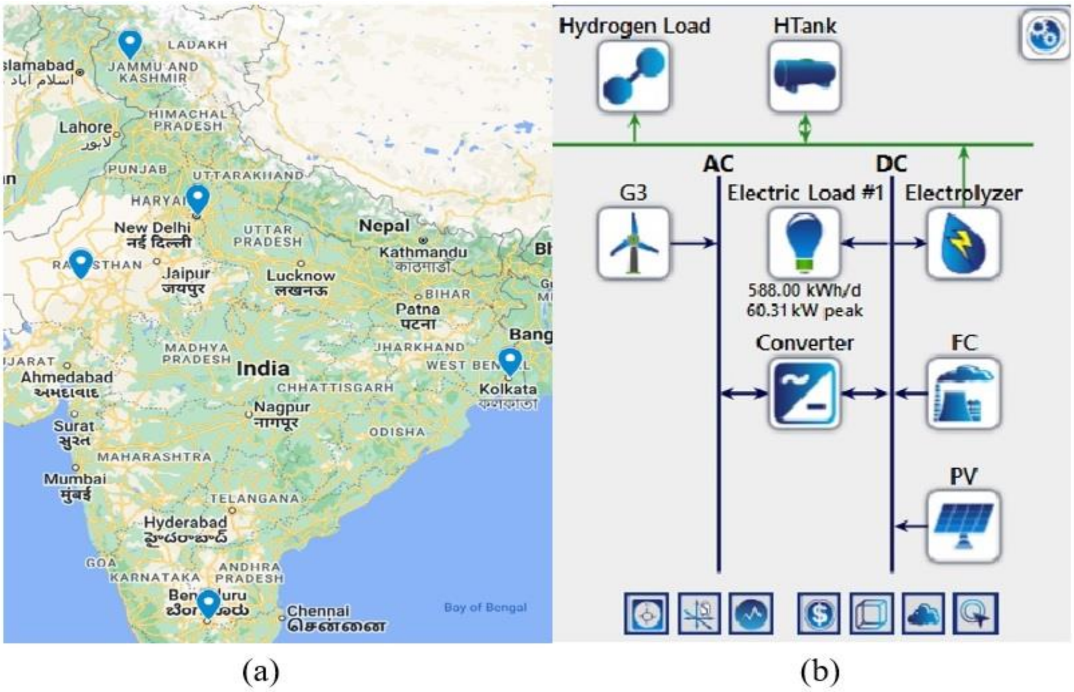


Figure 3. 1 (a) Selected site locations in India and (b) Layout of HRES

3.2.1 Availability of resources at the selected stations

Table 3.2 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. Figure 3.2 and Figure 3.3 show the NASA prediction of the worldwide energy resource database for solar global horizontal irradiation resources and monthly average wind speed at 50m above the surface of the Earth.

Table 3. 2 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

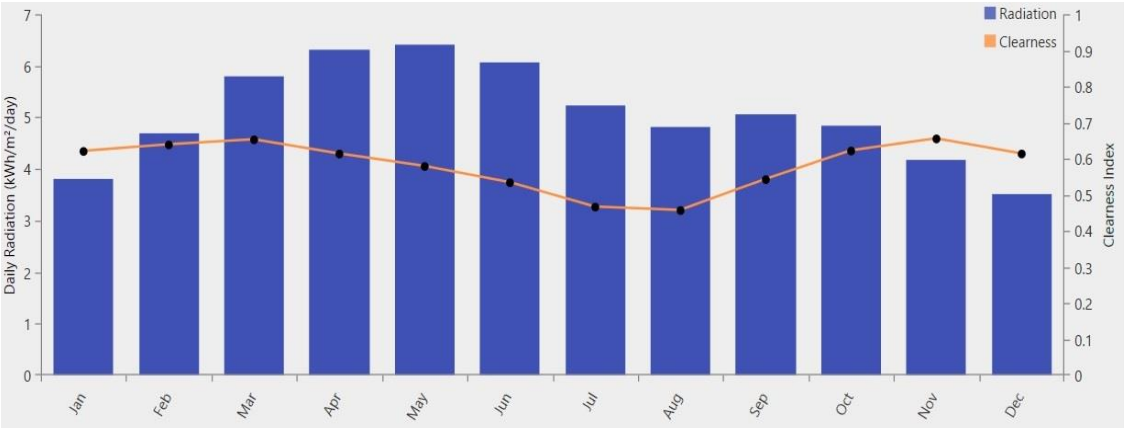


Figure 3. 2 Solar global horizontal irradiation resource

Figure 3. 3 Monthly average wind speed data

3.2.2 System Components

3.2.2.1 Solar PV system

Solar PV panels transform sunlight into electric energy. PV panel's current output as a function of voltage and solar radiation. Solar PV panel's power output is estimated by multiplying the current and voltage. Power supplied by the solar panel is given by Eq. (3.1) [89].

$$P_{PV} = P_R \times \left(\frac{H}{H_{ref}}\right) \times \left(1 + S_p\left(T_C - T_{ref}\right)\right) \quad (3.1)$$

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. Solar PV arrays are supposed to have a lifecycle of 25 years.

3.2.2.2 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. (3.2) [90].

$$\mathrm{V_f} = \mathrm{E_{ocv}} - \left\{\mathrm{N_{fc}} \times \mathrm{S} \times \ln\left(\frac{i_{hf}}{i_0}\right) \times \frac{1}{\frac{R_{Td}}{3}+1}\right\} - (r_{int} \times i_{hf}) \tag{3.2}$$

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

The E_{ocv} and i_o are given by Eq. (3.3) and Eq. (3.4), respectively [90].

$$E_{ocv} = W_c \times E_{nerst} \tag{3.3}$$

$$i_o = \frac{z \times F \times k(P_{H_2} + P_{O_2})}{R \times h} \times e^{\left(\frac{-\Delta G}{R \times T}\right)} \tag{3.4}$$

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 UtH_2 and UtO_2 are given by Eq. (3.5) and Eq. (3.6), respectively [90].

$$UtO_2 = \frac{60{,}000 \times R \times T \times i_{hfc}}{z \times F \times P_{fair} \times V_{fair} \times y\,\%} \tag{3.5}$$

$$UtH_2 = \frac{60{,}000 \times R \times T \times i_{hfc}}{z \times F \times P_{ffuel} \times V_{ffuel} \times x\,\%} \tag{3.6}$$

3.2.2.3 Electrolyzer

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 the 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. (3.7), modelling is done for the input electrical energy dependence on the hydrogen mass flow [90].

$$Cons_E = B_E.Q_{N-E} + A_E.Q \tag{3.7}$$

3.2.2.4 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$18000 and has 20 year lifespan. The power output of a wind turbine is calculated as in Eq. (3.8), and the wind speed acting on the wind turbine is calculated as in Eq. (3.9) [2].

$$P_{WT}(t) = \begin{matrix} 0 & V_{cin} \geq v(t) \ or \ V_{cout} \leq v(t) \\ P_r \frac{v(t)-v_{cin}}{v_r-v_{cout}} & V_{cin} \leq v(t) \leq v_r \\ 0 & V_r \leq v(t) \leq v_{cout} \end{matrix} \quad (3.8)$$

$$v_r = v_{anem} \left(\frac{z_{hub}}{z_{anem}}\right)^{\gamma} \quad (3.9)$$

3.2.2.5 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. (3.10)[14].

$$\eta_{conv} = \frac{P_{output}}{P_{input}} \quad (3.10)$$

3.3 Cost analysis of a 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 is given by Eq. (3.11).

$$C_{HRES} = C_{FC} + C_{Htank} + C_{SPV} + C_{WTS} + C_{Elec} + C_{Conv} \tag{3.11}$$

The cost of each component of HRES is found by using Eq. (3.12),

$$C_p = S_T \times [CC_T + (R_e C_T + SR_T) + OMC_T] \tag{3.12}$$

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 setup costs (IC), replacement part 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. (3.13) [63], and the capital recovery factor (CRF) is given by Eq. (3.14) [7].

$$C_{NPC} = \frac{C_{AT}}{CRF(i_r P_L)} \tag{3.13}$$

$$CRF = \frac{i_r(1+i_r)^N}{(1+i_r)^N - 1} \tag{3.14}$$

3.3.1 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. The Eq. (3.15) connects the nominal interest rate to the annual real interest rate [91].

$$i = \frac{i' - f}{1+f} \tag{3.15}$$

3.3.2 Levelised cost of energy (LCOE)

To assess the financial sustainability of the HRES, the LCOE is calculated by using Eq. (3.16) [91].

$$LCOE = \frac{C_{ann,tot}}{E_{prim,AC}+E_{prim,DC}+E_{grid,sales}} \tag{3.16}$$

3.3.3 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. (3.17) [92]:

$$Salvage = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{3.17}$$

3.3.4 Payback period

The payback period can be defined as the amount of time needed to recover the project's initial costs and expenses as well as the investment made to bring it to the breakeven point, or point at which there is no more profit than loss. It is given by Eq. (3.18).

$$Payback\ period = \frac{Cost\ of\ investment}{Average\ \ annual\ cash\ flow} \tag{3.18}$$

3.3.5 Total annualised cost

Annualised cost is computed by multiplying the net present cost by the capital recovery factor, as illustrated in Eq. (3.19) [91].

$$C_{ann,tot} = CRF\ (i, R_{proj}) \times C_{NPC,tot} \tag{3.19}$$

A detailed description of technical specifications, capital cost, replacement cost and maintenance cost of various components is given in Table 3.3.

Table 3. 3 Technical specifications and economic parameters of the proposed HRES

S. No.	**Component**	**Rated power (kW)**	**Lifespan**	**Capital cost (US$)**	**Replacement cost (US$)**	**Maintenance cost(US$)**
1.	PV module	100, 200	25 years	3000	3000	10 $/year

2.	Wind turbine	3	20 years	18000	18000	180 $/year
3.	Electrolyzer	60	15 years	2000	2000	-
4.	Converter	60, 100	15 years	300	300	-
5.	Fuel cell	100	40,000 hours	3000	3000	0.10 $/op.hr
6.	Hydrogen tank	50 kg	25 years	1500	1500	-

3.4 Simulation modelling of a solar photovoltaic system

Delhi Technological University, Delhi-India (77.23º E and 28.65º N), is considered a site (Fig. 1) for analysis and simulation using PVsyst and the system is designed for a 108 kW_p load. Input data is required for the design simulation in PVsyst. After substituting the value of the longitude and latitude of the above-selected site, solar irradiance is calculated. Fundamentally, designing the solar PV system depends on the availability of solar irradiance.

PVsyst 7.2.11 is a complete software package to design and simulate a solar PV system. It is also a straightforward and user-friendly simulation tool with few known parameters. It provides a detailed solution of grid-connected, pumping, standalone, and DC grid PV systems about the sizing, no. of inverters, no of PV arrays, and detailed analysis of solar PV systems.

It is selected for simulating and modelling the solar PV system in this research because it is reliable, accurate, and widely used in both industrial applications and academic studies. It can model precisely from location-specific meteorological data to system orientation, tilt, shading, and losses and give true estimates of energy yield and performance ratio. Its major feature is the detailed loss diagram that indicates different types of energy losses in the system and assists in the diagnosis of inefficiency. The ease of use and flexibility to include custom inputs and real-time site information further complement its applicability towards location-specific analysis. Moreover, PVsyst also includes basic economic assessment as well and is an industry-standard tool, with results often used for feasibility studies as well as economic assessments.

These features render PVsyst a powerful and proven option for performing credible techno-economic and environmental analysis of solar PV systems.

3.4.1 Design Procedure

Delhi Technological University, Delhi-India (77.23º E and 28.65º N), is considered a site (Figure 3.4) for analysis and simulation using PVsyst and the system is designed for a 108 kW_p load. Performance analysis of grid-connected plants has been done at various tilt angles and orientations of solar panels. Two cases have been considered for the analysis and simulation. Solar PV panels are mounted at an inclination of 20º tilt angle for the yearly irradiation yield value for the 108 kW_p unit. An identical solar PV system has been analysed at an inclination of 28º to check the existing plant performance according to the existing plant latitude. RPI-M50A inverter and Eldora 300P as a PV array are chosen to meet the 108 kW_p. The detailed specifications of solar module parameters are given in Table 3.4.

Table 3. 4 Specifications of solar module [92]

S.No.	Parameters (All data refers to STC)	Data
1.	Peak Power (0-4.99W_p) P_{max} (W_p)	315
2.	Maximum Voltage V_{mpp} (V)	38.33
3.	Maximum Current I_{mpp} (A)	8.22
4.	Open Circuit Voltage V_{oc} (V)	46.04
5.	Short Circuit Current I_{sc} (A)	8.85
6.	Module Efficiency (%)	16.23
7.	Length × Width × Height	1956 mm × 992 mm × 40 mm
8.	Weight	27 kg
9.	Junction Box	IP67, 3 bypass diodes
10.	Cells	72 polycrystalline solar cells, 3 bus bars
11.	Cell Encapsulant	EVA (Ethylene Vinyl Acetate)
12.	Back Sheet	Composite film

13.	Frame	Anodised aluminium frame with twin wall profile
14.	Mechanical Load Test	5400 Pa
15.	Maximum Series Fuse Rating	15 A

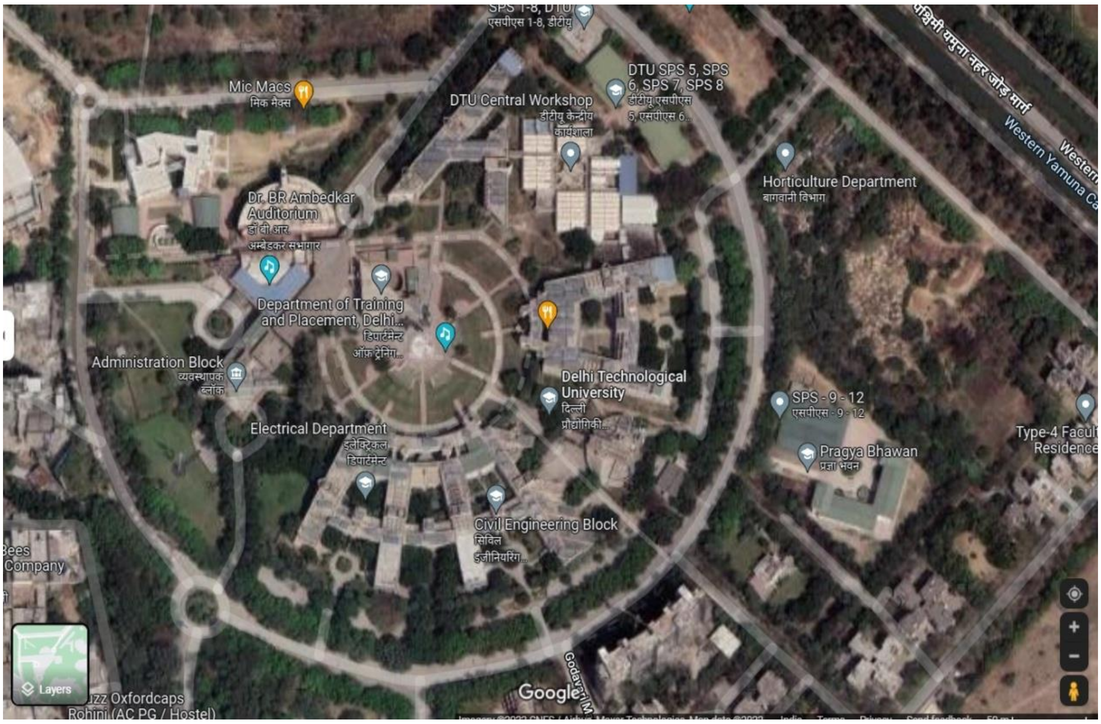


Figure 3. 4 Location of the site

Following design parameters of the solar PV system are considered in simulation and modelling:

- **Azimuth Angle**: Azimuth angle is required to define the trend of the sunshine. If the solar panels are in the northern hemisphere and face south, the value is zero. The "Azimuth angle" is the angle created by the sun's rays and true south. A positive azimuth angle indicates an east-south orientation, whereas a negative azimuth angle indicates a west-south orientation.
- **PV Array specifications:** To design a unit of 108 kW_P for Delhi Technological University, Delhi. Solar PV panels of “Vikram Solar” manufacture, model no. Eldora 300P, rated peak power of 300 W each, polycrystalline solar PV modules are considered [93].

- **Inverter specification**: To design a unit of 108 kW_P for Delhi Technological University, Delhi. Delta Inverter capacity of 50 kW_P each with model number RPI-M50A by Delta Power Solutions is considered [94].
- **Solar irradiance:** The average solar irradiation at 28.650º N and 77.230º E is around 5.477 $kWh/m^2/day$, which is an adequate number for producing electrical energy. Solar irradiance is the amount of solar energy received per unit area. This irradiance has the maximum value in the summer and the lowest value in the winter, and it is measured in W/m^2.

The steps followed for the simulation in PVsyst are shown in Figure 3.5.

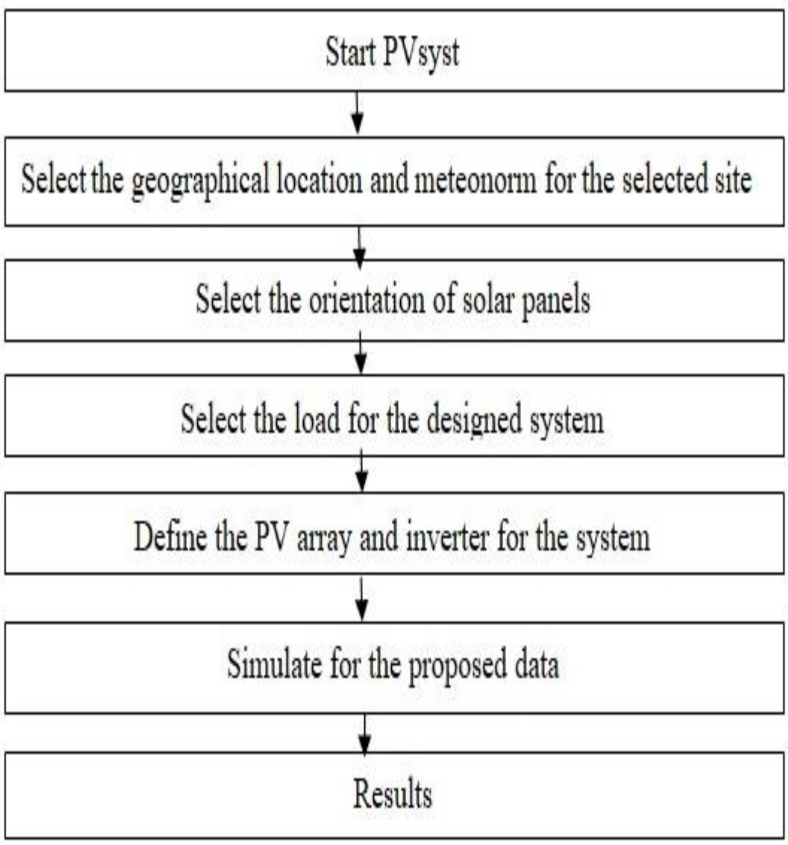


Figure 3. 5 Flowchart of simulation in PVsyst

3.4.2 Performance analysis parameters

Various performance analysis parameters for evaluating grid-connected solar PV systems are discussed as follows:

- **Energy fed to the utility grid (E_{AC}):** The entire day evaluation of AC energy generation is evaluated by Eq. (3.20) [95]:

$$E_{AC,d} = \sum_{t=1}^{t=T_{rp}} V_{AC} \times I_{AC} \times T_r \tag{3.20}$$

AC output generated in a month is presented by Eq. (3.21) [95] as:

$$E_{AC,m} = \sum_{d=1}^{N} E_{AC,d} \tag{3.21}$$

- **Energy produced through PV system (E_{DC}):** The complete monitored everyday DC power is given by Eq. (3.22) [95]:

$$E_{DC,d} = \sum_{t=1}^{t=T_{rp}} V_{DC} \times I_{DC} \times T_r \tag{3.22}$$

The monthly generated DC energy is given by Eq. (3.23) [95]:

$$E_{DC,m} = \sum_{d=1}^{N} E_{DC,d} \tag{3.23}$$

Where N denotes the number of working days of a plant in a month, subscript m indicates the monthly value and subscript d indicates the daily value.

- **Final yield (Y_f):** The ratio of the final produced power to rated PV power specified by the manufacturer under standard temperature conditions. It denotes the amount of time the PV system requires to create the concluding output concerning its nominal power capability. Eq. (3.24) and (3.25) give the daily (Y_f,d) and monthly (Y_f,m) average final yields as [47]:

$$Y_{f,d} = \frac{E_{AC,d}}{P_{PV,rated}} \tag{3.24}$$

$$Y_{a,m} = \left(\frac{1}{N}\right) \times \sum_{d=1}^{N} Y_{a,d} \tag{3.25}$$

- **Array yield (Y_a):** The array yield is calculated by taking the ratio of generated DC energy to the rated value of the PV power plant system. The daily array yield ($Y_{a,d}$) is presented by Eq. (3.26) [47]:

$$Y_{a,d} = \frac{E_{DC,d}}{P_{PV,rated}} \tag{3.26}$$

The monthly mean value of array yield ($Y_{a,m}$) is presented by Eq.(3.27):

$$Y_{a,m} = \left(\frac{1}{N}\right) \times \sum_{d=1}^{N} \mathrm{Y_{a,d}} \tag{3.27}$$

Array yield denotes the time the PV system takes to operate at nominal power generation in hours/day.

- **Reference yield (Y_r):** The total in-plane solar insolation ratio to reference irradiance under standard temperature conditions of 1 kW/m^2. It is represented by Eq. (3.28) as:

$$Y_{r,d} = T_r \times \frac{\sum_{day} G_i}{G_{STC}} \tag{3.28}$$

Furthermore, the corrected reference yield is evaluated by taking into account the module's modification impact and the ambient temperature, as shown in Eq. (3.29):

$$\mathrm{Y_{cr}} = \mathrm{Y_r}\,[1 - \mathrm{C_t}(\mathrm{T_m} - \mathrm{T_{STC}})] \tag{3.29}$$

- **PV module efficiency (η_{PV}):** The efficiency of a PV module reveals how much energy the module generates compared to the available radiation. Eq. (3.30) expresses it as follows:

$$\eta_{\mathrm{PV}} = \left[\frac{\mathrm{P_{DC}}}{\mathrm{G_i \times A_m}}\right] \times 100\% \tag{3.30}$$

The monthly module efficiency is given by Eq. (3.31) as follows:

$$\eta_{PV,m} = \left[\frac{E_{DC,m}}{G_i \times A_m}\right] \times 100\% \tag{3.31}$$

- **Inverter efficiency (η_{inv}):** The inverter efficiency is estimated by dividing the inverter's generated AC power by the PV array system's generated DC power. When calculating inverter efficiency, it is considered that system efficiency and module efficiency are the greatest, since it is the conversion efficiency of DC to AC power. Eq. (3.32) gives the instantaneous inverter efficiency as follows:

$$\eta_{inv} = \left[\frac{P_{AC}}{P_{DC}}\right] \times 100\% \tag{3.32}$$

The inverter efficiency may also be estimated using Eq. (3.33) with monthly values of DC energy generated ($E_{DC,m}$) and AC energy generated ($E_{AC,m}$).

$$\eta_{inv,m} = \left[\frac{E_{AC,m}}{E_{DC,m}}\right] \times 100\% \tag{3.33}$$

- **System efficiency (η_{sys}):** The photovoltaic system efficiency is characterised by the product of PV module efficiency (η_{PV}) and inverter efficiency (η_{inv}), as shown in Eq. (3.34):

$$\eta_{sys} = \eta_{PV} \times \eta_{inv} \tag{3.34}$$

- **Capacity factor (CF):** It is the ratio of real yearly energy production to the quantity of energy that can be produced by the rated capacity of the PV system for 24 hours per day during one year, as stated by Eq. (3.35) as:

$$CF = \frac{Y_{f,annual}}{24 \times 365} = \frac{E_{AC,annual}}{P_{PV,rated} \times 8760} \tag{3.35}$$

$$CF = \frac{\frac{h}{day} \text{of the peak sun}}{24\ \text{hours/day}} \tag{3.36}$$

The CF fluctuates in a similar ratio to the ultimate yield. It is a means of displaying the energy carried by an electrical power distribution system. If the system delivered full-rated power constantly, the CF would be 1.

- **Performance ratio (PR):** It is defined as the ratio of the final yield (Y_f) to the array yield (Y_a), as stated in Eq. (3.37) [96]:

$$PR = Y_f / Y_a \tag{3.37}$$

As demonstrated in Eq. (3.38), it may alternatively be characterised as a function of degradation efficiency (η_{degr}), soiling efficiency (η_{soil}), temperature efficiency (η_{temp}), and inverter efficiency (η_{inv}):

$$PR = \eta_{degr} \times \eta_{temp} \times \eta_{soil} \times \eta_{inv}$$
(3.38)

A grid-connected system with different tilt angles has been chosen for the simulation. According to the site specification and solar irradiation, two tilt angles, 20º and 28º and azimuth angle 0º are considered for the analysis. This ratio depicts the real proximity to the ideal efficiency and the influence of PV system losses. Optimising system orientation with variation in the tilt angle of PV panels is studied. The panels are facing true south, tilted with angles of 20˚and 28º. The comparative analysis is done based on different tilt angle positions of PV panels to maximise the module's output. Figure 3.6 and Figure 3.7 indicate the PV system's orientation at 20º and 28º tilt angles for the 108 kW_p systems.

Case: I and II – 108 kW_p System at an inclination of 20º and 28º

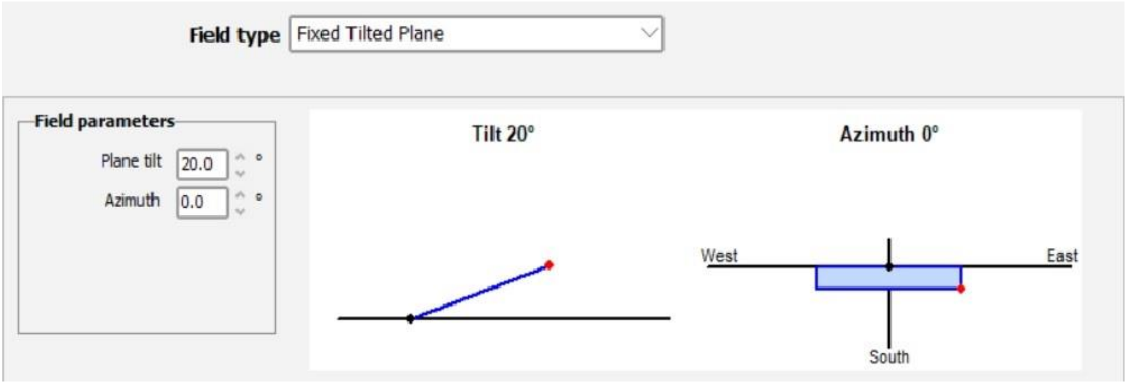


Figure 3. 6 Orientation of PV system at 20º tilt angle

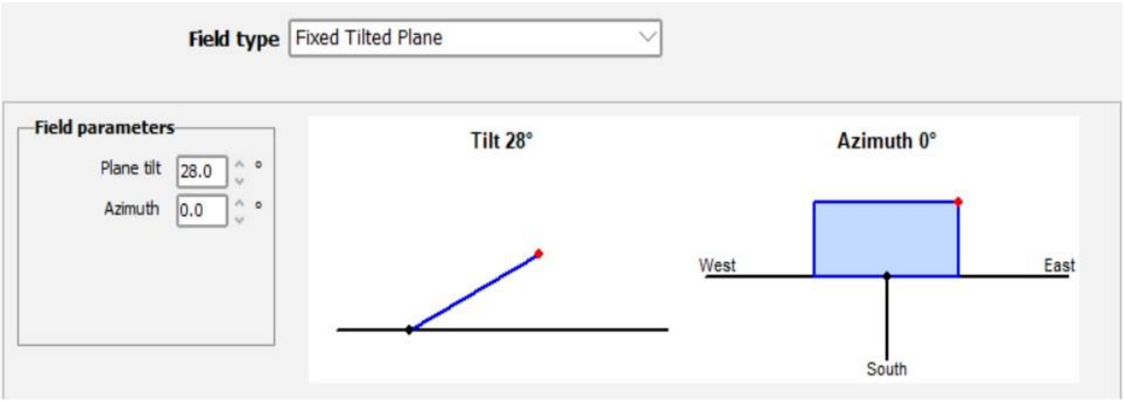


Figure 3. 7 Orientation of PV system at 28º tilt angle

3.4.3 Optimisation using RSM

Response surface methodology (RSM) is a compilation of arithmetical and statistical methodologies. RSM's capacity to establish a model between the response and input variables using analysis of variance (ANOVA) is one of its beneficial qualities. The polynomial regression model is used, and it is written in Eq. (3.39) [97]:

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i \square_i + \sum_{i=1}^{n} \beta_{ii} \square_i^{\,2} + \sum_{i=1}^{n-1} \sum_{j-i+1}^{n} \beta_{ij} \square_i \square_j$$

(3.39)

The adjusted multiple determination coefficient tests the precision of the regression model (R^2_{adj}) and the coefficient of multiple determinations (R^2_{adj}) is calculated by the following expressions Eq. (3.40):

$$R^2_{adj} = 1 - (1 - R^2)\frac{n-1}{n-P} \tag{3.40}$$

where y is the response; β_0, β_i, β_{ii}, and β_{ij} are the constant, linear, quadratic, and interaction coefficients, respectively; n designates the number of the factors $(x)_i$. P is the regression coefficient number. The coefficient of determination is determined by using Eq. (3.41).

$$R^2 = 1 - \frac{SS_E}{SS_T} \tag{3.41}$$

where SS_T and SS_E are the sum of the squares and the sum of the residuals

$$SS_T = \sum_{i=1}^{n} \mathrm{y_i^2} - \frac{\sum_{i=1}^{n} \mathrm{y_i^2}}{\mathrm{n}} \tag{3.42}$$

$$SS_E = \sum_{i=1}^{n} (\mathrm{y_i} - \hat{\mathrm{y}})^2 \tag{3.43}$$

where, y_i and $\hat{y}$ are the observations and fitted values, and N designates the number of observations. The impacts of two major installation parameters on a solar PV system's performance have been determined. As input variables, tilt angles of 20º and 28º and albedo of 0.2 and 0.8 are examined.

3.4.4 Economic analysis

Economic variables should be considered to assess the advantages of investing in PV power systems. The feasibility of the PV system investment may be guaranteed by appropriate economic analysis, which includes life cycle cost (LCC), cost of energy (COE), and payback period.

3.4.4.1 Net present cost

Net Present Cost (NPC) is the difference between total paid expenses and total received income during the project's life. Capital expenses, replacement costs, maintenance and operations costs, fuel costs, and grid electric purchase prices are all possible. The cash might come from selling the energy to the grid and the salvage value. Eq. (3.44) defined the NPC as follows:

$$\mathrm{NPC} = \frac{\mathrm{C_{total}}}{\mathrm{CRF(i,T_p)}} \tag{3.44}$$

3.4.4.2 Payback period

The payback period is the amount of time it takes for a project to recoup its original investment through income. The payback method's core concept is to assess the likelihood of investment. It is defined by Eq. (3.45) [98].

$$\text{Payback period} = \frac{\text{Initial Investment}}{\text{Annual Savings}} \tag{3.45}$$

3.4.4.3 Levelized cost of electricity

The levelized cost of electricity (LCOE) of a solar PV system is the total cost of installation and operation in terms of the present currency per kilowatt-hour. It is expressed by Eq. (3.46) [98].

$$\text{LCOE} = \frac{\text{Total life cycle cost (in Rs.)}}{\text{Total lifetime energy production (in kWh)}} \tag{3.46}$$

3.4.4.4 Annualised capital cost

It is determined by adding the capital recovery factor (CRF), which depends on the actual discount rate, I and the payment period (in years), n, to the total cost of all components, Ci. It is represented by Eq. (3.48).

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.47}$$

$$C_a = C_i * \text{CRF} \tag{3.48}$$

3.4.5 Environmental analysis

Power grid provides the electrical energy utilised in government facilities and academic campuses. Conventional, nuclear, hydroelectric, and renewable energy sources power the grid. As a result, a significant quantity of CO_2 is emitted during the creation of this power. Grid electricity would be replaced with solar PV-based electricity. The emissions reductions from not utilising grid electricity are evaluated using emission factors from the Central Electricity Authority of India (CEA 2019). Grid power is being replaced with solar PV-based electricity, and the reductions in CO_2 emissions and not utilising grid electricity are evaluated using emission factors given by the Central Electricity Authority of India (CEA 2019). The CO_2 emission factor is given by Eq. (3.49) [98].

$$CO_2 \text{ emission factor} = 0.9247 \text{ tCO}_2/\text{MWh} \tag{3.49}$$

3.5 Solar photovoltaic and biomass gasifier system for power generation

3.5.1 System details

In this HRES, solar PV, along with a biomass gasifier generator and batteries, has been used for energy storage. Figure 3.8 represents a schematic diagram of power generation using a PV array, biogas genset, battery and power converter. Biomass is burned or utilised after transforming it into various forms of solid, liquid, and gaseous fuels, and CO_2 is emitted into the atmosphere that the biomass had recently taken from the atmosphere during its photosynthesis process. As a result, there is no net CO_2 increase [99]. The system should have low or zero carbon emissions and be easily integrated with current technologies or grid, and in the end, the cost of the system should be optimal [100].

The proposed system is an amalgam of solar PV power sources with other power sources. The system is set to be a standalone system. It is usually advantageous in remote or inaccessible areas. Components of this system include a biomass generator set, solar PV energy generator, battery and a converter. Figure 3.9 shows a brief procedure to develop, simulate, and optimise the HRES using HOMER.

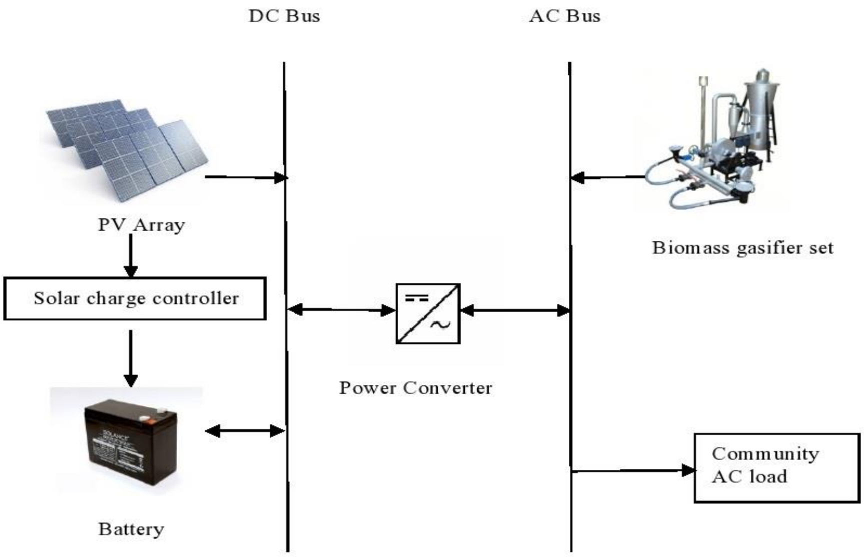


Figure 3. 8 Solar photovoltaic and biomass gasifier hybrid renewable energy system

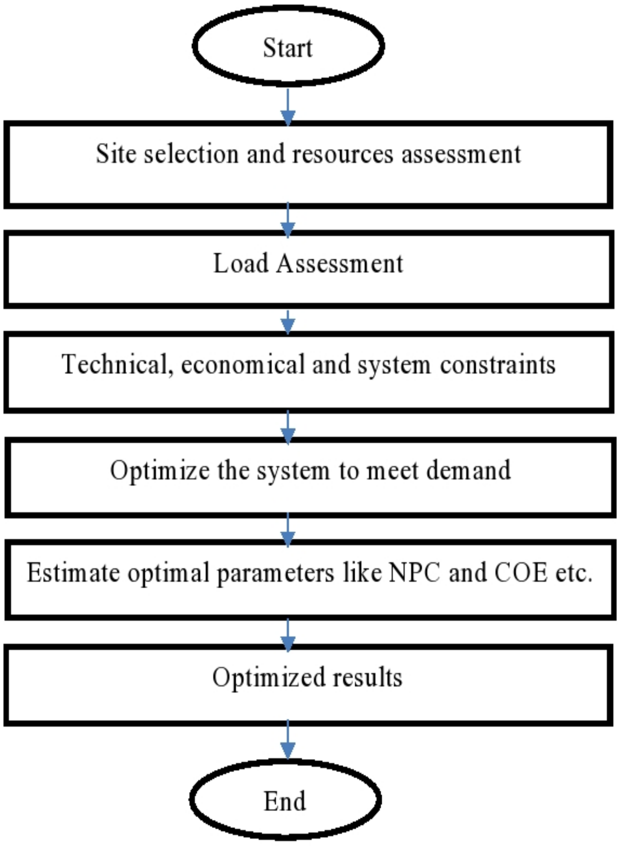


Figure 3. 9 Flowchart to design and optimise solar PV and biomass gasifier HRES

3.5.2 Components detail

HRES comprises solar PV, biomass energy sources, a converter and a battery to store the generated power. Optimisation is of utmost importance in determining the optimal system's size and cost. It can be an indication of a good ratio between the system's cost and its performance.

3.5.2.1 Solar photovoltaic system

Sunlight is converted into direct current power by solar PV cells. The cells consist of several varieties of semiconductor materials. Solar cell technology, which includes positive and negative charges, is designed with a low cost and a high conversion efficiency rate [101]. Photovoltaic system output is mainly dependent on incident solar radiation. Furthermore, the output is in terms of voltage. Hence, the power generated is determined by the product of current and voltage. A 1 kW solar PV system and maintenance costs are nearly 1735.56 US$. The lifetime of this system is approximately twenty years and does not include any tracking system [7].

The output of the solar PV in HOMER is given by Eq. (3.50):

$$P_{PV} = A_{PV}\, f_{PV}\, (R_T / R_{T,STC})(1 + a_P(T_{cell} - T_{cell,STC}) \tag{3.50}$$

If the option chosen is not to model the coefficient of temperature, then the simplified equation is given by Eq. (3.51):

$$P_{PV} = A_{PV}\, f_{PV}\, (R_T / R_{T,STC}) \tag{3.51}$$

PV system Output is obtained from the product of the current and voltage. Eq. (3.52) represents the energy distributed by the panel in the system [102].

$$P_{PV}Output = P_{NPV} \times R/R_{ref} \times (1 + K_T(T_{cell} - T_{ref}) \quad (3.52)$$

3.5.2.2 Biomass gasifier generator set

When an organic resource is burned at an extremely high temperature and combined with a limited flow of air, the structure of the source breaks down into a simpler form. This organic material is heated with a limited quantity of air in a biomass gasifier to propagate incomplete combustion, producing a mix of highly combustible gases. Complete combustion of biomass resources will produce N_2, H_2O, CO_2, and excess O_2. Since incomplete combustion occurs in the gasifier, resulting gases are CO, H_2 and minimal methane gas [103]. Collected food waste on the campus is used as biomass to produce biogas, and the LHV of biogas is assumed to be 5.50 MJ/kg. Biogas/fossil ratio is 8.50%. The density of syngas is about 0.72 kg/m^3, then the gasification ratio is calculated at 0.70 kg/kg biomass.

The electrical efficiency of the system is defined by Eq. (3.53) and Eq. (3.54) [7]:

$$?_{elec} = (P_o - P_n)/(Input\ Biomass)_{LHV} \quad (3.53)$$

$$?_{elec} = (P_{tot})/(Input\ Biomass)_{LHV} \quad (3.54)$$

Here, $P_{tot} = P_o - P_n$

3.5.2.3 Power converter

In this HRES, the power converter is of utmost importance. An electronic converter aims to maintain a continuous stream of power between the component's DC and AC power generated. HOMER assumes that the rectifier and inverter capacity do not exceed what the device can handle for an extended period. Instead, they are considered continuous capacities; the apparatus can resist for the required period [103]. With research about present market rates, we anticipate the approximate capital cost to be 173.56 US$. with maintenance and upkeep costs at 115.70 US$. The approximate lifespan of a converter is 20 years, and it maintains nearly a 90% efficiency level [104].

3.5.2.4 Battery

A battery storage bank is used to reinforce the system. Similarly, a battery is used to keep the voltage constant over the electrical component. Common usage of the battery bank is for storing the electrical power generated in a highly effective. Its discharging capacity is unable to exceed a base breaking point. Battery bank's storage capacity (C_{Wh}) is determined by Eq. (3.55) [105]:

$$C_{Wh} = (E_{tot} \times \text{AD})\square_{in} \times \square_{batt} \times DOD_{batt} \tag{3.55}$$

The software performs calculations to determine the maximum amount of electricity that can be stored in the storage bank for each time step. The maximum quantity of electricity stored is used to figure out whether the storage bank can take in extra renewable energy or the extra power needed to be generated by a generator. This maximum charge power fluctuates in between steps due to the varying state of charge and previous discharge [106]. The maximum amount of power that the two-tank system can withstand is provided by Eq. (3.56):

$$P_{batt} = (rE_1\, exp^{-r\Delta t} + Qrs\, (1 - exp^{-r\Delta t}))\, /\, (1 - exp^{-r\Delta t} + s\, (r\Delta t - 1 + exp^{-r\Delta t}) \tag{3.56}$$

Another limitation imposed by HOMER is the maximum charge rate. Battery storage bank power related to it is given by Eq. (3.57):

$$P_{batt} = (1 - exp^{-\alpha\Delta t})\, (E_{max} - E)/\Delta t \tag{3.57}$$

The last limitation imposed by HOMER is the maximum charge of the storage component. The formula for maximum storage bank charge power for this charge current is given by Eq. (3.58):

$$P_{batt} = N_{batt} I_m V_n / 10 \tag{3.58}$$

In HOMER, the least of the previous three values is used as the maximum storage charge power after taking into account losses due to charging, leading to Eq. (3.59):

$$P_{batt,cmax} = MIN\ (P_{batt,cmax,kbm}\ , P_{batt,cmax,mcr}\ , P_{batt,cmax,mcc}) / \eta_{batt,c} \tag{3.59}$$

Capital cost 59124.69 US$, substitution cost 58271.61 US$ after 15 years and battery life is estimated to be 15 years in this project [107].

3.5.3 Site selection and resource assessment

Figure 3.10 shows the site of the study area, i.e., the Department of Mechanical Engineering, Delhi Technological University, Delhi. DTU is situated in the North-West of Delhi with a 165-acre campus. It is a large campus comprising many hostels, residential buildings, educational buildings, biogas, waste plant, etc. Hence, sufficient raw material is available daily to produce the required biomass. NASA Surface Meteorology used to perform irradiation at site location 28°44'N latitude and 77°06'E longitude.

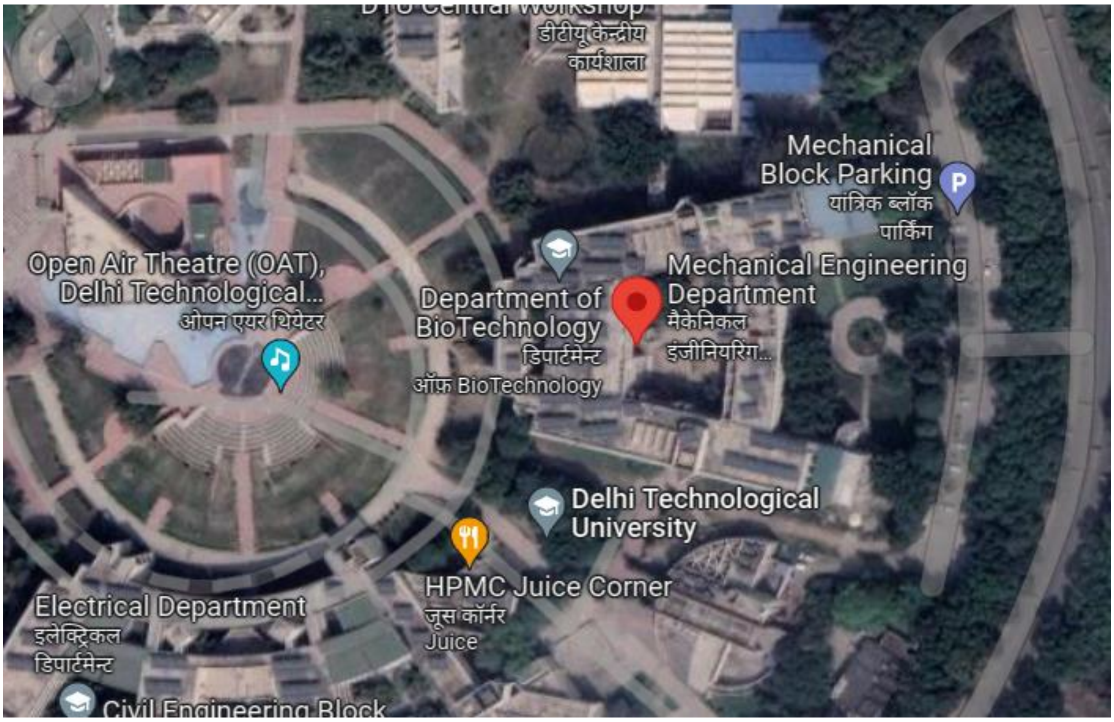
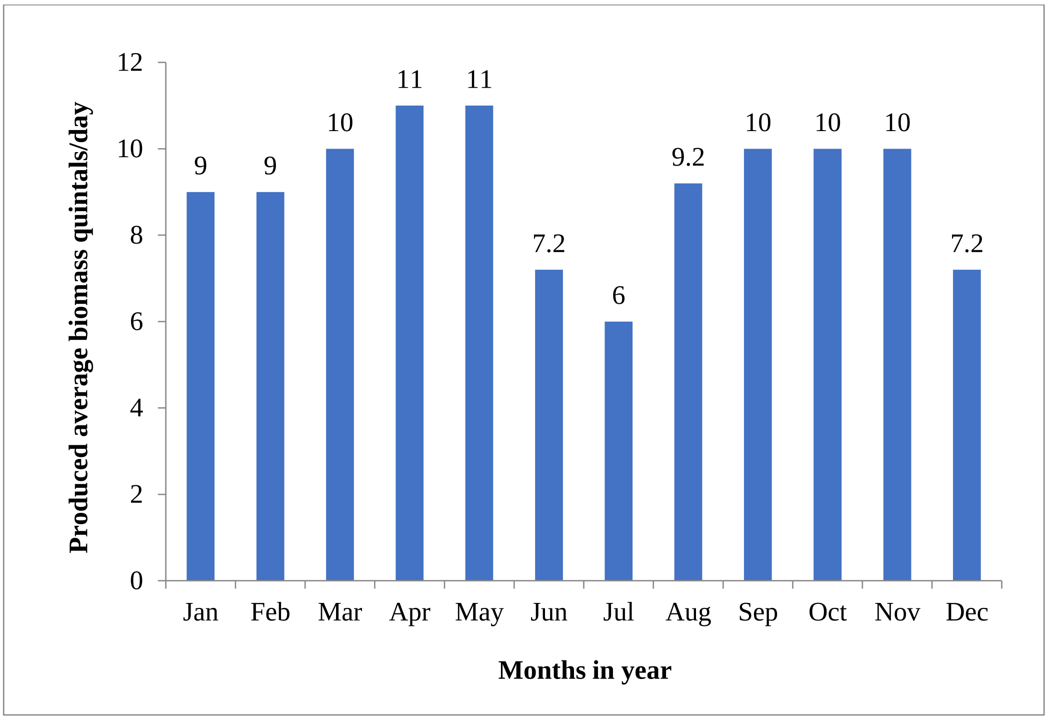
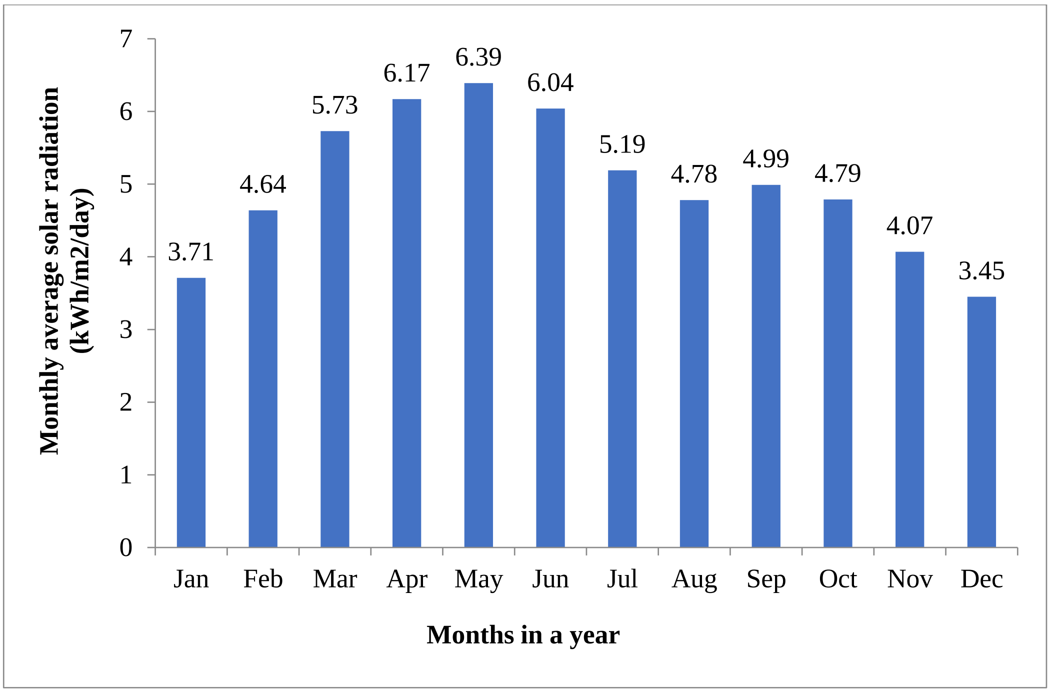


Figure 3. 10 Location of the study area, Mechanical Engineering Department, DTU, Delhi (India)

Figure 3.11 (A) shows biomass resources available for power generation of the proposed system. The average annual biomass production amount is 9.08 quintals/day. Figure 3.11 (B) illustrates the monthly average solar radiation. Yearly average solar power can be scaled up to 4.99 kWh/m^2 per day, which is considerable.



(A) Monthly average biomass resources

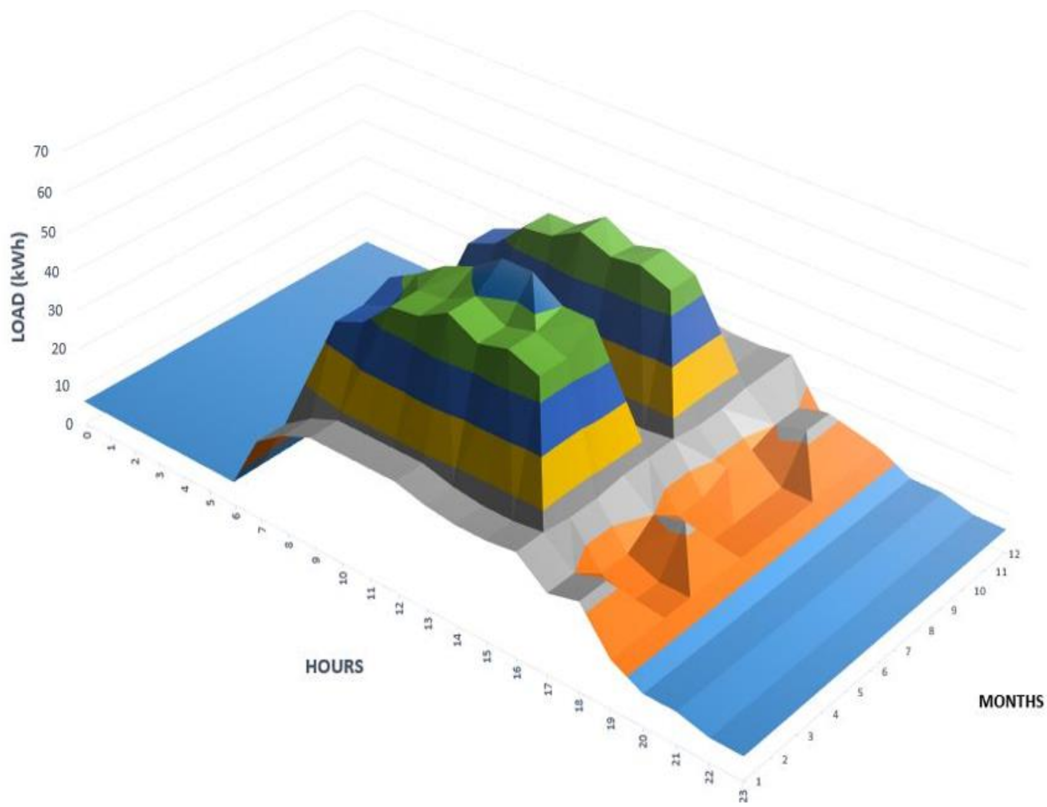


(B) Monthly average solar radiation

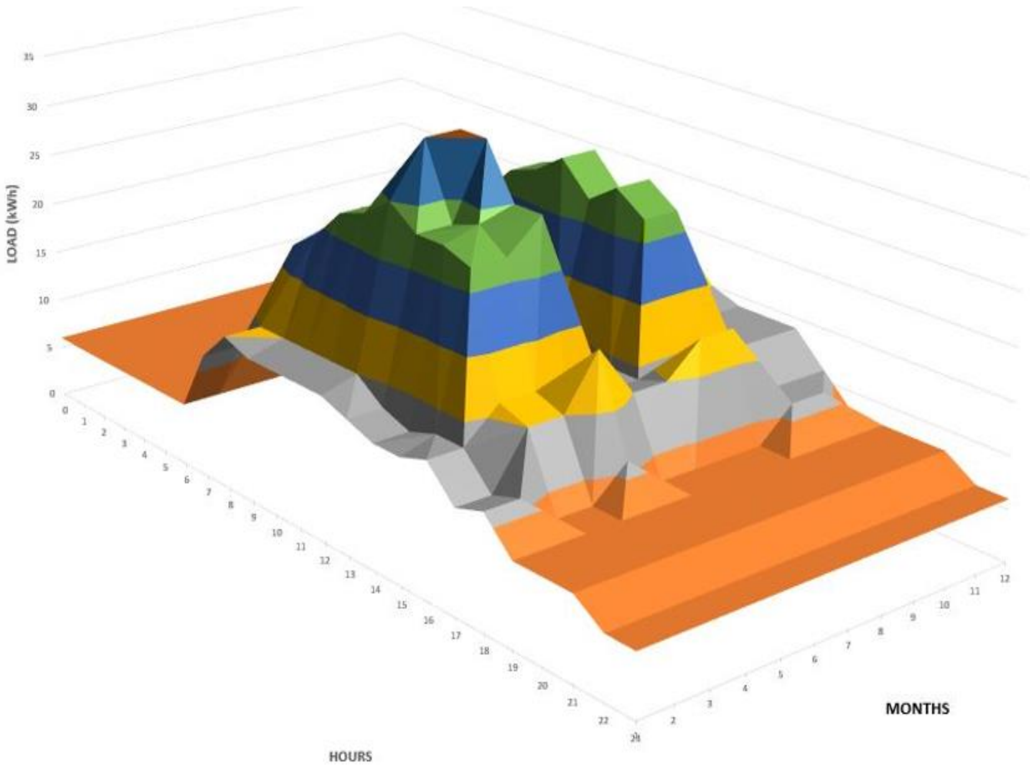
Figure 3. 11 Renewable energy resources assessment

Figure 3.12 (A) shows a 3D surface plot of each month of the year for the weekday load profile for the Mechanical Department, DTU, India. Figure 3.12 (B) shows the exact data for weekends. It translates to a 65 kW peak load on weekdays and 35 kW on weekends. The average load calculated over the year amounts to 588 kWh per day.

Load profiles vary based on the users, for example, homes versus commercial sites. There is the consideration that specific equipment runs continuously, like refrigerators. Academic building comprises laboratory equipment and electrical appliances that contribute to its load requirement.



(A) Weekdays



(B) Weekends

Figure 3. 12 Load profile for Mechanical Department, DTU, Delhi (India)

3.5.4 Cost analysis of the HRES

- **Net present cost (NPC):** The net present cost of the hybrid system is the cost difference between all present costs incurred by the system over its lifetime and all present revenue collected during the project's lifetime. It is given by Eq. (3.60) [84].

$$C_{NPC} = \frac{C_{AT}}{CRF(i_r P_L)} \tag{3.60}$$

- **Levelized cost of energy (LCOE):** HOMER calculates the LCOE by dividing the annualised cost of producing electricity by the total useful electric energy production, which is computed by Eq. (3.61) [87].

$$\text{LCOE} = \frac{C_{ann,tot}}{E_{prim,AC}+E_{prim,DC}+E_{grid,sales}} \tag{3.61}$$

- **Salvage value:** Salvage value is the cost of a power system component that is still operational at the end of the project's lifespan. To assess the worth of each component after the project's life cycle, HOMER employs Eq. (3.62) [92].

$$Salvage = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{3.62}$$

- **Total annualised cost:** As shown in Eq. (3.63), the annualised cost is calculated by multiplying the net present cost by the capital recovery factor [91].

$$C_{ann,tot} = CRF\ (i, R_{proj}) \times C_{NPC,tot} \tag{3.63}$$

The first step in this research is to decide on the site location. The decision of the site location is based on two main factors. Firstly, the given site has a significant load and is operational and relatively consistent throughout the year. Secondly, the location is easily accessible for the required data collection. Once the site location is finalised, analyse the available resources to design the system. It is done by analysing all the naturally available resources in that particular area of Delhi, such as rain, wind, biomass, and sunlight. This particular data is sourced from the NASA meteorological website. After that, data collection about how much energy is consumed daily in the decided location is required. This secondary data is sourced from the technicians responsible for the location. After breaking down the load profile according to weekdays and weekends, and then further to summers and winters, the yearly energy required is calculated. This is done by monitoring and controlling the necessary variables. A significant review of past work in the field is done to understand the limitations faced and where the gap can be overcome.

This material is sourced from various sites, including published articles in reputed journals, reports, case studies, and government websites. These materials are chosen based on their data range, where preference and higher weightage are given to the more recent materials. After the system design, data is prepared and analysed using HOMER. Data is used to conduct three technical, economic, and environmental analyses. Results and findings are summarised, and relevant conclusions are drawn by concluding the assessment.

The results and discussion for the three suggested systems, i.e., solar PV, wind and fuel cell system, installed solar photovoltaic system, and the third one is a solar photovoltaic system with biomass gasifier, are included in the next chapter. It includes the assessment of yields, system efficiency, specific production and the system's economic and environmental analysis. Additionally, response surface methodology (RSM) is used to optimise the system's process parameters, and performance metrics are contrasted with those from earlier research. The assessment of specific production, produced capacity ratio, performance ratio, total production and various economic analyses parameters like LCOE, COE and NPC and environmental analysis is also included. Additionally, a comparison of various published papers with the existing systems is also given in this chapter.

CHAPTER: 4

RESULT AND DISCUSSION

4.1 Performance analysis of HRES based on climatic conditions

4.1.1 Power output of components

With the help of the HOMER software, a 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 the search space and assesses the more feasible ones. Figure 4.1 shows the power output of the flat plate PV throughout the year with a 100 kW to 200 kW rated capacity of solar PV panels. The total rated capacity of wind turbines varies from 150 kW to 300 kW for all the stations. The lowest wind penetration is found in Srinagar, while the highest is in Kolkata, as shown in Figure 4.2. Fuel cell generator capacity ranges from 0 kW to 60 kW. Figure 4.3 shows the generator power output for each hour of the day throughout the year. Electrolyser input power capacity ranges from 0 kW to 60 kW, as shown in Figure 4.4.

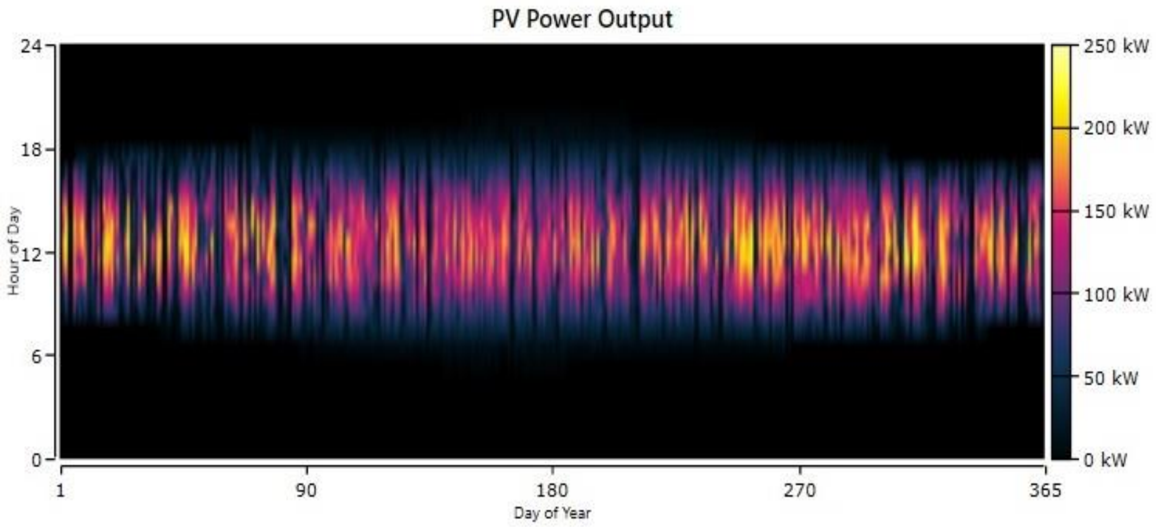


Figure 4. 1 Power output of a generic flat plate PV

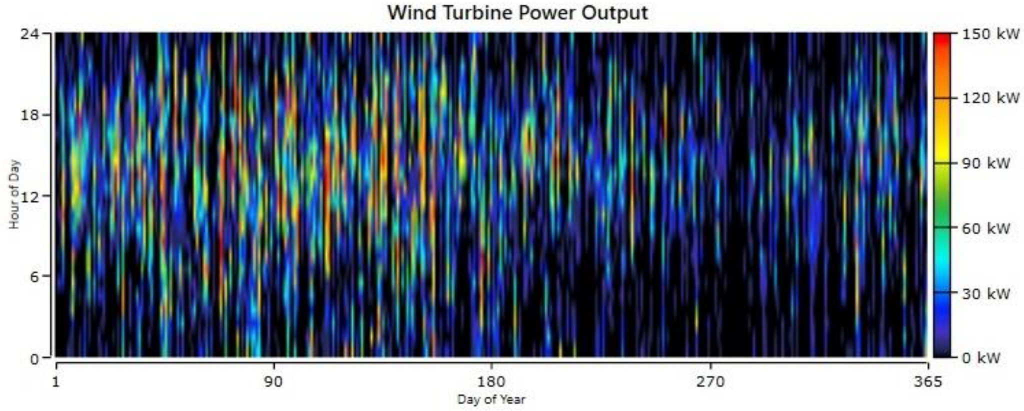


Figure 4.2 Power output of wind turbine

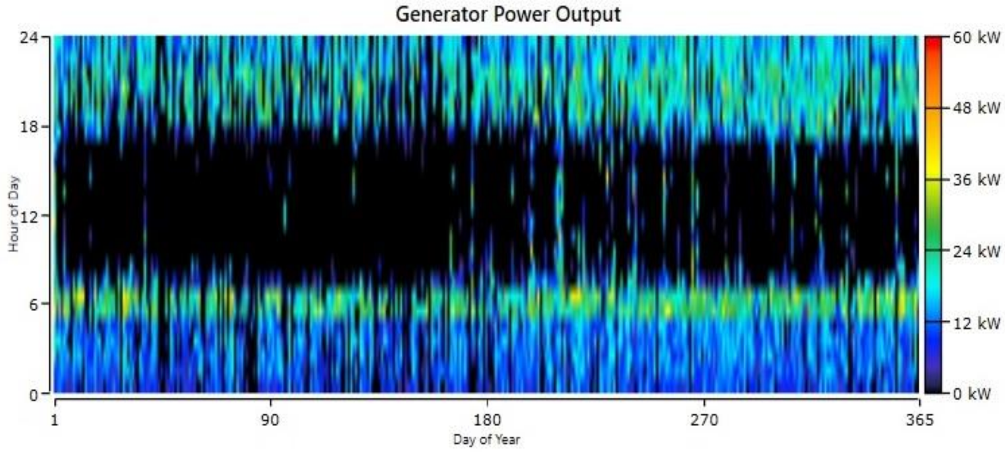


Figure 4.3 Fuel cell generator power output

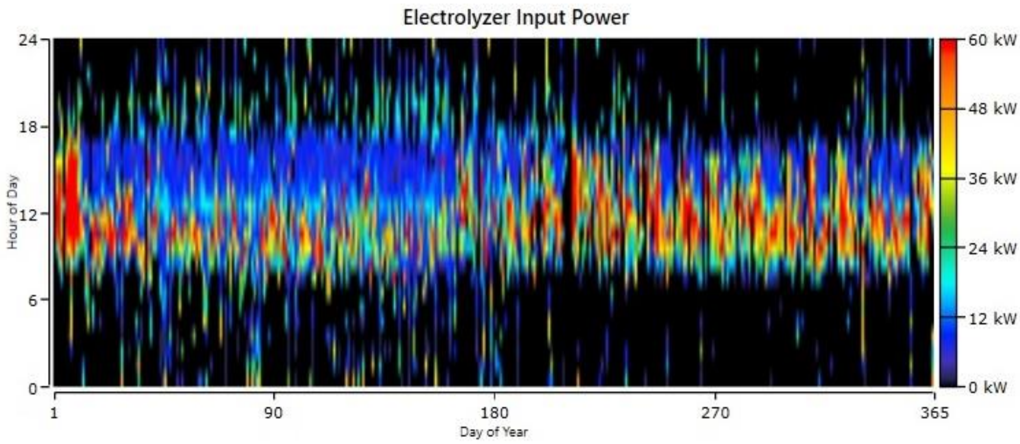


Figure 4.4 Input power of electrolyser

4.1.2 Total production and capacity factor of solar PV and wind turbine

As seen in Figure 4.5, the capacity factor for New Delhi is 21.2% whereas 18.9% for Kolkata. The 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 (Figure 4.6).

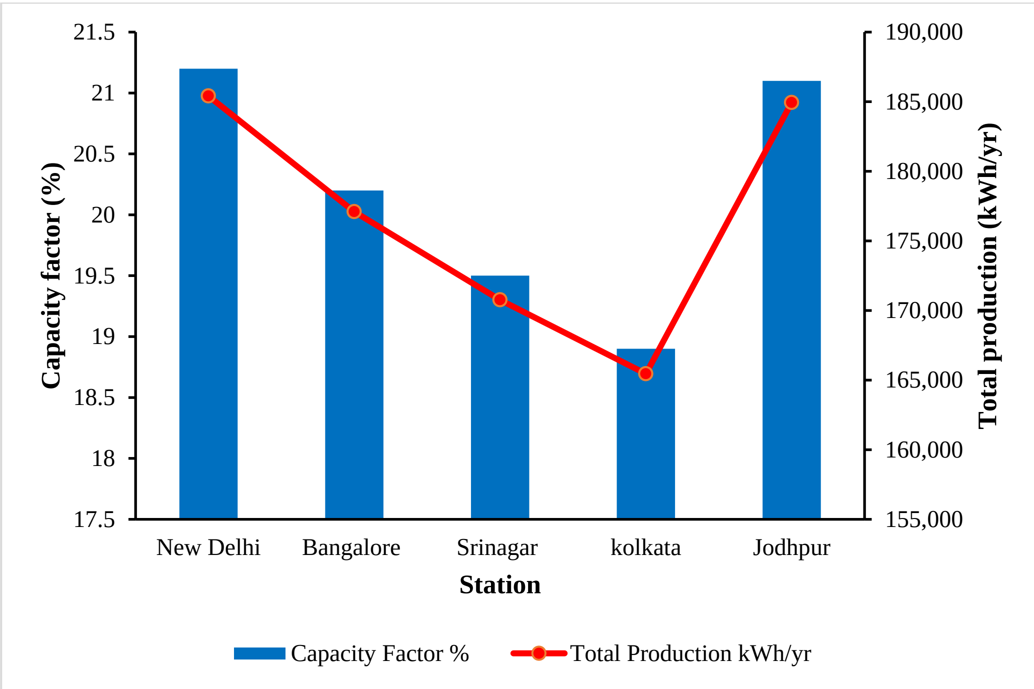


Figure 4.5 Total production and capacity factor of solar PV for all the stations

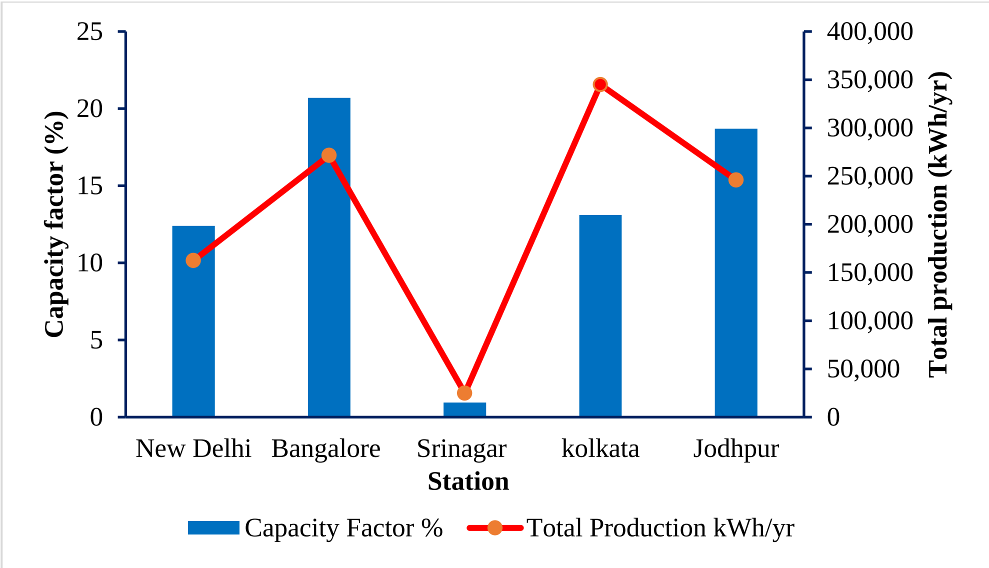


Figure 4.6 Total production and capacity factor of wind turbine for all the stations

4.1.3 Net present cost, operating cost and levelized COE analysis

Figure 4.7 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.

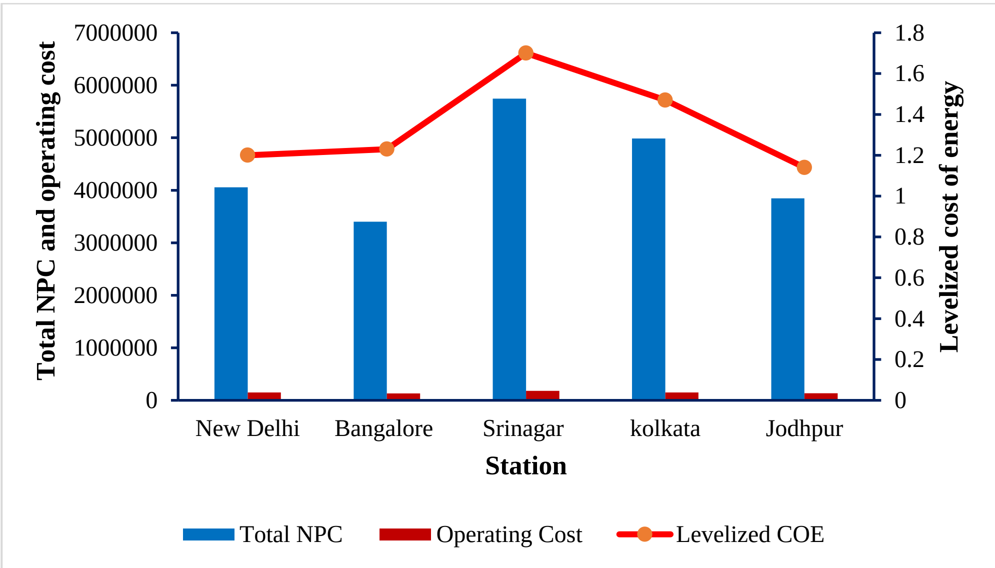


Figure 4.7 Overall total NPC, operating cost and levelized COE of all stations

As it is depicted in Figure 4.8, LCOE based on generic flat plate PV for Jodhpur and New Delhi is equivalent, i.e., 0.108 US$/kWh and on the other hand, the LCOE of Bangalore is 21.16% greater than that of Jodhpur and New Delhi. A generic wind turbine is a viable option for Jodhpur; hence, it is 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 4.1).

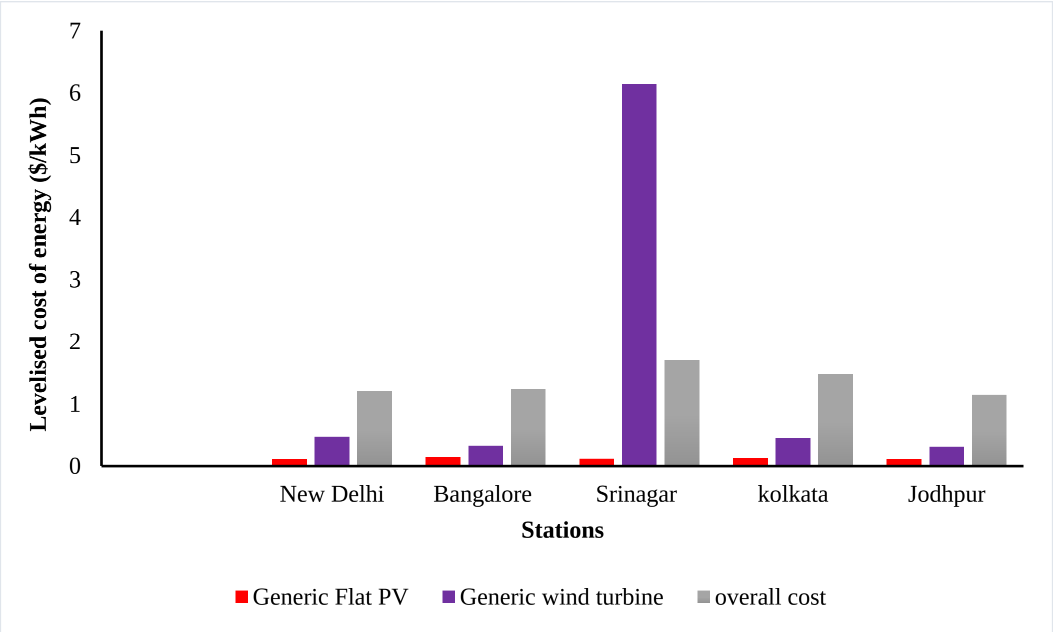


Figure 4.8 LCOE for PV, wind turbine and the overall system

Table 4.1 Payback period and LCOE of all stations

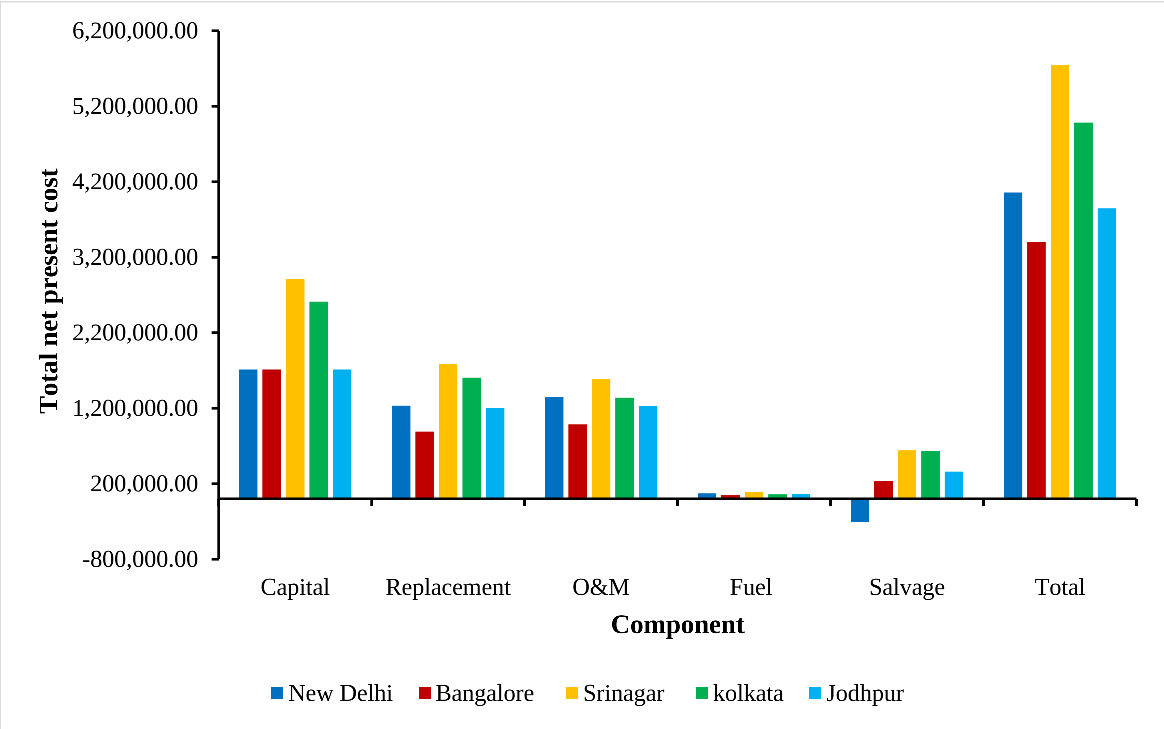
S. No.	Station	Payback period (years)	LCOE (US$/kWh)
1	New Delhi	10.76	1.2
2	Bangalore	12.8	1.23
3	Srinagar	10.3	1.7
4	Kolkata	16.6	1.47
5	Jodhpur	5.9	1.14

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; 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 4.2.

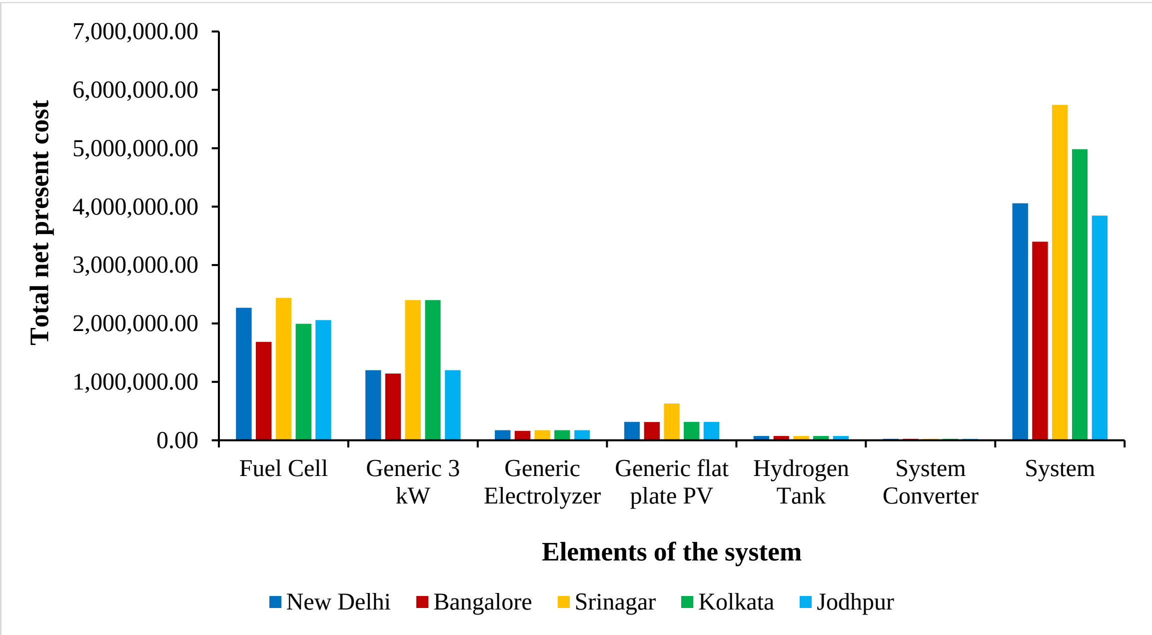
Table 4.2 Total optimised NPC of HRES in 25 years of operation at different stations

Station	Capital	Replacement	O&M	Fuel	Salvage	Total (US$)
New Delhi	17,13,000	12,34,078.98	13,46,042.30	72,494.75	3,08,220.17	40,57,395.86
Bangalore	17,13,000	8,90,039.26	9,85,076.76	47,694.60	2,34,706.80	34,01,103.82
Srinagar	29,13,000	17,90,376.28	15,89,731.88	92,714.58	6,41,717.21	57,44,105.53
Kolkata	20,13,000	12,02,136.41	12,56,883.74	63,408.15	3,55,954.76	41,79,473.54
Jodhpur	17,13,000	11,99,254.14	12,32,310.00	62,714.67	3,59,968.47	38,47,310.34

Figure 4.9 (a) 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, 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$, and Bangalore has the 40.78 % lowest NPC as compared to Srinagar. The detailed cost analysis based on the various components is shown in Figure 4.9 (b). In 2012, the cost of per unit power from conventional power plants was roughly 11.02 US$/kWh; however, in this HRES, the average cost of per unit power is 1.348 US$/kWh [108].



(a)



(b)

Figure 4.9 Total NPC of all stations of HRES (a) Based on different types of cost (b) Based on various system elements

4.1.4 Fuel consumption and fuel energy input

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 seen in Figure 4.10.

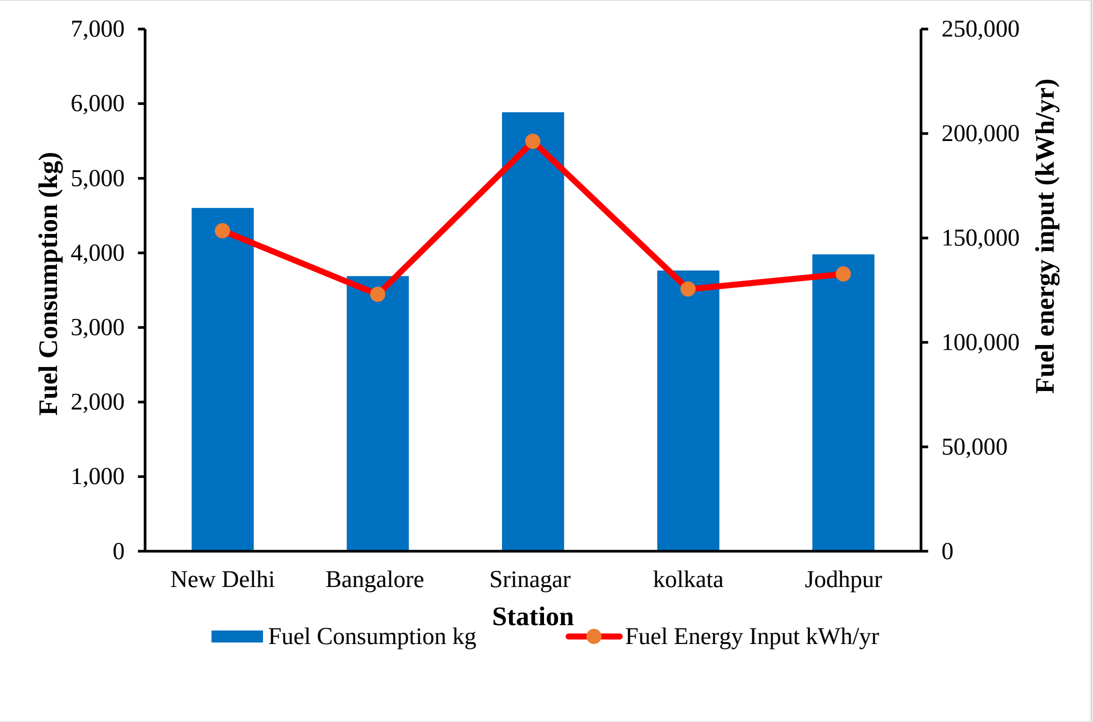


Figure 4.10 Fuel consumption and fuel energy input for all stations

4.1.5 Emission Analysis

Contrasting RESs, HRES and conventional fuel energy sources are associated with certain amounts of emissions like carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide and nitrogen oxides, regardless of the reduction in greenhouse gas emissions. Although they are very low compared to the emissions generated by the conventional power generation system (Figure 4.11). 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 [109].

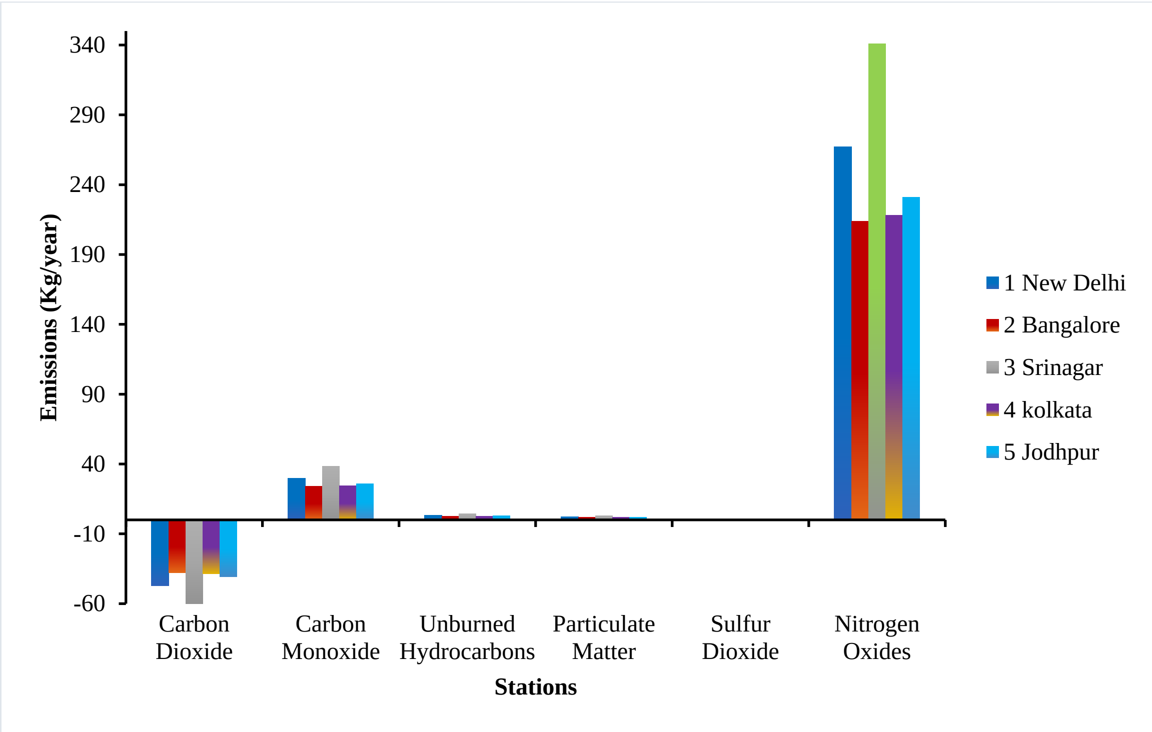
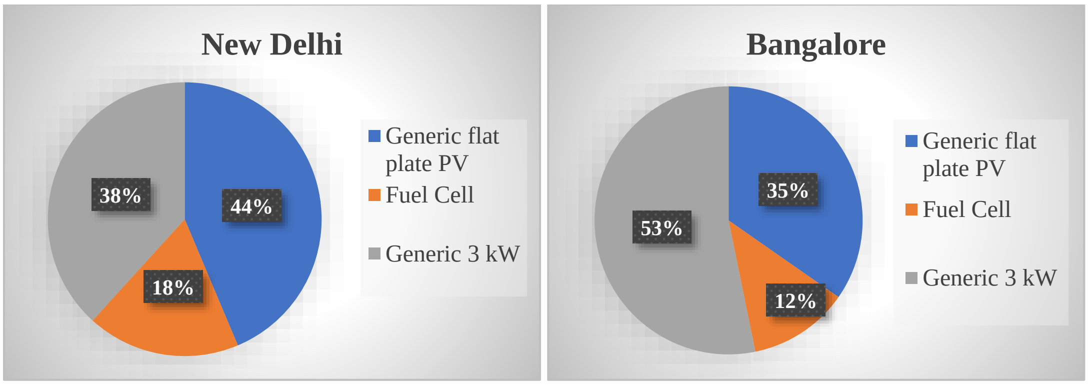


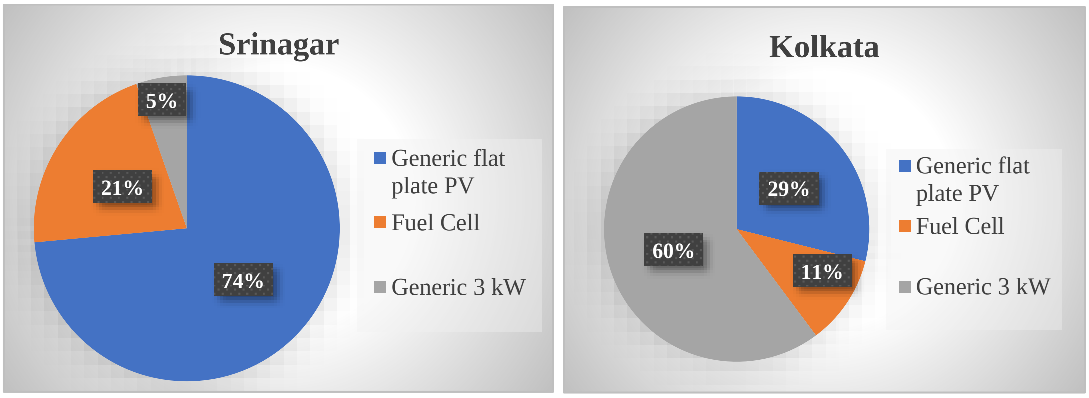
Figure 4.11 Annual emissions produced from the HRES

4.1.6 Monthly power production

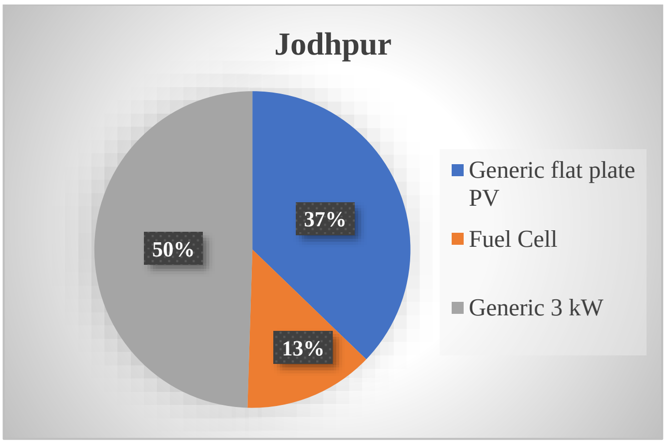
Figure 4.12 illustrates the monthly electricity generation for all the stations. Here, Srinagar is contributing 74% of the total electricity generated by solar PV, while Kolkata is contributing the least. All of the station's average electricity generation from fuel cells ranges from 11% to 21%. It is feasible to produce electricity using wind turbines in New Delhi, Bangalore, Jodhpur, and Kolkata, and for the Srinagar station, wind power is not ideal.



(a) (b)



(c) (d)



(e)

Figure 4.12 Monthly Power production (a) New Delhi (b) Bangalore (c) Srinagar (d) Kolkata (e) Jodhpur

4.1.7 Validation of the proposed system results with published work

This proposed system has developed a new HRES configuration that differs from previous discussed studies in the literature review chapter (Table 2.4), 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 has been published (Figure 4.13).

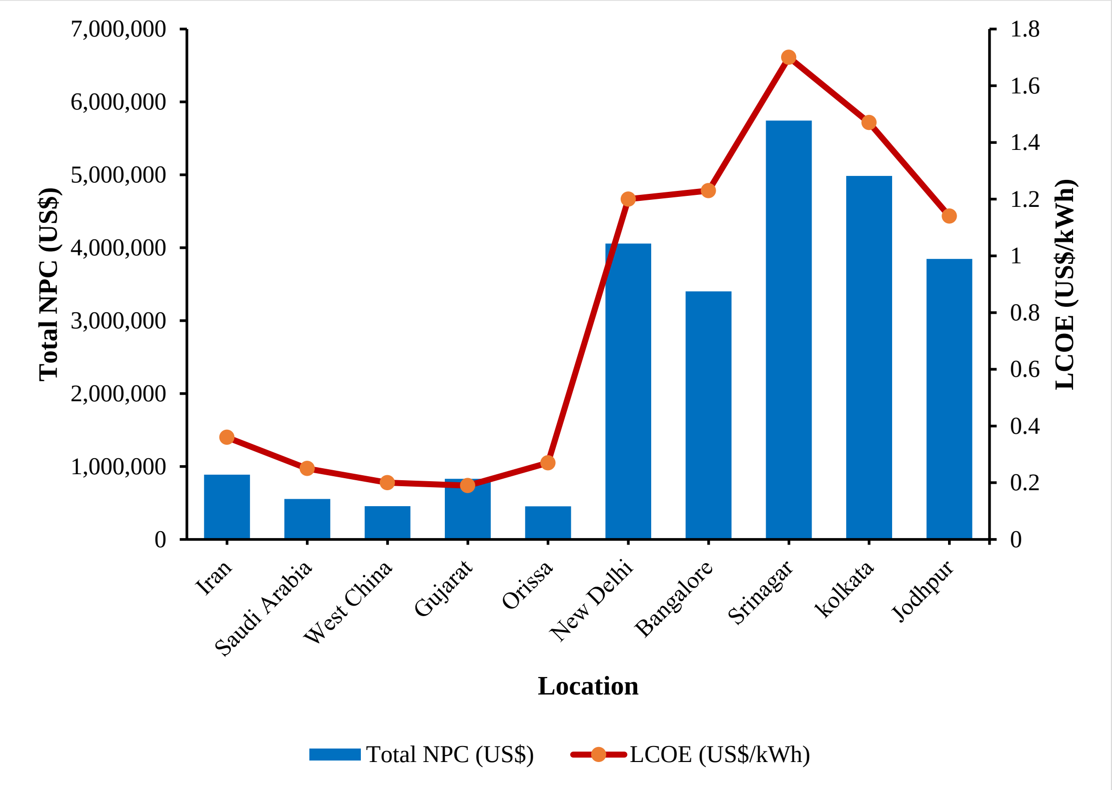


Figure 4.13 NPC and COE of the optimal HRES at various locations

4.2 Analysis of solar photovoltaic system

4.2.1 Performance analysis at different tilt angles

The performance analysis of the solar PV system depends upon factors like longitude, latitude conditions and climatic conditions like wind speed, temperature and solar irradiance. Analysis is performed for the specified location by evaluating these factors. Simulation results at different tilt angles are given in Table 4.3.

Table 4.3 PVsyst simulation results at different tilt angles

Power (kWh)	**108 kW$_p$**	
Tilt Angle	20^0(Simulated)	28^0 (Simulated)
Produced Energy	172.4 MWh/year	174.3 MWh/year
Performance Ratio	80.77%	80.92 %
Specific Production	1600 kWh/kW$_p$/year	1618 kWh/kW$_p$/year

4.2.2 Balance sheet simulation in PVsyst at 28^o tilt angle

Table 4.4 represents the values of global horizontal radiation, diffuse radiation, ambient temperature, and global incident coll. Plane, effective global correlations for IAM shadings, effective energy at the array output, energy injected into the grid and performance ratio at the tilt angle of 28^o. Yearly total incident global horizontal radiation (GlobHor) of 1808.1 kWh/m^2 is fed into the system, and the result increases to 1999.1 kWh/m^2 after adding a particular inclination to the global horizontal radiation (GlobInc). The performance ratio (PR) determines a PV facility's efficiency. It is the ratio of the system's energy production to the radiation incident in the specified region.

Table 4.4 Balance sheet simulation result in PVsyst at 28^o tilt angle

	GlobHr kWh/m^2	**DiffHor kWh/m^2**	**T_Amb ^{o}C**	**GlobInc kWh/m^2**	**GlobEff kWh/m^2**	**EArray MWh**	**E_Grid MWh**	**PR Ratio**
January	106.2	45.0	13.08	147.1	140.0	13.91	13.67	0.863
February	126.2	46.9	17.36	162.7	154.7	14.95	14.68	0.838
March	174.6	63.9	23.65	201.5	191.0	17.88	17.55	0.809
April	198.4	76.5	29.58	204.9	194.1	17.62	17.27	0.782
May	203.4	98.5	33.40	192.7	181.8	16.38	16.07	0.774
June	182.7	104.9	33.11	167.6	157.8	14.41	14.15	0.784
July	154.5	100.1	31.48	142.8	134.1	12.43	12.21	0.794
August	153.9	93.0	30.53	150.6	141.9	13.16	12.93	0.797
September	148.4	75.0	29.09	159.2	150.4	13.90	13.65	0.796
October	147.0	67.6	26.31	177.2	168.4	15.68	15.39	0.807
November	111.2	52.7	19.88	148.2	140.8	13.56	13.34	0.836
December	101.6	44.1	14.72	144.7	137.8	13.58	13.34	0.856
Year	**1808.1**	**868.3**	**25.22**	**1999.1**	**1892.8**	**177.46**	**174.26**	**0.809**

4.2.3 P50-P90 evaluation

P50-P90 evaluation is a probabilistic approach for the interpretation of the simulation results, as a Gaussian probability distribution during the entire project life. The probability distribution at P50, P90 and P95, i.e., 176.84 MWh, 163.50 MWh and 159.75 MWh, respectively, for the existing system is shown in Figure 4.5.

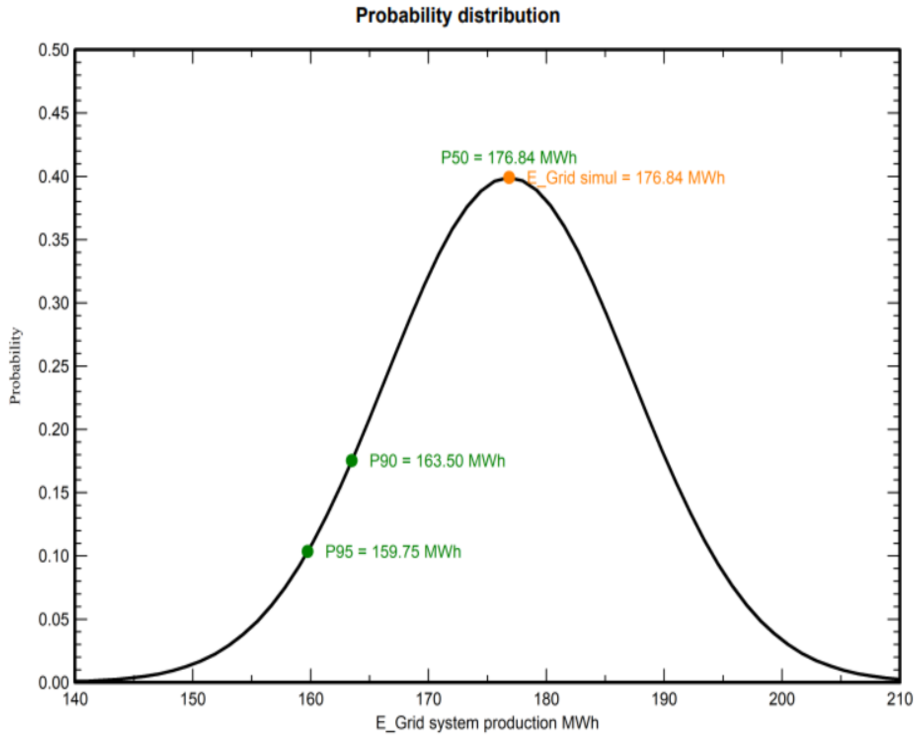


Figure 4. 14 Probability distribution of the system

Albedo varies from zero (blackbody - a surface that absorbs all incident radiation) to one (a surface that reflects all the incident radiation). Bifacial solar panels are intended to be installed on the building's roof. If the roof surface is black or grey, the albedo will be close to 10% (gravel, tar, or bitumen). In addition, if the roof surface is painted white or heat-reflecting paint (cool roof-high albedo and high solar reflectance index SRI), the visible solar reflectance spectrum albedo value may exceed 90%. Solar cell does not react to extended wavelengths (>900 nm). The use of cool roof technology boosts the effectiveness of bifacial solar PV systems (white paint with a high solar reflectance index).

4.2.4 Optimisation using response surface methodology

This high albedo level is achievable with cool roof technology (white roof paint) and a clean roof surface (no dust collection on the roof surface). Minimum and maximum tilt angle level is taken from 20º to 28º, and albedo from 0.2 to 0.8 as shown in Table 4.5. Various combinations of tilt angle and albedo have been run to find out the optimum value of specific energy production as per the minimum and maximum levels of tilt angle and albedo (Table 4.6).

Table 4. 5 Input variable and output response for the simulation

Type	Description	Unit	Levels	
			Minimum	Maximum
Input Variable	Tilt Angle	Degree	20º	28º
	Albedo	-	0.2	0.8
Output Response	Specific Production	kWh/kW$_p$/year	1600	1670

4.2.4.1 ANOVA approach for the system

Analysis of variance (ANOVA) is used to describe the significance and fitness of the coupled RSM model using mathematical results given by PVsyst. Table 4.7 displays the ANOVA findings and linear variables (Albedo, tilt Angle). In the event of the RSM model's yearly specific production by the solar PV system, coefficient determination (R^2) and adjusted coefficient determination (Adj R^2) are established as 0.9989 and 0.9983, respectively. F-test value of 1652.49 is obtained, indicating the importance of the proposed model. As a result, a regression model is designed to characterise the correlation between the parameters and the yearly specific production of the solar PV system. This indicates that the RSM's fitness has been estimated, the model's accuracy is adequate, and it provides a decent match. Eq. (4.1) gives the second-order equation in coded terms (+1 for the high level of input factors and 1 for the low level of input factors) developed to forecast the yearly specific production by the solar PV module. Eq. (4.1) calculates specific production.

$$\text{Specific Production} = 1470.20 + 8.89\text{A} - 7.81\text{B} + 5.33\text{AB} - 0.164\,\text{A}^2 - 52.41\text{B}^2 \quad (4.1)$$

Table 4.6 Specific production of solar photovoltaic system at different tilt angles and albedo

Run	Tilt Angle (^{0}C)	Albedo	Specific energy production (kWh/kW$_p$/year)
1.	20	0.8	1628
2.	20	0.5	1618
3.	24	0.5	1636
4.	20	0.2	1600
5.	24	0.5	1636
6.	28	0.8	1670
7.	28	0.2	1618
8.	28	0.8	1670
9.	20	0.8	1628
10.	20	0.2	1600
11.	20	0.2	1600
12.	28	0.8	1670
13.	20	0.2	1600
14.	24	0.8	1651
15.	28	0.8	1670
16.	20	0.2	1600
17.	28	0.8	1670
18.	28	0.2	1600
19.	24	0.5	1636
20.	28	0.2	1628
21.	24	0.5	1636
22.	28	0.5	1648
23.	28	0.2	1618
24.	24	0.5	1636

25.	28	0.2	1618
26.	24	0.5	1636
27.	20	0.8	1628
28.	24	0.5	1636
29.	20	0.8	1628

Table 4.7 ANOVA for the specific production of the solar PV system

Source	Sum of squares	Df	Mean Square	F-value	P-value	
Model	14537.19	5	2907.44	162.29	<0.0001	**Significant**
A-Tilt angle	4465.78	1	4465.78	249.27	<0.0001	
B-Albedo	8084.04	1	8084.04	451.23	<0.0001	
AB	772.98	1	772.98	43.15	<0.0001	
A^2	17.05	1	17.05	0.9516	0.3395	
B^2	59.06	1	59.06	3.30	0.0825	
Residual	412.05	23	17.92			
Lack of fit	0.8538	2	0.4269	0.0218	0.9785	**Not significant**
Pure error	411.20	21	19.58			
Cor Total	14949.24	28				

The comparison of specific energy production by the solar PV module generated by the PVsyst (actual) and the predicted assessments using the polynomial regression model stated in Eq. (4.1) (Figure 4.15), verifies the adjacency of predicted data and actual data. Expected values of the solar PV annual energy output are close to and well-matched to the actual simulation values. The R^2 indicates how effectively a linear regression model fits a data set. As a result, $R^2 = 1$ means that the predictor variable can describe the response variable without a mistake. The R^2 and adjusted R^2 values for yearly specific energy production are 0.9724 and 0.9664, respectively. As a result, the produced response surface model is credible, and the suggested correlation in Eq. (4.1) is valid and correct for the yearly specific energy production by solar PV using two input parameters. The effects of tilt angle and albedo on specific energy production are presented in perturbation plots as shown in Figure 4.16. It can be noted that the albedo and tilt angle are the most important parameters for specific energy production.

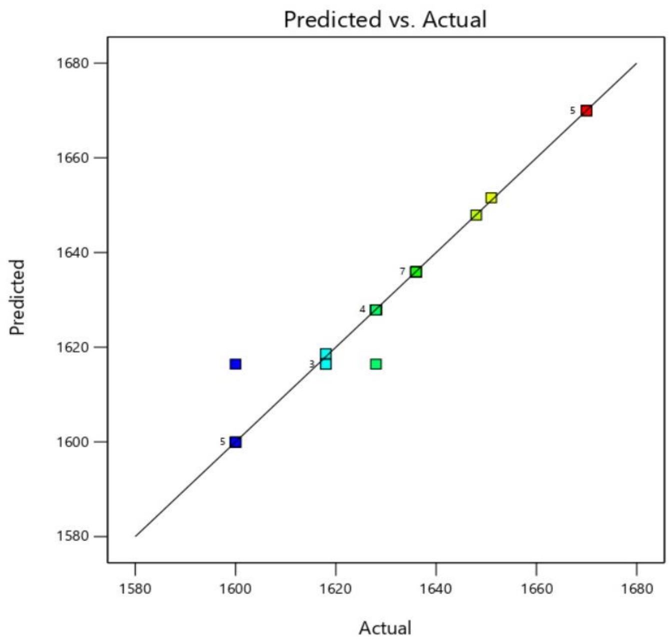


Figure 4.15 Predicted vs. actual specific production

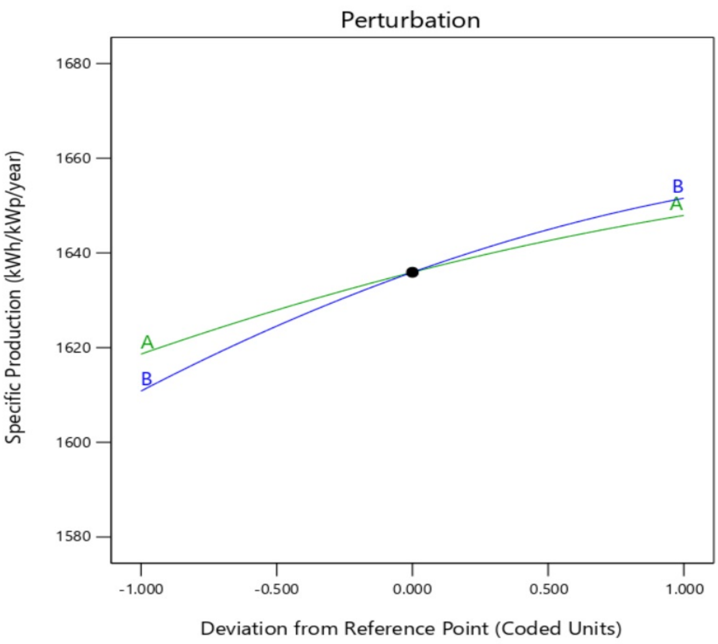


Figure 4.16 Perturbation plot of specific production

4.2.4.2 Contour and response surface plots

The slope of curvature indicates that the intention of the reaction is sensitive to the specified factor. It is worth noting that the albedo is the main critical parameter for specific energy production. Increasing the tilt angle and albedo increases the yearly specific energy production. However, the effect of both parameters is analysed on specific energy production. 3D-response surface graph that depicts the interface impact of tilt angle and albedo (Figure 4.17). Figure 4.18 depicts the contour plot of specific albedo and tilt angle. The specific energy production of PV is most significant with a tilt angle of 28° and an albedo of 0.8. Specific energy production is low at a 20° tilt angle and 0.2 albedo. In comparison, the specific energy production is increased by 1.85% with increased tilt angle from 20° to 28° and 1.75% increase with albedo increase from 0.2 to 0.8 using PVsyst. Optimum results are found at a tilt angle of 25°, albedo 0.54, with specific production of 1643.3kWh/kW$_p$/year for the solar PV system (Figure 4.19).

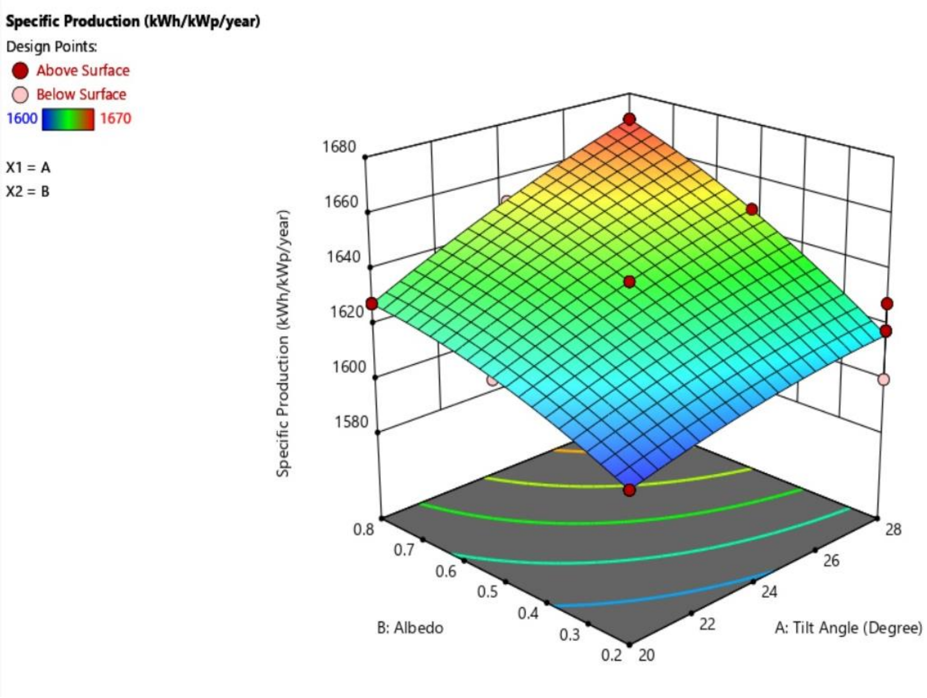


Figure 4.17 3D Surface plots of specific production vs. albedo and tilt angle

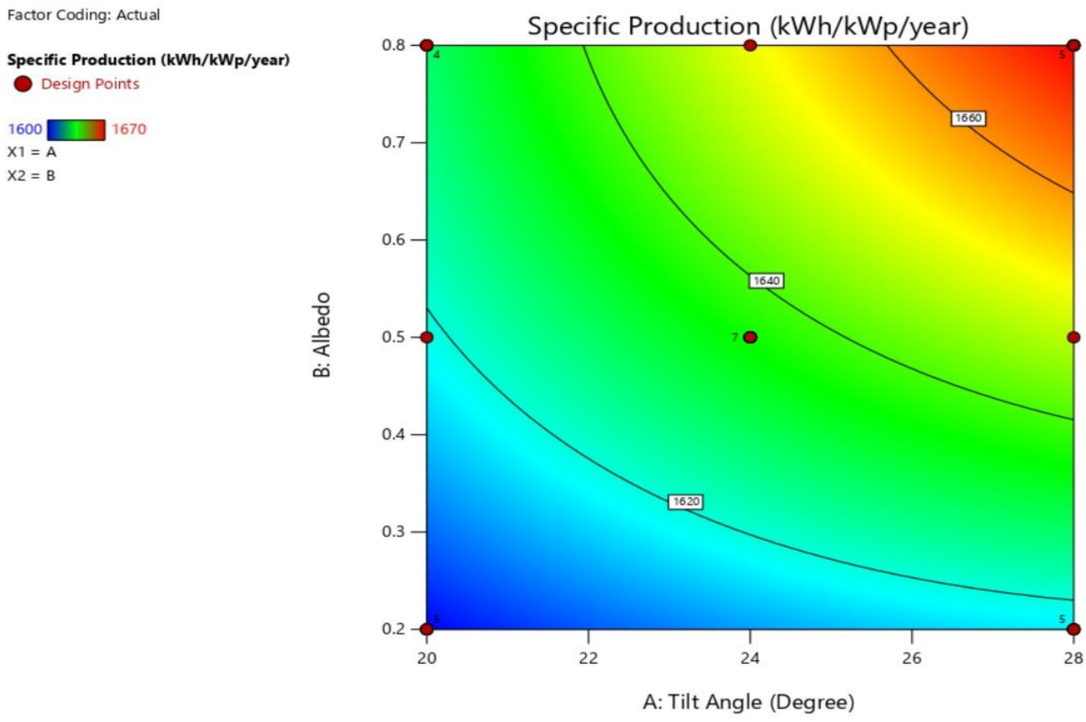


Figure 4.18 Contour plots of specific albedo and tilt angle

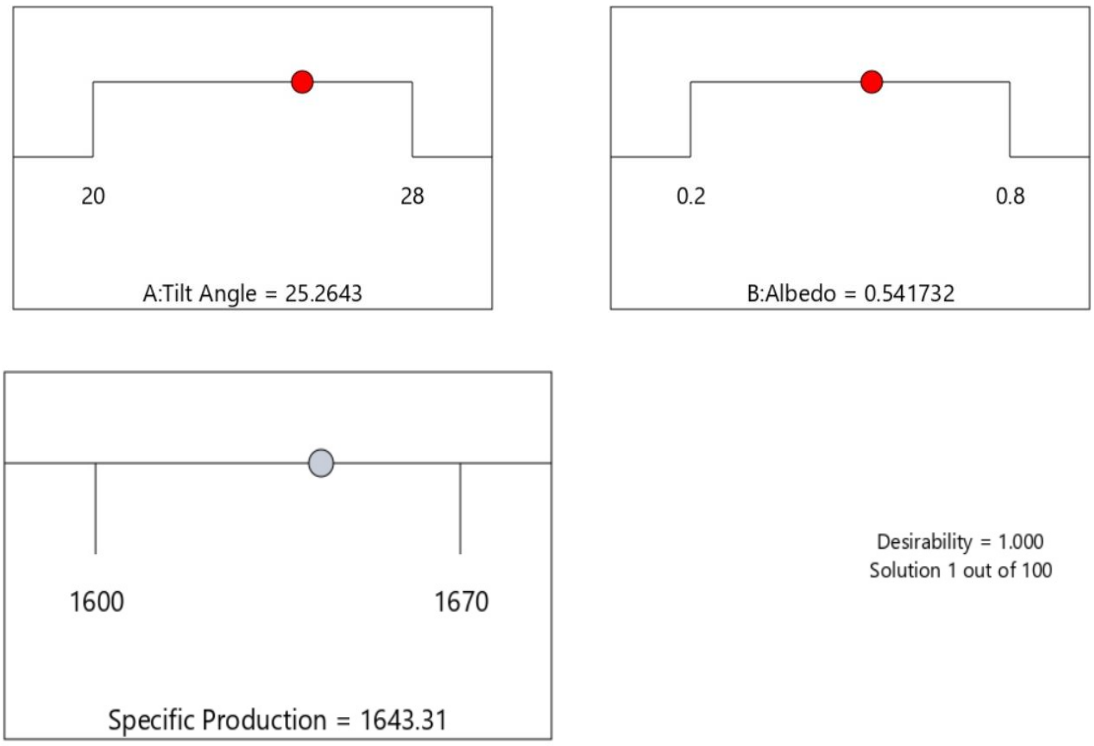


Figure 4.19 Optimum conditions of tilt angle, albedo for maximum specific energy production

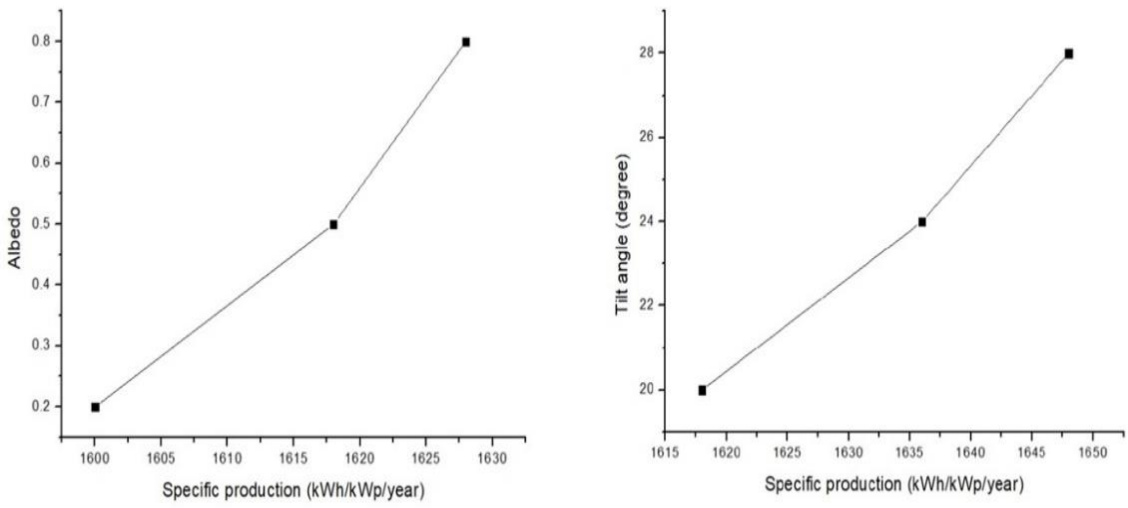
4.2.4.3 Effect of albedo and tilt angle on specific production

- **Effect of albedo**

The effectiveness of a PV array is also dependent on various factors like climatic conditions, the height of the structure, etc. The ability of a surface to reflect solar radiation is referred to as albedo. The primary source of rear irradiance is reflected radiation from the ground, increasing albedo, and specific production is also increasing (Figure 4.20 (a)).

- **Effect of tilt angle**

The tilt angle determines the solar irradiance received by the plane of the PV array. As a result, it directly influences the PV system's performance. The angle of inclination has been examined and determined by the geographical characteristics of the area. Specific production increases yearly with increasing tilt angle, reaching a peak at 28º (Figure 4.20 (b)). As a result, 28º may be the best tilt angle for solar PV under the considered geographical location. The optimal tilt angle for solar PV depends on other characteristics, such as albedo. Hence, investigating these components is essential to identify optimum circumstances.



(a) (b)

Figure 4.20 (a) Specific production of energy (a) effect of albedo (b) effect of tilt angle

4.2.5 Economic and Environmental Analysis

4.2.5.1 Financial summary of the system

Table 4.8 elaborates the financial summary of the system for a project lifetime of 25 years, including various costs like total installation cost, operating cost, produced energy, levelized cost of energy and feed-in-tariff. The total net present value of the system is 278976.53 US$ with a payback period of 5.8 years and 469.2% of return on investment.

Table 4.8 Financial summary of the system for project lifetime (25 years)

S.No.	Cost component	Details
1.	Total installation cost	59461.07 US$
2.	Operating cost (including inflation 2% per year)	798.56 US$/year
3.	Produced energy	177 MWh/year
4.	Cost of produced energy	0.027 US$/kWh
5.	Feed-in tariff	0.090 US$/kWh
6.	Payback period	5.8 years
7.	Net present value	278976.53 US$
8.	Return on investment (ROI)	469.2%

4.2.5.2 Cumulative cash flow and yearly net profit

Cumulative cash flow is calculated by adding the present value of cash flows to the previous year's cash flow balance. As seen in Figure 4.21 (a) cumulative cash flow is increasing with every ongoing year. The yearly net profit of the system is increasing constantly up to the year 2034, and then it grows rapidly to the maximum during the remaining years of the project life as shown in Figure 4.21 (b). Total installation cost is 59461.07 US$, and the operating cost is 798.56 US$/year, including 2% inflation annually. The system produces 177 MWh of energy per year with a payback period of 5.8 years.

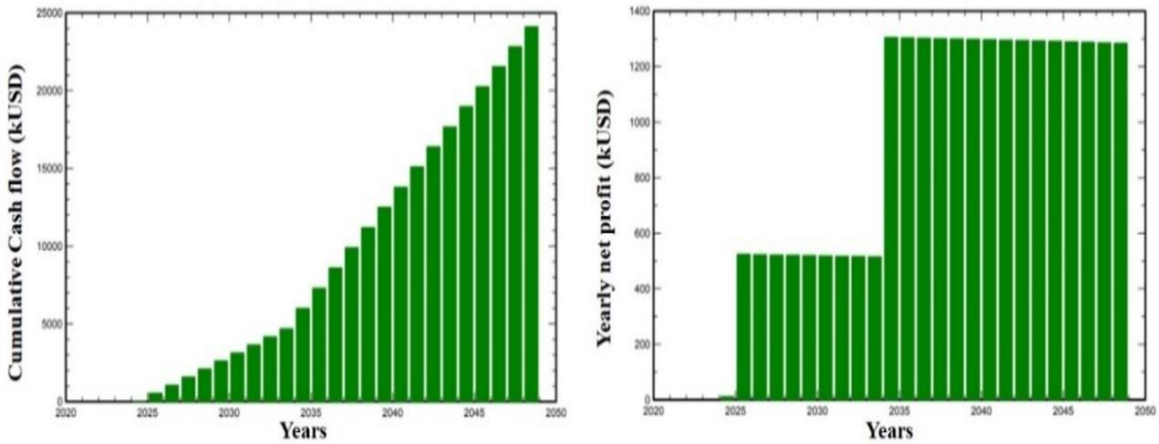


Figure 4.21 (a) Cumulative cash flow of the system (b) Yearly net profit for the system

4.2.5.3 Emission Analysis

Figure 4.22 shows the emission details of the system for 25 years. Table 4.9 shows that a significant reduction in carbon emissions leads to a green and clean environment with annual degradation of 1%. Table 4.10 indicates the life cycle emission details of major components like modules, supports and inverters of the system. The maximum emission is generated by the PV modules as compared with the inverter and other components of the system.

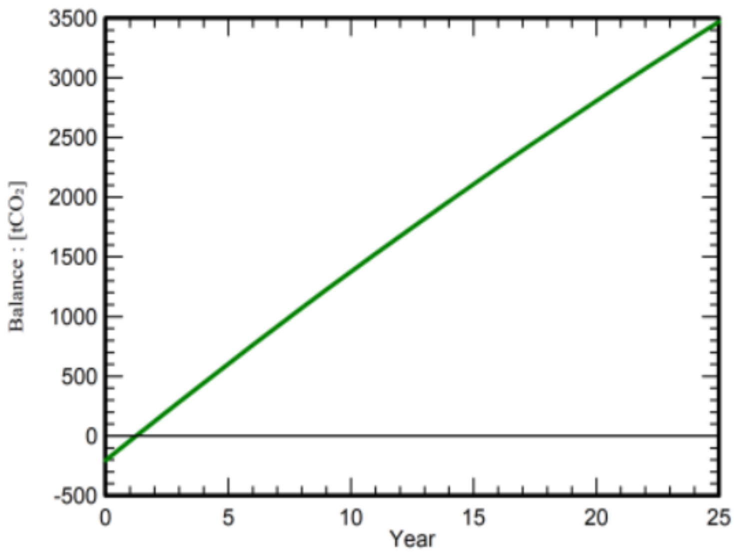


Figure 4.22 Saved CO_2 emission vs. time

Table 4.9 Details of system emission balance

Total	3470.5 tCO_2
Generated Emissions	
Total	207.10 tCO_2
Replaced Emissions	
Total	4138.1 tCO_2
System production	176.84 MWh/yr
Grid Life cycle emissions	936 gCO_2/kWh
Lifetime	25 years
Annual degradation	1.0 %

Table 4.10 Life cycle emission details of the system

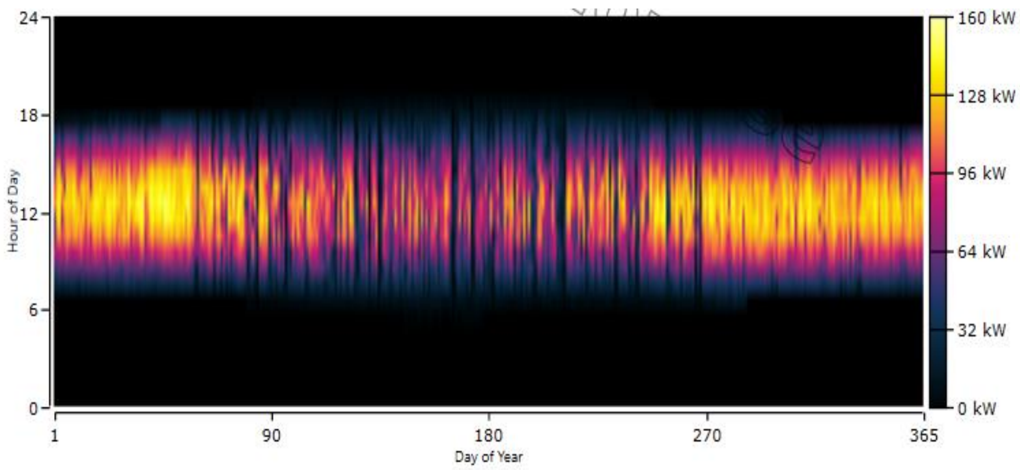
S. No.	Item	LCE	Quantity	Subtotal ($kgCO_2$)
1.	Modules	1713 $kgCO_2/kW_p$	108 kW_p	184511
2.	Supports	6.24 $kgCO_2$/kg	3420 kg	21351
3.	Inverters	619 $kgCO_2$/units	2.00 units	1237

4.3 Analysis of solar PV and biomass gasifier system

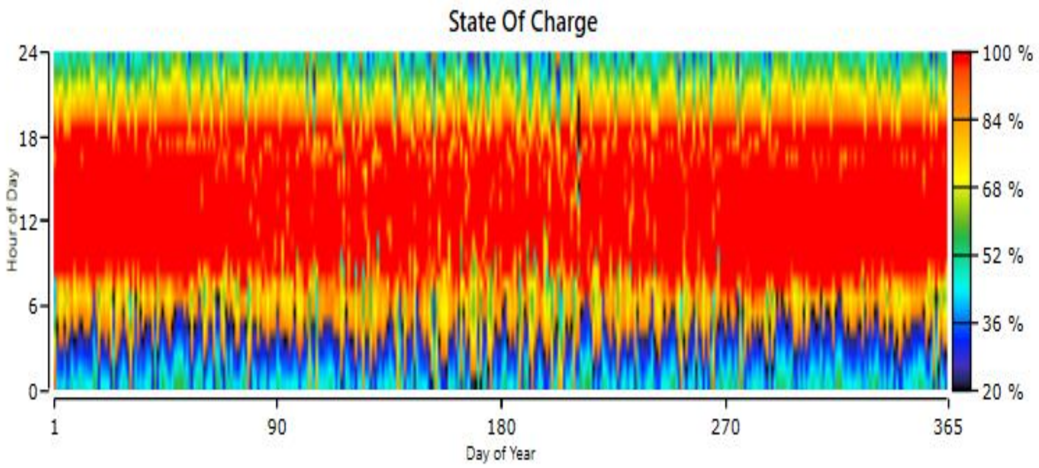
4.3.1 Performance analysis of different components

HOMER software is used along with the relevant parameters, inputs, and constraints to simulate the system. HOMER simulates multiple combinations and arrangements of the system and arranges the solutions based on the aggregate net present cost, and the system matches the current energy sources. The ideal arrangement of the HRES components for our proposed system is a solar PV power source, which can vary from 0 to 150 kW. The biomass gasifier generator set produces 160 kWh daily, and also an idealised 600V battery and a 75 kW converter.

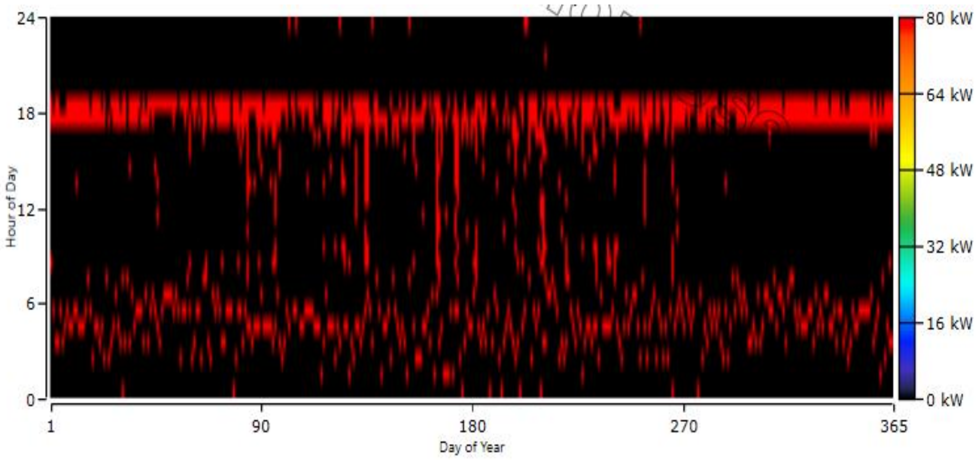
Figure 4.23 (A) shows the output of the solar PV system. A PV module can produce energy in the morning even when there is not enough sunlight. However, most energy is produced between 10:00 AM to 04:00 PM, i.e., 6 hours, when PV modules work at full capacity. Figure 4.23 (B) depicts the amount of charge present in the battery at a particular time. It can be deduced that the charge is always full during the daytime but constantly depletes once daylight is gone, and the load is met using batteries only. The charge reduces to 15%-20% until it gets replenished in the morning. For a healthy battery life, trickle charging is suggested, and the minimum charge should never be lower than 15%. Biomass generator charges batteries and meets the load demands when PV output is unavailable. Figure 4.23(C) shows that the generator works at its peak during twilight and just before dawn.



(A) Output of Solar photovoltaic system



(B) Battery state of charge (SOC)



(C) Biomass gasifier power generation

Figure 4.23 Output of different components of the hybrid power generation system

4.3.2 Energy production

The yearly average load utilised is 190,116 kWh, and the average energy production of the biomass gasifier and solar PV system is as follows: Solar PV system = 288,620 kWh/year and biomass gasifier generator set = 88,160 kWh/year, as shown in Figure 4.24. The annual energy production of HRES is 376,780 kWh. Biomass gasifier supports approximately 23.4% of and solar PV approximately 76.6% of the total energy production.

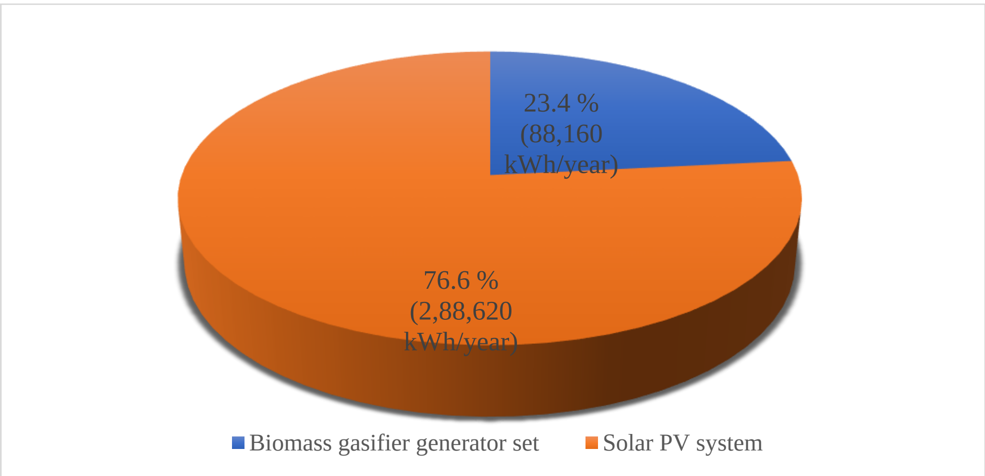


Figure 4.24 Average energy production from different resources

During the day, when ample solar power is accessible, there is a direct supply to the load through the solar PV system. Additionally, the biomass gasifier generator is accessible during the daytime. However, biomass gasifier works to provide a consistent supply at night when load demand is high, since solar energy is not accessible. When the energy generation surpasses the energy demand, the surplus energy is utilised in charging the battery. Load demand presented for the HRES of solar PV and biomass for the Mechanical Engineering Department. In this HRES, an unmet electrical load of 48.8 kW per year is present, and surplus energy of 173,147 kWh per year energy and a shortage in the capacity of 0.0375% is observed.

Figure 4.25 shows energy produced from PV and biogas generators every month. Throughout the system's lifetime, i.e., 25 years, biomass gasifier and solar PV contribute 23.4% and 76.6% of the total energy produced. Excess energy produced per annum is about 173,147 kWh, mainly due to the dynamic load profile, which considers the holidays and vacations in June, July and December, when the classes are suspended, and the halls and rooms in the academic buildings are not in that much use. It reduces the load requirements significantly. In June and July, the Northern Hemisphere is warm and sunny in summer; therefore, solar irradiation is at its fullest. Therefore, the PV at its total capacity will produce more energy than the whole Mechanical Engineering Department needs. To utilise this excess energy, the authors suggest that other departments can use this energy to power themselves, particularly during the months of vacations, rather than drawing power from the grid.

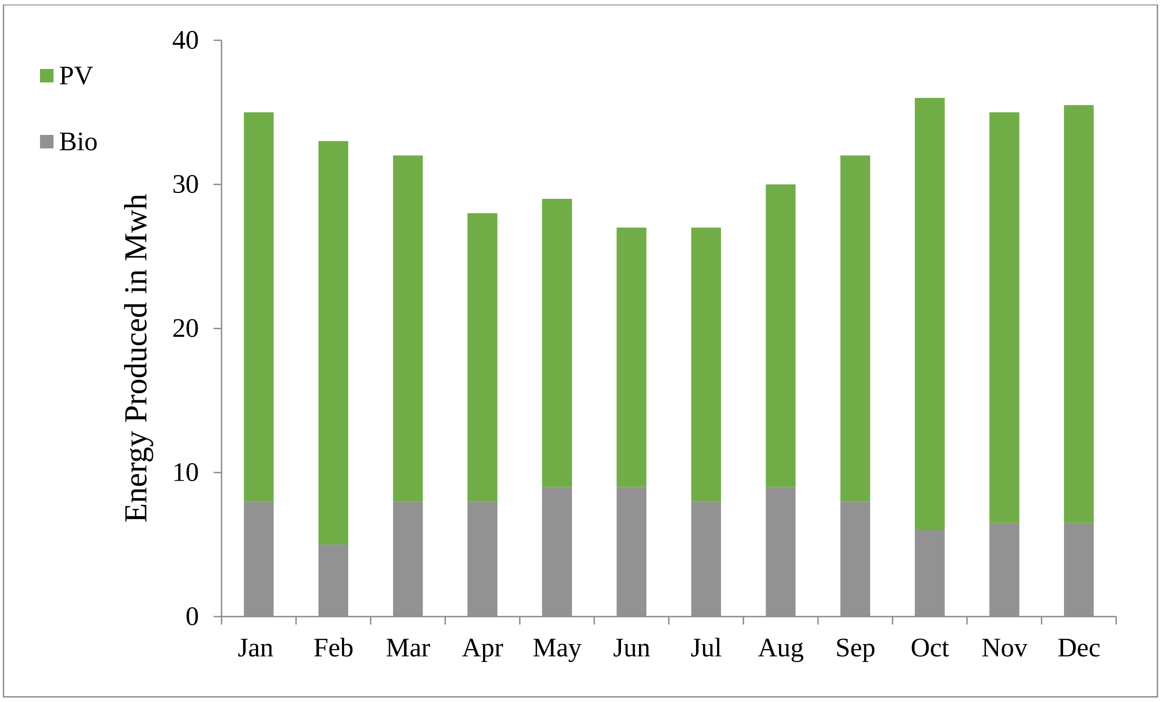


Figure 4.25 Monthly electricity production of HRES

The benefit of this hybrid plant is not limited to a lower carbon footprint compared to conventional energy generation methods. Biogas used for the gasifier comes from food waste collected on campus. Digestate is a by-product of the anaerobic digestion of food waste and can be used as fertiliser for gardening. At the same time, the biogas is extracted and utilised in power generation. In Table 4.11, the feedstock supplied on an average timely basis to the gasifier has been shown. In the gasifier, it has been estimated that from 1 ton of biomass, 400 kg of fertiliser is produced. Hence, with an annual food waste of 277 tons collected, around 110.8 tons of fertiliser is produced as a digest.

Table 4. 11 Biomass consumption

Feedstock	Quantity	Units
Gross feedstock consumed	277	Tons
Daily average feedstock	0.759	Tons/day
Hourly average feedstock	0.0316	Tons/hour

4.3.3 Emission analysis

HOMER calculates the analysis and consequently the results of emissions based on the following six pollutants: Carbon dioxide (CO_2), Carbon monoxide (CO), Particulate matter (PM), Unburnt hydrocarbons (UHC), Sulphur dioxide (SO_2), Nitrous oxide (NO_X). These pollutants are emitted due to electricity production by the generators, thermal energy released by the boiler and electricity consumption. HOMER simulates the gaseous emissions of both the boiler and the generator. HOMER first establishes the emissions factor, which is the weight of each pollutant in kg produced per unit of the fuel used, after which it simulates the power system. Next, it evaluates the yearly gaseous emissions of the particular pollutant from the emissions factor product and total yearly fuel consumption. The user inserts the emissions factor of 4 pollutants: CO, UHC, PM and NO_X. Using this input as well as the contents of the fuel (carbon and sulphur), the software analyses to evaluate emissions factors for the two other air pollutants, CO_2 and SO_2. HOMER also makes use of some assumptions in these calculations, which are they are as follows:

Carbon contents in the fuel which are not released as CO or UHC are treated as CO_2. The carbon ratio of the UHC produced is equivalent to that of the fuel. Sulphur contents in burnt fuel that are not released as PM are treated as SO_2 [110]. Table 4.12 shows the yearly emissions that have been considered in the software for the feasibility analysis and output of the modelled HRES. According to research, 1 kWh of electricity produces 0.85 kilograms of carbon dioxide annually [111]. According to the load profile, the total output of CO_2 generated by the Mechanical Engineering Department is estimated from Eq. (4.2).

$$190116\,\frac{\text{kWh}}{\text{year}}\,(\text{yearly average load}) \times 0.85 = 161598.6\ \text{kg}\ (\text{Output amount of } CO_2) \quad (4.2)$$

Total amount of CO_2 emission is calculated as 161,598.6 kg/year using Eq. (4.2). This shows a significant improvement of nearly 99% which is roughly 161 carbon credits per year. One carbon credit means that 1 metric tonne of CO_2 is prevented from entering the atmosphere. Similarly, 1 kWh of electricity produces approximately 7 grams/kilowatt-hour of SO_2 and 4.3 grams/kilowatt-hour of NO_x (Mittal, 2012). On the contrary, the HRES designed and analysed produces no SO_2 and only 0.346 kg/year of NOx. Hence, it is a significant improvement in environmental impact and successful environmental sustainability analysis.

Table 4. 12 Yearly emissions

Pollutant	Yearly Emissions (kg/yr)
CO_2	49.90
CO	0.554
UHC	0.00
PM	0.00
SO_2	0.00
NO_X	0.346

4.3.4 Cost analysis with feasible configurations

The cost of various elements in the system is as follows: Capital Cost (CC), COE, and NPC_{total} for the HRES are 0.207 US$/kWh, 3,90,878 US$ and 5,07,737 US$, respectively.

All the feasible configurations with cost analysis for the proposed system are given in Table 4.13. The cost analysis of each component for a lifespan of 25 years is given in Table 4.14, and the Gross cost of the system is 5,07,736.58 US$.

Table 4.13 Feasible configurations with cost for HRES

Photovoltaics (kW)	Bioenergy (kW)	Number of batteries	Converter (kW)	Net Present Cost (US$)	Cost of energy (US$)	Operating cost (US$/yr)
144	160	1	73.7	5,07,737	0.207	9,040
133	160	3	88.0	6,59,382	0.268	10,570
261	160	2	115	7,06,777	0.287	7,054
145	160	2	79.2	5,60,841	0.228	7,506

Table 4.14 Cost analysis data of HRES components for 25 years

Component	Capital (US$)	Replacement (US$)	Operation& Maintenance (US$)	Fuel (US$)	Salvage (US$)	Gross (US$)
Generic 100kWh Li-ion	70,000	68,990.23	12,927.52	0.00	-1,577.08	150,340.67
Generic Biogas Genset	122,000	0.00	28,492.25	0.00	-1,173.83	149,318.41
Generic flat plate PV	173,069.37	0.00	10,949.84	0.00	0.00	173,380.12
System Converter	25,808.42	10,949.84	0.00	0.00	-2,060.87	34,697.38
System	390,877.79	79,940.07	41,730.51	0.00	-4,811.78	507,736.58

4.3.5 Validation of the proposed system results with previous published papers

In contrast to earlier research, this study has created a novel HRES configuration with different component sizes, load requirements, and renewable resource usage. Therefore, it is impossible to compare those systems precisely. However, a comparison that is established based on the systems' economic designs can be considered acceptable and appropriate. This proposed system's NPC and COE have been compared to published research findings from previous studies (Table 4.15).

Table 4. 15 Various hybrid power configurations using HOMER

S.No.	Author	Year	Components	Total NPC (US$)	LCOE (US$/kWh)
1	Hassan et al. [85]	2022	PV/FC	10,166	0.23
2	Sawle et al. [81]	2021	PV/WT/BG/DG	8,31,217	0.19
3	Basser et al. [83]	2019	PV/WT/BG/DG	5,55,492	0.25
4	Sahu et al. [84]	2021	WT/PV/BS	4,54,242	0.27
5	Proposed system	2023	PV/BG	5,07,737	0.20

Chapter five is the conclusion of all the observations that have been made about all the suggested systems in this thesis. Also, at the end of all the observations, suggestions are given for future work that might help the researchers to move forward with more possible advancement in this area for the benefit of society and the environment.

CHAPTER: 5

CONCLUSIONS AND FUTURE RECOMMENDATIONS

This chapter represents the conclusions of the complete research work conducted for three cases. Hybrid renewable energy system installed according to climatic conditions gave the best performance as compared to the system that is installed directly without considering the climatic conditions of that particular location. Further, the overall observations are finished with future recommendations that may enlighten the researchers to move ahead for the additional probable improvements in this subject for the betterment of society, environment, and the sustainable progress of human beings.

5.1 Conclusion of HRES based on five different climatic zones

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

5.2 Conclusion of the solar photovoltaic system installed on the academic building

- Tilt angle and albedo show a linear relationship with the specific energy production.
- Specific production is 1600, 1618 and 1628 kWh/kW$_p$/year at albedo 0.2, 0.5 and 0.8. It indicates that specific production increases with the increase in albedo.
- Specific production is 1618, 1636 and 1648 kWh/kW$_p$/year at tilt angles 20^o, 24^o and 28^o. It increases with the increase in tilt angle.
- Using RSM, the optimum condition for the maximum specific production, i.e., 1643.3 kWh/kW$_p$/year, is found at the tilt angle of 25^o, albedo 0.54 for the solar PV system.
- The system's payback period is 5.8 years, ROI is 469.2% and LCOE is 0.027 US\$/kWh.
- During the operational years (25 Years), the solar PV system will reduce 3470.5 tCO_2 carbon emission compared to the conventional plant.

5.3 Conclusion of solar photovoltaic and biomass gasifier-based system for academic building

- The cost of energy of the proposed HRES is 0.207 US\$/kWh, and the gross NPC is determined to be 5,07,737 US\$.
- During a lifetime (25 years), biomass gasifier and solar PV contribute 23.4% and 76.6% of the total energy produced.
- The system is optimised to meet the mean energy constraint of 588 kWh per day with a peak of 65 kW and 35 kW on weekdays and weekends, respectively.
- Total power generated by the system is 3,76,780 kWh per year to match the load demand of 1,90,116 kWh per year.

- HRES has an unmet electrical load of 48.8 kW per year. A surplus of 1,73,147 kWh per year of energy is produced, and a shortage of 0.0375% is observed in the capacity.
- HRES produces no SO_2 and only 0.346 kg per year of NOx, demonstrating a significant improvement in environmental effect and a successful environmental sustainability analysis and around 161 metric tonnes of CO_2 are prevented from entering the atmosphere.
- As per the findings, the goal of climatically appropriate HRES design is to produce an effective and dependable 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.

5.4 Recommendations for future work

- 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 ensure the promotion of sustainable development.

- It would benefit the allocation of solar PV power plants in various climatic conditions. According to the latitude of the site, the specific output of the solar PV system will rise as the tilt angle and albedo increase. Also, noted that installing such a system would greatly reduce CO_2 emissions, advance environmental sustainability, and raise the number of claimed carbon credits. These findings will help in the selection of solar PV technologies suitable for different climate locations and provide important insights to policymakers and the public on the effectiveness and viability of installing grid-connected PV systems on building roofs.
- Reduce the hazards of global warming by successfully exploiting HRES using AI-based multi-objective optimisation techniques like machine learning, artificial neural networks, and deep learning models.
- Technological advancements in fuel cells make them economical, more dependable, and safe. Taking into account research topics such as connecting fuel cells with the grid, safety concerns of storing H_2 in fuel cells, and maximum power utilisation from fuel-utilising AI-based optimisation algorithms. Therefore, there is a significant opportunity for intellectuals to further investigate proposed study areas in depth.